INVESTIGATION INTO THE POTENTIAL OF INDUSTRIAL COGENERATION IN SOUTH AFRICA

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Abstract

Cogeneration is a promising technological option for SA and the world at large. This technology permits the combined production of two forms of energy from a single fuel source. This possibility is advantageous in industry where electricity and process heat can be produced with outstanding efficiency. It has been shown to offer sizable energy savings and cost advantages in a wide variety of industries around the world. Despite these attractive benefits SA's use of cogeneration remains limited.

In addition the true potential for cogeneration in SA has not been properly quantified. This represents a significant shortfall in our understanding of the future of the SA energy system. The integrated resource plan for electricity (2012) presents findings that 2GW of cogeneration capacity can be realised by 2020. This figure is unconfirmed and the sources of this proposed cogeneration development have not been scrutinized. These research gaps must be explored if SA is to realise its cogeneration potential.

This research seeks to investigate the potential for cogeneration in SA. A research method was developed specifically to determine what cogeneration currently exists in SA and how much capacity could be developed into the future.

Current cogeneration installations in SA were identified, and potential sources of future cogeneration in SA were evaluated. Technical potential of cogeneration from these sources was estimated to the year 2030. The evaluation of technical potential considered both fossil fueled cogeneration and renewable waste fueled cogeneration.

The initial analysis of cogeneration potential did not however consider the economics of energy generation. Therefore economic potential of cogeneration was estimated in the South African TIMES computer model (SATIM). Here the future development of cogeneration was simulated with the full impact of SA energy costs and competing technologies. In addition the effect of specific policy instruments to promote cogeneration development was tested through alternate scenario modelling.

Results of this research gave valuable insight into cogeneration. A total of 4.5GW of electrical capacity was found to be technically feasible by 2020. When economic factors were considered, 3.4 GW of electrical potential was found to be achievable by 2020. This value is greater than the 2012 integrated resource plan's (IRP) estimate and presents further questions about the IRP estimate.

Alternative scenarios demonstrated that cogeneration is competitive without fiscal assistance. However a number of institutional barriers were identified that could hamper the development of cogeneration in SA.

The research concluded that cogeneration can and should be developed in SA and that a substantial portion of industrial energy needs could be met through the implementation of these systems. However institutional barriers must be removed to pave the way for the expansion of this technology in SA.

1 Table of Contents

List of Acronyms

Acronym	**Definition**
CI	Compression ignition
CIMS	Canadian Integrated Modelling System
COD	Chemical oxygen demand
DOE	Department of Energy (South Africa)
EPA	Environmental Protection Agency (United States of America)
EU	European Union
FAO	The Food and Agriculture Organization of the United Nations
IC	Internal Combustion (Engine)
IRP	Integrated Resource Plan
LCOE	Levelised cost of electricity
SA	South Africa
SAISI	South African Iron and Steel Institute
SATIM	South African TIMES
SI	Spark Ignition
TIMES	The Integrated MARKAL-EFOM System
WWT	Waste water treatment

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1 INTRODUCTION

1.1 Background

Cogeneration is defined as the combined production of heat and power from a single energy source. It offers many opportunities such as increased energy efficiency; however the technology's penetration in South Africa (SA) remains limited. Furthermore little is known about the current use and potential implementation of this technology in SA. Internationally it has been shown to be advantageous in efforts to increase efficiency of industries and in doing so to boost their competitiveness. Cogeneration also offers an opportunity to curb CO_2 emissions. Despite these incentives S.A's cogeneration potential has yet to be properly explored. Given the pressures on the world energy system and on SA, cogeneration may be a feasible and attractive option for industries in SA.

The Integrated Resources plan for electricity 2012 (IRP) published by the Department of Energy (DOE) stated that cogeneration will play an importance role in the electricity generation mix of SA into the future. The IRP stated that over the next ten years 2GW of cogeneration would be developed. This value is unconfirmed and the question of how much potential cogeneration in S.A exists remains unanswered.

The purpose of this research is to investigate the future state of cogeneration in SA. It will explore what is currently used as well as what could potentially be deployed into the future.

1.2 Problem statement

There is currently no estimate of how much cogeneration can be implemented in SA.

1.3 Objective and research questions

The broad objective of this research is to determine the potential capacity of cogeneration in the SA. The primary research questions are:

What are the sources of cogeneration in SA industry?
How much cogeneration is there in SA at present?
What is the technical potential of cogeneration technologies in SA at present and into the future?
What is the total economic potential of cogeneration technologies in SA and is the IRP figure of 2000MW by 2020 reasonable?
How sensitive is cogeneration to changes in discount rate?
What is the impact of a CO_2 tax on cogeneration development?
What is the impact of a subsidisation on cogeneration deployment?

2 LITERATURE REVIEW

The following chapter will review literature relevant to the understanding of cogeneration. Firstly, the structure and processes of SA industry will be examined. Secondly, the available cogeneration technologies and their characteristics will be discussed. With these two subsections in mind the potential sources of cogeneration deployment will be examined. The chapter will then discuss some common principles around the study of cogeneration feasibility. It will go on to examine the various methodologies that have been employed to determine cogeneration potential. The final section will elaborate on the theory of computerised modelling of cogeneration in the TIMES modelling platform.

2.1 Structure and processes of the industrial sector in South Africa:

Winkler et al (2005) in his analysis of SA energy policies disaggregates SA industry into eight divisions. They were Pulp & paper, Chemical, Mining, Other industry, Non-metal minerals, Non-ferrous metals, Iron & steel, and Food & tobacco. (Department of Minerals and Energy, 2005). The following sections will describe the main industries in these sectors and their main processes. The purpose is to familiarise the reader with the industrial sector of SA and the processes involved. This understanding will become important when examining the potential sources of cogeneration in S.A.

2.1.1 Pulp and paper:

The process to make paper involves several steps from wood harvesting to final paper cutting. Firstly wood is harvested from a plantation. The trees are then debarked and chipped. The chips are pressure-cooked with a mixture of water and chemicals in a digester. The resulting pulp is then washed and cleaned and treated. Colorants may also be added. This slush is then pumped onto a moving screen. As the pulp moves water is drained away and reused. The resulting crude paper sheet or web is then passed through a number of rollers to remove most of the water. The web is then run through heated dryer rollers to remove the remaining water. Finally the finished paper is cut into manageable sizes (Wisconsin Paper Council, 2004).

The main producers of paper products in SA are Sappi and Mondi each on average accounting for 44% of total paper production (Camci et al., 2009). Sappi has six facilities around the country with a total reported production capacity of 1,080,000 tons of pulp per year (Sappi, 3011). Mondi produced 510,000 tonnes of paper in 2006 (Mondi, 2012).

According to the Department of Minerals and Energy's (DOE) energy balance assessment for 2005, the pulp paper and print industry uses two main energy sources, these being gasworks gas (2321.73 TJ) and electricity (6312.89 TJ) (Department of Minerals and Energy, 2005). The DOE's energy balance is limited in its description as the sector makes use of several other energy sources including coal and wood. Figure 1 illustrates the energy use of the pulp and paper sector.

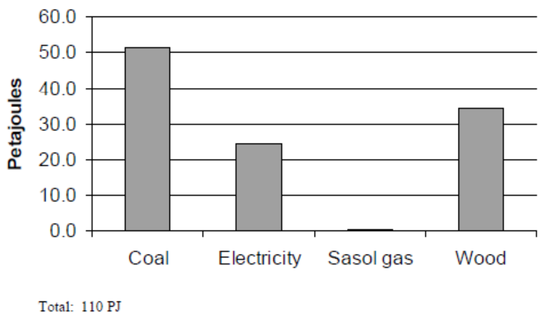


Figure 1: Energy mix of SA pulp and paper sector

Source: (Winkler et al., 2005)

In terms of growth, pulp wood accounted for 71% of timber demand from 1994-2004 with an annual growth rate of 5.7% (Department of Labour South Africa, 2008).

2.1.2 Chemicals industry:

The main process in the chemicals industry, in terms of production as well as energy intensity, is the oil refining process. Figure 2 illustrates the process involved in producing chemicals from oil. The main energy requirement is process heat. Oil is heated and distilled into its constituents by a process of fractional distillation. These fractions are then treated, through catalytic cracking (breaking up long carbon chains into smaller shorter ones). Some constituents may be hydro treated and desulphurised. Finally the liquid fuels are blended into the desired mixes (Lloyd, 2001).

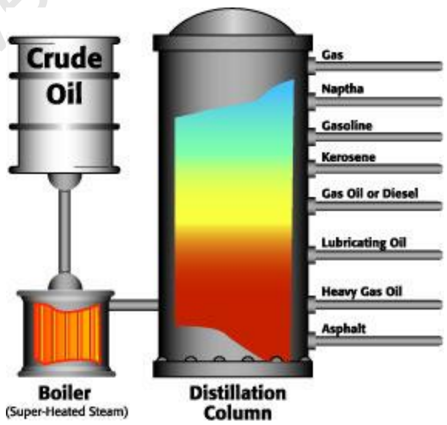


Figure 2: Fractional distillation of crude oil

Source: (Anon, n.d.)

The main facilities involved in the refining industry in SA are Calref, Caltex Refinery, Engen, Natref and Sapref (MBendi, 2011).

The second chemicals process that is of importance in the SA context is the synthetic fuels process. According to Lloyd (2001) the fundamental reaction that makes coal to liquid possible is the Fischer-Tropsch reaction. In this process, first the coal is gasified, turning the hydrocarbons into a mixture of carbon monoxide and hydrogen. Then through a number of reactions the mixture is recombined into carbon chains of controlled length. In gas to liquid conversion a similar production process is used. There are two synthetic liquid fuel producers in S.A, Mossgas and Sasol, Moss gas produces petroleum from natural gas while Sasol uses coal (Lloyd, 2001).

Although the petrochemicals sector in SA represents the bulk of the chemicals sector, both in terms of energy use and product produced, there are a number of smaller chemicals sectors and processes that must be considered. There is a plethora of chemicals that are produced in SA that can be divided into five groups. The first group is base chemicals; they are the building blocks of other chemicals. These include organic chemicals; many sourced from the petrochemicals sector for example propylene and benzene. It also includes inorganic chemicals such as chlorine, ammonia and sulphuric acid. The second group of chemicals is intermediate chemicals. These, as the name implies, are chemicals that are halfway through the product chain to final chemical end-products and include products such as ammonia, waxes, solvents, phenols, tars, plastics and rubbers. The final group is chemical end-products; examples of these are processed plastics, paints, explosives, and fertilisers. Finally there are speciality chemical end-products. These are low volume high value products most notably pharmaceuticals and agro-chemicals (MBendi, 2011).

The energy consumption pattern of the chemicals industry is shown in Figure 3. Coal dominates the fuel inputs into the chemicals sector.

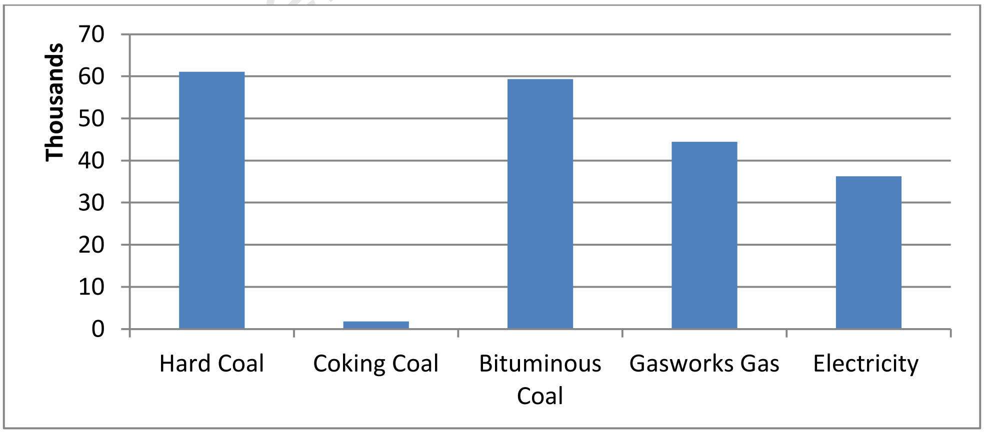


Figure 3: Chemical and petrochemical energy consumption

Source: (DOE, 2005)

2.1.3 Iron & steel

Iron and steel production processes vary significantly between facilities. Most, excluding Correx and Middrex processes, involve some combination of blast furnace, electric Arc furnace and basic oxygen furnace. The Correx and Midrex processes differs from the conventional steel manufacturing process in that they use some combination of correx and/or midrex reducers as well electric arc furnaces.

The conventional production process for steel involves several chemical steps and needs large amounts of heat and electricity. In the production of steel, coke and lime stone are added to the iron ore and heated in the blast furnace. The carbon and calcium in the limestone strip the molten iron ore of its oxygen and silicates respectively. A calcium and silicate mixture then separates from the primary mixture and is removed. The purer iron is drained out; this is called pig iron (Anon, 2012). Pig iron is then fed into the basic oxygen furnace where high purity oxygen is blown through the molten iron to lower its carbon, silicon, manganese and phosphorous content (Metals Advisor, n.d.). Finally the steel is rolled out into slabs. The processes involved are illustrated in Figure 4

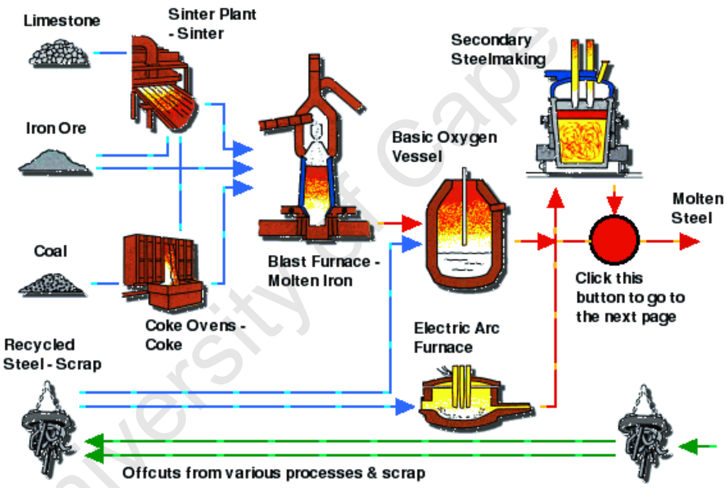


Figure 4: Conventional steel production process

Source: (UK steel, nd)

In SA Saldanha steel makes use of the correx/midrex process. In this process iron ore is directly reduced to pure iron without the use of high purity coking coal, although some coke is used. This has the result of reducing the need for coking coal manufacturing. In the Saldanha steel process first the correx reduction process produces its own reduction gases directly from coal and coke that are feed back into the reduction chamber. These gases reduce the iron ore into pure iron. Gases that are non-utilized then reduce iron ore in the midrex process in the same way. These two processes replace the blast furnace process. The main source of energy is coal; in the future gas could play a larger role (Winkler et al., 2005).

According to the SA iron and steel institute (SAISI) there are six major producers of steel in SA with a total production of primary carbon steel of 3,883,500 tonnes (SAISI, 2011).

There is potential for vast growth in this industry. Kumba iron ore (2011) reports that the iron ore industry has the potential to double output over the next ten years but that it is dependent on several conditions such as infrastructure development and energy and water available.

Growth in the final steel product sector is hampered by limited competitiveness. This is because SA steel is not cost competitive on the sea born export market that drives steel demand. There are four distinct cost disadvantages that cause this situation. Firstly the large input costs (coke, logistics, labour and capital) are more expensive in S.A; this limits the steel markets global competitiveness. Secondly the steel market is more regional than global, and therefore driven more by transport costs than a global market. This results in SA having a distinct geographic disadvantage, both in terms of rail transport and shipping as manufacturing assets are inland and sea trading routes are long. Thirdly the SA steel market is not geared up to produce high quality niche products; this limits the competitiveness of the sector. The small domestic and regional market for such niche products in sub-Saharan Africa makes investing in appropriate facilities uneconomical. Finally there are large domestic markets around the world e.g. (Korea) that produce steel for domestic consumption. These domestic markets have significant structural over capacity. This situation makes it difficult for the SA steel market to compete with these industries (Kumba Iron Ore, 2011).

In terms of energy use, the energy balance for the iron and steel sector in SA is illustrated in Figure 5. Coal dominates the energy input into this sector.

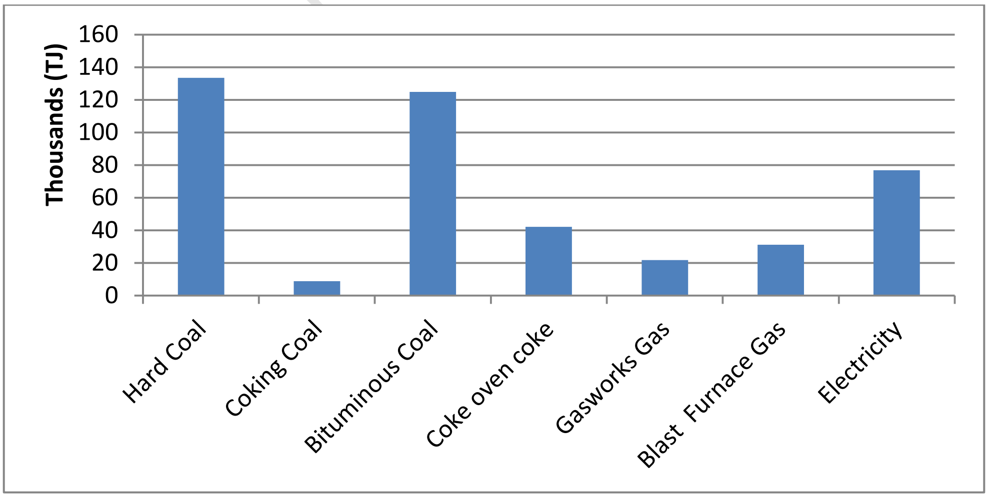


Figure 5: Energy use of SA iron and steel sector.

Source: (DOE, 2005)

2.1.4 Mining:

SA has large reserves of chrome, gold, manganese, platinum metals and vanadium which have enabled a substantial mining industry (Winkler, 2005). Winkler (2005) divides the mining sector up into gold and other. Energy use for all other mining is greater than gold; however gold mining is in decline while the others have good growth prospects.

Gold mining is energy intensive and a large part of the mining sector in SA gold mining has declined over the years but energy intensity has increased, this is due to declining ore grades combined with deeper drilling and exploration. Over 90% of energy demand for mining is in the form of electricity and gold mining is the single greatest user of electricity in SA mining sector (Winkler et al., 2005).

Most coal mining in SA is open cast. In general, coal is mined and sent to a processing plant. The coal ore is inherently impure and unsorted and contains ash, moisture, foreign materials and sulphur. The preparation process seeks to minimize the portion of these in the coal ore (Stationary sources Branch Air pollution Control Division, 1998). Figure 6 illustrates the coal chain.

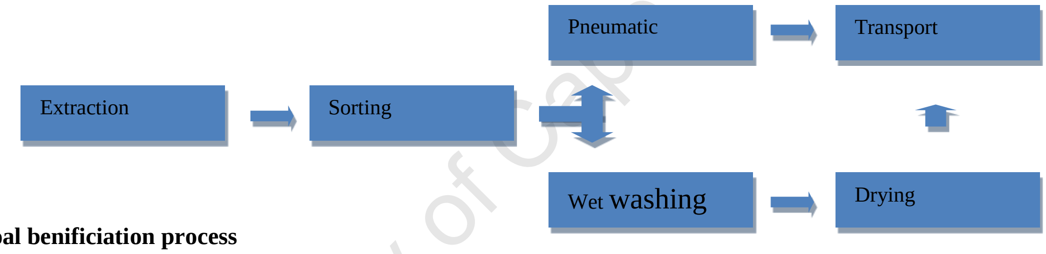


Figure 6: Coal benificiation process

Source: (Stationary sources Branch Air pollution Control Division, 1998)

The energy demand for the mining sector is mostly in the form of electricity, coal and diesel. The 2005 energy balance for SA shows electricity coal and diesel as the main energy sources. The energy demand of the mining sector is illustrated in Figure 7

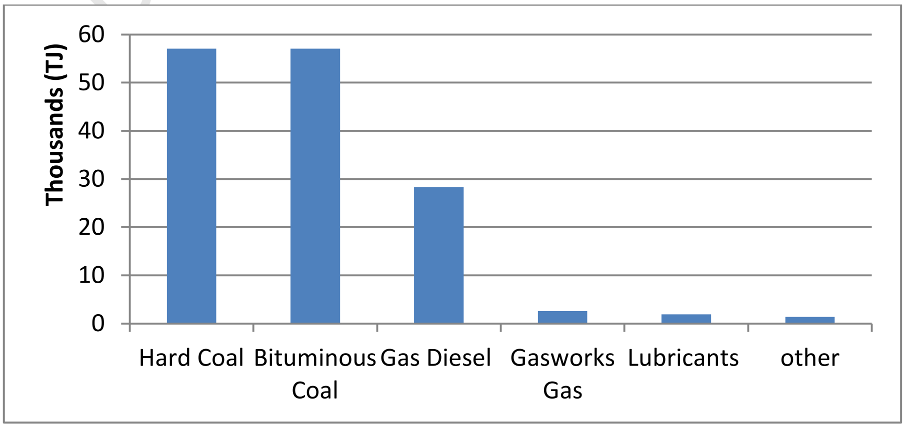


Figure 7: Mining and quarrying energy consumption

Source: (DOE, 2005)

2.1.5 Non-metallic minerals:

The non-metallic minerals sector includes cement, bricks and glass. SA cement manufacturing is efficient and done in dry kilns. Brick making in some cases is still done through inefficient clamp kilns. SA provides for all its domestic needs in this regard (Winkler et al., 2005). Glass manufacturing is mostly done using the float glass process (Colton, 2011).

In cement making first the raw materials, limestone clay, marl or shale and other supplementary materials (sand, pulverised fuel ash or ironstone) are crushed and homogenised (WHD Microanalysis Consultants Ltd, 2013). This mixture is then fed into a rotary kiln. The kiln is heated by a flame. The kiln is tilted such that the rotation causes the material to move along and out the opposite side. After it exits it is quickly cooled. This heating converts the raw material into the correct amount of silicates, aluminates and ferrites of calcium. The final product is called clinker. Gypsum and other additional cementitious materials are then added to the clinker. The mixture is then ground into a homogenous powder called cement (The European Cement Association, n.d). The cement manufacturing process is shown in Figure 8.

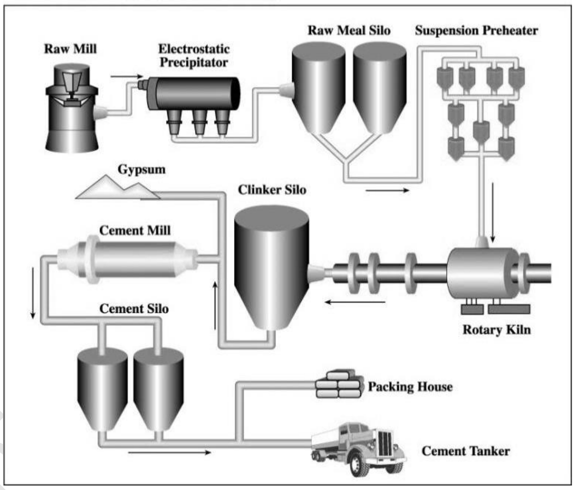


Figure 8: Cement production process

Source: (Gosselin, 2010)

There are three types of glass manufacturing; flat glass, container glass, and pressed and blown glass The methods for glass manufacturing are similar and differ only at the forming and finishing stages. Firstly sand, limestone, and soda ash are crushed and mixed. The mixture is then put into a melting furnace. The resultant molten glass either leaves the furnace through fore hearths and goes to pressing and forming or leaves the furnace and moves into the float glass process. Pressing and blowing are performed mechanically, using blank moulds. (Mineral Products Industry, 20).

In the float glass process the molten glass is floated on top of a bath of molten tin and begins to cool. Glass is then cooled slowly in an annealing lehr; this prevents the build-up of stress. Glass is then inspected to detect flaws and finally cut to the necessary sizes (Colton, 2011).

Brick manufacturing is done in five steps; preparing of raw materials, forming of bricks, drying, firing and cooling and lastly de-hacking and storage. In the preparations stages raw clay is sent through several size reduction machines. This process breaks up large clumps of clay and stones. In the forming process the clay is mixed with water and either cut or moulded into the bricks final shape. Bricks are then dried to remove moister, this is done in dryer chambers at temperatures ranging from about 38 ºC to 204 ºC. The dried bricks are then packed into the kiln in a process called hacking; the method of hacking has some influence on appearance of the brick. Finally the bricks are fired in the kiln. Bricks are fired between 10 and 40 hours. There are several types of kilns; the most common type is the tunnel kiln. Once fired the bricks must cool, cooling time rarely exceeds 10 hours for tunnel kilns. Cooling is an important stage in brick manufacturing because the rate of cooling has a direct effect on colour. Finally the bricks are dehacked and stored for later transport (the Brick industry association, 2006).

SA brick making in some cases is still done through inefficient clamp kilns. There are many types of clamp kilns but the essential method remains the same. In this process the formed bricks are stacked in in a pyramid shape, with spaces between the bricks to allow passage of hot gases, and with fuel (wood, coal, agricultural waste) at the bottom. The burning of the fuel fires the bricks (Jones, 1995).

In terms of energy use the 2005 energy balance shows the majority of non-metallic energy demand to be in the form of coal this is illustrate in Figure 9.

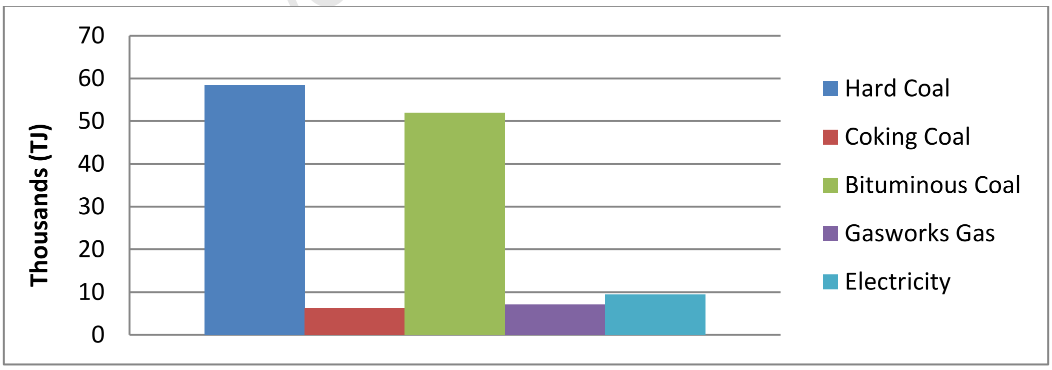


Figure 9: Energy use in the non-metallic minerals sector

Source: (DOE, 2005)

Growth prospects in the non-metallic minerals sector are varied. Camco et al (2011) outlines the potential in the sector and indicates that glass production has increased greatly over the years and that the cement sector has shown growth but as of 2008 was at the same level as 1994. It is possible that this slowdown is due to the 2008-2010 recession and that over the long term there is room for growth. Cement is greatly impacted by the economy as a whole due to the direct link to construction. The trend in the sector and in manufacturing between 1970 and 2008 is shown in Figure 10 .

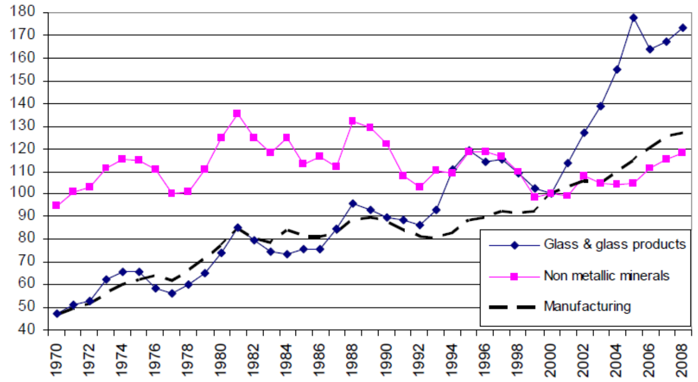


Figure 10: Growth, in glass and glass products, in other non-metallic minerals and in manufacturing

Source: (Camco et al., 2009).

2.1.6 Non-ferrous metals:

SA's non-ferrous metal industries comprise aluminium and other metals (copper, brass, lead, zinc and tin)

The main non-ferrous industry in SA in terms of energy use and product is the aluminium industry. SA is number eight in the world in terms of aluminium production (Dept. Trade and Industry, n.d.). Aluminium is produced from bauxite ore in a three step process. First alumina is extracted from the bauxite, this is done mostly through the Bayer process where sodium hydroxide is used in a chemical reaction to produce aluminium oxide and ore residue. The aluminium oxide is then evaporated off. Impurities are removed at this stage through the addition of starches and other chemicals. The aluminium oxide is then crystallized and made into aluminium metal through the Hall-Heroult process where the aluminium oxide is put in an electrolytic cell together with molten cryolit. A carbon rod in the cell is charged and the resulting electrolytic reaction creates carbon monoxide, carbon dioxide and aluminium. The aluminium drops out of the bottom of the cell where it is taken away. The molten aluminium is then mixed into the required alloys (ISTC, n.d.). An example of the Aluminium Production process is illustrated in Figure 11

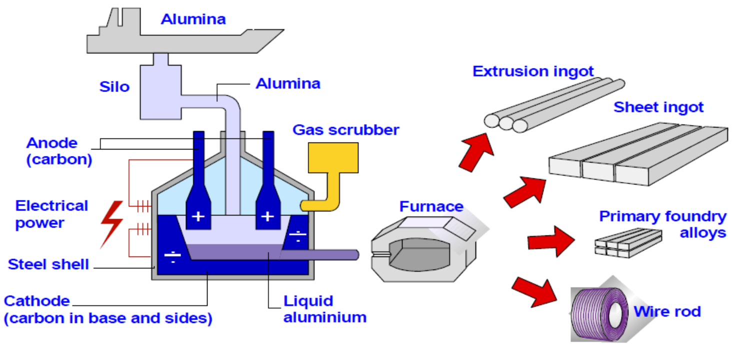


Figure 11: Aluminium production process

Source: (Balcoindia, n.d)

The main energy input into non-ferrous metals industry is electricity. A total of 67,104 TJ is reportedly utilized in SA (DOE, 2005).

2.1.7 Food & tobacco

According to Winkler (2005) the single biggest energy user in this sector is the sugar refining industry. One sub-sector that is included in this sector is the brewery industry.

The sugar refining process involves several steps from harvesting to packaging. According to Anon (2012) the sugar refining process involves first loading the sugar cane stalks onto conveyer belts and subjecting them to hot water sprays to remove dirt and other field debris. Then, the stalks are passed under rotating knife blades that cut the stalk into short pieces or shreds. Then the sugar juice must be extracted. This is done by either diffusion where the pieces are dissolved in hot lime juice or milling where the stalks pass under several heavy rollers which squeeze the sugar juice out. Throughout this process water is sprayed, this encourages the dissolving of the juice. The next stage is clarification of the juice where milk of lime and carbon dioxide is added to the juice. The juice is then heated and mixed with lime and passed through carbon filters. This process creates a mud like substance called carb juice. The carb juice is heated and then passed to a clarifying machine. Here the mud settles to the bottom and the clear juice is heated again and treated with carbon dioxide. The resulting mud is filtered out leaving a pale yellow liquid called thin juice. This juice is then reduced through several stages of vacuum boiling (low temperature so that the syrup is not scorched) finally the sugar crystallizers out of the syrup creating substance called massecuite. This substance is then put in a centrifuge, the sugar crystals all fall away from the syrup, and the remainder of the syrup is forced out through holes in the centrifuge, this by product is molasses (Anon, 2012).

The food and tobacco sector as a whole has a noteworthy energy demand pattern with coal and bagasse providing the majority of its energy needs. The DOE energy balance for the food and tobacco industry is shown in Figure 12.

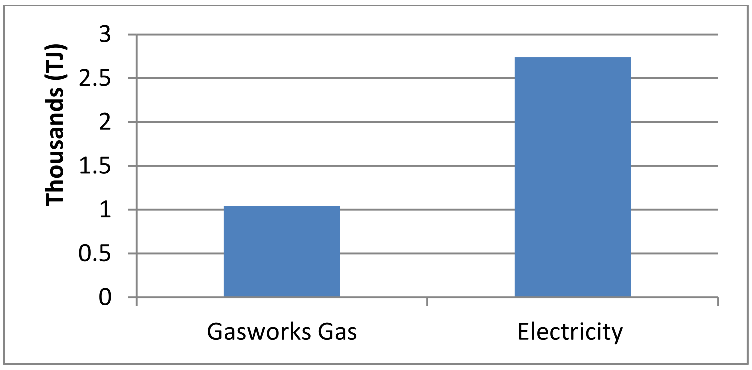


Figure 12: Food and tobacco sector energy consumption as reported by DOE

Source: (DOE, 2005)

The DOE data on the food and tobacco industry is limited. Figure 13 shows a more comprehensive sector specific energy balance.

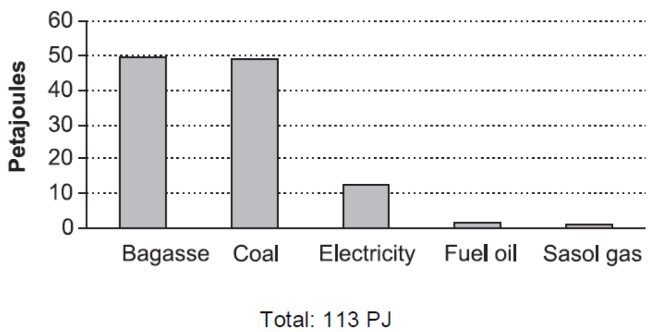


Figure 13: Energy mix of food and tobacco sector

Source: (Winkler et al., 2005)

Importantly coal and Bagasse are used in equal quantities, and together form the majority of fuel use.

2.1.8 Other industry:

Other industry includes a variety of industries such as manufacturing, construction, textiles, wood products and other activities and is therefore diverse with many different products and processes. It includes both large and small scale production. Many industries in this sector have high value economic activity and it is expected that they will grow faster than most other divisions (Winkler et al., 2005).

2.1.9 Summary points

In summary the SA industrial sector is large and diverse containing industries which have very different energy use profiles. Furthermore the industries have varying contributions to the SA economy as a whole. Therefore cogeneration use in the industries will be varied in type and scale. The next section will deal with the available cogeneration technologies that may be employed in these sectors.

2.2 Cogeneration Technologies

The EPA (2004) defines cogeneration as the simultaneous generation of two forms of useful energy usually mechanical and thermal.

A complete cogeneration system is made up of a number of different technologies, but is defined by its prime mover. This is the heat engine section of the system, in other words the fundamental section that drives the whole system e.g steam turbines or engines. Some of the additional components include boilers, absorption chillers, gasifiers etc. The rotational energy generated by the prime mover is often used to generate electricity but can also be used to drive mechanical processes such as pumps and compressors. The heat generated by the system can be used directly in processes or used to produce other sources of thermal energy, e.g. steam or water (EPA , 2004).

Cogeneration technologies have been developed for many years and for a variety of applications. Consequently there are a number of different forms, each designed to suit a particular task or need. Furthermore each type of cogeneration technology is at a different stage of technological development, in other words some are well developed and economically viable while others are still in the prototype stage. In terms of cost effectiveness, a properly maintained cogeneration system can have pay back periods of three to five years and have an operational life time of around twenty years (UNEP, n.d.).

Most cogeneration processes are very flexible in terms of fuel input. Systems can be designed to run on a multitude of fuels and sometimes on more than one fuel. Currently fossil fuels dominate the fuel inputs however cogeneration from biomass fuels is growing in importance. This has been precipitated in part by the growing need globally to lower emissions and use carbon neutral technologies. Waste products are also being used; this has the added benefit of increasing the cost-efficiency of the cogeneration system (UNEP, n.d.).

Broadly speaking cogeneration technologies can be organised into the following categories: Steam turbines, gas turbines, combined cycle systems, micro turbines, fuel cells and sterling engines (Hernoe, 2004). The next section will further define the current available technologies. This information will become important when analysing potential sources of cogeneration in the SA industry.

2.2.1 Steam Turbine:

In a steam turbine system, high-pressure, high temperature steam propels turbine blades which produce shaft power, which in turn can be used to turn a generator.

The main thermodynamic cycle used to generate mechanical energy from steam is called the Rankine cycle. In this cycle water is converted into high pressure steam in a boiler, the steam is then fed into a turbine causing the blades to turn creating mechanical power that in turn, can be used to drive the generator. A condenser and pump is used to collect the steam that exits the turbine. This is then fed back into the boiler to complete the cycle (EPA , 2004).

One of the major distinctions of steam cogeneration from gas or internal combustion (IC) engines is that electricity is generated as a by-product of heat generation (steam). In most other applications heat is generated as a by-product of electricity generation. A steam turbine needs a separate heat source as energy is transformed from fuel into heated steam and then into mechanical and electrical energy through the turbine and generator. This layout means that a steam turbine can run on a variety of fuels. In cogeneration applications steam is extracted from the turbine and either used directly in processes or is converted into other forms of useful thermal energy.

There are four categories of steam turbine: Condensing steam turbines are used for power-only applications. In these systems all steam energy is converted to power as no steam is extracted from the turbine (EPA , 2004). Extraction turbines or pass out condensing turbines are systems where a portion of the steam used by the turbine is extracted at an intermediate pressure from the turbine while the remainder is fully condensed before exiting (ESRU, 1998). Back pressure steam turbines are systems where the entire flow of exhausted steam is used for process heat at the required pressure. A pass out steam turbine system's layout is the same as the back pressure except, steam may be extracted at an intermediate phase (esru, 1998). In other words useful steam is extracted at both the intermediate and exhaust stages. (EPA , 2004) The four different systems are shown in Figure 14: Steam turbine cogeneration systems Essentially the first uses only exhaust steam, the second exhaust steam as well as intermediate steam from the turbine and the last only extracts intermediate steam from the turbine stage.

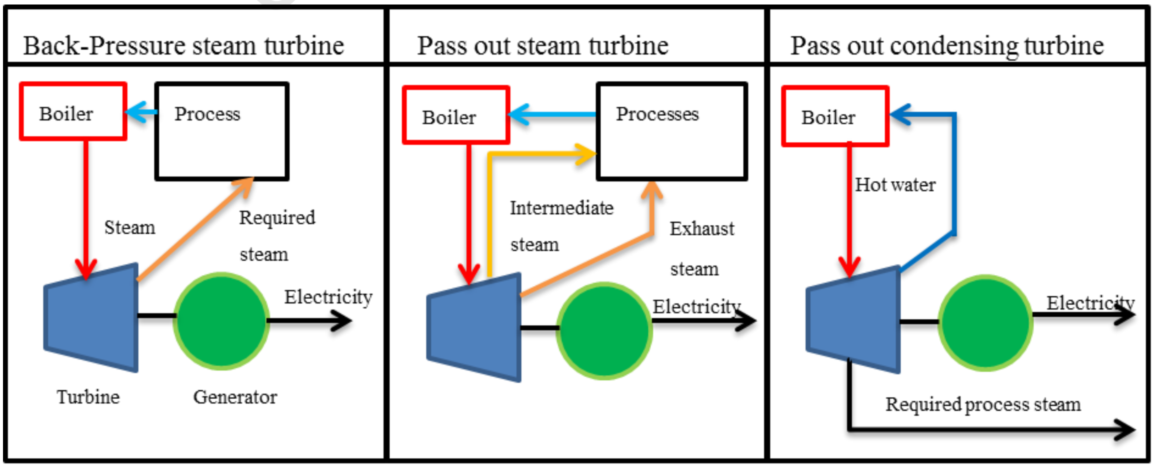


Figure 14: Steam turbine cogeneration systems

There are several advantages and disadvantages of steam systems. The advantages are that these systems can be powered by a number of fuels. Furthermore it is a mature technology and is flexible in size and output. The disadvantages are low electrical efficiency, as well as low part load performance and high operating cost (Hernoe, 2004).

2.2.2 Gas turbine:

Gas turbines are often used today due to their low capital cost, and low emissions. Common fuels include biogas and natural gas. They are used in a broad scope of applications, these include, electricity generation, compressors and many other processes that require shaft power. Gas turbines are built at a variety of scales, from 30kW to 250 MW.

A gas turbine is an internal combustion engine that operates with rotational rather that reciprocating motion. Essentially there are four components to the system; a compressor that compresses the air as it enters the turbine, a combustion chamber, the gas turbine itself and finally the generator.

The turbine consists of turbine blades that extract mechanical energy from the hot combustion products. Some of that rotational energy is used to power the compressor stage while the remaining energy is used to drive an electric generator or mechanical load. The compressor and all the turbine blades can be on one or two shafts. Where there are two shafts; one is for the compressor and the other for the turbine that drives the generator (EPA , 2004).

Fuel gas must be compressed before combustion. For low calorific value fuels such as biogas only a small pump is required. However with high calorific value fuels a small compressor is required (EPA , 2004).

There are a variety of configurations in which gas turbines can be arranged. These are simple-cycle operations, simple cogeneration configuration and lastly combined cycle configuration.

In the simple-cycle gas turbine configuration only electrical energy is produced, and no useful heat is extracted. Here gas fuel is burned in a combustion chamber; the expanding gas propels turbine blades that in turn rotate a shaft which finally drives a generator to produce electrical energy. This system is often called an open cycle gas turbine system.

In a simple cogeneration gas turbine configuration heat can be recovered from the hot gas exhaust and converted into useful thermal energy, most often in the form of steam or hot water (EPA , 2004). This configuration is illustrated in Figure 15:

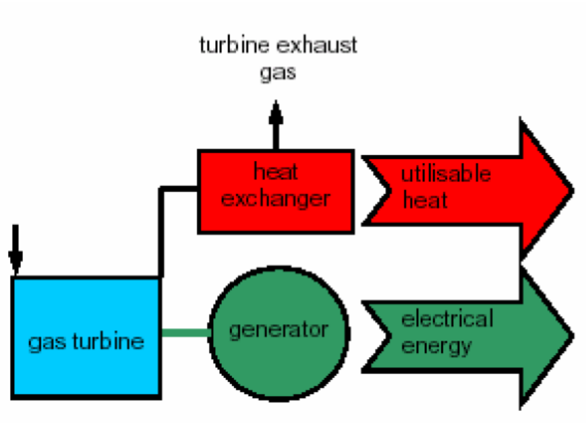


Figure 15: Simple cogeneration gas turbine configuration

Source: (Hernoe, 2004)

There are several advantages and disadvantages of simple cogeneration gas turbines. The advantages of these systems are that they are highly reliable, and have a wide fuel input range, essentially all liquid and gas fuels. Also it has a low investment cost and low emissions. The disadvantages include, high fuel cost relative to other fossil fuels (coal) and waste fuels. This is exacerbated by poor efficiency at low loading and high maintenance costs (Hernoe, 2004).

Finally gas turbines can be arranged in a combined-cycle configuration as illustrated in Figure 16: . In this option high pressure steam is generated from recovered exhaust heat and used to create additional power in a steam turbine. Some applications extract steam at intermediate pressure for industrial processes, in these cases the system becomes a combined cycle cogeneration system.

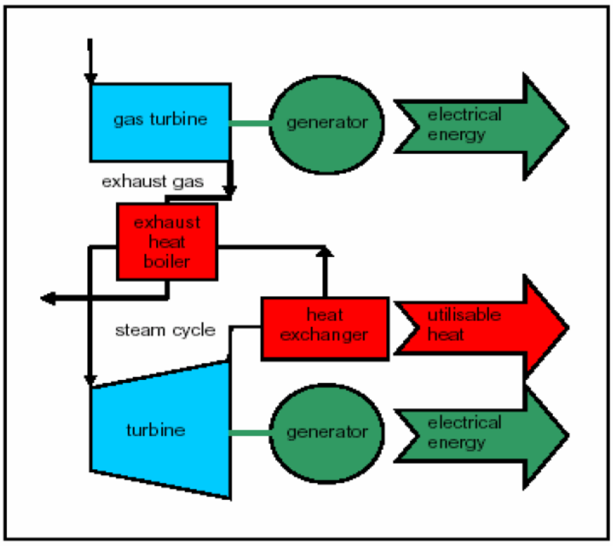


Figure 16: Combined cycle gas turbine cogeneration configuration

Source: (Hernoe, 2004)

The advantage of these systems is that they have high electrical efficiency and the disadvantage is that they can only be deployed on a large scale.

According to the EPA (2004), in terms of bio-gas fuelled turbines there are a number of complications.

1. Firstly the biogas must be filtered of particulate matter. This is done to avoid damage to the systems.
2. Biogas gasifiers produce low calorific value biogas; the fuel compressor and turbine must therefore be able to handle about ten times the gas flow compared to a natural gas system.
3. Lastly the air-to-fuel ratio is lower for biogas than for natural gas, this result in wasted compressed air as not all is needed.

According to the EPA (2004) these complications have the following results

- Existing natural gas turbines cannot easily be retrofitted to operate on low calorific gas e.g. biogas.
- Gas turbines specifically designed to run on biogas, generally cost about 50% more that their natural gas equivalent.
- Operational and maintenance costs increase for gas turbines using low to medium calorific fuels. This is due to the increased cleaning and maintenance cost.

2.2.3 Micro Turbines

Micro Turbines are small gas turbines. They are commercially available and range in capacities of between 30 – 250 kW. As with large gas turbines they can be used in power only applications as well as cogeneration applications. They can operate on a wide range of fuels; these include natural gas, biogas, medium calorific value gases and liquid fuels. They generally have lower electrical efficiencies than their equivalent reciprocating engine or large turbine. It has been shown that micro turbines can handle low calorific value fuels such as land fill gas. This kind of operation involves a 15 – 20 % increase in price due to a reduced power factor among other things. Maintenance cost and time would also increase (EPA , 2004).

Their advantage lies in their simplicity and few moving parts. They offer potential for reduced maintenance compared to reciprocating engines. The basic difference between a micro-turbine and their larger equivalent is that these systems have an internal heat exchanger called a recuperator. A recuperator essentially uses exhaust heat to reheat the inlet air after compression. (EPA , 2004).

2.2.4 Reciprocating internal combustion (IC) engine

This is a common technology employed in a wide spread of applications from cars and marine vessels to stationary power generation. Reciprocating IC engines range in size from a few kW's to more than 5MW (EPA , 2004).

There are two main types of IC engines namely spark ignition and compression ignition. Spark ignition (SI) engines for power generation use natural gas as the preferred fuel although they can run on a variety of liquid and gas fuels. Compression ignition (CI) engines often referred to as diesel engines operate on diesel or heavy fuel oil. They can also be set up to run in duel-configuration, burning primary natural gas or biogas with a small amount diesel as pilot fuel (EPA , 2004). A basic engine cogeneration system is illustrated in Figure 17: Internal combustion engine cogeneration system .

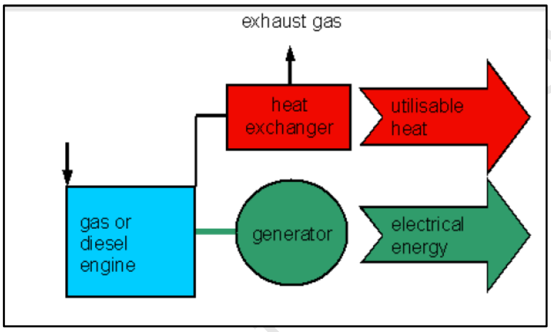


Figure 17: Internal combustion engine cogeneration system

(Hernoe, 2004)

The two kinds of engines spark ignition (SI) and compression ignition (CI) and each are suited to different applications. In the past diesel engines were favoured over many other engines. However due to emission restrictions, natural gas fuelled SI engines, which can also run on biogas, have become more popular for applications involving high load stationary power supply (EPA , 2004).

Heat can be recovered from a number of sources in the engine. Exhaust gases; jacket water; and the engine oil are all potential sources for heat recovery. These options offer an opportunity to more closely match the heat load of the site through careful design.

IC engines offer distinct advantages and disadvantages. The advantages of these systems include high power efficiency over a wide load range and low investment costs as well as the fact that energy production can be non-continuous. Disadvantages include the fact that only low pressure steam or low temperature hot water is produced. The system also involves high maintenance cost. (Hernoe, 2004). Another characteristic of these systems is that they tend to have a low heat to power ratio.

These engines can be used with medium calorific value gas that can be captured during waste water treatment or from landfills. Biogas fuelled IC engines however encounter similar problems as turbines; including the need for filtering systems and the need for modifications to accommodate higher flow rates. Despite these drawbacks in most cases these modifications are achieved more easily than similar modifications to a gas turbine. Another disadvantage is that the total operational and maintenance costs, excluding fuel, for a biogas engine can be up to seventy percent higher than for an equivalent natural gas fueled engine (EPA , 2004).

2.2.5 Fuel Cells

Fuel cells are a small scale technology with high electrical efficiency that is not yet in the mature level of development. Fuel cell technology has very low emissions. The technology can be rolled out in a number of scales from 50 watts to 2 MW.

The fuel cell process involves generating electricity through a chemical reaction. In a fuel cell, fuel is chemically reacted with oxygen to generate electricity with some useful heat being given off.

This technology has a number of advantages and disadvantages. Advantages of this technology include: low noise pollution, no moving parts, and a high electrical efficiency. Major disadvantages include, high cost and low durability. Fuel cells also have trouble maintaining performance over their life expectancy. Lastly, the size, weight, thermal management and water management systems are hindering the technology's development (EPA , 2004).

One aspect of fuel cells is that they require hydrogen to operate, however it is often not practical to use hydrogen directly therefore hydrocarbon fuels are used as a source of hydrogen. In terms of practical experience, most fuel cells around the world have operated on natural gas; there have been a few experiments with digester gas and landfill gas. However these systems require more complicated mechanisms to extract the hydrogen and clean gas. Gas cleaning equipment that effectively removes contaminants has yet to be demonstrated. The overall conclusion of the EPA in terms of biogas fueled systems is that the overall cost would be at least ten percent higher than a comparable natural gas fuelled system (EPA , 2004).

2.2.6 Stirling engines

The Stirling engine is a reciprocating engine where the heat for the engine is generated using an external heat source. In their operation thermal energy from a heat source is transferred to a gas inside the engine's cylinder. Heat energy is then transformed into motion via the Stirling thermodynamic cycle. Stirling engines are not commercially available for stationary power applications but there are many in development and prototype stages (EPA , 2004).

The Stirling thermodynamic cycle involves four phases. The cycle is best understood with reference to Figure 18: First a heat source provides thermal energy which is transferred to the gas inside the hot cylinder, see position 1. The gas inside the hot cylinder then expands due to the increased temperature. This causes the volume of the gas in the hot cylinder to increases as the piston in the cylinder is pushed away by the gases' pressure. This process moves the engine into position 2. Then a cold source is introduced to the cold cylinder which extracts thermal energy from the cylinder gas. At this stage the two pistons have completed one half revolutions around the crank shaft and begin to return to their original position, see position 3. The mechanical energy of the returning pistons compresses the gases in both the cold and hot cylinder. The pressure of the gas in both cylinders increases and its volume decreases during this stage, see position 4. The mechanical energy finally returns the pistons to position 1 and the cycle starts again with the heating of the gas in the hot cylinder (anon, nd).

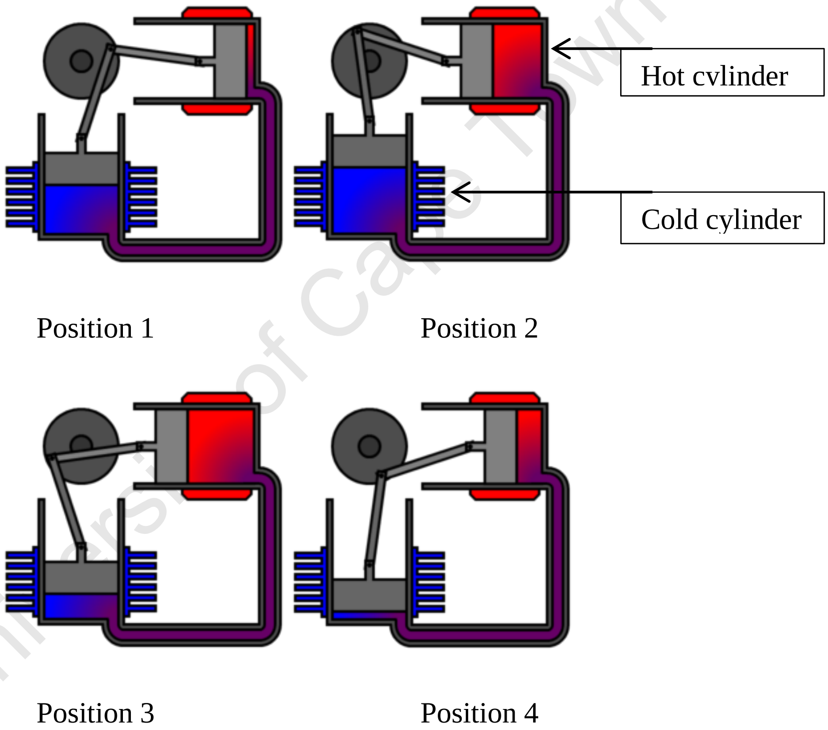


Figure 18: Sterling engine cycle

Source: (anon, 2012)

The Stirling engine has a number of advantages and disadvantages. Due to the external heat source, the system can be run using a variety of fuels and heat sources e.g. fossil fuels, solar, waste heat or biofuels. The external burning of fuel allows for more complete combustion of the fuel, which in turn results in lower overall emissions. Another advantage of this kind of system is that noise pollution and vibration is reduced. A great advantage in terms of cogeneration operation is that heat can easily be extracted in a cogeneration situation due to the external nature of the heat source. The major difficulty of the Sterling engine is the design and production of an engine that can compete with other technologies (EPA , 2004).

2.2.7 System comparisons

The next section briefly compares the characteristics of the various cogeneration technologies.

This section has dealt with the many different types of cogeneration technologies that are available around the world. The systems vary from well established, such as natural gas powered cogeneration to developing technologies such as fuel cells. The systems also vary greatly in use and size. Figure 19: simplifies the options in terms of types and fuels. Table 1: outlines the systems' technical and cost characteristics. Each technology has also been shown to have differing advantages and disadvantages.

Table 2 summarizes those attributes.

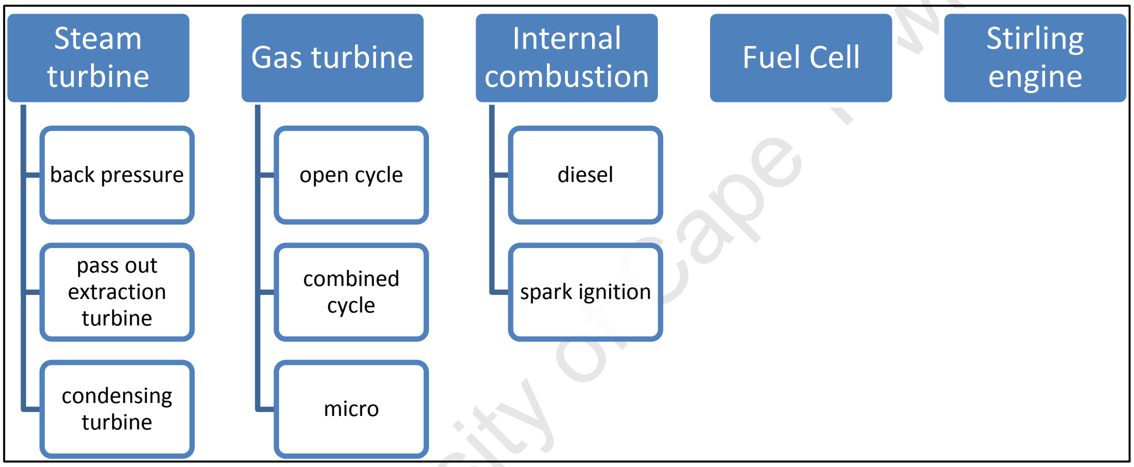


Figure 19: Available cogeneration systems

Table 1: Attributes of available cogeneration systems

	Spark Ignitiion Engine	**Compression Ignition Engine**	**Gas Turbine**	**Combined Cycle**	**Back Pressure Steam Turbine**	**Pass Out Steam Turbine**
Fuel Type	Natural gas, Biogas...	Natural gas, Biogas, Gas oil, Heavy oils	Natural Gas, Biogas, Gas Oil	Natural Gas, Biogas, Gas Oil	All types	All types
Capacity Range	30 kWe to 2 MWe	100 kWe to 20 MWe	>1 MWe	>3 MWe	>500 kWe	>1MWe
Heat:Power Ratio	1:1 to 3:1	0.5:1 to 1.5:1 (3:1 with boost firing)	1.5:1 to 2.5:1 (5:1 with supplementary firing)	1:1 (3:1 with supplementary firing)	3:1 to 10:1	3:1 to 8:1
Heat Output Quality	LPHW, Steam (rare)	LPHW, Steam	High Grade Steam	Medium Grade Steam	Medium Grade Steam	Steam at 2 pressures
Electrical generating Efficiency %	25-33	35-42	25-40	35-50	7-20	10-20
Overall Efficiency %	70-78	65-75 (75-82 with boost firing)	65-80 (75-82 with suppl. firing)	73-80 (80-85 with suppl. firing)	75-84	75-84

Source: (esru, 1998)

Table 2: Advantages and disadvantages of available cogeneration systems

System	Advantage	Disadvantages
Backpressure steam turbine	Fuel substitution; mature	High operating cost; low electrical efficiency
Pass out extraction turbine	Fuel substitution; mature	Low electrical efficiency; high operating cost
Condensing steam turbine	Fuel substitution; mature	Low electrical efficiency; high operating cost
Open cycle gas turbine	Mature; highly reliable, wide fuel input; liquid and gas fuels; low investment cost and low emissions	High fuel cost (natural gas); poor efficiency at low loading; and high maintenance cost
Combined cycle turbine	Mature; high electrical efficiency	Only large scale.
Micro turbine	Many fuels	Only small scale
IC engine	High power efficiency over wide load range; low investment costs per kW; energy production can be non-continuous.	Low pressure steam or low temperature hot water is produced; high maintenance cost; low heat to power ratio which can be a disadvantage or advantage
SI engines	High power efficiency over wide load range; low investment costs per kW; energy production can be non-continuous.	Low pressure steam or low temperature hot water is produced; high maintenance cost; low heat to power ratio which can be a disadvantage or advantage
Fuel Cell	Low emissions	Unproven
Sterling engine	Fuel substitution; more complete combustion of the fuel; lower overall emissions; noise pollution and vibration is reduced	Development and prototype stages

2.3 Potential sources of cogeneration

The next section will draw on previous literature and experience to determine where cogeneration could be implemented in SA industry. In the extreme case it is conceivable that all boilers in a country could be converted into cogeneration systems and boost the efficiency of the entire country. Schitzer & Titz (n.d.) concludes that in order to make cogeneration feasible the rule should be "No Heat without Electricity" What Schitzer & Titz are suggesting is that boiler technology is out-dated and that heat demands should be meet exclusively by cogeneration systems. Realistically however this is not possible due to many technical barriers faced by cogeneration. Therefore this section will identify where cogeneration systems have shown to be technically feasible. The section will evaluate each industrial sector separately.

2.3.1 Pulp and paper cogeneration sources

The potential for cogeneration in the pulp and paper industry is substantial. There are a variety of cogeneration technologies that have been successfully used in this industry. In the SA pulp and paper industry there are great opportunities for both fossil fueled cogeneration and waste wood (bark) fueled cogeneration.

There is potential for gas turbine cogeneration in the SA pulp and paper industry. Mondi has recognised this and has plans for a cogeneration system at their Richards Bay operations. The mill currently operates a coal fired generator and imports electricity from the grid. Mondi would see the implementation of a cogeneration system where the mill would switch from coal and imported electricity to using an onsite combined cycle gas turbine with heat recovery. The project has since been completed. The system produces 27.5 MW electricity and 36t/h steam (anon, 2006). Another SA company that has recognised this market is Sappi who are heavily invested in co-generation projects. They are investigating a combined cycle gas turbine at Tugela mill which would ultimately result in the mill being electrically self-sufficient.

Waste biomass cogeneration has the possibility of lowering waste streams and improving overall efficiency of facilities. Although bark is the most promising waste fuel, any wood waste can be used such as wood chips and shavings. These various wood residuals are termed hog fuel. The Food and Agriculture Organization of the United Nations (FAO) (n.d) suggests the possibility of cogeneration from hog fuel. They state that high pressure steam could be produced in a hog fuel boiler and used in a steam cogeneration system. The author remarks on the fact that the use of cogeneration increases the efficiency of hog fuel burning from 25 to 75 percent. Both condensing and back-pressure turbines are put forward as feasible options.

There is particular opportunity for waste bark fueled cogeneration. Lomati saw mill will use waste wood for cogeneration. Saiccor mill could also see the introduction of the use of bark wood as fuel for a new cogeneration project (Sappi, 2010).

A problem associated with hog fuel is that energy self-sufficiency, with respect to electricity, is difficult to attain with a cogeneration system. This is due to the fact that back pressure turbines have a low power to heat output ratio and this generally results in a lack of electricity (FAO, n.d). The FAO suggests three solutions to this problem: Firstly plants could be designed to match the power and heat demand of the facility. This is problematic as it requires a sophisticated plant, making it difficult to implement in developing countries. Secondly the operation could supplement fuel supply with purchased wood and residual fuel oil. But this option is challenging as it increases the load on existing treatment and combustion systems. Finally one could make up the balance of the mill's power needs by purchasing power from the grid or producing electricity from additional conventional generation (FAO, n.d). The FAO also recommends designed the system to meet the electricity demands of the plant and selling the resultant excess heat.

There can be a number of institutional barriers that can hamper the development of cogeneration in this industry. According to Jaccard et al (1989), British Columbia in Canada has large amounts of wood waste that are produced and used to generate steam and electricity in the pulp and paper industry. Research was conducted on possible expansion of these operations and a number of barriers such as declining energy prices, institutional difficulties and excess productive capacity for electricity were found. Such barriers are common to SA.

In summary, there is great potential for fossil fueled cogeneration and waste wood fueled back-pressure steam cogeneration in the SA pulp and paper industry. There are a number of problems associated with their development including institutional barriers and technical considerations such as the matching of heat and electricity demand to cogeneration supplied energy.

2.3.2 Chemical industry cogeneration sources

The industry is suited to cogeneration due to the exceptional heat requirements for processing chemicals. The main source of energy for cogeneration would be from fossil fuels as there are few usable waste fuels in the chemical industry.

Internationally the potential for cogeneration in the chemicals sector has been recognised. ExxonMobil estimates that energy savings due to the implementation of cogeneration around the world in their refining and petrochemical facilities, has been around 13000 GWh. ExxonMobil had 2900MW of cogeneration installed by 1950 and in 2001 it provided 70 percent of electrical needs of Exxon's refining and chemical plants.

Despite international success there is limited cogeneration in the SA chemicals sector at present. However there is 90 MW natural gas combined cycle turbine capacity at the Moss-gas petrochemical plant that uses some exhaust steam in processing (ERC, 2010).

There are also promising possibilities in the chemicals sector for cogeneration in developing countries. Pandya (n.d) discusses cogeneration at the Vadodara chemicals plant, specialising in fertilizers, in India. According to Pandya (n.d) the advantages of higher thermal efficiency and additional power as well as increased operational flexibility, made cogeneration an attractive option for the plant. The ageing boilers were replaced by new boilers with two turbo generators and suitable extraction and condensation stages for cogeneration of 40 MW of electric power. Given the unreliability of the nation's grid, self-sufficiency was pursued. An additional combined cycle cogeneration system was installed. These projects have resulted in substantial improvements in power availability and savings. It is conceivable that such results could be replicated here in SA

The SA chemicals sector has begun to recognise the possibility of cogeneration in the chemicals sector. Sasol wishes to implement a cogeneration system at their synthetic fuels plant in Secunda. The project aims to substitute some of the electricity imported from Eskom with self-generated electricity. The electricity will be generated using a natural gas turbine. The system will then be operated in combined mode effectively generating 268 MW (anon, 2009). These projects could be replicated in all major refineries around the country.

Exporting excess heat is also being considered by SA chemicals companies. The Karbochem combined heat and power project involves replacing two coal fired boilers with modern state of the art cogeneration systems. The system will include gas turbines, waste heat recovery boilers, steam turbines, as well as back up boilers. This project will improve the efficiency of the plant and reduce the use of coal. Importantly the project includes the installation of two 55ton/hr boilers; these will be used to produce steam to be exported to three occupants of the site (anon, 2008). The prospect of exporting or selling steam further improves the attractiveness of cogeneration.

There are some waste fuel options in the chemicals sector including waste heat and oil residuals, but in general the technologies that can effectively cogenerate from these fuels are not mature and face serious technological and economic barriers. Pandya (n.d) highlights the use of waste steam from the ammonia production process. Waste steam in the ammonia production process is mostly used directly as process heat but can be used in a back pressure steam turbine. However Pandya (n.d) states that such systems face series barriers such as the rejection of waste steam into cooling water for the chemicals plant, limiting the steam available for cogeneration. Another waste fuel possibility is refinery residuals. Sanchez and Toral (2007) explore the concept of cogeneration using refinery residuals in Mexico as a fuel source. Residuals include chemicals such as vacuum residue, petroleum coke, or petcoke and fuel oil. Integrated gasification combined cycle was the technology of choice that was considered. These two waste fuel generation processes (waste heat and refinery residuals) are not mature technologies, and it is unlikely that industry will adopt these concepts in the near to medium term.

There are significant prospects for cogeneration in the chemicals sector due to the large heat demands. The preferred source of cogeneration is fossil fueled cogeneration either coal or gas. There are limited options for waste fuels and those that exist involve immature technologies.

2.3.3 Iron and steel cogeneration sources

There is potential for cogeneration, from both fossil and waste fuels, in the iron and steel industry. The Office of Air and Radiation, of the United States of America (2010) reports that all steel plants require both electricity and steam to operate, therefore cogeneration is an obvious and attractive option for this industry. The Office also notes that there are a number of cogeneration options for iron and steel plants. These include gas turbines with waste heat recovery and high pressure steam boilers (both fossil fuel fired and waste fuel fired) and steam turbines (EPA, 2010) .

Other sources contradict the EAP's statement that cogeneration is suitable for the iron and steel industry. Although there is large use of steam in the sector there are limited process heat requirements that can be supplied by cogeneration. This is partly due to the fact that there is a substantial amount of waste heat that is already used to supply the steam requirements. Furthermore Worrell (1999) documented a number of energy efficient techniques for the iron and steel sector. Only one involved process heat which was iron ore preheating or sintering. This indicates that there are few areas where process heat can be utilised. In support of this an energy balance of a Japanese iron and steel plant shows no need for steam or heat of any kind (Gielen & Moriguchi, 2001) .This presents a significant problem. If the steel industry has no need for process heat then potential for cogeneration may be limited. However cogeneration from waste sources with heat export remains an option.

A further problem is that fossil fueled cogeneration can be difficult in the iron and steel sector due to the varying electrical demand of modern electric furnaces. This is because cogeneration systems would need to be able to respond to varying demands quickly. Cogeneration systems are better suited to long high load operations. Grid connection and power purchasing agreements with utilities could reduce this problem.

Despite the difficulties associated with fossil fueled cogeneration waste heat and waste gases can be used to cogenerate effectively. Waste heat and off-gases from the steel manufacturing process can be used to generate electricity. Shaaban (2011) concludes that for the iron and steel sector which uses both direct reduction and EAF's, and releases significant waste heat and gases, the use of waste fuel is the best option for cogeneration. Specifically he recommended a pass-out condensing steam turbine as the mover. The EPA (2010) also suggested waste generation and stated that the newest of coke plants all recover heat from the coke batteries to produce steam and/or electricity.

According to Gottschling (2011) off-gases from closed electric furnaces contain large amounts of carbon monoxide and hydrogen. He notes that traditionally these gases have been flared but that, in recent times, it has become advantageous to use these gases for gas-fired generation to produce electricity, thus improving efficiency. He suggests this kind of system for SA industry. Off-gas can also be combusted, after suitable treatment, to generate steam and process heat in an internal combustion engine (Gottschling ,2011). Heat that cannot be used can be exported but the electricity is of great value to the plant.

The EPA notes that the type and size of a cogeneration system fueled by off-gas depends on a number of factors. These include: the amount and quality of off-gas from the coke oven, blast furnace, or basic oxygen furnace; the steam requirements of the facility; and the economics of generating power on-site versus purchasing power from the grid.

There are also a number of technical and institutional barriers to the implantation of such a cogeneration system. Stubbles (n.d) notes one substantial disadvantage is that the payback period of such processes can be over ten years. A further barrier is that taking these production facilities out of service for the conversion is not practical.

Off-gas cogeneration offers distinct advantages, these includes helping the factory meet its emissions goals. Furthermore Gottschling (2011) stated that up to 25% of the cost of electrical power can be saved through implementation of such a system in the SA context. Gottschling (2011) also alludes to the fact that earning carbon credits can help to make projects more feasible. The possibility of clean development mechanism investments is also a further advantage as shown by Vilayanager (2003). Gottschling (2011) concludes that by installing state of the art off-gas cleaning systems and furnace gas plant operations in SA, plants will comply with even the most stringent of environmental legislation. Also the installation of off-gas system would allow producers to offset some of their power needs and costs. The planned electricity price increases in SA will make the use of off-gases even more attractive.

There is encouraging potential for waste cogeneration in the iron and steel sector in SA. The most promising possibility is the capture and use of furnace off-gas in an internal combustion engine to produce electricity for the plant and heat for nearby facilities. There is limited potential for fossil based cogeneration due to limited process steam requirements and varying electrical demands.

2.3.4 Non-metallic cogeneration sources

There is potential for cogeneration in the cement industry. This industry is the only one in the non-metallic industry with any noteworthy potential. There is the possibility for both waste heat cogeneration and fossil fuel cogeneration. Furthermore Katja in Khurana (2001) states that of the industries prime energy usage, 25% is electricity and 75% is heat. This demand ratio is perfectly suited to heat and power supply from a cogeneration.

There is considerable waste heat available in the cement industry. Khurana (2001) completed an evaluation of a one mega tonne per annum cement plant. Katja in Khurana (2001) records that the kiln reached temperatures greater than 1450 degrees Celsius. The plant had a great amount of recycled heat but there was still waste heat that was not utilized e.g. preheater exhaust and hot air from the cooler. He noted that recovering the energy from these lost streams would improve efficiency. Khurana (2001) describes a proposed system where waste heat was used to generate steam and then power. Zhejiang Energy Research Institute (2005) supports this concept of waste heat as a fuel for cogeneration in their description of a similar system of 9MW size. The payback period for this project was only 1.7 years. The institute also reported that in China in 2008 there were 935 dry cement production lines and 263 of these were equipped with power generation systems using waste heat with a total installed capacity was 1510MW, this demonstrates the feasibility of this kind of system

Michal (2010) noted barriers to the development of these systems for example; the systems involve the utilization of relatively low temperature grate-cooler exhaust air that does not have a stable temperature. This presents difficulties with respect to stable steam turbine operation. Furthermore Michal (2010) remarks that instability and low efficiency at partial load operation, as well as the necessity to have a dedicated steam operator on a shift basis are both problems (Michal, 2010).

Another sub-sector of the non-metallic minerals sector that could benefit from cogeneration is the glass industry however there are barriers to its development. Coles (1985) conducted a feasibility study of cogeneration from a regenerative glass furnace. The proposed system he was studying would recover waste heat from the stack gas. He reports that there is little demand in the industry for process steam or space heating and as such one could only use the steam to generate electricity (Coles, 1985).The fact that there is little need for steam makes cogeneration difficult. Heat could be exported and this would make waste heat cogeneration possible, but potential cogeneration remains limited.

The main form of cogeneration that has been successfully implemented around the world in the non-metallic minerals sector is waste heat fueled cogeneration in the cement industry. There is also the possibility of fossil fuelled cogeneration to supply heat and electricity needs of the industry.

2.3.5 Non-ferrous metals sector cogeneration sources

S.A's main non-ferrous metals sub-sector is the aluminium industry. Internationally opportunities for cogeneration have been recognised in this sub-sector. Both fossil fuel cogeneration and waste heat cogeneration can supply the alumina refining process with heat. This makes cogeneration very attractive; however SA has no alumina refining making fossil fueled cogeneration impossible due to the lack of process heat demands.

There is opportunity for cogeneration fueled by waste heat ejected from the aluminium reduction cells. Fleer (2010) proposes that heat can be recovered from the exhaust gas of aluminium reduction cells. This waste heat could be used to power a steam turbine cogeneration system. However the heat from the cogeneration system must be utilized somewhere at the plant. This presents a difficulty as the alumina refining process which is the major utilizer of steam in the process is not present. Hence in the SA context waste exportation to other facilities nearby would have to be present in order to make this cogeneration feasible. (Fleer, 2010)

2.3.6 Food and beverage cogeneration sources

There is a large amount of potential for cogeneration in the food and beverage sector. This potential comes from two areas, onsite waste water treatment (WWT) at breweries and the sugar cane industry. The breweries onsite WWT have potential for waste methane fueled cogeneration while the sugar cane processing sector has the potential for both bagasse and fossil fueled cogeneration.

Breweries are facilities with a high degree of suitability for cogeneration. Dumbliauskaite et al (n.d.) stated that it is possible to recover heat from an internal combustion engine, to be used in low temperature processes in breweries (Monika Dumbliauskaite, n.d). The fact that breweries need only low temperature heat makes the industry a good match with most cogeneration technologies. Dumbliauskaite et al (n.d.) recommends that a cogeneration system could replace the conventional boilers at breweries.

One of the most promising concepts is the use of organic waste to make biogas that can then be used in a cogeneration system. The Irwindale California brewery installed an anaerobic digester in order to produce biogas to be utilised in a cogeneration plant. The plant would generate electricity to be used by the facility as well as hot water that would be used for heating the digester as well as other heating processes (Sustainable plant staff, 2011). The feasibility of this kind of system is supported by Williams (2012) who reported that the a new brewery in Colorado utilizes its waste water in an on-site process water treatment plant to produce methane that is used to power a 292kW cogeneration internal combustion engine.

There is potential for both waste methane cogeneration and fossil fueled cogeneration in the SA brewery sector. According to SAB (2008) the boiler at Alrode brewery is currently running on methane gas produced from an onsite waste treatment plant (SAB, 2008). At a national scale according the Burton et al (n.d.) approximately 3.3 litres of water with a COD (chemical oxygen demand) value of 3 g/l is produced per litre of beer. Burton used these figure to determine that 17MW of thermal capacity in SA breweries is possible (S. Burton, n.d.). This waste methane could be used in internal combustion engine cogeneration systems (EPA, 2011). There is also some potential for fossil fueled cogeneration in the brewery industry, such as natural gas powered cogeneration. According to Williams (2012) the alcohol company Diageo planned to install a cogeneration plant at their Guinness breweries in Nigeria. The project will involve the installation of two 3.3 MW gas engine plants power by natural gas.

One major barrier to methane cogeneration is that it increases heat demand. Williams (2012) compared both natural gas powered cogeneration and biogas powered cogeneration. She found that that bio digestion process increased the demand for heat and electricity as the process requires both. Despite this Williams concludes that the bio-methanation system is the most economic as well as environmentally friendly solution. A further advantage of onsite water treatment is the reduced cost of levies on factory effluent; therefore the environmentally friendly solution also results in reduced cost.

The second industry in the food and beverage sector that warrants great attention is the sugar cane industry. Sugar cane processing requires large amounts of heat and electricity, making it suitable for cogeneration.

The use of waste bagasse offers a great opportunity for cogeneration. Importantly Pandya (n.d) notes that bagasse based cogeneration is being promoted in India given that it is the largest producer of sugar in the world. Pandya (n.d.) in his study of cogeneration potential in India found that 68% of the total potential (7574MW) was in the sugar industry. According to Mbohwa (2003) cogeneration in the sugarcane industry has become the norm all around the world. He suggested in his study of Zimbabwe that cogeneration from bagasse could be used during the crop season and coal during the off crop season. This is important as bagasse cannot be supplied throughout the year. SA also has a large sugar industry where such bagasse based cogeneration is used, currently 9MW at Maidstone Felixton and Amatikulu mills (Tongaat Hulett Suger, 2011). This industry could be expanded dramatically.

This section has demonstrated the possibility for cogeneration in three distinct industries. There is potential for waste methane cogeneration in the breweries sector. There is also the possibility of cogeneration fueled by bagasse and coal in the sugar sector.

2.3.7 Municipal waste water treatment

Another sector where cogeneration could be implemented is in municipal waste water treatment where waste methane can be produced and used. The EPA (2011) stated that cogeneration has been successful in the waste water treatment sector. These systems can take many different forms including, anaerobic digester gas fueled cogeneration, non-biogas fueled cogeneration as well as combined heat and mechanical power systems. The favoured technology for cogeneration from waste water methane is the reciprocating engine. In terms of prime movers for waste water methane cogeneration in the USA the reciprocating engine has the highest share of capacity. This is expected given the suitability of this technology to alternative fuels. According the Burton et al (n.d) there is a potential for 336.8MJ/s of power available from waste methane from municipal waste water in SA.

2.3.8 Summary points

In summary, this chapter has outlined the potential sources of cogeneration in SA industry. Each industrial sector has distinct potential. These lessons on potential cogeneration sources will become important when analysing SA's total potential cogeneration capacity. The next section will discuss principles of cogeneration relevant to the study and quantification of potential cogeneration capacity.

2.4 Feasibility of cogeneration principles

The field of potential cogeneration capacity estimation is diverse as there are many different estimation techniques. The following section will focus on the background concepts that must be understood before cogeneration feasibility studies can be conducted. The lessons learnt in this section will become important when analysing methodologies that have been employed for the estimation of potential cogeneration capacity as well as in the formulation of a methodology for this research paper.

2.4.1 Definitions of potential capacity

One important point that must be understood when studying cogeneration potential is the definition of potential. There are a number of different kinds of potential. Each has a different use and calculation methodology. As such it is important to distinguish between them. Poole (2003) mentions a number of kinds of potential, these are technical potential, thermodynamic potential, market potential and economic potential (Poole, 2003). The two fundamental potentials however are technical and economic.

The definitions of potential may vary between different studies. This can cause problems, as demonstrated by Poole (2003); he notes that the Permanent Commission for Cogeneration Studies' (CESC) methodology for determining technical potential in Brazil was not a true estimate of technical potential. These different definitions make it important to be clear on what definition is being estimated as well as the definition of the figure.

Technical potential is defined here as the maximum possible employment of a technology limited only by technical considerations such as energy demand and fuel supply. Economic considerations, primarily cost, are not factored in when calculating technical potential.

Economic potential is defined here as the maximum possible employment of a technology limited by both technical considerations as well as economic considerations such as cost.

Economic potential is expected to be smaller than technical potential given the extra limitations. The difference between technical and economic potential is stark. As an example of the difference the National Energy Policy Office (NEPO) in UNESCAP (nd) found technical potential in Thailand to be 3000MW and economic potential to be around of around 1500MW. Given these differences in values and definitions it is vital to distinguish between them at all times.

2.4.2 Power to heat ratio of cogeneration technology

Power to heat ratio is an important concept as it defines the relationship between heat and power in a facility or cogeneration system. As the name implies it is the ratio of generated heat to power, or in some cases the ratio of heat to power demand.

Power to heat ratio outputted by a cogeneration technology greatly affects the estimated potential and viability of cogeneration. Salem (2003) remarked that his study into the Brazilian chemicals sector considered only open-cycle gas turbines and that with the addition of other technologies such as combined cycle turbines the power to heat ratio could be boosted. I.e. produce more power and less heat. This would in turn increase the overall potential due to increased electricity production when cogeneration is designed to meet heat needs. Thus the power to heat ratio greatly affects total potential technical cogeneration capacity.

Some industries require high power to heat ratios. Schmitz (2008) evaluated a number of pulp and paper mills in India and found that their power to heat demand ratio was lower than that which was needed for feasible cogeneration (0.2) (D.Schmitz, 2008). In other words the pulp and paper mills were in favour of systems that produce large amounts of electricity in comparison to heat. Given the respective power to heat needs of industries the power to heat ratio of a cogeneration technology is of great importance when considering an industry's potential.

2.4.3 Grid connection and electricity sales to Grid

Grid connection is very important to make cogeneration feasible. In order to make some plants suitable for cogeneration implementation, grid connection is needed. This is to enable electricity to be exported from facilities with high power to heat ratio technologies. Pandya (n.d) highlights this in his list of criteria for successful cogeneration.

Sales to the grid and their proceeds become an equally important factor. Poole (2010) states that a study of potential Brazilian cogeneration did not factor in sales to the grid. This is likely to affect the economic potential significantly as sales of surplus electricity can improve the feasibility of a project. The ability to sell excess power is thus a crucial factor in making cogeneration more attractive.

Grid sales can also help to accommodate a higher power to heat ratio of a cogeneration technology. Schmitz (2008) states that if pulp and paper industries with their low power to heat ration could increase it to 0.20 then an additional 333 GWh of cheap electricity could be generated. One possible way this could be done would be to allow the selling of excess power, which would attract the potentially expensive technologies with high power to heat ratios.

In SA most industrial consumers have a grid connection. The main difficulty is the promotion of electricity sales to the grid. Currently the electricity market is dominated by a single supplier, ESKOM. ESKOM has a tight hold on electricity distribution which hampers the development of Independent power producers. This situation will in turn slow the development of cogeneration in SA.

2.4.4 Power and heat requirements of facilities

Power and heat requirements of a plant or facility impact strongly on the cogeneration potential at the site. Pandya (n.d) outlines the key requirements for successful cogeneration implementation; these include the need for simultaneous base load requirement for electricity and heat (Pandya, n.d.). Plants need to have large regular heat and power demands. This is supported by the Minnesota Environmental Quality Board together with the Minnesota planning department (2001) who did a study to determine the potential sites in Minnesota that could install cogeneration. The paper lists the study's criteria for the evaluation of cogeneration viability, these include, size and relationship between thermal load and power load.

Heat demands are often treated as more important that electrical demands. The primary reason for this is that cogeneration systems generally run on a power to heat output ratio of around 0.2. In other words for every unit of electricity output five units of heat energy are generated. It seems appropriate therefore to design one's system to fit one's heat demands and treat the electricity as a by-product. If the reverse were done the system would likely be faced with an oversupply of heat, which is more difficult to export than electricity. Schmitz (2008) emphasized this design paradigm as he based his entire methodology for estimating potential cogeneration capacity on meeting the thermal demands of the pulp and paper industry in India. This matching of heat demand and supply is illustrated by E-Bridge consulting et al (2005) in their study of cogeneration potential in Austria which showed a near perfect match between steam demand and cogeneration supplied steam. This is expected given that the E-Bridge study based the estimation on meeting demand for process heat.

2.4.5 CO_2 emissions

Cogeneration has an important role to play in reducing CO_2 emissions around the world. Cogeneration is a very efficient technology; efficiencies of up to 80% can be achieved. Consequently there are significant carbon savings that can be made through technology and fuel switching. The total carbon savings of the Mondi Richards Bay cogeneration project is estimated to be around 130,876 tonnes per year (anon, 2006). This is from a single source and therefore the combined saving of SA and other countries would be vast.

2.4.6 Summary points

This section has discussed some of the common principles that must be understood in order to grasp the methodologies used to estimate cogeneration potential.

2.5 Methodologies used to estimate cogeneration potential

The following section will discuss the methods used by researchers around the world to determine cogeneration potential. This information will be used later to formulate a methodology for determining total potential cogeneration capacity in SA

2.5.1 Onsite study

On-site methodology involves a feasibility study of an individual industrial facility. Pandya (n.d.) notes that each cogeneration project is unique and that because of this there can be no substitute for an on-site study. In this he highlights a substantial difficulty in the estimation of what potential cogeneration exists as systems must be designed to fit the specific project needs. It is clear that the most accurate estimation methods would involve accounting for every facility in a given country.

There are many different approaches to on-site studies; one such example is the evaluations of a 1Mt per annum cement plant conducted by Khurana (2001). First an energy balance was drawn up, then energy flows were analysed and finally a proposed cogeneration system was presented and its energy output estimated. Khurana method is an example of a comprehensive study of the energy use and demand specifics at a single facility. This has the advantage of being very accurate. The study only considered the pyro processing portion of the plant. Khurana found a large amount of recycling of heat e.g. tertiary air from the cooler was fed into the pre-heater. But still there was a considerable amount of heat being lost e.g. preheater exhaust and hot air from the cooler. Khurana (2001) compiled an energy balance of the system. This is shown in Table 3

Table 3: Energy balance of a cement manufacturing plant

Stream	Flow rate (kg/kg clinker)	Specific heat (kJ/kg K)	Temperature (°C)	Enthalpy (kJ/kg clinker)
Entering the system				
Raw feed	1.56	0.9	50	66
Ambient air	2.98	1.0	30	89
Coal	0.15	0.9	50	7
Combustion of coal	Net calorific value = 23800 kJ/kg coal			3611
Total				3773
Leaving the system				
Clinker	1.00	0.8	100	82
Preheater exhaust	2.27	1.0	280	636
Hot air from cooler	1.42	1.0	400	568
Reaction energy				1850
Total				3136

Source: (Shaleen Khurana, 2001)

Khurana (2001) used the energy balance of the cement plant to determine how much waste heat was available for electricity generation. She found a total of 3,136KJ/kg energy leaving the system unutilized. Khurana (2001) then used some basic assumptions about the efficiency of waste heat recovery to determine how much useful energy could be generated from the waste heat. Khurana (2001) proposed that the waste heat be used in a steam turbine system. Khurana's final conclusion was that 30% of the total power requirement of the plant could be generated in this manner (Shaleen Khurana, 2001).

Site specific results can be used to estimate country wide potential through extrapolation. By extrapolating results based on total cement production of the country (110 Mt per annum) Khurana arrived at about 450 MW of power which could be generated from the various plants in India. It is however difficult to transfer the accuracy of a site specific method to a country wide estimation. This is due to several reasons, primarily the fact that all facilities in a country have very different energy balances.

2.5.2 Sample survey methods

A further methodology that could be employed to determine country wide cogeneration potential is the sample survey method. Survey driven methodologies attempt broad analysis of cogeneration through the capture of data from a number of individual facilities. In these cases a sample of facilities are surveyed and the collected data is used to estimate sector wide potential. This kind of method has the advantage of obtaining accurate data on which to base calculations while still being practical.

Survey techniques allow one to be specific about the forms of data required to estimate cogeneration potential. Kattner (n.d) asked questions focused on determining, power use, electricity use and patterns, as well as the relationship between the two. In this way Kattner obtained the exact forms of data necessary to determine potential cogeneration development. This data was used to conduct site specific analysis for each facility. This is the crux of the survey method; one can still conducts site specific research but on a broader base.

Survey based methods offer the possibility of reducing the labour intensiveness of data acquisition while maintaining similar accuracy to an onsite feasibility study. Pandy (n.d.) describes a study conducted by TERI in order to determine cogeneration potential in India. Here a survey of 300 industrial units covering a broad range of industrial sectors was done. This demonstrates the broad and accurate reach that a survey based methodology can offer with only limited effort.

Survey based methods also have the advantage of allowing one to study complicated industries in some detail. Alexander et al (2004) estimated the technical and economic potential for natural gas-fired cogeneration in the Brazilian chemicals industry. The study noted that due to the wide diversity of production processes used, the energy use profiles of the different subsectors were quite different. Therefore the study had to break down the sectors into more detail. Surveys methods allow this to be done and allow one to target specific industries and collect maximum data.

Kattner (n.d) in her study of cogeneration in Minnesota questioned 142 facilities of which 32 responded. This illustrates one problems associated with survey techniques, the reluctance of participants to respond. Regardless of the limited response, a survey based technique maintains the advantage of collecting raw data.

Sample surveys are limited in their ability to estimate cogeneration potential as they identify opportunities for cogeneration in a localised manner and therefore cannot be used accurately for national estimations. Results from surveys can however be used in broad estimations of national cogeneration potential. Kattner (nd) highlights this; she states that her study into cogeneration potential did not make it possible to provide a proper quantification of total national technical and economic potential. However she did attempt a rough estimate of total national technical potential. Specifically the relationship of cogeneration potential to fuel use in the respondents was applied to other facilities' fuel use which was known. Here Kattner demonstrated the flexibility of this method.

Although survey driven methods are less labour intensive than site specific analyses they are still relatively intensive. It is possible to use simple surveyed data and extract more meaning thus reducing the overall intensity. For example an alternative to a straight forward survey based method is to employ mathematical estimates that require less data acquisition. For example Schmitz (2008) evaluated 18 Indian wood based paper mills in India. Then Schmitz evaluated the heat and electricity demand of the facilities based on figures for energy intensity of pulp and paper process. Finally using cogeneration technology characterises and assuming all heat requirements would be met through the cogeneration technology, the potential electricity generation capacity was estimated. Here we can see that Schmitz methodology utilized simple surveyed data and combined it with theoretical values such as energy intensity of the pulp and paper process to determine technical cogeneration potential.

2.5.3 Methodologies for estimating potential waste based cogeneration capacity

Many forms of cogeneration make use of waste fuels. In these cases the limiting factor on cogeneration development is the supply of fuel. Therefore many methods for estimating the potential of cogeneration from waste primarily involve the estimation of fuel availability.

Dumbliauskaite (n.d.) demonstrates an example of a method for estimation of waste fuel supply and waste fueled cogeneration in her study of brewery waste husk methane powered cogeneration. She made use of known digester biogas relationships to calculate total biogas availability. She provides an example, with one ton of husk one can produce 75Mm3 of methane. This equates to a capacity of 1,660kW, which results in a combined production of 766kW of electricity and corresponding heat demand. This is a simple case but is demonstrates the nature of waste powered cogeneration estimation, in which waste fuel availability is paramount.

In most cases waste fuel is calculated based on theoretical relationships and cogeneration potential is estimated based on the assumption that all waste fuel will be used in a particular kind of cogeneration system. Gottschling (2011) spent some time evaluating the potential of cogeneration from furnace off-gas. He calculated the gas condition from theory for an arc furnace. Then using the theoretical calorific value of furnace off-gas he calculated the total available energy. From this he determined the total capacity of a gas engine cogeneration system fueled by the off-gas.

In support of the concept of using mathematical relationships to determine waste supply, Burton (n.d) calculated the amount of energy stored in waste water methane from waste water treatments plants.

The calculation was split into two sections, the municipal waste water treatment and the total domestic black water (human faeces). The first calculation involved multiplying the total waste water treatment capacity of SA (7600Ml/day), by an average COD value of 0.860g/l. then the total COD value was multiplied by the energy content of COD (15 MJ.kg). This resulted in a total energy production figure of 1,134MJ/s. The second calculation was for total domestic black water load. In this method the researchers took the total population of SA and multiplied it by the known dry weight production value for an individual (100g/day). The resulting figure for total dry weight was multiplied by the energy content of the dry weight (15 MJ/kg) this resulted in a value for total available energy of 842MJ/s. This study demonstrates the flexibility of these calculations as they can be both specific where possible or broad where needed, such as in the calculation of human faeces waste where limited data was available.

Determination of waste fuel availability can be expanded to sector wide situations. Sanchez & Toral (2007) presented a systematic method for determining the potential cogeneration capacity fuelled by refinery residuals. Their method involved first estimating the amount of refinery residual available based on estimated crude oil processing and the relationship of this to refinery residual production. Then they determined the steam and heat demands of the refineries. Finally they determined the potential for residual fired cogeneration in Mexico using integrated gasification combined cycle. Once again a mathematical relationship between waste production and sector wide activity has been applied together with known technology specifications to determine sector cogeneration potential.

2.5.4 Regional computerised modelling techniques

Computer modelling is a comprehensive method in the sense that it can be used to calculate both technical and economic potential of cogeneration. This methodology also allows the freedom to take into account a number of different factors affecting cogeneration and find the best solution. Computer modelling also presents the possibility of scenario planning. For these reasons computer modelling is seen as one of the most comprehensive methodologies that can be used to calculate cogeneration potential.

Computer modelling has been used to model the behaviour of technologies in a competitive energy market. Stickland & Nyboer (2006) estimated the potential for cogeneration in Canada using the technology modelling system known as Canadian Integrated Modelling System or CIMS. Essentially in the CIMS model, cogeneration technologies compete with boilers to supply the process heat to the economy. The addition of competing technologies which supply heat demonstrates the flexibility and rigorous nature of computer modelling. This allows a true study of cogeneration’s attractiveness. This concept is supported by Volkers in Dijkstra (2010) who used modelling to compare the feasibility of cogeneration to both conventional power and heat sources. This is important as cogeneration must be tested against both conventional electricity and heat generation, which is made possible through modelling.

The use of modelling can be combined with various other techniques such as feasibility studies and surveys. Dijkstra (2010) reports on an example of modelling where only the heat demands were predicted and the remaining calculations were done outside the modelling software. In this instance technical potential of cogeneration for the Netherlands was primarily determined from heat demands together with the maximum share of production that could be achieved with cogeneration technologies. Modelling was used to predict heat demands and then, based on assumptions about the power to heat ratio, the efficiency and the number of operating hours of the technology, total technical potential of cogeneration was estimated. Lastly economic potential was derived from a feasibility study for each technology carried out in the modelling system. This example outlines the flexibility of computerised modelling techniques.

Computer modelling also allows one to create different scenarios or projections based on varying initial conditions and assumptions. Computer modelling essentially projects the future behaviour of any power production technology. The future is however uncertain and as such any projection is tentative. One must therefore use modelling to create different scenarios based on different assumptions, for example different technology costs or policy measures. This analysis allows one to better gauge the behaviour of a technology such as cogeneration.

Any number of preconditions can be inputted into a model making it a very flexible method. Stickland & Nyboer (2006) used modelling to generate two scenarios, one where all heat requirements in Canada were met with cogeneration and one where limitations/restrictions were set to limit the level of cogeneration penetration. In this way Stickland & Nyboer (2006) tested both pure technical potential as well as some form of restricted potential.

Scenarios can be used to test specific policy measures such as the promotion of a technology through subsides or carbon crediting. Stickland & Nyboer (2006) in addition to their estimate of technical potential produced several scenarios based on differing policy and economic conditions. The results for economic potential of cogeneration in the Canadian industrial sector are tabulated in Table 4

Table 4: Scenarios used in Stickland & Nyboer study of Canadian cogeneration

Scenario	1995	2000	2005	2010	2015
BAU	723	1,252	1,470	1,824	2,163
Unconstrained	723	1,364	1,921	2,385	2,989
Promotion	723	5,967	10,724	15,532	20,950
HEP	723	2,049	3,712	5,277	7,138
HFP	723	1,242	1,662	2,038	2,530

Source: (Stickland & Nyboer, 2002)

Scenario modelling can be expanded to include a vast range of futures; the use of scenarios trees can allow in-depth analysis of cogeneration. Salem (2004) used a very comprehensive scenario tree that allowed him to test the sensitivity of cogeneration in Brazil. A scenario tree is a diagrammatic representation of expanding scenarios based on every combination of a number of preconditions, for example high oil prices can be coupled with low or high discount rate, and each of those combinations can be coupled with several other differing assumptions.

Computer modelling can also be used to validate other methodologies and vice versa. For example technical potential estimated by a survey technique can be tested by a model and vice versa. Technical potential estimated by alternative means can also be used to test economic potential calculated by a model. Volkers in Dijkstra (2010) stated that the estimates for technical potential in the Netherlands were used to validate the results for economic potential, determined through modelling. Specifically technical potential acts as a ceiling for economic development.

Scenario modelling has and can be used to model the effects of climate change mitigation measures. Dijkstra (2010) prepared a report for the Ministry of Economic Affairs for the Netherlands on the potential of cogeneration in the Netherlands. Dijkstra explains that the European commission requested that each EU member state provides three scenarios based on differing carbon dioxide prices. The use of scenarios in determining mitigation efforts is very promising. The results showed that carbon dioxide price has a distinct effect on economic potential. The results once again demonstrate the advantage of the use of differing scenarios.

2.5.5 Summary points

In summary this section has analysed a variety of methods used to estimate cogeneration potential. Each method offers distinct advantages and individual drawbacks. Regional computerised modelling was found to be a very comprehensive method for cogeneration potential estimation at a national and regional scale.

The next section will build on the computer modelling aspect of cogeneration potential estimation. Specifically it will analyse one particular modelling package called TIMES. It will describe how the TIMES model incorporates cogeneration technologies in its programming.

2.6 Modelling in TIMES

2.6.1 TIMES Background

The Integrated MARKAL-EFOM System or TIMES, is a computer programme designed to represent any real world economic energy system. This is done through computerised representations of the energy system components and their individual characteristics. The TIMES platform allows the representation of any energy system, including energy flows, energy equipment and other constituents that make up any complex energy system. The comprehensive nature of TIMES allows one to represent energy systems at varying scales (e.g. National/regional).

In addition to the representation of any energy system, TIMES can be used to model the supply and demand behaviour of an energy system over a time horizon. TIMES is able to do this through the exploitation of linear optimisation.

The basis of the TIMES optimisation is the mathematical discipline of optimisation. This is the process of optimising any objective, while being constrained by any number of limitations. A simple example of linear optimisation is linear programming. This discipline was originally developed during World War two as a means of planning transportation and allocation of resources. This provides a valuable example as it demonstrates the flexibility of the mathematics. In this case objectives ranged from minimum cost, minimum transport, vessel loss, minimum fuel use, or maximum supply delivery. These objectives would then be limited by certain requirements or restrictions such as, minimum fuel available for transport, limited escort vessel availability, and fixed supply mix (e.g.Tanks/food). Linear programming was later developed extensively by George Dantzig and was used in industries around the world to solve optimisation problems. (Britannica, 2013)

Although more mathematically evolved, the TIMES system makes use of the linear optimisation principal. In simple terms the objective of the TIMES model generator is to minimise the total cost of the represented energy system over the time horizon. The main requirement that must be satisfied is that energy supply must meet energy demand at all times. In addition to the above objective and restriction, additional restrictions can be inputted e.g emission restrictions, reserve margin, or a chosen energy mix. Thus the TIMES platform can be used to model very complex energy systems.

In more detail the TIMES model generator can be described as a partial equilibrium model. This means that when generating an energy system scenario (single instance of projected future behaviour of an energy system), TIMES calculates both energy supply and the energy prices in such a way as to produce exactly the amounts of energy that the consumers are willing to consume at the calculated prices. (Loulou et al., 2005).

It is important to expand the definition of the TIMES objective function. The above paragraph offered a simple definition of the TIMES objective which was to minimise the cost of the energy system. The expanded definition of the TIMES objective is to maximize the total economic surplus in the system. The total surplus can be defined as the net benefit to the system. This surplus is the sum of the supplier and the consumer surpluses. For the producer it is the sales above the supply curve that are made and for the consumers it is the net cost under the demand curve that they save. This is illustrated in Figure 20. Thus TIMES seeks to balance the energy system at market equilibrium as this is the point at which maximum surplus is achieved.

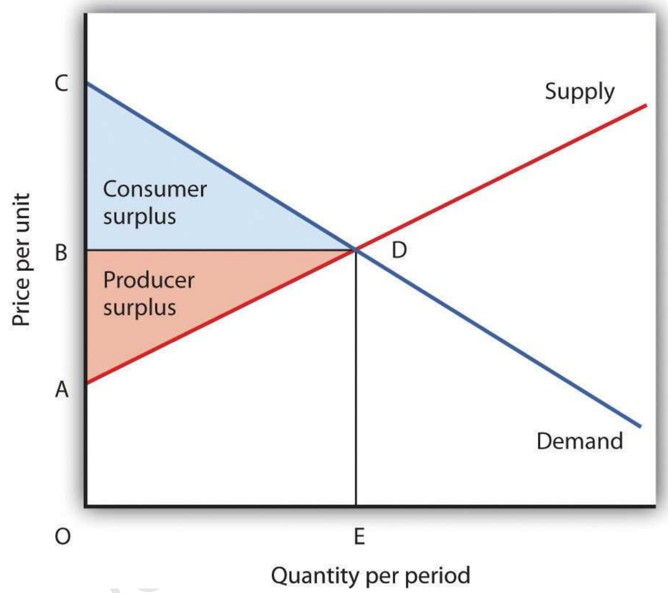


Figure 20: Total economic surplus diagram

Source: (Anon., n.d.)

2.6.2 TIMES components

A complete TIMES model of an energy system is made up of four inputs, these are energy service demand, primary resource potentials, policy setting and technology descriptions (Loulou et al., 2005).

The <u>demand component</u> of TIMES is based on drivers of energy demand e.g. population and GDP growth. The values for demand drivers are determined externally from the model through other means such as general equilibrium modelling. Final demand is then computed for each kind of final energy form e.g. demands for residential heating. These final demands are computed by choosing elasticities of these demands to their respective drivers. The equation governing this relationship is Equation 1 (Loulou et al., 2005).

Equation 1

$$Demand = Driver^{\ elasticity}$$

Source: (Loulou et al., 2005)

For example if population growth will drive the growth in demand for residential heating with an elasticity of two, then a three percent growth rate in population will result in demand for residential heat growing by 9%.

Demands are provided for a reference case scenario; this is a basic scenario from which other scenarios are derived. When the model is run for alternate scenarios e.g. a carbon constrained future, demands may change. TIMES has the ability to estimate the response of demands to changes in conditions of a model. To do this the model needs to know several other inputs, most important of which is the assumed elasticities of the energy demands to their own prices (the gradient of the demand curve). TIMES is then able to adjust the demands to the alternate cases without external computation. Thus TIMES is not driven by demand but demand curves (Loulou et al., 2005).

The supply component of a TIMES model is based on a set of supply curves for primary energy. Stepped supply curves are modelled in TIMES, each step representing a certain available resource supply at a particular cost. Potential supply can be in many forms. These are: cumulative potential over a time horizon, e.g. oil reserves; cumulative potential over a resource base, e.g. available area for wind farms; or annul potential, e.g. coal mining with a maximum extraction rate (Loulou et al., 2005).

The Policy component of TIMES allows a user to place a multitude of policy measures on energy supply. These policies can be both negative measures e.g. carbon tax or positive measures such a subsidy for a technology. There are a wide variety of options in TIMES that can be used to represent real world policy decisions (Loulou et al., 2005).

The fourth component to the TIMES model generator is the techno-economic component. This component constitutes the technical and economic parameters assumed for the transformation of primary energy into final energy services that will satisfy demand. In TIMES these parameters are defined in the form of technologies or processes. These processes each transform one energy carrier into another and through a chain of processes primary energy supply is converted into useful energy. Technologies can be fixed, e.g existing infrastructure, or their general characteristics can be defined and the model can choose to use them to satisfy demand (Loulou et al., 2005).

The final modelling process in TIMES is summarized as follows. The user inputs the four components of TIMES. Specifically the user inputs final energy demand of the system together with system's technological characteristics, including existing capacity and possible future technological implementations. The user defines the supply curves for primary energy and adds policy aspects to the model. In other words the user supplies the building blocks of an energy system. The TIMES model then uses these inputs and aims to supply energy services at minimum total cost. This is done by simultaneously making equipment investment, operating energy supply, and trade decisions to supply the final energy demand. (Loulou et al., 2005).

2.6.3 SATIM (2012 version)

TIMES has been used to model the SA energy system. Currently the energy research centre (ERC) at the University of Cape Town maintains a TIMES based model of SA. This model is called SATIM (South African TIMES). The SATIM model is a result of several nation-wide energy modelling projects completed by the ERC.

Currently SATIM is in its third generation (ERC, 2012). SATIM is a TIMES model with demand and supply sectors. It is characterized by technologies and energy flows (ERC, 2012). SATIM is divided up into five demand sectors; industry, agriculture, residential, commercial and transport. There are two supply sectors, electricity and liquid fuels. SATIM has a detailed characterisation of the processes used in both the demand and supply sectors (ERC, 2012).

SATIM has been used by the ERC to test many different energy related policies in the SA context, such as carbon taxation. The SATIM model is therefore a perfect platform to test cogeneration hypothesis in SA.

2.6.4 Cogeneration in TIMES

This section will discuss how cogeneration is included in TIMES. Cogeneration can be inputted into the TIMES model as a potential energy supplier (energy equipment). In general, the way in which cogeneration is treated in TIMES suggests that the methods were designed to apply to steam turbines. However the concepts can be used to define other forms of cogeneration.

Understanding the basic technological parameters that constitute the techno-economic component of a TIMES model is vital in order to understand the modelling process under taken later in this research. Any energy conversion technology requires a number of initial parameters. Table 5 represents these figures and their descriptions.

Table 5: Input parameters for TIMES energy process

Parameter	Description	TIMES CODE	UNIT
Commodity input	The commodity that is inputted into the technology for conversion into the output commodity.	TOP_IN	PJ
Commodity output	The commodity that is outputted by the technology after conversion.	TOP_OUT	PJ
Efficiency	Efficiency is the conversion factor from input energy to output energy.	ACT_EFF	fraction
Capacity factor	Availability of capacity represents the fraction of a time period that a process can operate. The process cannot operate for 100% of a time period due to scheduled maintenance and other interruptions.	NCAP_AF	fraction
Investment cost	Investment cost represents the total build cost of a process that must be spent.	NCAP_COST	Million Rands/ GW
Fixed operation and maintenance cost	Fixed operation and maintenance cost represents the costs associated with a process that do not alter depending on output but are determined by total capacity regardless of where that capacity is in use, e.g. rental of land.	NCAP_FOM	Million Rands/ GW
Variable cost	Variable cost represents costs associated with the process that increase with increased energy output.	ACT_COST	Million Rands/ Peta Joule output
Life Time	The life time of any energy equipment dictates how many years the process may stay in operation.	NCAP_TLIFE	years
Lead time	The lead time variable dictates the time the model needs to bring a particular technology into operation. It represents the construction time of any energy equipment.	NCAP_ILED	years

There are a multitude of parameters that TIMES allows a user to specify for a technology however these are the minimum required to create a technology. These fundamentals will become important when modelling cogeneration technologies in TIMES.

These input parameters can easily model any single energy conversion technology option, for example coal fueled electricity power plant. However when cogeneration is considered the behaviour of the process is more complex.

Gragiulo et al (2008) explains the modelling of cogeneration in TIMES. The author distinguishes between two types of cogeneration plants in TIMES, back pressure systems, and condensing systems.

Back pressure cogeneration systems

In a back pressure arrangement the ratio of electricity to heat is fixed and electricity production is directly proportional to steam production. This is illustrated by Figure 21. In this system with every incremental step of heat output there is a proportional increase in electrical output. The gradient of the line is the power to heat ratio which remains constant.

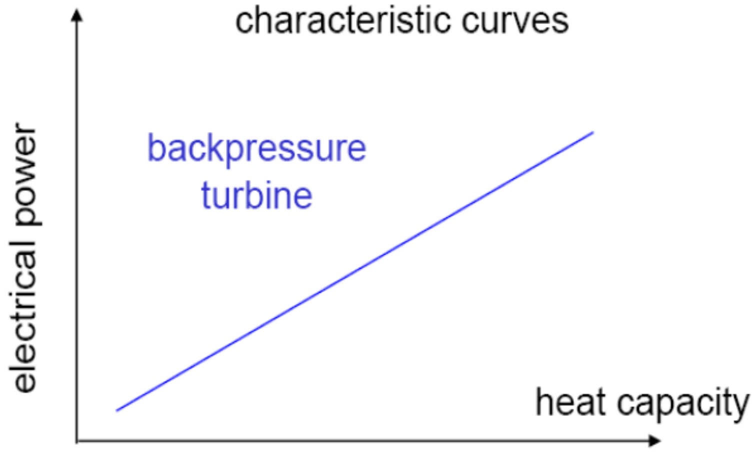


Figure 21: Heat to power relationship of a back pressure cogeneration system in TIMES

Source: (Maurizio et al., 2008)

In TIMES a back pressure system is defined by a number of variables. Gragiulo et al (2008) explains that a back pressure system can be defined by the electrical efficiency, the thermal efficiency and the load factor. The system's efficiency is the sum of electrical efficiency and thermal efficiency and the heat to power ratio is calculated by dividing thermal efficiency with electrical efficiency. Examples and the TIMES codes are shown in Table 6

Table 6: TIMES back pressure steam turbine cogeneration system input parameters

NAME	CODE
Electrical efficiency	ETAel
Thermal efficiency	ETAth
Total efficiency	EFF (EFF = ETAel + ETAth)
Load utilization period expressed as a ratio	NCAP_AFA
Rate of electricity loss to heat gain	CEH
Heat to power ratio	CHPR

Note that if the CHPR (heat to power ratio) parameter is fixed then the production of heat and electricity is in a fixed ratio, as illustrated by Figure 21.

CEH is "the ratio of electricity lost to heat gained" (Maurizio et al., 2008) Gragiulo et al (2008) states that the CEH can be either 0 or 1, for a fixed back pressure set-up. If it is set to 0 then the activity, which is defined as the amount of energy that is produced by the system in a single period, represents electricity generation and the capacity represents electrical capacity. A single period is defined as a discrete unit of time in TIMES, the length of which depends on the time slices used. These time slices can range from a under a day to a year. If the CEH variable, is set to 1 then the activity represents the total energy output and the capacity represents the total capacity (Power & heat).

Condensing cogeneration systems

The next form of cogeneration that can be modelled in TIMES is a condensing turbine. In this system it is not necessary to produce any heat. Therefore all the steam energy can be transformed into electricity or the amount of heat can be adjusted to meet the various heat demands. Therefore you can exchange heat for electricity and electricity for heat. Figure 22: shows a condensing combined heat and power characteristic curve.

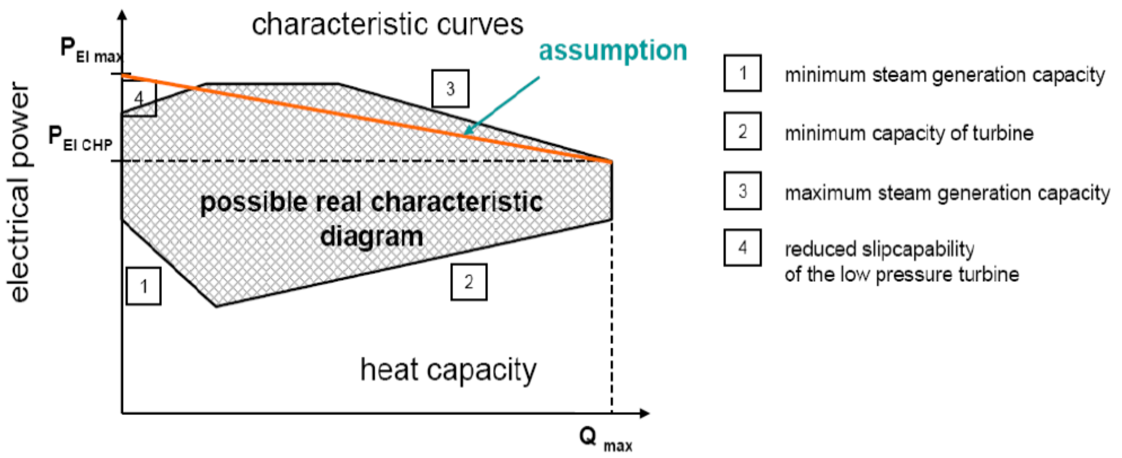


Figure 22: Heat to power relationship of a condensing steam turbine cogeneration system

Source (Maurizio et al., 2008)

Figure 22: illustrates that there is some freedom as to what ratio and quantity steam and heat can be produced. This is illustrated by the large shaded area on the curve.

Condensing systems must therefore be described differently to back pressure systems. In order to model this kind of process, first the CEH parameter must be between zero and one or greater.

<= 1: electricity loss per unit of heat gained,

>= 1: heat loss per unit of electricity gained.

The second group of parameters that are required are efficiencies. Efficiencies change depending on the specific output of a system at any one time. Efficiency is defined at a particular point on the power curve. Therefore it must be specified either at the condensing point, where all energy is converted into electricity or at the back pressure point where no more electricity can be mislaid for process heat gains. These two points are illustrated on Figure 23: .

A maximum value of heat to power ratio must be specified, but a minimum can also be specified (Where you can exchange no more heat for electricity) in Figure 23: only a max has been specified hence the ability for no heat to be produced.

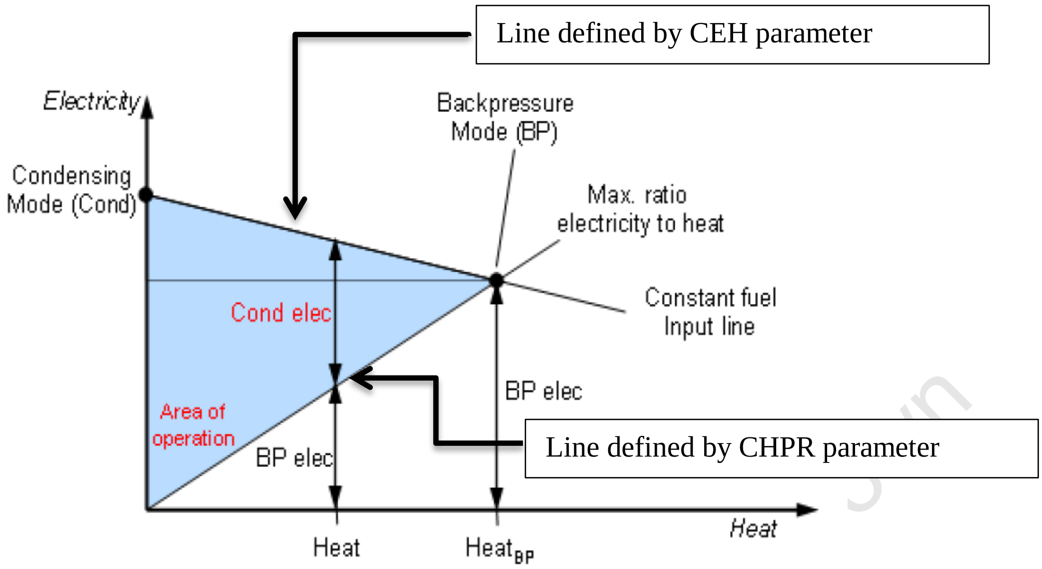


Figure 23: Heat to power relationship of a condensing steam turbine cogeneration system in TIMES

Source (Maurizio et al., 2008)

It should be noted that Figure 23: is actually the same as Figure 22: except with the extremes (the vertices of the triangle) cut off. This eliminates the extreme cases and makes the graph more realistic. In TIMES the simpler case is assumed.

The parameters to describe a condensing system are tabulated in Table 7

Table 7: TIMES condensing steam turbine cogeneration system input parameters

Efficiency:	EFF = ETAel
Heat to power ratio upper bound (slope of CHPR defined line)	CHPR~UP = ETAthBP/ ETAelBP
Unit of electrify lost per unit heat gained	VDA_CEH = (ETAel – ETAelBP)/ETAthBP
Load factor (electricity)	AFAC~ELC
Load factor (heat)	AFAC~HEAT

Source: (Maurizio et al., 2008)

For the condensing cogeneration processes Gargiulo et al (2008) states that one could also use commodity specific efficiency, this is important when multiple fuels are inputted, that have different efficiencies.

3 METHOD

The following methodology has been designed in order to solve the research questions proposed in Chapter 1. It will draw on the experience of other studies and literature in the field of cogeneration research. This methodology will determine both the technically achievable cogeneration potential in SA as well as the economic potential under various economic scenarios.

3.1 Overview

The methodology adopted in this study with the express purpose of solving the research questions is outlined below and illustrated in Figure 24

1. Determination of current cogeneration penetration in SA.
2. Determination of which cogeneration technologies and which fuels are suitable for industries in SA.
3. Determination of the heat requirements of SA industry and the use of this data to determine potential for cogeneration from conventional fossil fuels.
4. Determination of the fuel restrictions on waste based cogeneration technologies and the use of this to determine technical potential from waste materials.
5. Inputting of both waste based technology and fossil fueled technologies into the SATIM model to estimate economic potential of cogeneration.
6. Scenarios based on varying parameters will be projected in the TIMES model to analyse the economic potential cogeneration under different economic conditions. The scenarios are:
    a. Reference case.
    b. High discount rate.
    c. Low discount rate.
    d. Introduction of a carbon tax.
    e. Introduction of a cogeneration subsidy

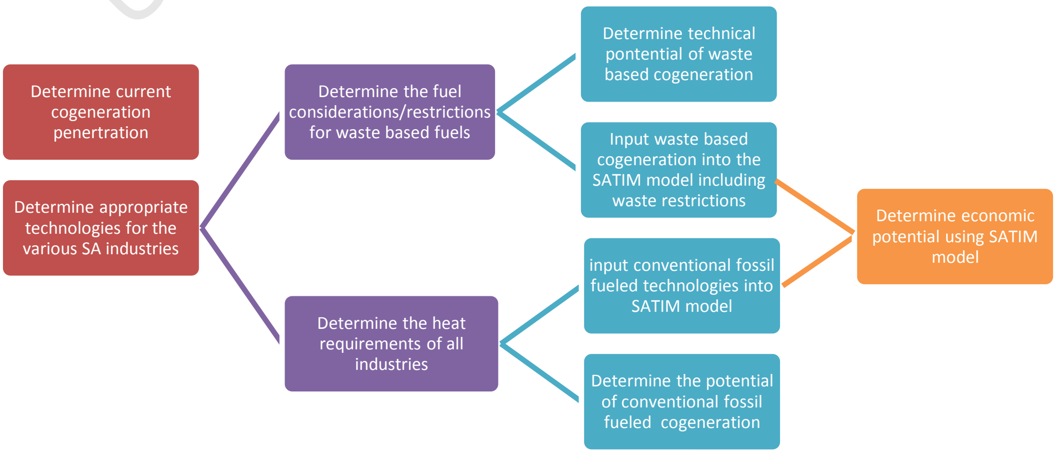


Figure 24: General methodology

3.2 Estimation of current cogeneration penetration in SA

3.2.1 Introduction

Estimation of current cogeneration usage is challenging in S.A as there are a number of barriers. These include reluctance of industry specialists to participate in data capture and the lack of prior research into the area. A further difficulty is the widespread nature of the sources of cogeneration which make broad research difficult. Finally conflicting reports can pose a problem in determining the true extent of cogeneration. The next section will document the method and results of the study into current cogeneration penetration in SA.

3.2.2 Method

Data on current cogeneration capacity was collected through personal communication with industry players and a review of relevant publications. Using these, a catalogue of current cogeneration installations was compiled. This section's evaluation of current cogeneration usage is divided up into industrial sectors.

3.2.2.1 Pulp and paper

The Sappi Stanger mill is reported to produce process heat and electricity from biomass wood waste. It also uses coal as a feedstock (ERC, 2010). However Oberholzer (2012) contradicts this as he states that "Stanger Mill has no power generation. Power is currently only generated (all cogeneration) at Ngodwana and Saiccor." Oberholzer goes on to say that there is capacity for more cogeneration but potential is dependent on the power purchasing price from Eskom. There is wood waste available for cogeneration but this must be balanced against leaving some waste in the plantations as natural cover and soil replenishment. Using more waste must also be balanced against boiler efficiencies. In other words coal offers higher efficiencies than wood waste (Oberholzer, 2012).

Oberholzer's figures contradict the raw data for the SATIM (2012) model. The model data from the ERC (2012) states that Stanger's cogeneration capacity to be 155MW of electricity. However Oberholzer states that Sappi Ngodwana has active capacity of 80 MW with a total capacity for 100MW, and Sappi Saiccor currently uses 40 MW with a total capacity for 55MW. Long (2008) supports this figure, by recording 46MW capacity at the Saiccor Mill (Long, 2008). This would indicate that the 155 MW figure is in fact the total for Saiccor and Ngodwana and not for the Stanger mill as recorded by the ERC (2012).

In terms of Mondi facilities the ERC (2012) records that the Mondi Merebank mill has a cogeneration system that produces heat and electricity from biomass wood waste. The quoted electrical capacity is 50 MW. Mondi mills are also quoted as having cogeneration systems online; Mondi Felixton has an inputted electrical cogeneration capacity of 10MW. Mondi Umlathuze is recorded to have a 13 MW system. Both utilize biomass wood waste and coal as feed stock. (ERC, 2012)

The sum of the capacities in the pulp and paper industry is 228MW. This is in line with data found in the SATIM model for cogeneration from coal and biomass.

3.2.2.2 Petrochemicals

Mossgas refinery uses natural gas to produce heat and electricity using combined cycle technology and produces 90 MW of electricity. Some exhausted steam is utilized for processes (ERC, 2012).

3.2.2.3 Food and Beverage

The SATIM model data set also states that there is a capacity of 100MW of electricity cogeneration in the sugar sector. Here biomass bagasse is used as feedstock. In SA sugar mills Tongaat Hulett Sugar currently generates 9MW of cogenerated electricity from Maidstone, Felixton and Amatikulu mills (Tongaat Hulett Suger, 2011).This is most likely incorporated in the 100 MW sugar industries value. However no evidence supporting the 100MW SATIM figure is present. This suggests that the SATIM figure is wrong and should be revised to the 9MW amount.

3.2.2.4 Industries with negligible cogeneration development

There are four industrial sectors in the SA economy that have no cogeneration capacity at present. These include the non-ferrous metals sector, the iron and steel sector, the non-metallic industry, and the mining sector. This is partly due to the unsuitability of some of the sectors such as the mining industry as well as economic and institutional barriers such as cost and regulation of the electricity market.

3.2.2.5 Summary

The final estimate of existing cogeneration that includes all data sources is shown in Table 8

Table 8: Current cogeneration use in SA

	Source	**Total electrical capacity (MW)**
Saiccor	(Oberholzer, 2012)	55
Ngodwana	(Oberholzer, 2012)	100
Mondi Merebank	(ERC, 2010)	50
Mondi Felixton	(ERC, 2010)	10
Mondi Umhlathuze	(ERC, 2010)	13
Biomass bagasse	(Tongaat Hulett Suger, 2011)	9
Mossgas	(ERC, 2010)	90
TOTAL		**327**

3.3 Analysis of suitable cogeneration technologies

3.3.1 Introduction

Section 2.3, *Potential sources of cogeneration,* discussed the potential sources of cogeneration in SA and section 2.2, *Cogeneration technologies,* discussed the various technological options available around the world. This chapter will combine lessons learnt in the aforementioned chapters and determine what kind of systems will be suitable for SA industries into the future.

Furthermore this chapter will examine the cost of these options in order to inform choices about which cogeneration technologies should be assumed for each industry in this study. To examine the costs associated with these options a levelised cost of electricity (LCOE) analysis will be presented. In this process the capital costs, operational and maintenance costs and fuel costs of each process will be annualised and levelised over the life time of each technology. This process will result in a value for the cost of generating of one kWh of electricity for each technology. The sensitivity of technologies to differing discount rates and changes in costs are also of importance and will be examined through this analysis.

Results from this study will inform choices about which technology's total potential capacity will be examined.

3.3.2 Method

Firstly the cogeneration technologies that have been shown to have potential in SA were selected. The technological options and their reasons for selection are tabulated in Table 9. The systems are broad and do not apply to any particular sector. These systems are the building blocks of sector specific systems. For example waste steam cogeneration is examined and will be applied later to several sectors including the cement industry and the aluminium sector. This is done as the broad technology costs and characteristics will not change between SA industries. Actual cost will differ between industries and facilities; however this analysis will give a broad estimated of cogeneration costs.

Table 9: Attributes and potential sector placement of cogeneration sytems

Technology	Attributes	Potential sector
Open cycle gas (natural gas) turbine cogeneration	Suitable for a variety of cogeneration applications. Natural gas cogeneration is a flexible and relatively easy technology to install. Mature technology. Open cycle configuration is best suited to facilities where the power to heat ratio is lower i.e. more heat is needed.	All
Combined cycle gas (natural gas) turbine cogeneration	Mature technology. Run on a variety of liquid fuels. Suited to applications that need more electricity than heat.	All
Fossil (coal) fuelled steam turbine cogeneration	Steam turbines can run on a variety of fuels. This means that there are a variety of systems that can be installed. This technology is mature and highly efficient. Coal is a cheap fuel that can be used and common in SA. SA has large coal reserves and massive infrastructure to refine and supply industrial coal. For these reasons steam powered cogeneration is an attractive option.	All
Waste fueled steam turbine cogeneration e.g bagasse	Steam turbines can run on a variety of fuels, for this reason they are attractive for waste fuels such as bagasse.	The sugar cane industry as shown by Pandya (n.d) as well as the cement industry as shown by Zhejiang Energy Research (2005)
Waste heat steam turbine cogeneration (bottoming cycle steam turbine)	Steam turbines can run on a variety of fuels, for this reason they are attractive for waste heat applications.	The cement industry as shown by Zhejiang Energy Research (2005). The SA aluminium industry as it produces some waste heat.
Waste fueled internal combustion engine cogeneration	Suitable for waste methane and off-gas cogeneration.	SA iron and steel industry could make use of internal combustion engine cogeneration systems that could be powered by furnace off-gas (Gottschling ,2011). Waste methane from municipal waste water treatment and onsite brewery waste water treatment could be utilized in an internal combustion engine

The cost characteristics of the cogeneration technologies were sourced. Super critical coal power and coal boilers were also considered. They will act as a base line for comparing cogeneration to conventional heat and power generation. These costs include the capital costs, operation and maintenance cost (O&M) costs and fuel costs of the various technologies. The expected life time of each technology was also sourced.

In the case of cogeneration technologies a number of sources were combined in order to arrive at single figures for each technology. For example several figures for overnight capital cost of natural gas cogeneration were aggregated to arrive at a single value. The combinations of costs are tabulated in Table 10

One difficulty is that some sources included the costs of boilers and others did not. Therefore in these cases boiler costs had to be added in the proportion of their power to heat ratios e.g. if a cogeneration steam turbine produces 1kW of electricity with a heat to power ratio of 1:5 one would add the overnight capital costs of five 1 kW boilers. The calculations of the various individual costs for cogeneration systems are tabulated in Table 10: Basic cost characteristics of cogeneration systems applicable to SA.

Table 10: Basic cost characteristics of cogeneration systems applicable to SA

Type	Capital Cost ($/kW electrical capacity)	Comment	Boiler cost ($/kWheat)	Total cost ($/kW e)	Average ($/kW e)	Heat to power ratio	Investment $/kW total energy capacity	Average $/kW total energy	Fixed cost $/kW electrical capacity	Fixed cost $/kW total energy capacity	Variable $/kWh electrical	Average $/kWh electrical	Sources
Steam turbine coal	1075	boiler included		1075	3063	5.19	174	495	6.55	1.06	0.006	0.004	1
	1500	boiler included		1500		5.19	243						2
	1350	boiler included		1350		5.19	218				0.003		3
	550	no boiler	738	4379		5.19	708				0.004		4
	385	no boiler	738	4214		5.19	681						5
	349	no boiler	738	4178		5.19	675						5
	918	no boiler	738	4747		5.19	767						5
Gas turbine open	510	open		510	921	2.27	156	282	0.32	0.10	0.003	0.006	1
	1200	Micro turbine		1200		2.27	367						2
	625			625		2.27	191				0.007		3
	1350			1350		2.27	413				0.009		4
Gas turbine combined	515			515	570	2.27	158	174	5.25	1.61	0.004	0.005	1
	625			625		2.27	191				0.007		3
IC Engine	475			475	900	2.24	146	278	7.00	2.16	0.008	0.012	1
	1000			1000		2.24	308						2
	1000			1000		2.24	308						6
	875			875		2.24	270				0.011		3
	1150			1150		2.24	355				0.017		4
Steam turbine biomass	1075	boiler included		1075	1540	5.19	174	249	6.55	1.06	0.006	0.004	1
	1500	boiler included		1500		5.19	243						2
	1350	boiler included		1350		5.19	218				0.003		3
	550	no boiler	224	1713		5.19	277				0.004		4
	385	no boiler	224	1548		5.19	250						5
	349	no boiler	224	1512		5.19	244						5
	918	no boiler	224	2081		5.19	336						5
Steam turbine bottoming	825			825	825	5.19	133	133	2	0	0.006	0.004	1

Sources: 1. (princeton, nd) 2. (climatetechwiki, n.d) 3. (UNEP, n.d.) 4. (Department of Minerals and Energy, 2005) 5. (turbinesinfo, n.d)

The final technical and economic characteristics of the various technologies are shown in Table 11 these final costs were arrived at by averaging costs from different sources.

Table 11: Cost components and technology characteristics of cogeneration systems for SA

Types	Lead time	Source	IDC	Plant life	Source	Overnight Investment Costs of electrical capacity (turbine)	Overnight Investment Costs of boiler capacity	Source	Fixed Costs	Fixed costs of boiler running	Source	Variable O & M costs (switch c)	Source	Efficiency	Electrical efficiency	Thermal efficiency	Heat units for every one electrical unit (heat to power ratio)	Source	Fuel price	source
	Year					US$/kWe	US$/kWth		US$/kWe/yr	US$/kWth/yr		US$/kWh electrical							US$/kWh-in	
Supercritical Coal	4	1	1.22	30	1	1740		1	45.0		1	0.006	1	0.37	0.37			1	0.0007	1
Coal driven back pressure steam cogeneration	2	2	1.12	30	2	3063.07			6.6			0.004	2	0.80	0.14	0.66	4.89	3	0.0007	1
Waste heat driven back pressure cogeneration	2	2	1.12	30	2	825.00			1.6			0.005	2	0.80	0.14	0.66	4.89	3		
Waste fuel driven back pressure cogeneration	2	2	1.12	30	2	1539.81			6.55			0.004	2	0.80	0.14	0.66	4.89	3		
Waste fueled internal combustion cogeneration	2	2	1.12	20	2	900			7.0			0.012	2	0.70	0.39	0.32	0.82	3		
Natural gas driven open cycle cogeneration	2	2	1.12	20	2	921.25			0.3			0.006	2	0.73	0.33	0.40	1.23	3	0.0227	1
Natural gas driven combined cycle cogeneration	2	2	1.12	20	2	570			5.3			0.005	2	0.77	0.43	0.34	0.80	3	0.0227	1
Coal fueled boiler	1		1.08	30	6		738	4		278.5	4			0.64		0.64		5	0.0007	1

1: (Eskom Supply data, 2012) 2: table above 3: (ESRU,1998) 4: (PEDCo Environmental inc, 1979) 5: (SATIM, 2012) 6: (Merven,2012) 7: (ERC, 2010)

8. (aurecon, 2010), (anon, 2003)

The separate costs of the cogeneration technologies were then levelised using Equation 2 to determine the levelised cost of electricity generation (LCOE). An 8% discount rate was used in line with the IRP estimates. The levelised cost was calculated for a variety of capacity factors. This was done for two reasons. Firstly the true capacity factor of a future technology is unknown as the demand on the process may vary. Secondly the cost of energy production varies greatly depending on the capacity factor assumed and therefore technology costs need to be compared at differing capacity factors.

LCOE was calculated in Rands per kWh of total electricity produced. In the case of cogeneration the total cost was levelised in terms of total electricity production. Thermal production was treated as a revenue source. The values of thermal revenues/compensation were based on the cost of producing heat from coal. In other words the production of heat by a cogeneration system would replace the cost of producing heat with a separate boiler. The cost of producing heat in a coal boiler was chosen as the base line for thermal compensation. Coal boiler costs were used due to the fact that they are the most common boiler types in SA and therefore represent the cost of process heat in SA. The value of this compensation was calculated based on the levelised cost analysis of the coal boiler at the respective operating capacity. In other words if the cogeneration plant was operating at a 50% capacity factor the values of thermal revenue compensation would be based on the cost of coal boiler generated heat at a capacity factor of 50% and so forth.

Equation 2

$$LCOE = \sum_{1}^{t} \frac{PMT_t + O\&M_f}{(365 \times 24) \cdot f} + \frac{fuel_t}{E} + O\&M_v - R_{th}$$

$$PMT_t = \left(r + \frac{r}{(1+r)^t - 1}\right) \cdot PV \cdot IDC$$

Where:

$LCOE$:	Levelised cost of energy (\$/kWh)
PMT_t :	Payments on capital loan in year t (\$/kW)
PV:	Present value of loan repayment (\$)
IDC	Interest during construction
$O\&M_f$:	Fixed operation and maintenance cost for year t (\$/kW)
$O\&M_v$:	Variable operation and maintenance cost for year t (\$/kWh)
$fuel_t$:	Fuel cost for year t (\$/kWh input)
r:	Discount rate (fraction)
t:	Life time of technology (years)
E	Electrical efficiency (fraction)
f :	Capacity factor (fraction)
R_{th}	Revenue or cost benefit of heat production

Source (Merven, 2011)

The LCOE results for each technology were used to create screening curves. These are curves that represent LCOE at differing capacity factors.

After the screening curves were generated a sensitivity analysis for each process was conducted. Firstly the sensitivity of the technologies to differing discount rates was examined. To do this two more sets of screening curves for each process were generated based on a 2 % increase and decrease on either side of the 8% discount rate. Sensitivity of the cogeneration technology's levelised cost to changes in fuel cost was also examined. Screening curves were generated for a 20 % increase and decrease in all fuel costs to determine the sensitivity of the technologies to changes in fuel cost.

The results were then analysed. Technologies were compared with each other based on their costs and sensitivities. This was done in order to identify which technologies were the most economical choices for each SA industry.

3.3.3 Results and discussion

The next section will present the results of the LCOE analysis. Firstly, the comparison of the various technologies under stable economic conditions will be analysed. Secondly, the sensitivity of the processes to changes in the discount rate will be explored. Finally, the responsiveness of each of the technology's LCOEs to changes in fuel price will be examined.

3.3.3.1 LCOE curves

Figure 25 shows the LCOE screening curves for the cogeneration technologies that were outlined as having potential in SA. These are fossil fueled steam turbine cogeneration; waste driven steam cogeneration, both bottoming (waste heat) and topping (waste fuel); natural gas turbine driven cogeneration, both combined and open cycle and the internal combustion engine. Finally supercritical coal electrical generation and coal boilers were included as a means of comparing cogeneration to conventional power and heat generation in SA.

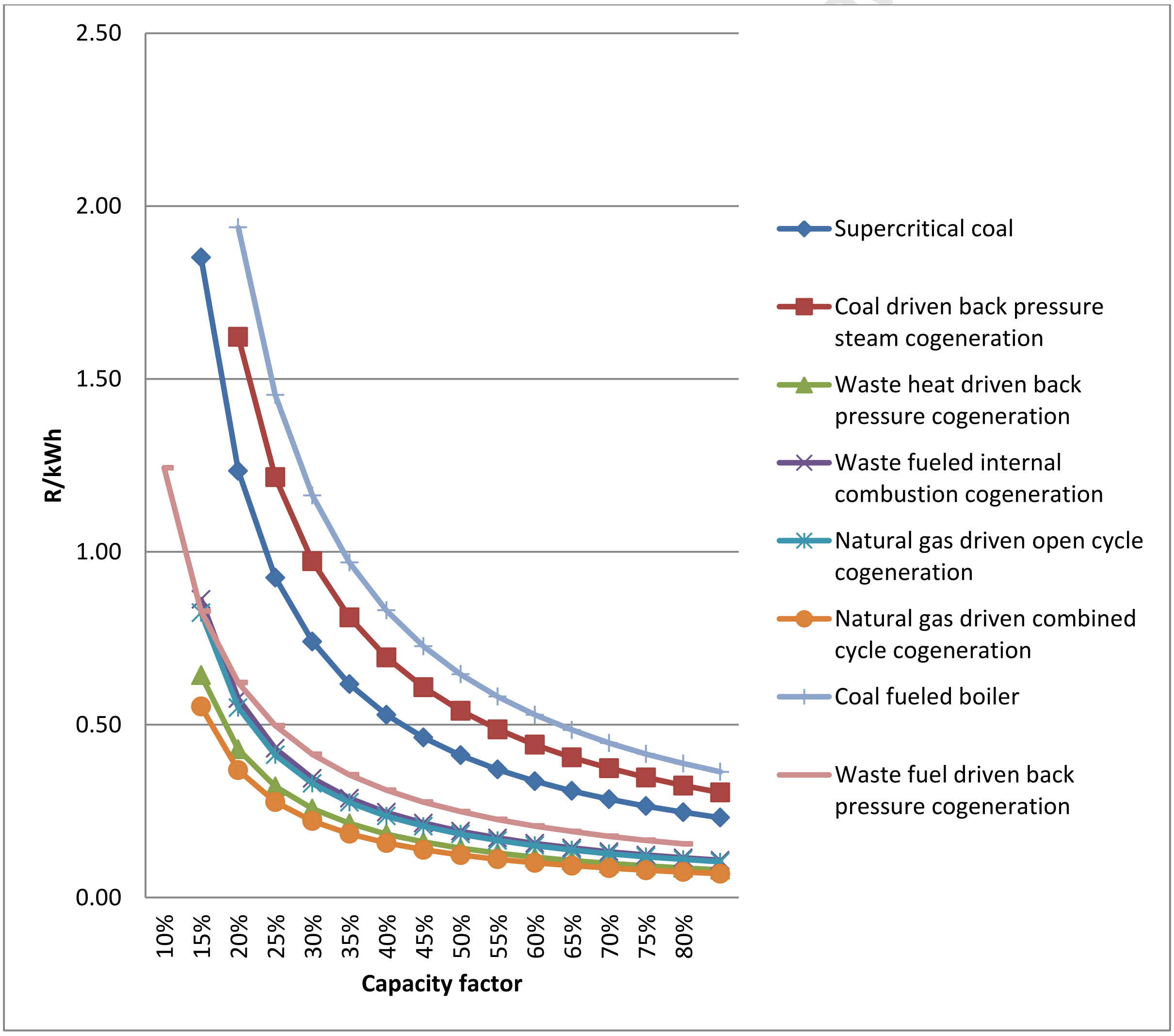


Figure 25: LCOE screening curves

Super Critical Coal is shown to be of average cost. At all capacity factors it remains in the middle of the screening curves. Open cycle gas turbines are found to be more expensive than combined cycle systems. This is attributed to the combined cycle system's high efficiency and higher power to heat ratio making its LCOE lower. In fact it is found to be the most affordable of the all the systems in terms of electricity production. However one of the problems with natural gas systems in SA is that natural gas supply is less secure than coal. Fossil fueled (coal) steam turbine cogeneration is suited to long hours of production because of its low fuel cost. Its screening curve demonstrates this by the sharp reduction in levelised cost from low capacity factors to high factors. However in terms of electricity production coal driven steam turbines are shown to be the most expensive of the cogeneration technologies. This is attributed to their low electrical capacity in cogeneration mode. The LCOE of waste fueled steam cogeneration (both waste heat and waste fuel e.g biomass) reduces drastically from low capacity factors to high factors. The negligible fuel cost makes these very affordable forms of cogeneration. These waste based technologies are expected to have a high potential were waste fuel is available. Waste fueled internal combustion engines are also found to be very affordable. This result is expected as the internal combustion engine has a low capital cost and a low fuel cost as it is expected to be fueled by waste fuels e.g furnace off gas.

The LCOE results give insight into what technologies are suited to which load profiles. The waste based technologies are shown to be the least expensive for long operating hours, due their insignificant fuel cost. Between the two fossil fuel based cogeneration systems (coal and natural gas) coal is shown to be the most expensive while natural gas power is found to be the least expensive. Despite this there are a number of reasons why coal can be considered as more attractive.

The sensitivity of the cogeneration technologies to a 2 % rise and fall in the assumed discount rate was calculated. These results are shown in Figure 26. On each graph two screening curves have been drawn, each generated from a different discount rate. By analysing how much each graph shifts one can determine how sensitive each process is to changes in the discount rate. Figure 26 generally shows little sensitivity to discount rates due to cogenerations low capital costs. The waste based technologies are shown to be somewhat more sensitive to change. This is attributed to the fact that most of their cost comes from capital cost and not fuel (free). Furnace off-gas cogeneration is the most sensitive to discount rate changes. Coal driven cogeneration is shown to be more sensitive to discount rate that natural gas cogeneration.

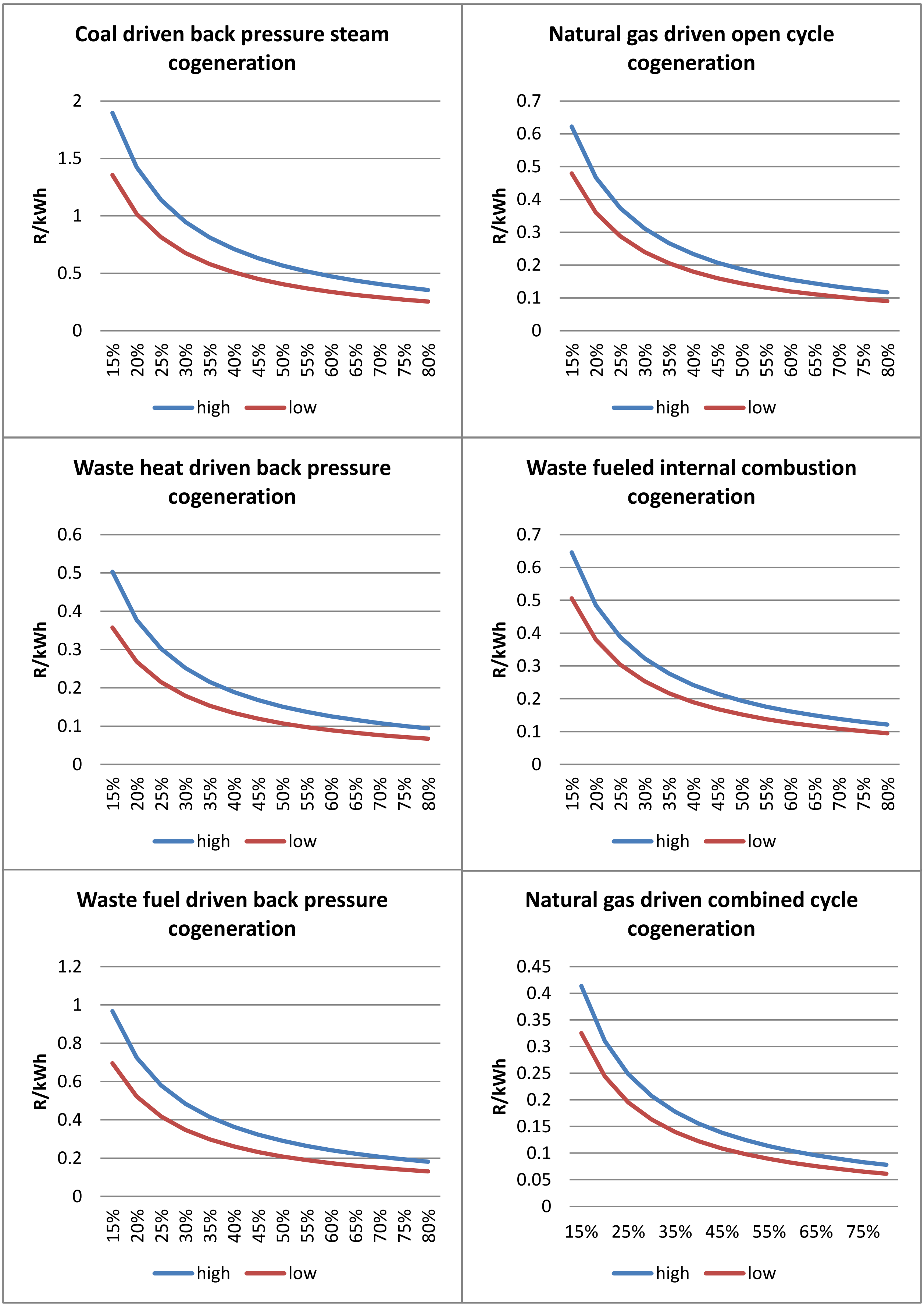


Figure 26: Sensitivity of cogeneration system's levelised cost to discount rate changes

3.3.3.2 Sensitivity to fuel cost change

A further set of results was generated to examine the sensitivity of cogeneration to changes in fuel cost. Three technologies were considered, coal fueled cogeneration and natural gas fueled cogeneration (open and combined). This was done because they are the only three cogeneration technologies that have a significant fuel cost. It was found that the three technology's LCOE had negligible sensitivity to changes in fuel cost. This is attributed to the high efficiencies of cogeneration technologies and the low costs of fuel in comparison to fixed cost, variable cost and capital cost.

3.3.4 Findings

The purpose of this chapter was to compare different cogeneration technologies and finalise which technologies would be attractive in the SA context. The next section will outline which technologies were found to be attractive for each industry and why.

Fossil fueled cogeneration

There are three competitors for fossil fueled cogeneration, coal driven steam cogeneration and natural gas cogeneration, both open and combined cycle.

Natural gas, both open and combined cycle, has been shown to be attractive in many sectors. This chapter has found cost advantages favouring the use of natural gas cogeneration. However coal powered cogeneration has significant advantages in SA industries that the LCOE analysis does not consider. These include:

- Existing coal infrastructure (transport)
- Substantial domestic supply of coal
- Existing use of coal in industry
- Existing coal technologies in industry that could be retrofitted (Coal boilers)
- Existing coal expertise in SA industry.
- Variety of coal grades available.

In terms of existing coal infrastructure it should be noted that this benefit is not even across the country. Areas in close proximity to coal works would enjoy a larger advantage from existing infrastructure while areas far from coal e.g. Western Cape would have less of a benefit. This suggests that coal cogeneration would be less advantageous in certain areas were other technologies would be suitable e.g. Natural gas. These geographical complexities are beyond the scope of this research but must be noted. Nonetheless on a national scale coal cogeneration has a distinct advantage over other technologies in its ability to make use of infrastructure that has been used for many years in comparison to other technologies such as natural gas that would need new infrastructure e.g. gas lines.

In addition a great proportion of SA industries that would make use of coal cogeneration are located in the north of country close to existing infrastructure and coal supply.

The analysis of this chapter has further shown other benefits of coal steam turbine cogeneration. In terms of discount rate coal it is somewhat sensitive but not excessively. Figure 27 shows the difference in levelised cost between a 10% discount rate and a 6% discount rate for both the steam and gas cogeneration. In other words each curve represents the change in cost due to a 4% change in the discount rate. One will note that although steam cogeneration is more sensitive; at high capacity factors which cogeneration will run at, the differences are negligible.

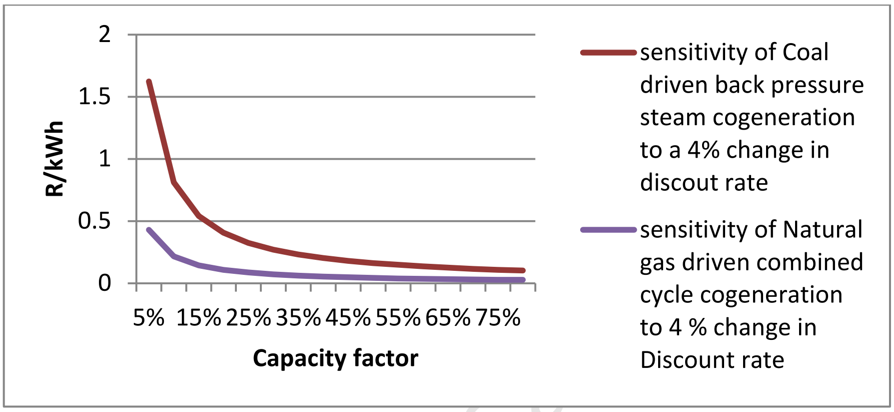


Figure 27: Sensitivity of coal and gas fueled cogeneration to changes in discount rate.

One disadvantage of the coal option is that environmental legislation would hamper its development in populated areas e.g. cities. However much of SA industry is placed well away from populated city centres.

Given the obvious advantages of coal based cogeneration this chapter concludes that coal steam cogeneration can be considered as the most appropriate solution for fossil fueled cogeneration in all SA industries.

Using this conclusion this chapter can finalise the technologies that could be implemented in SA. The final technologies found to be the most appropriate for SA industry are tabulated below along with the reasons for their choice.

Table 12: Final cogeneration technology choices for SA industries

Industry	Technology	Reason for choice
Pulp and paper	Wood waste steam cogeneration	Only waste based option; no sensitivity to fuel cost; low overall levelised cost
Pulp and paper	Coal steam cogeneration	Use of coal advantageous in SA context; existing coal infrastructure and expertise.
Chemicals	Coal steam cogeneration	No suitable waste based cogeneration. Use of coal advantageous in SA context; existing coal infrastructure and expertise.
Iron and steel	Off-gas internal combustion engine	Only waste based option; no sensitivity to fuel cost; low overall levelised cost
Non-metallic minerals	Waste heat steam cogeneration	Only waste based option; no sensitivity to fuel cost; low overall levelised cost
Non-metallic minerals	Coal steam cogeneration	No suitable waste based cogeneration. Use of coal advantageous in SA context; existing coal infrastructure and expertise.
Non-ferrous	Waste heat steam cogeneration	Only waste based option; no sensitivity to fuel cost; low overall levelised cost
Food and beverage	Coal steam cogeneration	Use of coal advantageous in SA context; existing coal infrastructure and expertise.
Food and beverage	Bagasse steam cogeneration	Only waste based option; no sensitivity to fuel cost; low overall levelised cost.
Food and beverage	Waste methane internal combustion engine	Only waste based option; no sensitivity to fuel cost; low overall levelised cost

3.4 Estimation of technical potential

Chapter 3.3 finalised what types of cogeneration can be implemented in SA. This chapter will build on these findings by estimating the technical potential of those technologies in SA. This section describes the methodologies employed by this research to determine the technical potential of cogeneration in the following sectors, pulp and paper; chemicals; food and beverage; iron and steel; non-ferrous metals and the non-metallic minerals sectors.

The technologies that Chapter 3.3 concluded were suitable and viable for SA industries can be broadly divided into two groups based on their fuel input. The first is waste based cogeneration, which includes all cogeneration technologies that would be powered by some form of waste energy, for example bagasse. The second category is conventional cogeneration which includes those technologies that are powered by fossil fuels (coal powered steam cogeneration). This distinction is important as the methods for determining technical potential of each kind are different.

Determination of technical potential of a conventional cogeneration technology is based on determining the heat requirements of the industry and assuming all those demands would be met by the technology. Determination of waste fueled cogeneration is based on calculating the amount of waste fuel available and assuming all waste is used by cogeneration. Hence the availability of waste fuel determines the amount of cogeneration that can be built.

In this chapter the two types of cogeneration will be examined separately. Finally the chapter will combine the two sets of results for technical potential to determine the total potential.

3.4.1 Estimation of technical potential of waste fueled cogeneration

The following section will outline the method used for the estimation of technical potential of waste based cogeneration. This section will first outline the general methodology applied to all waste based cogeneration technologies in order to determine the total technical potential. Then it will outline the individual methods applied to each technology to determine its technical potential.

3.4.1.1 General methodology

This section will outline the general methodology used to calculate the technical potential of waste based cogeneration.

Firstly the amount of waste fuel for the industry in question was quantified. Then assuming all the waste energy would be converted into heat and power by a chosen cogeneration technology as informed by chapter 3.3, the total output energy was calculated. This was done using Equation 3 and Equation 4.

Equation 3

$$E_{th} = E_w(e_{th})$$

Where E_{th} is the thermal energy produced by the system, $E_w$is the waste energy inputted and e_{th} is the thermal efficiency of the system.

Equation 4

$$E_e = E_w(e_e)$$

Where $E_e$is electrical energy produced by the system, e_e is the electrical efficiency of the system.

Thermal and electrical capacity was then calculated using Equation 5and Equation 6

Equation 5

$$C_{th} = \frac{E_{th}}{365 \times 24 \times A}$$

Where C_{th} is the thermal capacity of the cogeneration system; $E_{th}$is the thermal energy outputted from the system and A is the availability factor of the system.

Equation 6

$$C_e = \frac{E_e}{365 \times 24 \times A}$$

Where C_e is the electrical capacity of the cogeneration system; E_e is the electrical energy outputted from the system and A is the availability factor of the system.

3.4.1.2 Pulp and paper

In the pulp and paper industry the technology found to be suitable was waste wood biomass fueled steam cogeneration. The method to calculate technical potential of this technology is outlined below.

Firstly annual paper production figures from Sappi (2011) and Mondi (2012) mills in SA were collected. The quantity of wood waste that would be available for energy generation was calculated. This was done by multiplying the weight of residuals per ton of final wood product that are available for combustion by the total paper production in SA. The value for residuals available to be burned for energy production per ton of wood product was sourced from Weyerhaeuser (2011) for both wood based facilities and cellulose fibre mills. Weyerhaeuser is a North American Wood products firm. It should be noted that SA data on wood residuals would have been ideal however no equivalent SA data was located. Weyerhaeuser's (2011) value for total residual per ton of production was considered appropriate for use in the SA context because both SA operations and North American operations revolve around a common tree type, the pine. Therefore the waste fuel quantities are likely to be similar. Weyerhaeuser (2011) reports that 97 percent of each log in their operations is utilized. This suggests that they run at a high level of resource efficiency. Due to this, SA pulp and paper operations would not need to alter their harvesting operations to access their wood waste as SA operations are assumed to be similarly as efficient as Weyerhaeuser's operations.

A calorific value for industrial wood of 11.9GJ/ton was sourced (anon, 2003). However it has been shown that wood waste energy production in S.A would be dominated by bark wood as supported by Oberholzer (2012). The calorific value was confirmed to be appropriate when compared to John's (2004) figure for bark fuel of 11.1GJ/ton. The total energy that would be contained in the waste bark was then calculated by multiplying the calorific value by the total amount of residual.

The technology characteristics of the appropriate technology choice as finalised in chapter 3.3 were then sourced. The technological characteristics of the steam turbine that would burn the bark are shown in Table 13. The total energy production and capacity was then calculated using Equation 3 Equation 4 Equation 5 and Equation 6.

Finally these steps were applied to extrapolated waste supply values. Waste production quantities were calculated from extrapolated paper production. These projected paper production values were based on value added statistics for the pulp and paper industry sourced from the SATIM (2012) model. In other words paper product growth was assumed to follow value added growth in the industry. These value added statistics were generated from the computerised general equilibrium (CGE) model ESAGE developed by WIDER which projected GDP growth for SA's individual sectors (Channing Arndt, 2011).

Table 13: Data for calculation of technical potential of pulp & paper waste cogeneration

Assumptions		
Quantity of wood waste (pounds per ton of production)	3407	(Weyerhaeuser, 2011)
Calorific value of wood waste (industrial wood) GJ/t	11.900	(anon, 2003)
Electrical efficiency	0.135	(UNEP, n.d.)
Heat efficiency	0.565	(UNEP, n.d.)
Capacity factor	0.800	
Base year for extrapolation	2011	

Table 14: Results of the calculation of technical potential of pulp and paper waste cogeneration

Year	Growth index	Paper Production (kt)	Waste Bark production (kt)	Total Energy content of waste (PJ)	Electrical energy output (PJ)	Thermal energy output (PJ)	Total energy output (PJ)	Total Capacity (MW)	Electrical Capacity (MW)	Thermal Capacity (MW)
2006		2557	3952	47	6	27	33	1305	252	1053
2007		2604	4024	48	6	27	34	1329	256	1073
2008		2578	3984	47	6	27	33	1315	254	1062
2009		2442	3774	45	6	25	31	1246	240	1006
2010		2594	4009	48	6	27	33	1324	255	1069
2011	1.0	2678	4138	49	7	28	34	1366	264	1103
2012	1.0	2777	4292	51	7	29	36	1417	273	1144
2013	1.1	2881	4452	53	7	30	37	1470	283	1186
2014	1.1	2987	4616	55	7	31	38	1524	294	1230
2015	1.2	3100	4791	57	8	32	40	1582	305	1277
2016	1.2	3217	4971	59	8	33	41	1641	317	1325
2017	1.2	3340	5162	61	8	35	43	1704	329	1376
2018	1.3	3469	5361	64	9	36	45	1770	341	1429
2019	1.3	3605	5571	66	9	37	46	1839	355	1485
2020	1.4	3745	5788	69	9	39	48	1911	369	1542
2021	1.5	3888	6009	72	10	40	50	1984	383	1601
2022	1.5	4033	6233	74	10	42	52	2058	397	1661
2023	1.6	4183	6464	77	10	43	54	2134	412	1723
2024	1.6	4342	6710	80	11	45	56	2215	427	1788
2025	1.7	4510	6969	83	11	47	58	2301	444	1857
2026	1.7	4683	7237	86	12	49	60	2390	461	1929
2027	1.8	4861	7512	89	12	51	63	2480	478	2002
2028	1.9	5050	7804	93	13	52	65	2577	497	2080
2029	2.0	5253	8117	97	13	55	68	2680	517	2163
2030	2.0	5469	8451	101	14	57	70	2790	538	2252

3.4.1.3 Food and Beverage

Sugar

Cogeneration in the sugar cane industry is considered highly viable. This is because sugar processing requires considerable amounts of heat and electricity and bagasse is available for use as fuel. This section describes how cogeneration from bagasse in the sugar industry was estimated.

Firstly the sugarcane yield for a number of years was sourced from the South African Sugar Association (SASA, 2011). The amount of bagasse produced was then calculated based on a value for bagasse by-product per ton of sugar cane, sourced from Fond Pre Alternativne Energie (n.d). The use of Fond Pre Alternativne Energie's (n.d) data as opposed to domestic data is not ideal however no local equivalent data was located. It is useful here to note that bagasse yields are proportional to the amount of sugar cane farming. Therefore growth in bagasse supply will be directly related to growth in the sugar cane farming industry. The amount of energy available for cogeneration was then calculated by multiplying total bagasse by the calorific value of bagasse sourced from Fond Pre Alternativne Energie (n.d). .

The amount of heat and power that could be generated from a steam turbine was established. Steam turbine technology was chosen as the most appropriate for this application in chapter 3.3. The cogeneration capacity was calculated using Equation 3 Equation 4 Equation 5 and Equation 6.

This method was applied over the time horizon. This was done by projecting sugarcane production and applying the above methodology to each year. A value for total area used for cane farming (cane/ha) was sourced from Aginfo (2009). These values were used due to their relatively long time span of data (1994 -2009) which reduces the effect of short term undulations in growth. A linear trend line for these growth figures was calculated in excel using linear regression. This linear growth trend was then translated into growth in sugar cane yield sourced from SASA (2011) from the year 2011 until the year 2030.

Assumptions and results of the calculation are presented below.

Table 15: Data for the calculation of technical potential of bagasse cogeneration

Assumptions		Source
Bagasse yield per ton of sugar (kg/ton)	0.25	(FOND PRE ALTERNATÍVNE ENERGIE, n.d)
Calorific value of bagasse (GJ per ton)	17.50	(MIMOVLADNE ENVIRONMENTALNE ORGANIZACIE , n.d)
Power to heat ratio	0.24	(UNEP, n.d.)
Electrical efficiency	0.14	(UNEP, n.d.)
Heat efficiency	0.57	(UNEP, n.d.)
Capacity factor	0.80	

Table 16: Results of the calculation of technical potential of bagasse cogeneration

Year	Cane crushed (tons)	Waste bagasse production (tons)	Total energy content of waste (PJ)	Electrical energy output (PJ)	Thermal energy output (PJ)	Total energy output (PJ)	Total capacity (MW)	Electrical capacity (MW)	Thermal capacity (MW)
1998	22154775	5538694	96.927	13	55	68	2689	519	2171
1999	22930324	5732581	100.320	14	57	70	2783	537	2247
2000	21223098	5305775	92.851	13	52	65	2576	497	2079
2001	23876162	5969041	104.458	14	59	73	2898	559	2339
2002	21156537	5289134	92.560	12	52	65	2568	495	2073
2003	23012554	5753139	100.680	14	57	70	2793	539	2255
2004	20418933	5104733	89.333	12	50	63	2479	478	2001
2005	19094760	4773690	83.540	11	47	58	2318	447	1871
2006	21052266	5263067	92.104	12	52	64	2556	493	2063
2007	20278603	5069651	88.719	12	50	62	2462	475	1987
2008	19723916	4930979	86.292	12	49	60	2394	462	1933
2009	19255404	4813851	84.242	11	48	59	2337	451	1887
2010	18655089	4663772	81.616	11	46	57	2265	437	1828
2011	16015649	4003912	70.068	9	40	49	1944	375	1569
2012	20407062	5101766	89.281	12	50	62	2477	478	1999
2013	20467303	5116826	89.544	12	51	63	2485	479	2005
2014	20527543	5131886	89.808	12	51	63	2492	481	2011
2015	20587784	5146946	90.072	12	51	63	2499	482	2017
2016	20648024	5162006	90.335	12	51	63	2506	483	2023
2017	20708264	5177066	90.599	12	51	63	2514	485	2029
2018	20768505	5192126	90.862	12	51	64	2521	486	2035
2019	20828745	5207186	91.126	12	51	64	2528	488	2041
2020	20888986	5222246	91.389	12	52	64	2536	489	2047
2021	20949226	5237307	91.653	12	52	64	2543	490	2053
2022	21009467	5252367	91.916	12	52	64	2550	492	2058
2023	21069707	5267427	92.180	12	52	65	2558	493	2064
2024	21129947	5282487	92.444	12	52	65	2565	495	2070
2025	21190188	5297547	92.707	13	52	65	2572	496	2076
2026	21250428	5312607	92.971	13	53	65	2580	497	2082
2027	21310669	5327667	93.234	13	53	65	2587	499	2088
2028	21370909	5342727	93.498	13	53	65	2594	500	2094
2029	21431149	5357787	93.761	13	53	66	2602	502	2100
2030	21491390	5372847	94.025	13	53	66	2609	503	2106

Bagasse is already extensively used in SA and there is limited room for growth in terms of both improved utilization and increased farmland. It is possible however that better farming and harvesting practices could see an increase in bagasse supply. Furthermore the market is relatively volatile as illustrated by the drop between 2006 and 2011. The volatile nature of the past yields makes choosing an appropriate base year for extrapolation difficult as changing the base year can have a dramatic effect on final growth. Given these uncertainties in bagasse availability the modest growth rate is appropriate.

Breweries

Breweries have been shown to have the potential for biogas produced from waste water. According the Burton et al (n.d.) there is a total potential thermal capacity of 17MW that can be developed from SA breweries. The following section describes the method used to determine cogeneration potential from brewery waste water.

First the total waste methane energy that could be produced from the waste water through digestion was calculated. This was done with Equation 7

Equation 7

$$E_w = P \times w_i \times COD_i \times COD_{Cal}$$

Where E_w is the total potential waste methane energy stored in the waste water(MJ); P is the total beer production in SA (litres); w_i is the amount of waste water per litre of beer (litres); COD_i is the amount of COD in kg/litre (chemical oxygen demand) per litre of waste water. COD is the chemical component of organic waste that produces methane in a digestion process. It is therefore the main determinant of how much methane; waste water can produce in a digester. COD_{Cal} is the calorific value of the waste water in MJ/kg.

Secondly the internal combustion engine's technology characteristic, sourced from UNEP (2012) together with the total waste methane available were inputted into, Equation 3, Equation 4, Equation 5 and Equation 6 to determine how much cogeneration could be developed. The internal combustion engine was shown to be suitable for brewery waste methane cogeneration in chapter 3.3.

Finally these calculations were applied to deduced beer production figures based on a 4.6 % growth in the brewing industry (SAB miller, 2012).

Results and assumptions are presented bellow

Table 17: Results of the calculation of technical potential of brewery waste methane cogeneration

	Beer production	Waste water production	COD value of waste water	Total Energy content of waste	Electrical energy output	Thermal energy output	Total energy output	Total capacity	Thermal capacity	Electrical capacity
Units	Billion l	Billion l	kt	PJ	PJ	PJ	PJ	MW	MW	MW
2011	3	10	31	0.5	0.4	0.2	0.2	14	8	6
2012	4	14	41	0.6	0.5	0.3	0.2	19	10	8
2013	5	17	50	0.8	0.6	0.3	0.3	24	13	11
2014	6	20	60	0.9	0.7	0.4	0.3	28	16	13
2015	7	23	70	1.1	0.8	0.5	0.4	33	18	15
2016	8	27	80	1.2	0.9	0.5	0.4	37	21	17
2017	9	30	90	1.4	1.1	0.6	0.5	42	23	19
2018	10	33	100	1.5	1.2	0.7	0.5	47	26	21
2019	11	37	110	1.6	1.3	0.7	0.6	51	28	23
2020	12	40	120	1.8	1.4	0.8	0.6	56	31	25
2021	13	43	130	1.9	1.5	0.8	0.7	61	34	27
2022	14	47	140	2.1	1.6	0.9	0.7	65	36	29
2023	15	50	149	2.2	1.8	1.0	0.8	70	39	31
2024	16	53	159	2.4	1.9	1.0	0.8	74	41	33
2025	17	56	169	2.5	2.0	1.1	0.9	79	44	35
2026	18	60	179	2.7	2.1	1.2	0.9	84	46	37
2027	19	63	189	2.8	2.2	1.2	1.0	88	49	39
2028	20	66	199	3.0	2.3	1.3	1.0	93	51	41
2029	21	70	209	3.1	2.5	1.4	1.1	97	54	43
2030	22	73	219	3.3	2.6	1.4	1.1	102	57	46

Table 18: Data for the calculation of technical potential of brewery waste methane cogeneration

Assumptions	Value	Source
Beer production (billion litres)	3.10	(S. Burton, n.d.)
COD (g/litres)	3.00	(S. Burton, n.d.)
Waste water per beer (litre/litre)	3.30	(S. Burton, n.d.)
Calorific value of COD (MJ/Kg)	15.00	(S. Burton, n.d.)
IC engine thermal efficiency	0.44	(UNEP, 2012)
IC engine electrical efficiency	0.35	(UNEP, 2012)
Base year	2011	

3.4.1.4 Waste water treatment

The method for determining cogeneration from waste water sources is outlined below.

Firstly the total potential waste water generated methane available was determined. According to Burton et al (n.d) the potential methane production rate that can be generated from waste water treatment plants in SA is 1134MJ/s. The paper suggests that the waste water treatment plants would only run at a capacity of 75 percent. This would result in 850MJ of methane energy being produced per second.

The internal combustion engine was chosen as the technology to cogenerate from this methane, based on the findings of chapter 3.3. Technology characteristic for an internal combustion engine, sourced from UNEP (2012) together with the total methane fuel available per year, were inputted into

Equation 3, Equation 4, Equation 5 and Equation 6 to determine how much cogeneration could be built. It was assumed that waste water treatment capacity would not grow over the years but remain static. The assumptions are shown in Table 19.

Table 19: Data for the calculation of technical potential of WWT methane cogeneration

Assumptions	value	source
IC engine thermal efficiency	0.435	(UNEP, 2012)
IC engine electrical efficiency	0.350	(UNEP, 2012)
IC engine capacity factor	0.800	

Results and assumptions are presented below.

Table 20: Results of the calculation of technical potential of WWT methane cogeneration

Waste energy flow available (MJ/s)	Waste energy available annually (PJ)	Energy output (PJ)	Heat energy PJ	Electrical energy PJ)	Total (MW)	Thermal energy (MW	Electrical energy (MW)
850	27	21	12	9	834	462	372

3.4.1.5 Iron and Steel off-gas:

For the iron and steel sector, the potential for cogeneration from furnace off-gas was examined.

Firstly the flows of steel product through the SA iron and steel industry were ascertained. These included flows through the blast furnaces, BOF's, EAF's and Saldana Steel furnaces in SA. These flows were sourced from the South African Iron and Steel Institute (SAISI, 2012). These values were then multiplied by each furnace's off-gas production rate (in cubic meters of gas per ton of steel product). In this way the total amount of off-gas generated at each iron and steel facility was calculated. The total energy in the form of off-gases was then determined by multiplying off-gas amounts by respective calorific values of these off-gases. This process is represented by Equation 8

$$\boldsymbol{E_i = P_i \times I_i}$$

Equation 8

Where E_i is the total energy in form of off-gas from furnace i. P_i is the total product flow through furnace i and I_i is the specific intensity of off-gas production for furnace i.

The internal combustion engine was chosen as the appropriate technology for cogeneration from furnace off-gas as concluded by chapter 3.3. UNEP's (2012) technology characteristics together with the off-gas fuel sources were inputted into Equation 3, Equation 4, Equation 5 and Equation 6 to determine how much internal combustion engine cogeneration could be built.

Finally these steps were applied over a time series of steel production. Value added for the iron and steel industry sourced from the SATIM (2012) model was used as a proxy for steel product growth and applied to steel production values of 2010 up to 2030. The values are based on the CGE model ESAGE developed by WIDER which projected GDP growth for SA's individual sectors (Channing Arndt, 2011).

Calculations

Table 21: Results of the calculation of technical potential of off-gas cogeneration

Year	Growth index	Blast furnace gas by-product (ktons)	Electric furnace gas by-product (ktons)	Correx gas by-product (ktons)	Electric & conarc gas by-product (ktons)	BOF gas by-product (ktons)	Total gas by-product (ktons)	Total energy content (PJ)	Total useful energy after cogeneration (PJ)	Thermal energy (PJ)	Electrical energy PJ)	Capacity total (MW)	Capacity thermal (MW)	Capacity electricity (MW)
2003		4475	1052	707	4301	5083	15.6	54	43	24	19	1688	935	753
2004		4224	1053	734	4456	4950	15.4	56	44	24	19	1732	960	772
2005		4442	953	735	4137	5256	15.5	53	42	23	19	1647	912	734
2006		4436	984	740	4430	5174	15.8	55	43	24	19	1719	953	767
2007		3643	1010	705	4464	4521	14.3	55	43	24	19	1696	940	756
2008		3747	931	461	3651	4504	13.3	44	35	19	15	1376	762	613
2009		3185	829	430	3530	3954	11.9	42	33	18	15	1295	718	577
2010	1.0	3695	986	584	3250	4367	12.9	44	34	19	15	1357	752	605
2011	1.0	3834	1023	606	3372	4531	13.4	45	36	20	16	1407	780	628
2012	1.1	3979	1062	629	3499	4702	13.9	47	37	20	16	1461	809	651
2013	1.1	4133	1103	654	3635	4884	14.4	49	38	21	17	1517	841	676
2014	1.2	4285	1143	678	3769	5064	14.9	51	40	22	18	1573	872	701
2015	1.2	4449	1187	704	3913	5258	15.5	52	41	23	18	1633	905	728
2016	1.3	4620	1233	731	4063	5459	16.1	55	43	24	19	1696	940	756
2017	1.3	4800	1281	759	4221	5672	16.7	57	44	25	20	1762	976	786
2018	1.4	4990	1331	789	4389	5897	17.4	59	46	26	21	1832	1015	817
2019	1.4	5191	1385	821	4566	6134	18.1	61	48	27	21	1906	1056	850
2020	1.5	5398	1440	854	4747	6378	18.8	64	50	28	22	1981	1098	883
2021	1.5	5609	1497	887	4933	6628	19.6	66	52	29	23	2059	1141	918
2022	1.6	5820	1553	920	5119	6877	20.3	69	54	30	24	2137	1184	953
2023	1.6	6035	1610	954	5308	7132	21.0	71	56	31	25	2215	1228	988
2024	1.7	6270	1673	992	5514	7409	21.9	74	58	32	26	2302	1275	1026
2025	1.8	6521	1740	1031	5735	7706	22.7	77	60	33	27	2394	1327	1067
2026	1.8	6781	1809	1072	5964	8013	23.6	80	63	35	28	2489	1379	1110
2027	1.9	7049	1881	1115	6199	8330	24.6	83	65	36	29	2588	1434	1154
2028	2.0	7334	1957	1160	6450	8667	25.6	87	68	38	30	2692	1492	1200
2029	2.1	7634	2037	1207	6714	9021	26.6	90	71	39	32	2802	1553	1250
2030	2.2	7949	2121	1257	6991	9393	27.7	94	74	41	33	2918	1617	1301

Table 22: Data for the calculation of technical potential of off-gas cogeneration

Assumptions		**Source**
Production figures		(SAISI, 2012)
Growth index base year	2010	
Calorific value of BOF off-gas	2000 Kcals/NM3	(Jindal Vijayanagar Steel Limited, 2003)
Calorific value of blast furnace gas	3 MJ/M^3	(anon, 2003)
Calorific value of EAF gas	650-750NM3 contains 7550-8300MJ	(Gajanan Kapure, nd)
Calorific value of Correx gas	2101.4 Kcals/NM3.	(Jindal Vijayanagar Steel Limited, 2003)
BOF off-gas production	80 NM3/ton of crude steel	(Jindal Vijayanagar Steel Limited, 2003)
Blast furnace off-gas production	80m3/ton	(Anon., n.d.)
DC arc furnace off-gas production	650–750 Nm^3/t FeCr	(Gottschling, 2011)
Correx off-gas production	1812 NM3/ton of hot metal	(Jindal Vijayanagar Steel Limited, 2003)
Engine characteristics (SI) efficiency	0.79	(UNEP, n.d.)
Engine thermal efficiency	0.44	(UNEP, n.d.)
Engine electrical efficiency	0.35	(UNEP, n.d.)

3.4.1.6 Non-metallic minerals

Cement:

In this section the calculation of potential waste cogeneration in the cement industry is presented.

Firstly a value for total recoverable waste heat from cement manufacturing was obtained from anon (n.d.). The author states that heat lost from preheater exit gases ranges from 180 to 250 kCal/ kg and that 80 to 130 kCal/ kg of clinker heat is lost from exit gases of the grate cooler. These estimated energy loses were assumed to be recoverable in a waste heat cogeneration system. These energy losses were multiplied by SA cement sales, sourced from the Cement & Concrete Institute (n.d). This was done to calculate the total recoverable heat in the cement industry. Sales were used as a proxy for cement production. This is a safe assumption as SA does not import large quantities of cement therefore sales are equal to production.

Steam driven back pressure turbine cogeneration was chosen as the appropriate cogeneration technology as finalised in chapter 3.3. UNEP's (2012) technology characteristics together with the waste heat fuel source were inputted into Equation 3, Equation 4, Equation 5 and Equation 6 to determine how much cogeneration could be developed.

This methodology was expanded over the time horizon. The method was applied to projected cement production. The extrapolated production trend was produced by applying the industry growth index of the cement industry (sourced from the SATIM (2012) model) to the 2011 production figures from South African cement and concrete institute association. The industry value added figures were used as a proxy for growth in production. The value added figures were indexed to the year 2011. The values are based on the CGE model ESAGE developed by WIDER which projected GDP growth for SA's individual sectors (Channing Arndt, 2011).

Results and Calculations are presented below.

Table 23: Data for the calculation of technical potential of cement waste heat cogeneration

	Minimum	Maximum	average	Source
Waste heat available from preheater (kCal/kg)	180	250	215	(anon, n.d.)
Waste heat from grate cooler (kCal/kg)	80	130	105	(anon, n.d.)
Total waste heat (kCal/kg)	260	380	450	(anon ,n.d.)
Electrical efficiency	0.1350			(UNEP,2012)
Heat efficiency	0.7000			(UNEP,2012)
Capacity factor	0.8			
Power to heat ratio of technology	0.2			(UNEP,2012)

Table 24: Results of the calculation of technical potential of cement waste heat cogeneration

Year	Growth index	Sales (tons)	Total waste heat available (PJ)	Thermal output of cogeneration system (PJ)	Electrical output (PJ)	Total output(PJ)	Total Capacity(MW)	Thermal capacity (MW)	Electrical capacity (MW)
1997		9796891	13.126	9	2	11	434	364	70
1998		9581480	12.837	9	2	11	425	356	69
1999		9001533	12.060	8	2	10	399	335	65
2000		9376977	12.563	9	2	10	416	349	67
2001		9594081	12.854	9	2	11	425	357	69
2002		10219949	13.692	10	2	11	453	380	73
2003		10642854	14.259	10	2	12	472	396	76
2004		12010429	16.091	11	2	13	533	446	86
2005		13212792	17.702	12	2	15	586	491	95
2006		14413290	19.311	14	3	16	639	536	103
2007		15528812	20.805	15	3	17	689	577	111
2008	1.0	14871720	19.925	14	3	17	659	553	107
2009	1.0	15478486	20.738	15	3	17	686	575	111
2010	1.1	16123908	21.602	15	3	18	715	599	116
2011	1.1	16770751	22.469	16	3	19	744	623	120
2012	1.2	17419645	23.338	16	3	19	772	648	125
2013	1.2	18073143	24.214	17	3	20	801	672	130
2014	1.3	18802864	25.192	18	3	21	834	699	135
2015	1.3	19564399	26.212	18	4	22	868	727	140
2016	1.4	20354253	27.270	19	4	23	903	757	146
2017	1.4	21186416	28.385	20	4	24	939	788	152
2018	1.5	22052517	29.545	21	4	25	978	820	158
2019	1.5	22953406	30.752	22	4	26	1018	853	165
2020	1.6	23905605	32.028	22	4	27	1060	889	171
2021	1.7	24895249	33.354	23	5	28	1104	925	178
2022	1.7	25943663	34.759	24	5	29	1150	964	186
2023	1.8	27071616	36.270	25	5	30	1200	1006	194
2024	1.9	28223026	37.813	26	5	32	1251	1049	202
2025	2.0	29416408	39.411	28	5	33	1304	1094	211
2026	2.1	30670989	41.092	29	6	34	1360	1140	220
2027	2.1	31971224	42.834	30	6	36	1418	1188	229
2028	2.2	33352572	44.685	31	6	37	1479	1240	239
2029	2.3	34874650	46.724	33	6	39	1546	1296	250
2030	2.5	36515886	48.923	34	7	41	1619	1357	262

3.4.1.7 Non-ferrous metals sector

Aluminium

In this section the calculation of total cogeneration potential from waste heat in the aluminium sector is determined.

First the total production of aluminium in SA was sourced from anon (2009). The waste heat produced per ton of aluminium product was calculated by dividing the capacity of an Icelandic smelter by the heating potential of the waste heat generated from this plant (Fleer, 2010).

Steam driven back pressure turbine cogeneration was chosen as the conversion technology as suggested in chapter 3.3. UNEP's (2012) technology characteristics together with the fuel sources were inputted into Equation 3, Equation 4, Equation 5 and Equation 6 to determine how much cogeneration could be developed.

The methodology was expanded over the time horizon. The method was applied to extrapolated production figures, produced by applying the projected growth in the non-ferrous metals sector sourced from the SATIM (2012) model (Channing Arndt, 2011), to the 2011 production figures from anon (2009). In other words the projected industry value added was used as a proxy for growth in production.

Results and Calculations are presented bellow

Table 25: Results for technical potential of aluminium sector waste heat cogeneration

Year	Growth index	Aluminium production (tpa)	Total waste heat energy available (PJ)	Electrical energy output (PJ)	Total thermal energy output (PJ)	Total capacity (MW)	Electrical capacity (MW)	Thermal capacity (MW)
2006	1.000	1000000	5.139	0.991	4.148	204	39	164
2007	1.040	1040376	5.347	1.031	4.316	212	41	171
2008	1.079	1079435	5.547	1.070	4.478	220	42	177
2009	1.120	1119728	5.755	1.110	4.645	228	44	184
2010	1.159	1159030	5.956	1.149	4.808	236	46	191
2011	1.202	1201501	6.175	1.191	4.984	245	47	198
2012	1.249	1248751	6.418	1.238	5.180	254	49	205
2013	1.303	1303298	6.698	1.292	5.406	265	51	214
2014	1.358	1357510	6.977	1.345	5.631	277	53	223
2015	1.415	1414840	7.271	1.402	5.869	288	56	233
2016	1.475	1474723	7.579	1.462	6.117	300	58	242
2017	1.539	1539083	7.910	1.525	6.384	314	60	253
2018	1.609	1608700	8.267	1.594	6.673	328	63	264
2019	1.685	1685287	8.661	1.670	6.991	343	66	277
2020	1.765	1764555	9.068	1.749	7.319	359	69	290
2021	1.844	1844173	9.478	1.828	7.650	376	72	303
2022	1.918	1917606	9.855	1.901	7.954	391	75	315
2023	1.984	1983992	10.196	1.966	8.230	404	78	326
2024	2.057	2057092	10.572	2.039	8.533	419	81	338
2025	2.141	2140651	11.001	2.122	8.880	436	84	352
2026	2.229	2228983	11.455	2.209	9.246	454	88	366
2027	2.320	2320380	11.925	2.300	9.625	473	91	382
2028	2.419	2419486	12.434	2.398	10.036	493	95	398
2029	2.521	2520727	12.955	2.498	10.456	513	99	414
2030	2.621	2620760	13.469	2.598	10.871	534	103	431

Table 26: Data for technical potential of aluminium waste heat cogeneration calculation

Assumptions		**Source**
Bayside capacity (tons)	96,000	(anon, 2009)
Hillside capacity (tons)	704,000	(anon, 2009)
Hulamin (tons)	200 000	(anon, 2009)
Power to heat ratio	0.239	(UNEP,2012)
Capacity factor	0.8	(UNEP,2012)
Waste heat potential (PJ/kton steel product)	5.1392E-06 *	(Fleer, 2010)
Electrical efficiency	0.135	(UNEP,2012)
Heat efficiency	0.565	(UNEP,2012)
Base year	2006	

*270,000 metric tons aluminium produced per year at Icelandic steel plant. For this smelter the district heating potential is about 55 MWth therefore waste heat energy production PJ/kton = 5.1392E-06

3.4.2 Estimation of technical potential of conventional fossil fueled cogeneration

The following section will outline the assumptions and calculation steps involved in the estimation of technical potential of fossil fueled cogeneration. This section will first outline the general methodology used to determine technical potential of all fossil fueled cogeneration technologies. Then it will outline the individual methods applied to each viable fossil fueled cogeneration technology to determine total potential.

3.4.2.1 General methodology

The methodology employed to estimate the technical potential of fossil fueled cogeneration involved the following steps.

First the total heat requirements of the sectors were calculated, in all cases this was done by multiplying total production of the industry in question by the thermal energy demand intensity of production in that sector or facility. This process is formulated in Equation 9.

Equation 9

$$E_{th} = p(I_{th})$$

Where E_{th} is the thermal demand of the plant in kWh; p is the total production of a facility or sector in production units (e.g. tons) and I_{th} is the thermal needs (thermal intensity) of the industry or sector per unit of production, expressed in kWh/unit.

All sectors would make use of a coal driven steam turbine, as concluded by chapter 3.3.The technology characteristics of the back-pressure steam turbine are tabulated in Table 26. Back pressure was chosen as its fixed power to heat ratio allows one to have a fixed estimate. Also industries make more use of this version of steam turbine than any other type.

Table 27: Basic technological characteristics of a back pressure steam turbine cogeneration unit

Steam coal cogeneration		Source
Power to heat ratio	0.239	UNEP (2010)
Capacity factor	0.8	

Then it was assumed that cogeneration would supply all the heat demands of the sector in question. Using this assumption the total cogeneration thermal capacity and electrical capacity was calculated. This was done through the application of the Equation 10 and Equation 11.

Equation 10

$$\boldsymbol{MW_{th} = \left(\frac{E_{th}}{8760 \times A}\right)}$$

Equation 11

$$MW_{el} = r(MW_{th})$$

Where MW_{th} is the total potential thermal capacity of cogeneration and MW_{el} is the total potential electrical capacity of cogeneration expressed in MW. r is the power to heat ratio demand ratio of the industry. A is the capacity factor of the system.

Total electrical energy production was then ascertained using Equation 12. Electrical generation is treated as a by-product of thermal generation and therefore is dependent solely on thermal capacity and availability.

Equation 12

$$E_{el} = A(MW_{el} \times 8760)$$

This concept was applied over the time frame of the study to the extrapolated heat demand for each sector. Heat demand was assumed to be linked closely to growth in the industry. Projections of value added growth of the sectors were based on the CGE model ESAGE developed by WIDER which projected GDP growth for SA's individual sectors (Channing Arndt, 2011). These figures were used as a proxy for growth in each sector and used to extrapolate future growth.

3.4.2.2 Pulp and paper

The calculations for the technical potential of coal steam cogeneration in the pulp and paper sector was done in the following manner.

The paper mills in SA were divided into three categories based on the raw material that each mill uses. These are recycled paper, wood and agricultural based (e.g bagasse). Stranger mill falls into this final category as its feed stock is mainly bagasse.

Total heat demand figures were calculated for each mill category using Equation 9. Annual production from Sappi (2011) and Mondi (2012) were sourced from Sappi (2012) and Mondi (2012). Thermal energy demand intensity of their operations was based on Schmitz (2010) values for process heat requirements for different types of mills. The power to heat demand ratio of each mill was then calculated by dividing the electrical needs by the thermal needs.

Then total thermal and electrical capacity of cogeneration that would supply the pulp and paper sector was calculated using Equation 10 and Equation 11. Schmitz (2010) technology assumptions for back-pressure turbines in the pulp and paper industry were used. Schmitz used a 0.92 availability factor and power to heat ratio was of 0.2 (Schmitz, 2008). This data was then used to determine total electrical energy production though Equation 12

The estimation of potential was very sensitive to changes in the power to heat ratio. Therefore the generation potential was calculated again based on the existing power to heat ratios of the industries rather than the 0.2 figure. This was done in order to compare the two results. This would give insight into cogeneration potential if the cogeneration systems were designed to fit the needs of the plants rather than the plants changing to fit existing steam turbine power to heat outputs. It must be noted that although this is feasible the investment cost would increase due to the specialised nature of the cogeneration's design.

The method was applied to extrapolated production figures, produced by applying the projected value added in the pulp and paper sector sourced from Arndt et al (2011), to the 2011 production figures from Sappi and Mondi. In other words it was assumed that value added growth translated into a similar growth in production. Base year was set to 2011.

Results and Calculations are presented below.

Table 28: Production capacity of SA pulp and paper mills

	Mills	Raw feed stock	Production(tpa)
Sappi	Cape Kraft Mill	recycle	59 302
	Enstra Mill	wood	175 949
	Ngodwana	wood	420 674
	Stranger	agro	85 878
	Tugela	wood	290 230
	Sappi Refibre	recycle	0
	Sappi Samcore chemical cellulose	wood	726 411
Mondi	Mondi Richards bay	wood	720000
	Mondi Merebank	wood	219000
Total			2 697 444

Note: Sappi Refibre produces no paper but does produce pulp. It is assumed that its pulp is processed elsewhere; it has therefore been given a zero value for production.

Table 29: Calculation of technical potential of fossil fueled cogeneration in SA pulp & paper

			Power consumption		Thermal Consumption			Power to heat ratio	Thermal load	Cogeneration potential(0.2) electrical Capacity	Total (0.2 Power to heat ratio)	Cogeneration potential electrical capacity (existing power to heat ratios)	Total capacity (existing power to heat ratios)	Electrical output	Total output
	Annual paper production	No of mills	Intensity	Sector wide	Intensity		Sector wide								
Units	tons		kWh/t	GWh/a	Tons steam/ton paper	kWh/ton paper	GWh/a		MWth	MW el	MW	MWel	MW	GWh/a	GWh/a
Wood based	2552264	5	1400	3573	12	8412	21470	0.17	2664	533	3197	443	3107	4294	25764
Agro based (bagasse)	85878	1	1200	103	9	6309	542	0.19	67	13	81	13	80	108	650
Recycling based	59302	2	800	47	5	3505	208	0.23	26	5	31	6	32	42	249
Average	899148		1133	1241	9	6075	7406	0.19	919	184	1103	179	1098	1481	8888
Total	2697444	8	3400	3724	9				2757	551	3308	462	3219	4444	26663

Table 30: Results for technical potential of fossil fueled cogeneration from pulp & paper

Year	Value added	Wood based product (kt)	Agro based product (kt)	Recycled based product (kt)	Total product (kt)	Electricity demand (GWh/a)	Thermal Demand (GWh/a)	Thermal Capacity (MW)	Electrical Capacity (MW)	Total Capacity (MW)	Electricity (GWh/a)	total output (GWh/a)	Thermal output per year (PJ/a)	electricity output (PJ/a)	total energy output (PJ)
2006		2456	101	54	2611	3603	21486	2666	533	3199	4297	25783	77	15	93
2007		2500	105	54	2658	3668	21877	2714	543	3257	4375	26252	79	16	95
2008		2470	108	54	2632	3631	21648	2686	537	3223	4330	25978	78	16	94
2009		2353	89	47	2489	3438	20519	2546	509	3055	4104	24623	74	15	89
2010		2500	94	60	2654	3661	21836	2709	542	3251	4367	26203	79	16	94
2011	1.0	2552	86	59	2697	3724	22219	2757	551	3308	4444	26663	80	16	96
2012	1.0	2647	89	62	2797	3862	23043	2859	572	3431	4609	27652	83	17	100
2013	1.1	2745	92	64	2902	4005	23901	2966	593	3559	4780	28681	86	17	103
2014	1.1	2847	96	66	3009	4154	24784	3075	615	3690	4957	29741	89	18	107
2015	1.2	2955	99	69	3123	4311	25722	3192	638	3830	5144	30866	93	19	111
2016	1.2	3066	103	71	3240	4473	26691	3312	662	3974	5338	32029	96	19	115
2017	1.2	3183	107	74	3364	4644	27713	3439	688	4126	5543	33256	100	20	120
2018	1.3	3306	111	77	3495	4824	28785	3572	714	4286	5757	34542	104	21	124
2019	1.3	3436	116	80	3631	5013	29911	3711	742	4454	5982	35893	108	22	129
2020	1.4	3569	120	83	3772	5208	31074	3856	771	4627	6215	37288	112	22	134
2021	1.5	3706	125	86	3917	5407	32262	4003	801	4804	6452	38715	116	23	139
2022	1.5	3844	129	89	4062	5608	33463	4152	830	4983	6693	40156	120	24	145
2023	1.6	3987	134	93	4213	5816	34707	4307	861	5168	6941	41649	125	25	150
2024	1.6	4138	139	96	4373	6037	36025	4470	894	5364	7205	43230	130	26	156
2025	1.7	4298	145	100	4542	6271	37417	4643	929	5571	7483	44900	135	27	162
2026	1.7	4463	150	104	4717	6512	38857	4821	964	5786	7771	46628	140	28	168
2027	1.8	4633	156	108	4896	6759	40333	5005	1001	6005	8067	48399	145	29	174
2028	1.9	4813	162	112	5087	7022	41898	5199	1040	6239	8380	50278	151	30	181
2029	2.0	5006	168	116	5291	7304	43583	5408	1082	6489	8717	52299	157	31	188
2030	2.0	5212	175	121	5509	7604	45376	5630	1126	6756	9075	54452	163	33	196

3.4.2.3 Chemicals

The calculations for the technical potential of coal steam cogeneration in the petrochemicals sector was done in the following manner.

First capacity figures for the refineries in SA were sourced from Sapia (2011), these are shown in Table 31

Table 31: SA refinery capacity

Capacity of South African refineries (bbl/day)						
Refineries	1992	1997	2007	2009	2010	2011
Sapref	120000	165000	80000	180000	180000	180000
Enref	70000	105000	125000	125000	120000	120000
Chevref	100000	100000	100000	100000	100000	100000
Natref	78000	86000	108000	108000	108000	108000
Sasol	150000	150000	150000	150000	150000	150000
PetroSA	45000	45000	45000	45000	45000	45000

Source: (Sapia, 2011)

An assumption was made that refining capacity was not going to increase over the mid to long term. This was supported by Glass (2012), he stated that refinery capacity was unlikely to increase and supply shortage would be met by imports.

Minimum heat requirements needed for refining were sourced from Dickermans (2011), the total process heat demands of the refineries around the country was determined using Equation 9. The total heating requirements of Sasol were not calculated but sourced from the ERC (2012) Total thermal and electrical capacity was then determined using Equation 10 and Equation 11 and the standard steam turbine characteristics, shown in Table 26. Total electrical energy production was then calculated using Equation 12.

Results and Calculations are presented below.

Table 32: Results for technical potential of fossil fueled cogeneration in SA refining

	Oil refined in SA (m^3/d)	Oil refined in SA (m^3/a)	Thermal intensity of refining (kWh/m^3)	Thermal demand (Gwh/year)	Thermal capacity (MWth)	Electrical Capacity (MW)	Total capacity (MW)	Thermal output PJ/a	Electricity output PJ/a	Total energy output PJ
Sapref	28618	10445466	802.47	8382	1196.1	285.8	1481.9	30.2	7.2	37.4
Enref	19078	6963644	802.47	5588	797.4	190.5	987.9	20.1	4.8	24.9
Chevref	15899	5803036	802.47	4657	664.5	158.8	823.3	16.8	4.0	20.8
Natref	17171	6267279	802.47	5029	717.7	171.5	889.1	18.1	4.3	22.4
Sasol				22414	3198.4	764.2	3962.6	80.7	19.3	100.0
Petrosa	7154.4285	2611366	802.47	2096	299.0	71.4	370.5	7.5	1.8	9.3
			total	48166	6873	1642.2	**8515.3**	**173.4**	**41.4**	214.8

The total amount of energy potentially achievable was calculated to be 214.8 PJ and the total electricity capacity estimated was 1642.2 MW for the year 2011 and onwards (static potential).

3.4.2.4 Food and beverage

Sugar

The calculations for the technical potential of coal steam cogeneration in the sugar sector were done in the following manner. Total heat requirements for the sugar industry were calculated using Equation 9. Production figures were sourced from SASA (2011) and thermal intensity of sugar refining was sourced from Anon (2003) Total electrical energy production was then calculated using Equation 12.

Finally the methodology was applied to projected production figures. These production figures were produced by applying a linear trend to known sugar plantation area values from 1995 to 2009, sourced from AMT (2009). These extrapolated farm area values were then used to calculate the sugar yields by first determining the relationship between farming area to sugar yield and then applying this to the acreage statistics.

Results and Calculations are presented below.

Table 33: Data for the estimation of technical potential of coal cogeneration in sugar sector

Heat requirement GJ/ton	6.1
Capacity factor	0.8
Power to heat ratio	0.24
Electrical efficiency	0.14
Heat efficiency	0.57
Growth rate tons/year	1231.7

Table 34: Results of the technical potential of coal fueled cogeneration in sugar industry

Year	Production sugar (tons)	Thermal demand (PJ)	Electricity output (PJ)	Total output (PJ)	Total Capacity (MW)	Electrical Capacity (MW)	Thermal Capacity (MW)
1998	2403630	14.66	3.50	18.17	1029	198	830
1999	2638156	16.09	3.85	19.94	1129	218	911
2000	2524660	15.40	3.68	19.08	1080	208	872
2001	2721562	16.60	3.97	20.57	1165	225	940
2002	2403243	14.66	3.50	18.16	1028	198	830
2003	2754619	16.80	4.01	20.82	1179	227	951
2004	2412031	14.71	3.52	18.23	1032	199	833
2005	2226869	13.58	3.25	16.83	953	184	769
2006	2500504	15.25	3.64	18.90	1070	206	864
2007	2226853	13.58	3.25	16.83	953	184	769
2008	2273499	13.87	3.31	17.18	973	188	785
2009	2260244	13.79	3.29	17.08	967	187	781
2010	2178450	13.29	3.18	16.46	932	180	752
2011	1909236	11.65	2.78	14.43	817	158	659
2012	2362029	14.41	3.44	17.85	1011	195	816
2013	2369001	14.45	3.45	17.90	1014	196	818
2014	2375974	14.49	3.46	17.96	1017	196	821
2015	2382947	14.54	3.47	18.01	1020	197	823
2016	2389919	14.58	3.48	18.06	1023	197	826
2017	2396892	14.62	3.49	18.11	1026	198	828
2018	2403864	14.66	3.50	18.17	1029	198	830
2019	2410837	14.71	3.51	18.22	1032	199	833
2020	2417809	14.75	3.52	18.27	1035	200	835
2021	2424782	14.79	3.53	18.33	1038	200	838
2022	2431755	14.83	3.54	18.38	1041	201	840
2023	2438727	14.88	3.55	18.43	1044	201	842
2024	2445700	14.92	3.56	18.48	1047	202	845
2025	2452672	14.96	3.57	18.54	1050	202	847
2026	2459645	15.00	3.58	18.59	1053	203	850
2027	2466617	15.05	3.60	18.64	1056	204	852
2028	2473590	15.09	3.61	18.69	1059	204	854
2029	2480562	15.13	3.62	18.75	1062	205	857
2030	2487535	15.17	3.63	18.80	1065	205	859

3.4.2.5 Non-metallic minerals

Cement:

The calculation for the technical potential of coal steam cogeneration in the cement industry was done in the following manner.

Firstly sales figures for cementitious material for the SA were sourced from Cement & Concrete Institute (n.d). These were used as a proxy for production. This is a safe assumption given that little cementitious materials are imported into SA. Then energy intensity for the production of cement was source from UNIDO (2010). These two values were multiplied together to calculate total energy demands of the SA cement industry.

Then using a quantity for the electricity portion of the energy needs for cement manufacturing, sourced from Anon (1994), the proportion of heat and electricity needed in cement manufacturing was calculated.

Then the total technical potential capacity of all cogeneration units were calculated with Equation 10 and Equation 11

Finally these steps were applied over a time series of production. Production was extrapolated based on projected value added for the non-metallic minerals sector indexed to 2008. It was assumed that cement production growth would follow growth in the non-metallic minerals sector. Value added statistics were sourced from Arndt et al (2011)

Results and calculations are presented below.

Table 35: Data for the calculation of technical potential of coal cogeneration in cement sector

Average energy intensity for the production of cement 2007 (kWh/t)	109	(Cement & Concrete Institute, n.d.)
Electricity portion of the energy demands of cement manufacturing	7.6%	(anon, 1994)

Table 36: Results for the technical potential of coal fueled cogeneration in cement sector

Year	Growth index	Sales (tons)	Energy demands (kWh/ton)	Total energy demands (GWh)	Heat demands (GWh)	Electrical output(GWh)	Total output(PJ)	Total capacity (MW)	Thermal capacity	Electrical capacity
1997		9796891	109	1068	987	236	4.4	174	141	34
1998		9581480	109	1044	965	231	4.3	171	138	33
1999		9001533	109	981	907	217	4.0	160	129	31
2000		9376977	109	1022	944	226	4.2	167	135	32
2001		9594081	109	1046	966	231	4.3	171	138	33
2002		10219949	109	1114	1029	246	4.6	182	147	35
2003		10642854	109	1160	1072	256	4.8	190	153	37
2004		12010429	109	1309	1210	289	5.4	214	173	41
2005		13212792	109	1440	1331	318	5.9	235	190	45
2006		14413290	109	1571	1452	347	6.5	257	207	49
2007		15528812	109	1693	1564	374	7.0	276	223	53
2008	1.0	14871720	109	1621	1498	358	6.7	265	214	51
2009	1.0	15478486	109	1687	1559	372	7.0	276	222	53
2010	1.1	16123908	109	1758	1624	388	7.2	287	232	55
2011	1.1	16770751	109	1828	1689	404	7.5	299	241	58
2012	1.2	17419645	109	1899	1754	419	7.8	310	250	60
2013	1.2	18073143	109	1970	1820	435	8.1	322	260	62
2014	1.3	18802864	109	2050	1894	452	8.4	335	270	65
2015	1.3	19564399	109	2133	1970	471	8.8	348	281	67
2016	1.4	20354253	109	2219	2050	490	9.1	362	293	70
2017	1.4	21186416	109	2309	2134	510	9.5	377	304	73
2018	1.5	22052517	109	2404	2221	531	9.9	393	317	76
2019	1.5	22953406	109	2502	2312	552	10.3	409	330	79
2020	1.6	23905605	109	2606	2408	575	10.7	426	344	82
2021	1.7	24895249	109	2714	2507	599	11.2	443	358	85
2022	1.7	25943663	109	2828	2613	624	11.7	462	373	89
2023	1.8	27071616	109	2951	2727	651	12.2	482	389	93
2024	1.9	28223026	109	3076	2843	679	12.7	503	406	97
2025	2.0	29416408	109	3206	2963	708	13.2	524	423	101
2026	2.1	30670989	109	3343	3089	738	13.8	546	441	105
2027	2.1	31971224	109	3485	3220	769	14.4	569	459	110
2028	2.2	33352572	109	3635	3359	803	15.0	594	479	115
2029	2.3	34874650	109	3801	3512	839	15.7	621	501	120
2030	2.5	36515886	109	3980	3678	879	16.4	650	525	125

3.4.3 Summary of results for technical cogeneration potential

The next section will present the results of the estimation of technical potential of cogeneration fueled either by fossil fuels or by waste fuels. Figure 28 below illustrates the projected growth in technical potential of all cogeneration technologies considered from 1997 to 2030.

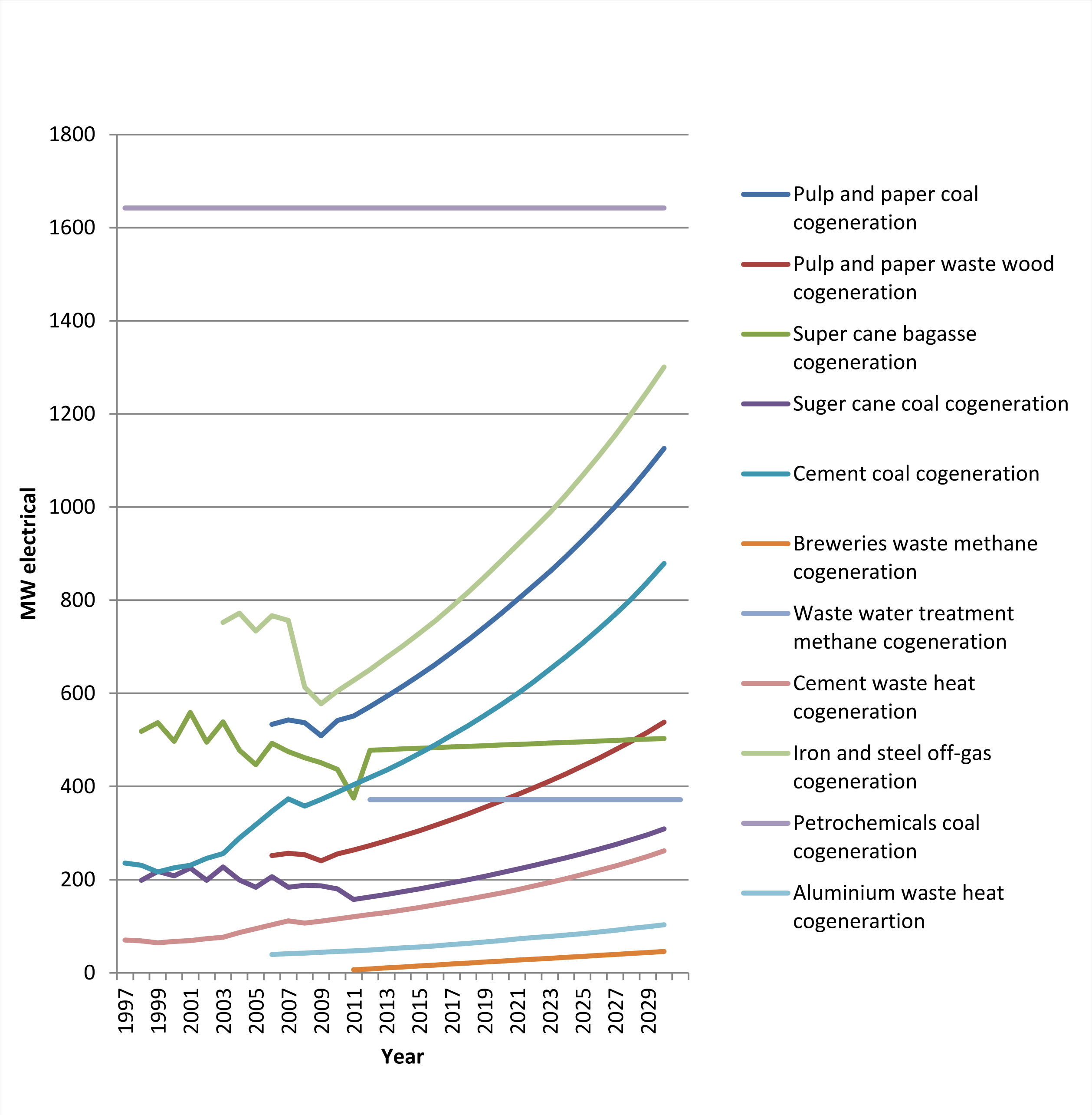
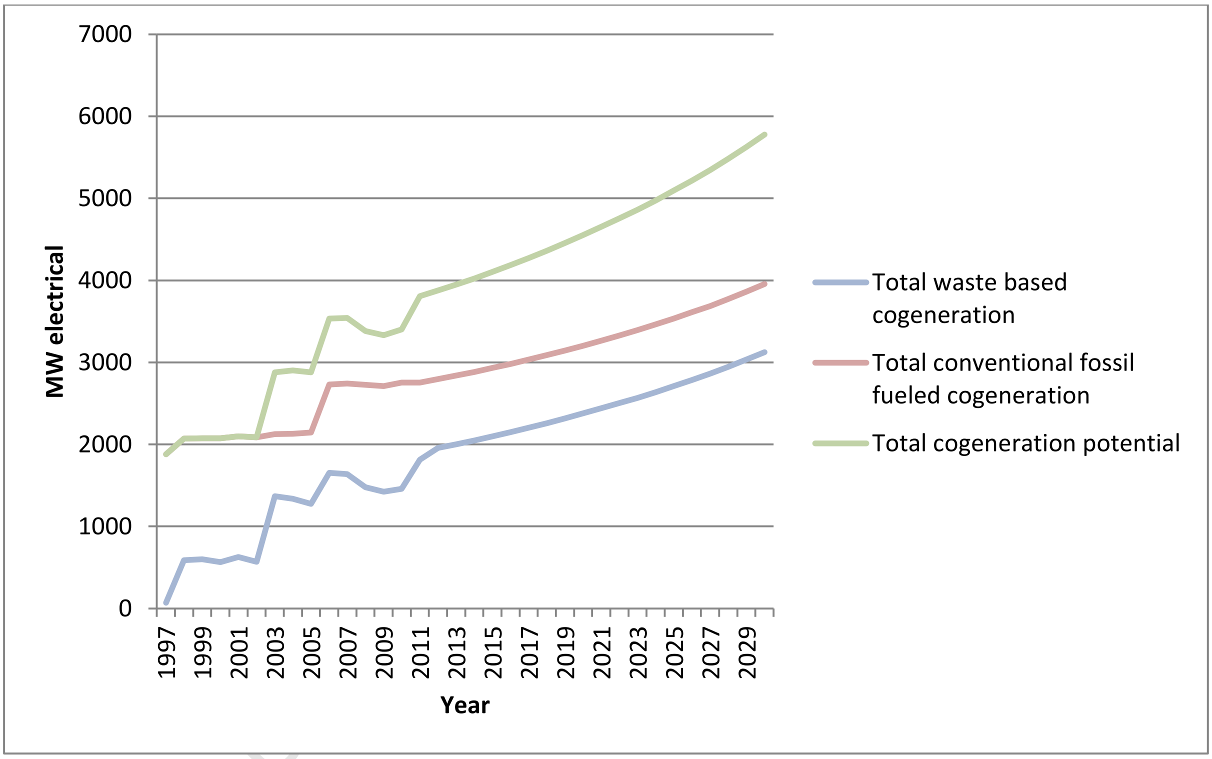


Figure 28: Potential electrical cogeneration capacity in SA by sector

Figure 29 illustrates the growth in total technical potential over the time frame of this study. Three different summations are shown Figure 29. Firstly total waste cogeneration is shown, secondly total conventional fossil fueled cogeneration is shown, and finally total cogeneration potential is shown.

In some sectors waste cogeneration will be able to supply the heat and electricity and therefore limit the development of fossil fueled cogeneration. This is the primary reason for the calculation of total cogeneration potential. Total cogeneration potential is the summation of two items, firstly all fossil fueled cogeneration and secondly all waste cogeneration, in industries where no fossil fueled substitute is available. The fossil fueled cogeneration portion represents the maximum cogeneration potential in their respective sectors, regardless of possible waste sources. This is because it is determined solely by heat requirements. The waste portion represents the extra cogeneration that can be developed in industries that do not have enough heat demand to warrant fossil fueled cogeneration but have waste sources that can be used to cogenerate. This figure therefore represents total technical potential.



Note: The jagged nature the curve is due to the inconsistence of start years for data series.

Figure 29: Potential electrical cogeneration capacity in SA

Figure 30 shows the cogeneration mix by in 2020.

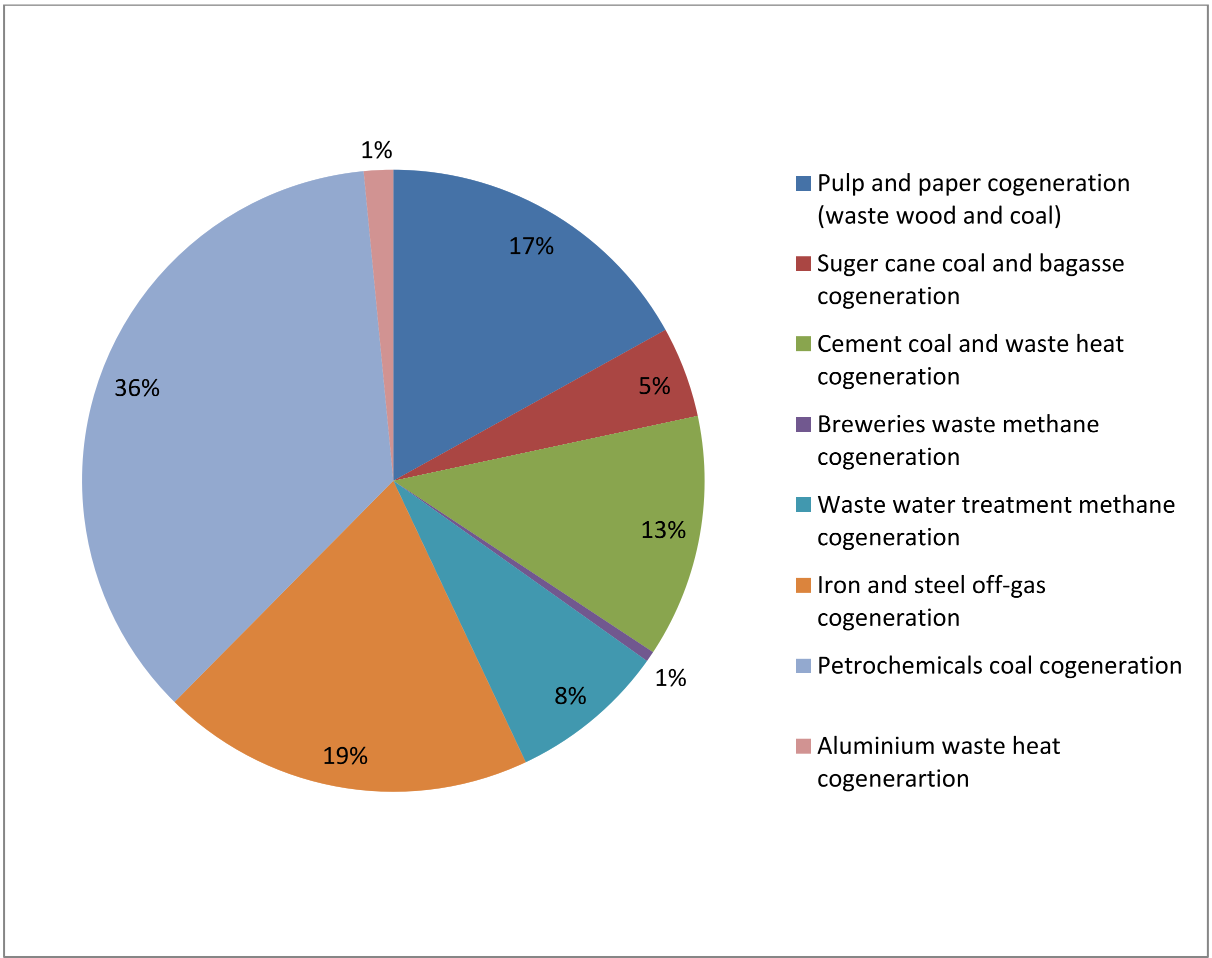


Figure 30: Potenital cogeneration energy mix in 2020

3.4.3.1 Discussion

Figure 29 shows total technical potential by 2020 to be 4.5GW. This is well above the IRP's estimate of 2GW over the next ten years. The vast difference can be attributed to the fact that the IRP estimate is more likely an estimate of total economically achievable cogeneration whereas the 4.5GW potential is pure technical potential and is therefore expected to be significantly higher. Furthermore this research of cogeneration potential is largely based on Arndt et al (2011), sectorial growth. The IRP result is based on a different sectorial growth. Therefore it is possible that these variances in growth rates contribute to the results being different.

One crucial result is that there are large amounts of waste based cogeneration. In the year 2020 it is projected that there will be 2461MW of waste cogeneration potential and 3203MW of fossil fueled cogeneration potential.

One important result is that the waste based cogeneration could supply much of the conventional potential. I.e. the conventional potential was based on meeting the heat demands of industry and the waste based technologies could supply this heat without resorting to fossil fuels.

The situation is made more complicated when considering the fact that some waste fuels have more potential cogeneration than their respective industry can handle. This is the case in the sugar cane industry where cogeneration potential from bagasse by 2020 is projected to reach 489MW while coal cogeneration in this industry can only achieve 215MW. This suggests that not all bagasse could be used in this sector. Altering the power to heat ratio of the technologies so that less heat is produced is one possible solution. However the ratios could not be altered sufficiently to accommodate the extra fuel completely.

It is clear that the limiting factor in the development of cogeneration is the demand for heat and power, specifically heat demands. Altering power to heat ratios and grid sales can accommodate this problem to some extent. One further possibility would be to consider heat exporting by industries. This would greatly improve potential. This has been considered to some extent in the cases of waste based cogeneration where the industries have limited need for heat e.g. aluminium. However heat exportation on a grander scale is not considered. For example if heat could be exported as easily as electricity can be, then cogeneration from bagasse would dramatically increase as it would not be limited by the thermal demands of the sugar industry. Such assumptions are however unrealistic and the total cogeneration result shown in Figure 29 remain an accurate gauge of technical cogeneration potential.

3.5 Estimation of economic potential of cogeneration with times

In this section the methodology for determining economic potential of cogeneration in SA will be outlined.

3.5.1 Method

Economic potential was determined by modelling the cogeneration technologies in the SATIM (2012) model. The modelling process is divided into four parts. First the modelling of cogeneration processes in SATIM (2012); secondly the modelling of competing boilers in SATIM (2012); thirdly modelling the cost of Eskom purchased electricity and finally the generation of scenarios in SATIM (2012) in SA

3.5.1.1 Cogeneration processes in SATIM

First the technology characteristics for each type of potential cogeneration were sourced. The technologies are outlined in chapter 3.3.4: The technology characteristics for these systems are tabulated in Figure 36.

Table 37: Cogeneration input data for SATIM (2012) model

Industry	Technology type	Description	Commodity input efficiency	Fix Output to power ratio	Source	Availability	Source	Investment cost mR/GW	FOM($/kW)	Variable cost mR/PJ	Life time	Source
Pulp & paper	Back-pressure steam turbine	Coal for pulp and paper	0.80	5	*4	0.8	*3	3482.4	8.8	1.6	20	*2
Pulp & paper	Back-pressure steam turbine	Wood waste	0.80	4.18	*1	0.8	*3	3566.2	8.8	1.6	20	*2
Iron and steel	Internal combustion engine	Furnace off-gas	0.79	1.24	*1	0.8	*3	1942.7	7.00	1.99	20	*2
Chemicals (petrochemicals)	Back-pressure steam turbine	Coal for petrochemicals	0.80	4.18	*1	0.8	*3	3566.2	8.8	1.6	20	*2
Non-metallic minerals (cement)	Back-pressure steam turbine	Coal for cement	0.80	4.18	*1	0.8	*3	3482.4	8.8	1.6	20	*2
Non-metallic minerals (cement)	Back-pressure steam turbine	Waste heat from cement	0.80	4.18	*1	0.8	*3	3566.2	2.7	6.99	20	*2
Food and beverage (sugar)	Back-pressure steam	Coal and bagasse generation in sugar sector	0.80	4.18	*1	0.8	*3	3566.2	8.8	1.6	20	*2
Food and beverage (Breweries and waste water treatment)	Internal combustion engine	Waste water from WWT and breweries	0.79	1.24	*1	0.8	*3	1942.7	7.00	1.99	20	*2
Non-ferrous metals (Aluminium)	Back-pressure steam turbine	Waste heat from aluminium	0.80	4.18	*1	0.8	*3	3566.2	2.7	6.99	20	*2

*1: (UNEP, n.d.)*2: LCOE levelised cost analysis (2013) see Table 10

*3: Assumption *4: (Schmitz ,2008)

Note: pulp and paper steam turbine capital cost differ due to a change in the power to heat ratio.

The technologies and their characteristics were inputted into the model. In order to model cogeneration in TIMES six distinct data input process were completed. This input procedure is best understood with reference to the final reference energy diagram, Figure 31.

Firstly commodities that were to be consumed by the waste based cogeneration systems had to be added to the model structure. Bagasse was already present in the SATIM model however the following waste fuel commodities were added.

- Wood residual from pulp and paper
- Furnace off-gas from iron and steel
- Waste heat from cement
- Waste water methane from waste water treatment and breweries
- Waste heat from aluminium process

Then extraction processes that would output the waste based cogeneration commodities were created. These processes would control the supply of the waste commodities. For example furnace off-gas was produced by the furnace off-gas extraction process.

The development of waste based cogeneration in the model could not exceed the technical potential of these technologies as calculated in chapter 3.4.1. The technical potential was therefore limited by total fuel supply in the industry. These fuel restrictions were inputted into each extraction process. These fuel restrictions can be found for each waste technology in chapter 3.4.1

Cogeneration in TIMES cannot output directly to a demand commodity e.g process heat for industry. Therefore intermediate heat commodities had to be created that the cogeneration could supply. In addition to this, new processes that converted the intermediate heat energy into final industrial process heat (demand commodity) were needed. It was assumed that these heat transfer processes had 100% efficiency to simulate onsite usage.

The TIMES model requires the output of cogeneration to be in the form of a commodity group. This is needed so that TIMES can identify the heat and power outputs from each technology and correctly model the power to heat output ratio. Commodity groups that paired both the intermediate heat output with the electrical output had to be made. Cogeneration thermal outputs were paired individually to electricity down stream of transmission.

Finally both the waste fueled and fossil fueled technologies had to be created. Each process was created and their operating characteristics inputted. Furthermore the existing capacities of these technologies, determined in chapter 3.2 were inputted, these figure are shown in Figure 37

Table 38: Existing cogeneration capacity input into SATIM (2012)

	Capacity (MW)
Conventional pulp and paper	118
Waste pulp and paper	118
Bagasse (waste sugar cane)	9
Methane gas (waste water treatment)	9
Natural gas cogeneration in chemicals sector	90

A capacity limit on each fossil fueled cogeneration process was inputted. These bounds were based on total technical capacity results from section 3.4.2. These bounds would limit the development of cogeneration beyond what has been determined as technically feasible.

Lastly all cogeneration technologies were limited to 300 MW of new capacity each year to prevent the technologies from unrealistically ballooning.

These steps resulted in the reference energy system shown in Figure 31

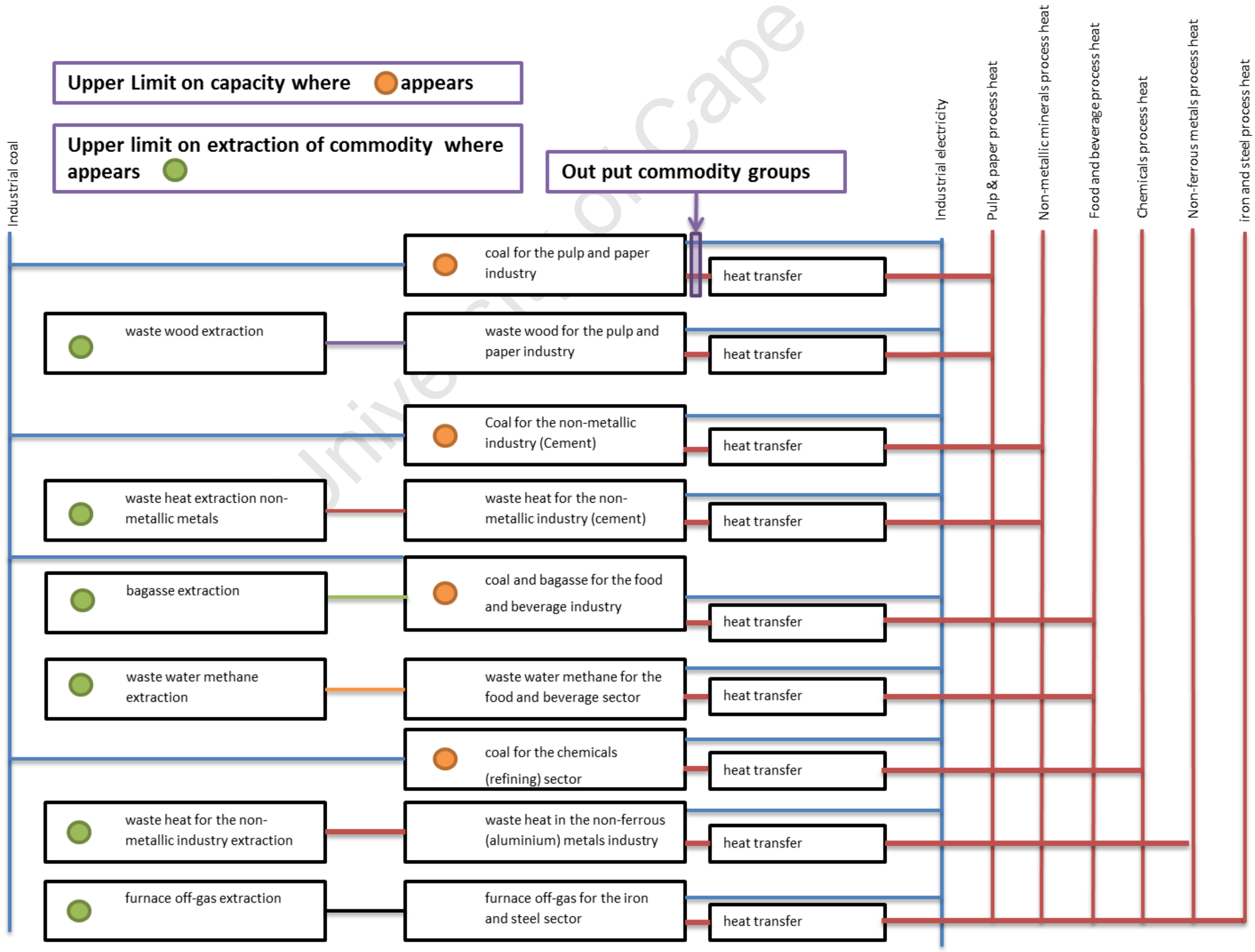


Figure 31: Reference energy diagram of cogeneration input into SATIM (2012)

3.5.1.2 Boiler modelling

One of the limitations of the SATIM (2012) model in its unaltered form is that it does not have costs or lifetimes associated with process heat boilers that supply thermal energy to industries. Furthermore the boilers have no investment lead times. This presents a difficulty in that economic competition between boilers is not reflected in the model. The problem is further exacerbated when cogeneration is considered. If cogeneration technologies were inputted into the SATIM model without altering the boilers, the economic competition between cogeneration and boilers would be poorly represented. The results of any projection would show no cogeneration development. This is because the least cost mechanism of TIMES would develop the "free" and long lasting boilers.

The next section will outline the process of adding technology characteristics to industrial boilers in SATIM in order to better model the competitiveness of the process heat market that both cogeneration and boilers supply. Firstly the types of boilers in the SATIM model were determined, these are:

- **Coal fueled boilers**
- **Biomass boilers**
- **Oil boilers**
- **Gas Boilers**
- **Electric boilers**

The technological characteristics of the boilers were then sourced. Specifically the capital and fixed cost were sourced as well as lead times and life times of each kind of boiler. The SATIM model already had values for capacity availability. These characteristics are the minimum needed in SATIM to correctly model the boilers. The final boiler characteristics are tabulated in Table 39

Table 39: Boiler cost assumptions

Final costs	Capital mr/GW	Source	Fixed cost Million rand/GW	Source	Life time	Source	Lead time
Coal	5169	*1	1950	*1	30	*5	1
Gas	1906	*1*2	1518	*1*2	30	*5	1
Oil	1988	*1	1518	*1:	30	*5	1
Biomass	1570	*3 *4	157	*3 *4	30	*5	1
Electric	700	*7			30	*6	1

*1: (PEDCo Environmental inc, 1979)*2: (MIT, 2011) *3: (aurecon, 2010)*4: (anon, 2003)*5(Merven, 2012) *6: assumption

*7 (anon, 2012)

These characteristics were then inputted into the existing boiler technologies in the SATIM Model.

3.5.1.3 Industrial tariff input

The SATIM (2012) model in its unaltered form does not have any competing independent power producing processes that would otherwise supply electricity over the national grid. For this reason it has not been vital to put a cost on the transmission of electricity from the central supplier (ESKOM) as all users are forced to buy electricity from the centralised supply network. With the addition of cogeneration technologies into the model it was necessary to include the cost of electrical distribution to industrial users in the form of an industrial tariff. In other words the SATIM (2012) model in its unaltered form has the cost of electricity production as the only cost factor, when in reality industrial users pay above the production cost. This aspect of the electricity market needs to be modelled in order to better represent the competitiveness of the electricity market. Industry users in the SATIM (2012) model will therefore have to choose between onsite independent power production with no distribution cost and purchasing electricity from an alternative supplier which includes the cost of production and distribution. The next section will outline how this data was determined and inputted into the model.

The SATIM (2012) electricity supply sector only incorporates part of the cost of electricity production, specifically it incorporates investment, operating and fixed costs. Additional costs of ESKOM operations e.g. salaries and distribution are not included and must be calculated. This is best illustrated by an example. Assuming that it costs 1R per kWh for Eskom to generate electricity in the SATIM (2012) model and another 1R/kWh for other cost (salaries/distribution) that are not seen in the model, the total cost of electricity supply would be 2R/kWh. In order to cover these costs ESKOM must charge a tariff of at least 2R/kWh. The SATIM (2012) model only has the 1R/kWh cost. Therefore an additional 1R/kWh must be levied to industrial users to represent the reality of the tariff structure. Inputting the 2 R/kWh tariff directly would be wrong as this would in fact model a cost of 3R/kWh. The true additional cost was calculated as follows.

A reference case was run in SATIM (2012). The SATIM (2012) model was run with no alterations to the power sector, in other words there was no transmission and distribution cost and there was no independent cogeneration. The total amount of electricity produced by the system over the time frame was outputted as well as the total costs of the electricity system. The total ESKOM costs were then divided by the total number of kWh demanded. This resulted in a value for cost of energy production (R/kWh) for the years 2013-2018 in the SATIM (2012) model.

The ESKOM industrial tariff for 2013 was sourced from ESKOM (2012). An average industrial tariff was calculated by taking the mean of all megaflex tariffs. Megaflex is the category of tariffs applied to most industrial users in SA. This tariff was then extrapolated into the future by applying the Nersa suggested 16% tariff increase for the five years of 2013 – 2017. After and before these years the industrial tariff was assumed to remain constant. This was done because the values were in real terms and do not need to be adjusted for inflation.

There was now an estimate for the cost of electricity generation from 2013-2018 in SATIM and a value for the industrial tariff from 2013-2018 and beyond. The difference between these two values is the 'other costs' not incorporated in SATIM. This difference was then calculated for the time frame and inputted as the cost of distribution. The calculations are shown in Table 40.

Table 40: Calculation of SATIM (2012) industrial electricity tariff input

Year	ESKOM TARRIFF R/kWh	Total Eskom cost R/kWh	Difference R/KWh
2006	0.74	0.03	0.70
2007	0.74	0.01	0.72
2008	0.74	0.01	0.72
2009	0.74	0.02	0.72
2010	0.74	0.02	0.72
2011	0.74	0.01	0.72
2012	0.74	0.01	0.72
2013	0.74	0.01	0.73
2014	0.85	0.01	0.84
2015	0.99	0.02	0.97
2016	1.15	0.02	1.13
2017	1.33	0.02	1.31
2018	1.54	0.03	1.52
2019	1.54	0.03	1.52
2020	1.54	0.03	1.52
2021	1.54	0.02	1.52
2022	1.54	0.02	1.52
2023	1.54	0.03	1.52
2024	1.54	0.02	1.52
2025	1.54	0.02	1.52
2026	1.54	0.02	1.52
2027	1.54	0.02	1.52
2028	1.54	0.02	1.52
2029	1.54	0.02	1.52
2030	1.54	0.15	1.40

3.5.1.4 Scenarios

Economic potential is affected by assumptions in the model e.g. discount rate; furthermore models are projections and hence are inherently uncertain. One cannot be sure that any assumption is correct, as one cannot be certain of the future. The generation of scenarios allows one to test changes in assumptions. This allows one to test new prospects as well as the sensitivity of initial estimates to differing assumptions. The less sensitive a model, the surer one can be about a models' projection.

Therefore in order to get a true understanding of the economic potential of cogeneration in S.A five scenarios were generated. They were modelled in order to understand the responsiveness of cogeneration to differing assumptions and differing policy instruments, these scenarios were:

A reference case: This scenario acts as a base line against which to compare alternative scenarios. There were no incentives for cogeneration in this case and therefore this case represents the economic potential of cogeneration on its own merits.

A pair of scenarios with a 1 % sensitivity in discount rate i.e a change to 7% and 9%: These scenarios were generated in order to determine the sensitivity of cogeneration to changes in the domestic discount rate. This is a fundamental marker for any economy; therefore this scenario gives insight into how cogeneration is affected by prevailing economic conditions. Furthermore one cannot be certain that the 8% discount rate is correct therefore one must assume that it could be seven or nine percent.

A scenario was run with a CO_2 tax of R100/kg: Cogeneration offers the opportunities for significant CO_2 saving due to its efficiency and in some cases renewable fuel input. Therefore a scenario was generated where a minimal carbon tax was implemented. All waste fuel based cogeneration technologies were given zero emission status given that the emissions would occur regardless of the presence of cogeneration technologies.

A scenario with a subsidy on cogeneration output: In this case a subsidy was inputted to stimulate cogeneration development. This scenario gives insight into how sensitive cogeneration development is to subsidies. The value of the subsidy was calculated based on the following method.

Firstly it was determined that in 2008 ESKOM would pay 65c/kWh for cogenerated electricity. This was part of ESKOMS medium term power purchase programme. In 2008 this value was well above the cost of ESKOM electricity, and was offered as an incentive for cogeneration development (Prakash, 2012).

The nominal industrial tariff for the year 2007 was then sourced from the ERC (2007) for each industrial sector. Using time series data the ERC were able to aggregate the nominal tariff for the SATIM model (ERC, 2007). It was then assumed that the difference between the ESKOM power purchase price (65c/kWh) and the industrial tariff would be the monetary incentive for cogeneration in 2007. In other words the rand value added to the normal cost of electricity at the time. This value would act as a proxy for the value of a subsidy. For example in 2007 the iron and steel sector had to pay 0.17c/kWh for ESKOM supplied electricity, but ESKOM would have paid any iron and steel 0.65c/kWh for cogenerated electricity in 2008, therefore the incentive for cogeneration in the iron and steel sector was 0.65-0.17 = 0.48c/kWh. These differences were then calculated for each sector and the subsidy for each industry determined. These calculations are tabulated in Table 41.

Table 41: Calculation of cogeneration subsidy input.

Industry sector	Nominal Industrial tariffs (2007) [c/kWh]	Medium term power purchasing programme offered price (2008) [c/kWh]	Subsidisation[c/kWh of electricity]
Agriculture	0.28	0.65	0.37
Iron and steel	0.17	0.65	0.48
Non-ferrous metals	0.19	0.65	0.46
Non-metallic minerals	0.19	0.65	0.46
Food and beverage	0.24	0.65	0.41
Pulp and paper	0.17	0.65	0.48

This subsidy was inputted into the model. This was done by subtracting the subsidy amount from the activity costs of all cogeneration technologies. In order for this to be done the subsidy had to be converted from Rands per kWh electricity production to R/kWh total energy (heat and power) production. This was done individual for each technology with their respective power and heat outputs.

All three scenarios were inputted and the models run. Results were generated and examined.

3.5.1.5 Results and discussion of the modelling process

The next section contains the results of the modelling process. Figure 32 shows the total economic potential in the form of total installed electrical cogeneration capacity from 2006 – 2030, under the five different scenarios. Figure 33 displays the possible generation mix by 2020 projected by the reference case. The majority of cogeneration will come from the petrochemicals sector.

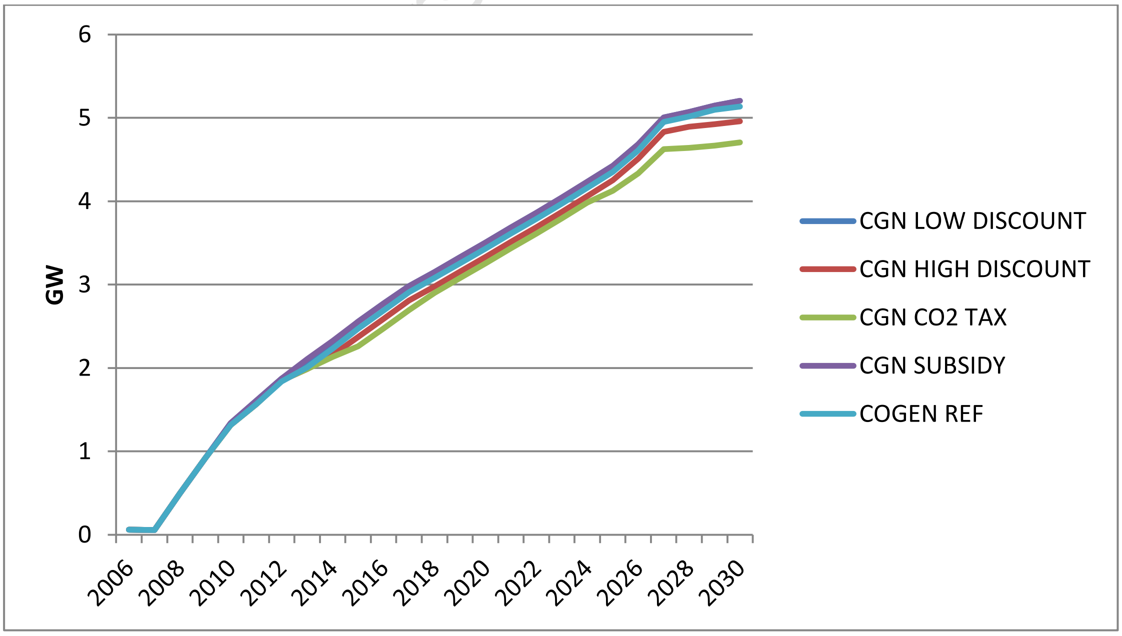


Figure 32: SATIM (2012) modeled total electrical cogeneration capacity.

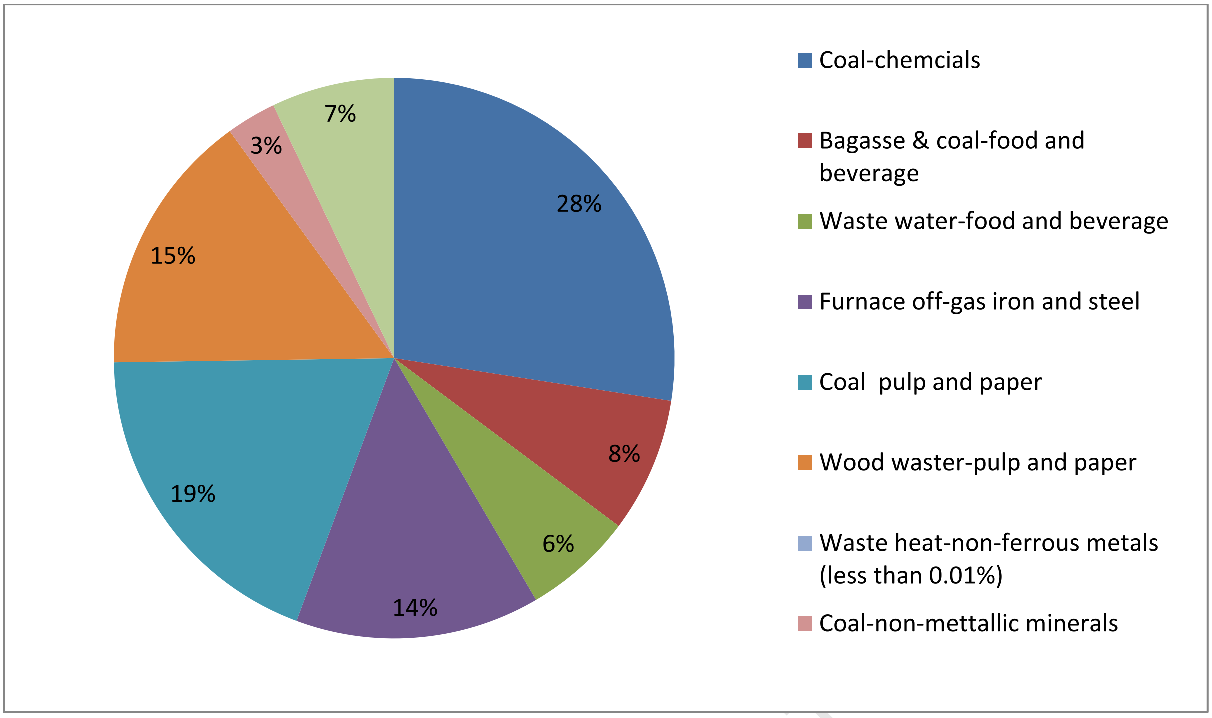


Figure 33: Reference case cogeneration energy mix in 2020

The first step in understanding how this development projection arises is to compare each technology's development to their technical potential. This is illustrated in Figure 37: Total capacity and potential capacity of fossil fueled cogeneration in reference case

and Figure 36. Cogeneration technologies are found to be so competitive that without policy assistance many of them reach their technical potential.

Reference case: The reference case shows a steady growth in cogeneration over the time frame. Approximately 3.4GW of capacity is developed by 2020. This is an important result as it demonstrates that the IRP estimate of 2GW is a reasonable expectation. The separate cogeneration technologies economic potential is shown in Figure 35

The research paper however found that there was a technical potential of 4.5GW of electrical cogeneration capacity. Figure 34 illustrates the short fall in cogeneration development in the model. By 2020 there is a short fall between potential capacity and actual of 1GW. The LCOE analysis of cogeneration found the technology to be relatively affordable but conventional power and heat generation was still cost competitive. This explains to some extent why cogeneration did not full reach its potential.

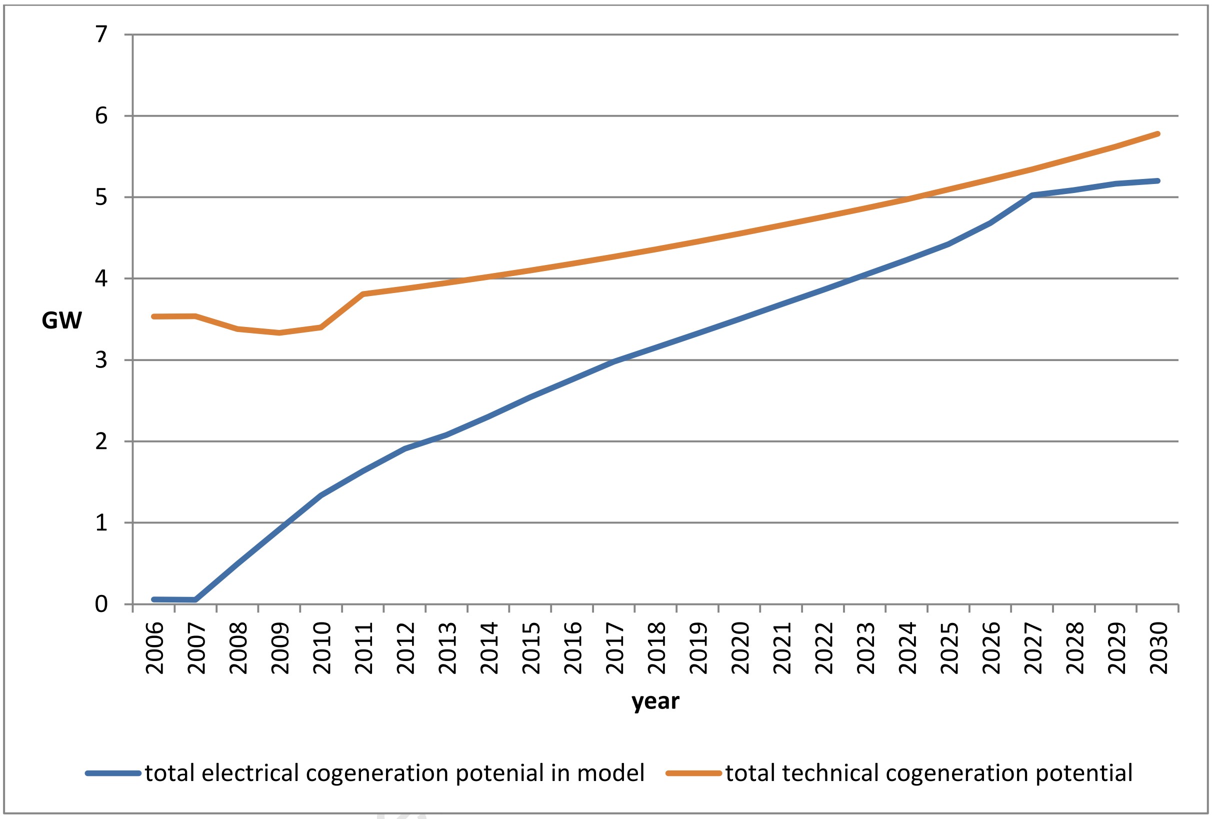


Figure 34: Cogeneration technical potential against reference case economic potential

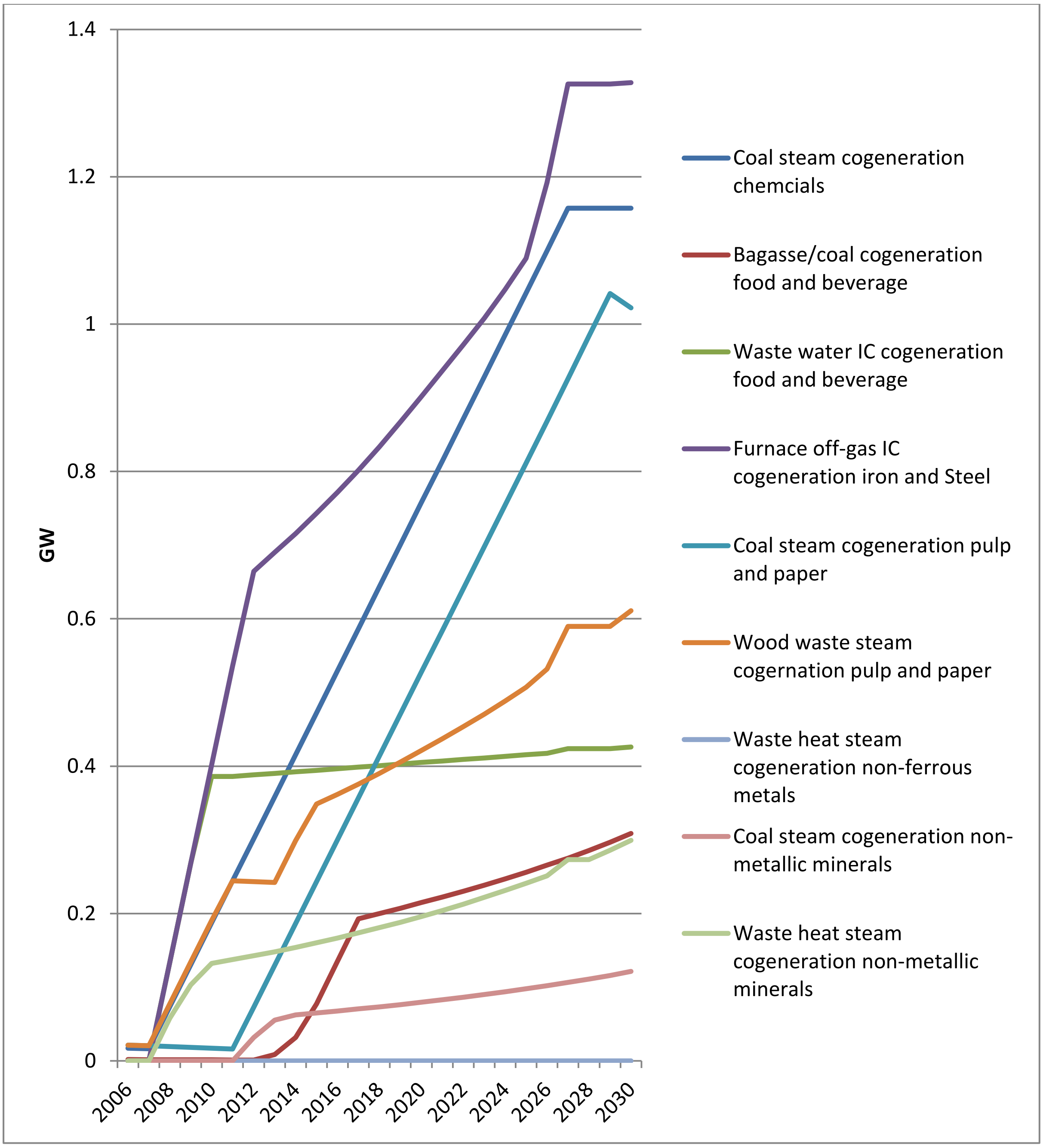


Figure 35: SATIM (2012) modeled electrical cogeneration capacity of each cogeneration system.

Waste fueled cogeneration in the model was limited by extraction processes with upper limits on activity. Figure 36 illustrates the fuel input into waste based cogeneration along with the initial limits on fuel supply, determined in chapter 3.4. The figure shows that the total flows into waste cogeneration are equal to the total production of the waste fuels. This suggests that all waste based cogeneration reaches its technical potential. Furthermore it suggests that fossil fueled cogeneration will supply some of the balance of industry heat and power supply as far as is economically feasible. Lastly one can conclude that the short fall in potential is in fossil fueled cogeneration.

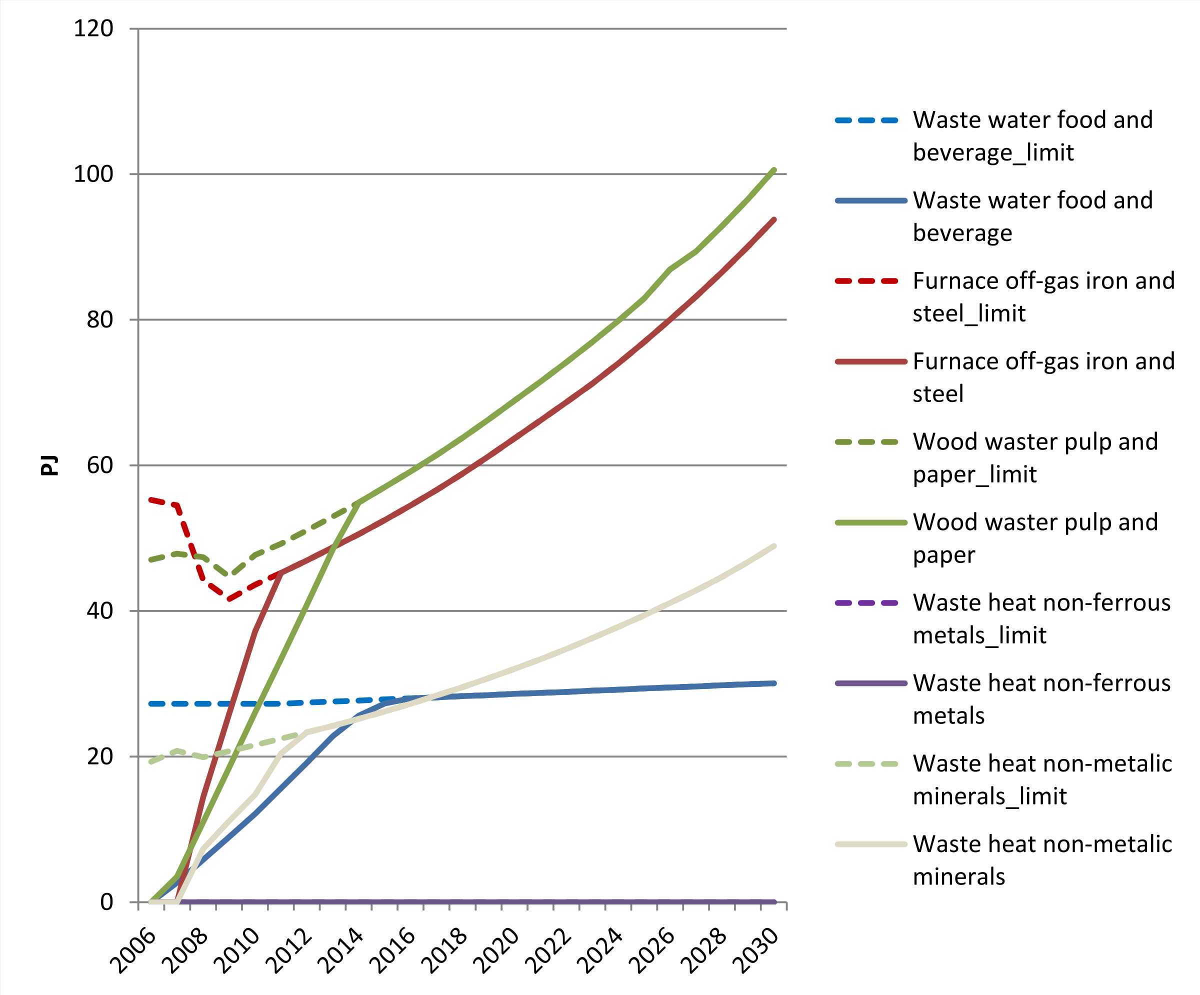


Figure 36: Waste commodity flows & extraction limits on waste fuels in SATIM (2012)

Figure 37 shows the capacity of fossil fueled cogeneration in the model. Superimposed on the figure is the maximum technically achievable potential of each process, estimated in chapter 3.4. The figure shows that all technologies except coal for the chemicals sectors and coal for pulp and paper sector reach their potential. The cumulative short fall is 1.1GW, this fully accounts for where cogeneration is not being developed.

This short fall is attributed to the 300MW upper bound on new installed capacity (heat and power) that results in a limit of 46MW on new electrical capacity installed each year. This inhibits cogeneration growth and prevents pulp and paper coal cogeneration and chemicals coal cogeneration, from reaching their total respective potentials.

One will note that early in the model all technologies have slow growth this is attributed to the following reasons. The main barrier to developing potential is the existence of industrial boilers that already supply heat and require significant loss of capital in order to be replaced with cogeneration. The LCOE analyse did not take this decommissioning cost into account.

Secondly The SATIM (2012) model has existing electrical capacity and planned build programmes that will supply electricity to the SA sector. This lowers the need for independent electrical power producers and slows development. In some case this results in cogeneration not being developed to its full potential in some sectors; this is illustrated in Figure 37.

Finally the slow growth in fossil fueled cogeneration is partly attributed to the strong growth in waste based cogeneration that limits the need for the more expensive fossil fueled systems.

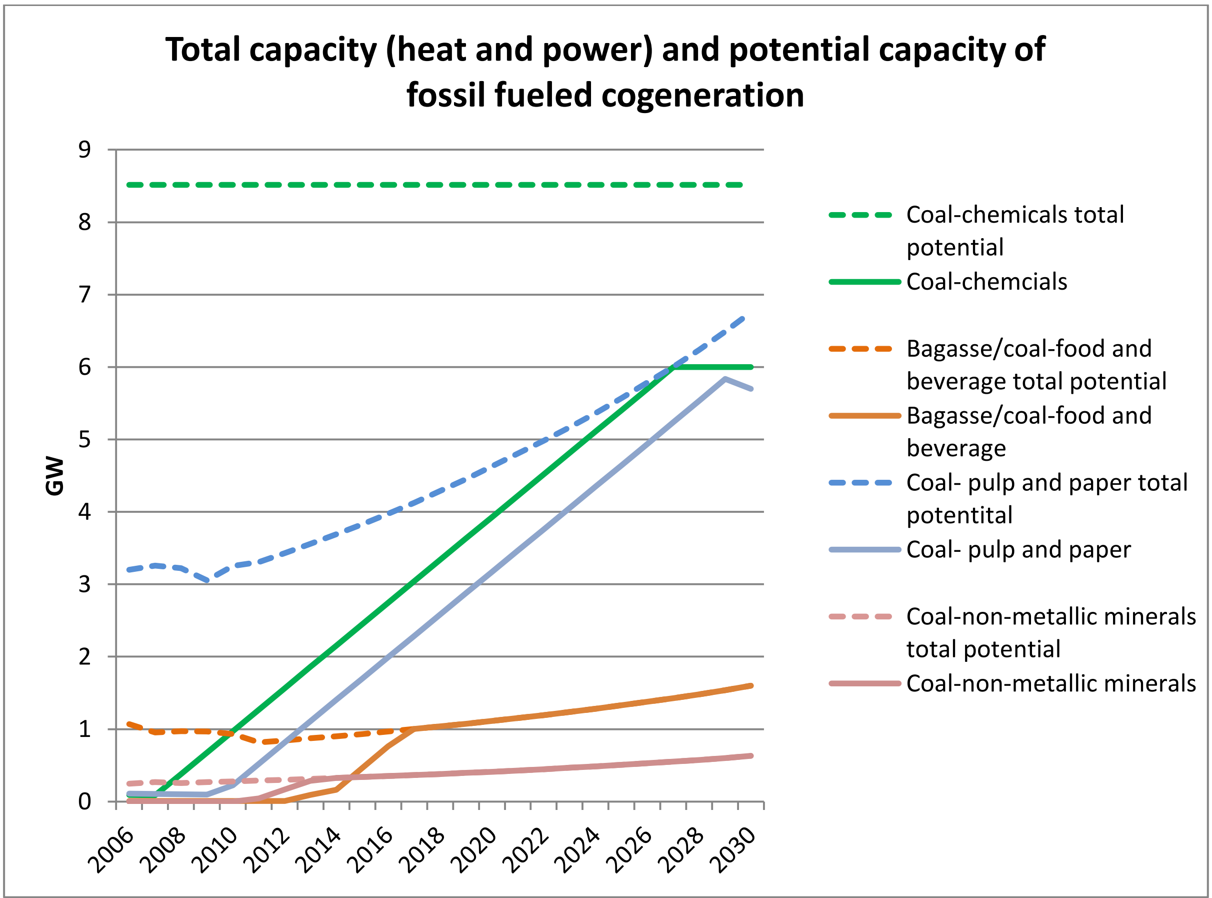


Figure 37: Total capacity and potential capacity of fossil fueled cogeneration in reference case

Low discount rate and high discount rate scenarios: Figure 32 illustrates the growth of cogeneration under high and low discount rates scenarios. Importantly the curves deviate only slightly from the reference case. Low discount rates increase the development of cogeneration as capital expenditure becomes more affordable while a high discount rate limits the development. The minor difference is expected due to the low sensitivity of cogeneration technologies to changes in the discount rate. This was shown in the levelised cost analysis of the technologies.

Carbon tax case

The addition of a carbon tax reduces the overall development of cogeneration. This is unexpected. The high efficiencies of cogeneration systems were expected to make them attractive in a carbon constrained economy. The reduction in cogeneration development is therefore attributed to the large coal driven nature of cogeneration in the model. The coal technologies are heavily taxed despite their high efficiencies. The conclusion is that a Carbon tax would not increase the development of coal fired cogeneration.

It is possible however those other technologies such as gas powered cogeneration that was no considered in this paper would increase in attractiveness.

Subsidy: The addition of a subsidy causes a small difference in cogeneration development. It has already been noted that most cogeneration is expected to reach its potential within the time frame. There is some room however for accelerating the rate of up take and final penetration of the technologies. This slight acceleration in growth is expected as the subsidy makes cogeneration more economical.

3.5.2 Barriers to successful cogeneration development

The modelling process has projected large growth in cogeneration development. However in SA there are a number of barriers to the successful development of cogeneration. These barriers are discussed below.

Grid connection and price agreements.

Oberholzer (2012) highlighted the fact that cogeneration projects have relied on price agreements between industry and Eskom. Grid connection is vital for cogeneration to be developed successfully. The TIMES model was constructed in such a way that cogenerated electricity feeds directly into the S.A grid. In reality this energy flow is dependent on industry and ESKOM's co-operation which in many cases is limited.

If better policies governing independent power producing (IPP) entities and ESKOM's relationship with them were developed, cogeneration would be able to fully develop to its maximum economic potential. In order to properly see the development of cogeneration in SA, pricing agreements must be met and effective IPP policy implemented.

Long term planning

In order to introduce cogeneration in industry around SA the sectors must embrace a long term strategic view. Industry players are often hesitant in initiating capital intensive projects, due to the short to midterm effect on revenues. This is different to national power producing agencies that plan decades in advance.

Shareholders are equally hesitant when investing in technologies that are untested, and although cogeneration has been shown as viable around the globe, there is limited experience in SA.

A further difficultly is the loss of capital involved in switching from existing boilers to new cogeneration technologies. Companies would be reluctant to decommission working boilers despite the advantages of cogeneration systems.

Therefore in order for cogeneration to fully achieve its economic potential industry needs to adopt long term strategic planning principles.

Learning curves:

Although the cogeneration processes examined in this paper are considered mature, there are still learning curves that each SA industry must take before cogeneration is fully taken up by SA sectors. These learning curves play a role in inhibiting the development of cogeneration.

Access to capital

In order to embark on cogeneration capacity building, access to capital must increase. Smaller companies may not be able to build infrastructure without appropriate sources of capital. In other words although cogeneration has been shown to be exceptionally competitive over the long term, capital expenditure remains a sticking point for the development of cogeneration.

4 CONCLUSION AND RECOMENDATIONS

The research presented here has been done with the expressed purpose of solving the research questions outlined in chapter one. The next section will outline the results and conclusion with respect to each research question.

4.1 Research Questions

What are the sources of cogeneration potential in SA?

This research work has found potential for cogeneration from fossil fuels and waste sources in several industries in SA these are listed below:

Fossil fueled cogeneration:

- in the petrochemicals sector
- in the sugar refining industry
- in the pulp and paper industry
- in the cement Industry

Waste based cogeneration

- waste water methane cogeneration in the brewery sector
- waste methane cogeneration in the waste water treatments industry
- waste bagasse cogeneration in the sugar industry
- waste heat cogeneration in the cement industry
- waste heat cogeneration in the aluminium industry
- waste furnace off-gas cogeneration in the iron and steel industry

How much cogeneration is there in SA at present?

This study's research into current cogeneration usage found there to be 427 MW of electrical cogeneration capacity in SA. The majority of this current usage is in the pulp and paper sector where a total of 238MW of capacity exits. Bagasse is also currently employed with a total of 100MW spread around the country. The moss gas refinery employs 90 Mw of natural gas powered cogeneration. The smallest proportion is held by in waste methane where a total of 9MW has been built.

What is the total technical potential of cogeneration technologies in SA?

Total cogeneration potential in SA by the year 2020 is found to be 4.5 GW of electrical capacity. The majority of this potential is found in the fossil fueled chemicals sector, pulp and paper fossil fueled cogeneration and iron and steel off-gas cogeneration.

What is the total economic potential of cogeneration technologies in S.A and is the IRP estimate reasonable?

The TIMES modelling process has resulted in a total of 3.5GW of electrical capacity by 2020. The study did however identify a number of institutional barriers that would make this figure difficult to attain completely. The IRP predicted approximately 2 GW by 2020. Therefore the results of this study suggest that this prediction is a reasonable estimate.

The IRP is unclear as to where the predicted potential will come from. This fact makes a proper analysis of the IRP figure difficult to conduct. However this research can state that the broad IRP capacity target is attainable by SA industries.

What impact does a change in discount rate have on cogeneration?

Scenario modelling has shown the economic potential to be unaffected by slight changes in the discount rate.

Levelised cost analysis shows that the cost of all cogeneration technologies are only slightly affected by changes in the discount rate. This is due to their relatively low capital cost in comparison to large scale power producing projects.

Therefore cogeneration development in SA will be unaffected by minor changes in the assumed discount rate.

What is the impact of a CO_2 tax have on cogeneration development?

Scenario modelling has shown that the introduction of a carbon tax will have little effect on cogeneration development.

Cogeneration was found to be sufficiently competitive in the S.A energy market that the introduction of a carbon tax has little effect on its development.

It is expected that industrial users would make cogeneration projects less expensive but would not change the decision of the industrial user to implement cogeneration.

What is the impact of a subsidy on cogeneration?

Scenario modelling has shown that the introduction of a subsidy for cogenerated heat and power in line with ESKOMS's medium term power purchase programme would have a very limited effect on cogeneration development.

4.2 Recommendation for further work

This research has identified the potential for cogeneration in SA industry. The study has created a base on which to structure further research into the field of cogeneration. The research gaps that have been identified are listed below:

The study has identified some of the main barriers to cogenerations development. These include IPP development; and access to capital. These institutional barriers play a large role in inhibiting the development of cogeneration. Work must been done on better understanding these barriers. Furthermore work must be conducted on developing policy frameworks to overcome these barriers.

The accuracy of this study is limited by the broad nature of the research. In order to better understand cogeneration in SA sectorial studies must be conducted. These sectorial studies will allow a more in-depth understanding of the problems associated with cogeneration development in facilities.

Competing boilers need to be better understood. The modelling process was limited by the lack of data on existing boilers use. Existing capacity of boilers must be quantified in order to understand the relationship between cogeneration implementation and boiler phasing out.

In the future natural gas will play a larger role in the world's energy mix. This research has not studied the full potential of natural gas power cogeneration. More work must be done in order to gauge its importance in the future energy mix of SA.

This research has not considered the retrofitting of existing boilers into cogeneration systems. Work must be done to determine the potential of this cogeneration option.

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