

CHAPTER ONE – INTRODUCTION

In the introductory chapter the research objectives are described with an outline of the scope required to achieve the outcomes of the research. In Section 1.2 a general background to the problem statement is given with the emphasis on coal beneficiation of South African coals and its associated environmental aspects. Section 1.3 describes the circumstances influencing the thermal coal industry with the advent of the low grade thermal coal export market. Section 1.4 describes the existing method to characterise coal ore bodies for thermal coal export resource to market exploitation and the potential of employing advanced coal characterisation methods.

1.1 Objectives and Scope of the Research

1.1.1 Objectives of the Research

The advent of low quality export coal demand has brought a new dimension of possibilities to the South African coal industry. Products traditionally only of value to the domestic utilisation or combustion industry, now have the potential to be exported with only minor amounts of upgrading required through beneficiation. The hypothesis in this thesis is that coal preparation and beneficiation of South Africa's low grade coals can be undertaken more efficiently and cost effectively by modelling mineral liberation in the context of different types of beneficiation plant. The export demand of low quality coal lies mainly within Eastern Asia, more specifically India and China. In some instances, close to export parity prices per GJ/ton can be obtained which enhances the financial feasibility of low thermal coal exports to a great extent. There are however increasing concerns about the feasibility of lower quality thermal coal export and its broader implications. These include:

1. Environmental Concerns: Lower quality export coal has:
 - a. Higher ash, mineral and hence sulphur content (with associated trace elements).
 - b. Probable lower user "efficiencies/outputs" (due to lower GJ/ton more tons to achieve unit x heat outputs, relative to higher grade products)

- c. Carbon emissions (with energy consumption reduction),
 - d. Discard/Tailings management concerns and associated environmental effects (evaluation includes discards generated from low vs. high grade export coal production),
 - e. Broader implications for the coal utilisation/combustion industries with emphasis on anticipated competition for local power generation industries, especially Eskom.
2. Logistical constraints: Rail capacity, port/terminal logistics
 3. Implications on coal beneficiation and mining methods
 4. Role of advanced coal cleaning in the production of multiple products, obtaining the right product combination (low, medium and high quality products)
 5. Overall techno-socio economic aspects.

The methodology followed in the research are best summarised in Figure 1. Here the optimisation models are populated by the data emanating from the analyses and models obtained earlier in the research programme which are subsequently integrated to provide the environmental and techno-economic models.

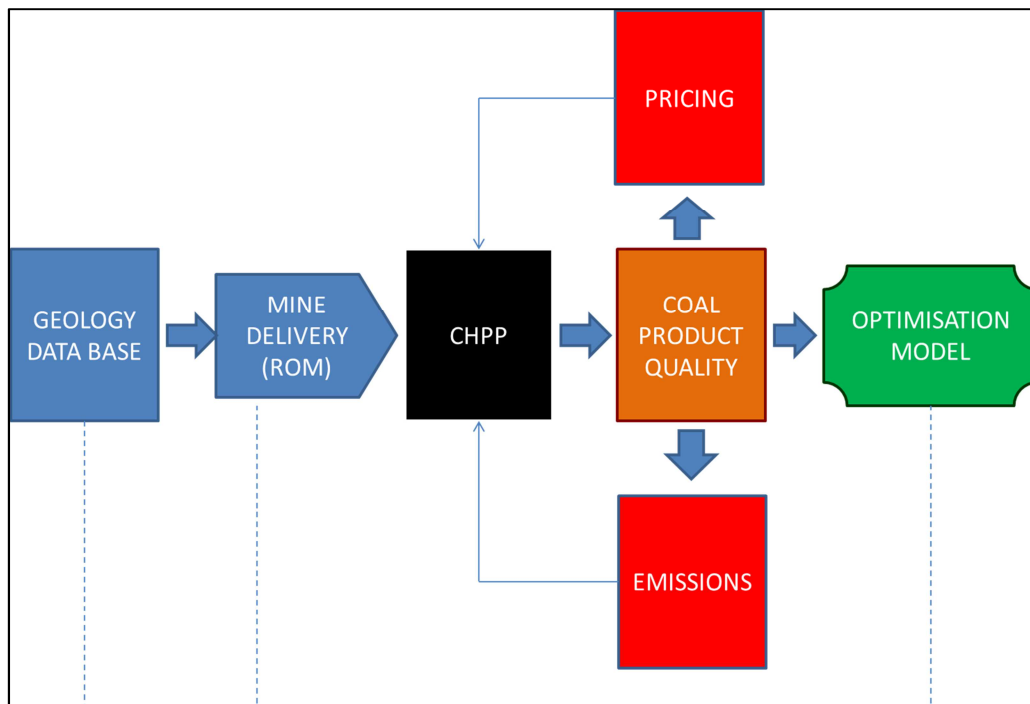


Figure 1: *Diagram showing an interactive model for thermal coal production.*

1.1.2 Scope of the Research

Based on the factors associated with low grade export scenarios, the research scope includes the use a model of a beneficiation plant, to which is added a low grade export quality model, a coal pricing model and an emission reduction model in order to produce an optimal combination of energy produced with minimal emissions and maximum triple bottom line benefit. This will be achieved through:

1. Developing an advanced method in order to characterise the coals in terms of (i) optimum export quality and (ii) beneficiation potential of South African coal reserves with high inherent mineral matter content.
2. Creating beneficiation indices which include factors impacting on beneficiation efficiency, environmental impact and ultimately economics of the South African steam coal trade. This would include specific mineral liberation functions (via float and sink tests and analysis), maceral content liberation, particle size factors and trace element content distribution.
3. Modelling of beneficiation capacity of the various coals in different size fractions through the evaluation of liberation functions.
4. Modelling based on quality, ash, mineral, trace element and maceral content of the beneficiated coal product.
5. Evaluation of different beneficiation technologies at different levels of beneficiation. The different levels of beneficiation are discussed in more detail in section 2.3 and section 11. This include the identification of optimum technology for greatest efficiency in beneficiating the specific coals under investigation.
6. An in-depth Techno-economic study of different beneficiation methods and the various outcomes:
 - (a) Amount of Energy required for each beneficiation process
 - (b) Amount of Natural Resources (Water and magnetite) for each process and their availability

- (c) The impact on carbon dioxide emissions in coal utilisation and the impact of coal processing and the production of low grade products.
- (d) Operational sustainability as a result of mining and beneficiation operations including rehabilitation, discard dump maintenance and pollution

1.2 General Background

Coal beneficiation plays a critical role in the total coal consumption value chain. The increased marketability of the beneficiated coal products allows for an export price which brings forth increased profitability. The price and market demand give rise to the large infrastructure and output is seen in most of the coal mines and processing plants in South Africa today. The mining operations mainly consist of large open cast operations and vast underground expansions to facilitate customer demand. The processing plants in return are becoming more advanced in operation and control to minimise losses of coal product produced, an activity labelled misplacement reduction in industry. The industrial improvements enable major economic benefit through increased GDP (Gross Domestic Product) and job creation. However, with increased global environmental awareness and pressures on the fossil fuel industry as a whole, an innovative look at the total coal consumption value chain is required. The export market for thermal coal could shrink in the future as a result of the growth and demand for alternative energy sources globally namely nuclear, off-shore gas wind and solar applications.

Currently, with limited natural resources, in particular water, required for coal preparation plants available in South Africa (especially Waterberg Coalfield Area), the need for improved resource management and processing with a minimal impact on the environment is required, the determining factor being sustainability. Large coal preparation plants with large infrastructure require readily available resources including electricity, water (potable water included), magnetite (dense medium processing in South Africa remains the norm in order to produce a product for export purposes), transport infrastructure and landmass for stockpiling. The requirements for a large coal processing plant in order to produce export products are vast, but the economic feasibility is favourable due to high export coal prices.

The value of the saleable coal is increased through beneficiation. The purification of the coal therefore allows for the following benefits regarding coal combustion and gasification respectively (Suman and Singh, 1989):

- The product requirement of an export coal is lower contaminant or mineral content, and higher thermal value. Adherence to this allows for improved marketability of a particular coal seam which *in situ* is of low quality.
- The product coal from beneficiation is more uniform in size, composition, and thermal value, thereby resulting in, for example, more uniform and steady combustion than would otherwise be possible.

By removing the sulphur impurities in the coal, beneficiation contributes to reduced slagging and fouling in the boiler combustion chamber. This increases the boiler's on stream availability and reduces its maintenance costs. During gasification sulphur is converted to Hydrogen Sulphide (H_2S) which has negative downstream impacts. Sulphur is highly corrosive to syngas coolers and causes serious damage to heat exchange systems (Collot, 2006).

Removal of associated mineral matter from the ROM (Run-Of-Mine) coal can result in lower transportation costs, higher combustion efficiency, and reduced ash disposal and flue gas clean-up requirements.

Reduction of the coal moisture by beneficiation results in improved coal handling and burning characteristics. It also leads to more efficient use of the fuel, since less energy is expended in the furnace to dry the coal.

The sum of the marketing benefits of employing coal beneficiation far exceeds the selling of raw mined coal. The opportunity lies within the beneficiation systems where at a smaller 'scale', similar coal qualities can be obtained without affecting the processing plant throughput, but retaining the marketability of the coal. The key factor is proper characterisation of the coal prior to beneficiation plant design. The trade off with sales and market price is critical and encompasses a wide range of economic impacts. For instance, a low yielding coal at specified quality after beneficiation might not secure the same revenue as a high yielding coal at a lower market price.

The vast majority of South African coals *in situ* are not marketable as prime high grade products for subsequent utilisation purposes. The 'as mined' or run-of-mine (ROM) coals therefore require beneficiation in order to produce coal suitable for economic utilisation in power station and gasification applications amongst others. South African coals are known to be difficult to beneficiate due to a high percentage of near gravity material. This is as a result of poor liberation of the mineral species occurring as inherent mineral matter in South African coals which contain considerably higher proportions of inherent mineral matter compared to most northern hemisphere Carboniferous coals. The result is that sharp separation is required to obtain the required the product quality. The liberation of the mineral species varies with size and as a result the beneficiation capacity of the coal varies with the different size fractions. With the deterioration of the coal reserves in South Africa these factors will play an even more substantial role.

If improper coal quality assessment occurs, i.e. lack of detailed characterisation and only simple commercial specifications, market opportunities will be lost and sales to cost ratios will be reduced significantly, affecting the overall profitability of the export coal producing operations. Proper characterisation would allow for a beneficiation process that might be less complex and less costly. An example would be where the ROM coal is not well liberated but of high *in situ* quality. In this case, a simple crushing, screening and single stage beneficiation operation would produce a product similar to a product of higher quality but at a lower yield and high capital expenditure and running costs compared to a high quality even lower yielding beneficiation process. Proper liberation characterisation is therefore essential to identify these issues at hand.

This thesis seeks to evaluate the coal value chain by focusing on improved coal characterisation methods, the economic impact of different coal beneficiation pathways, the environmental aspects thereof and advanced methods that can be employed to achieve more effective processing plants in South Africa with lower operating costs.

1.2.1 Coal in South Africa

South Africa's main export market is that of the thermal coal export market. This is a significant contributor to South Africa's gross domestic product (GDP). In summary, for South Africa, the coal mining industry (to a large extent thermal coal) plays an above-average role for the health of the economy (Baxter, 2011):

- 18 % of GDP (directly and indirectly);
- 50 % of Transnet exports by volume (primary and beneficial mineral exports);
- 18 % of fixed investments (directly and indirectly);
- Attracts significant foreign savings (more than 30 % of JSE value)
- 30 % of South African JSE's market capitalisation;
- 25 % of formal sector employment (directly and indirectly);
- 50 % of rail and port volume;

South Africa is a significant participant in global coal markets, being the world's 6th largest producer of thermal steam coal. As described by Eberhard (2011), South Africa's coal industry is competitive due a number of factors: it is a relatively low cost producer (along with Indonesia and Colombia), has the world's largest coal export terminal, and is positioned conveniently between Atlantic and Pacific coal markets. It is a potential swing producer, able to export competitively to either Europe or the East (Asia).

South Africa itself generates approximately 95 % of its electricity through coal fired power stations and has to this day not found a significant replacement for coal through the introduction of renewable energy. In addition, coal accounts for 30 % of liquid fuels produced by Sasol, the world's market leader in coal-to-liquids operations.

From a thermal coal export perspective, South Africa produces a high-ash and low-moisture coal. All exported coal volumes are in essence beneficiated coal with total moisture percentages in the order of 8 %. The generated discard material (left over from washing) has in the past had little or no value until present where Independent

Power Provider (IPP) power generation utilising discards from identified mines using Circulating Fluidised bed Combustion (CFBC) has been earmarked for combustion.

South African export thermal coal has a very good reputation in the market, because washing guarantees a very homogenous output product. Quality control at Richards Bay Coal Terminal is considered internationally possibly the best in the world as highlighted by Schernikau (2010).

In terms of the norms generally accepted for the Carboniferous coals of the Northern Hemisphere, South African Permian coal has long been regarded as being unique. However as described by Snyman and Botha (1993), these apparent abnormalities can be adequately explained in terms of the petrographic characterisation of the coal. For example, in the Free State Coalfield a unique situation exists, where coals of up to 95 % inertinite and ash are combusted which still allow for 30 % thermal efficiency (Engelbrecht *et al.*, 2008).

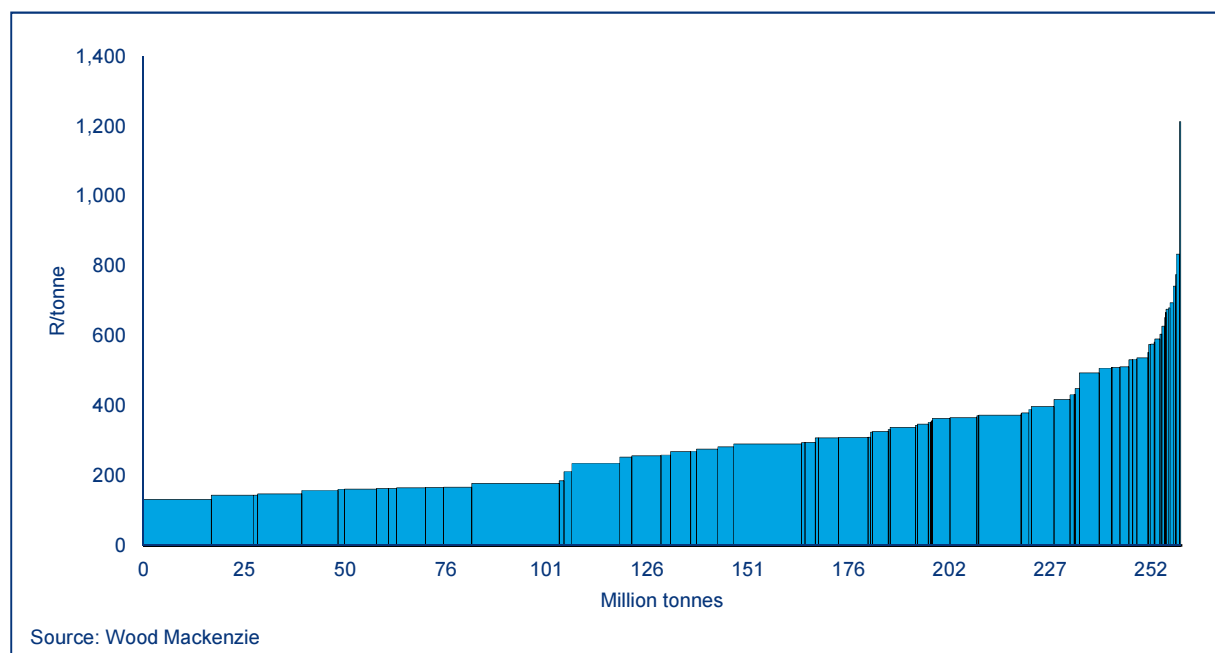


Figure 2: *Production cost ranges of various thermal coal export mines in South Africa. (Wood Mackenzie, September 2012)*

In common with other Gondwana coals such as Indian coals, South African coals are generally rich in the maceral inertinite, and maceral transitional between vitrinite and

inertinite *sensu stricto* (in that sense). This transition material as described by Snyman and Botha (1993) is known as reactive inertinite (semi-fusinite), which is partly reactive during technological processes such as combustion and carbonisation. This is in direct contrast to coals of the Carboniferous in the Northern Hemisphere. The maceral composition and rank of a coal greatly influences the aforementioned properties during combustion. South African coals, although comparatively high in ash content, are generally low in sulphur, nitrogen and phosphorus. On account of the specific mineral matter constituting the ash, the ash fusion temperatures could be generally high and this is an advantage in most areas of coal utilisation.

As highlighted by Schernikau *et al.* (2010) South Africa remains a very cost-efficient coal producer when viewed in the global context. According to a Wood-Mackenzie (2012 report) in Figure 2 costs in South Africa vary from R 596.84 (\$74.06) per ROM ton for underground and R 522.40 per ROM ton for opencast mines, the weighted average being R 472.54 per ton. In Figure 3 the comparative Free on Board (FOB) costs for the major thermal coal export countries are given.

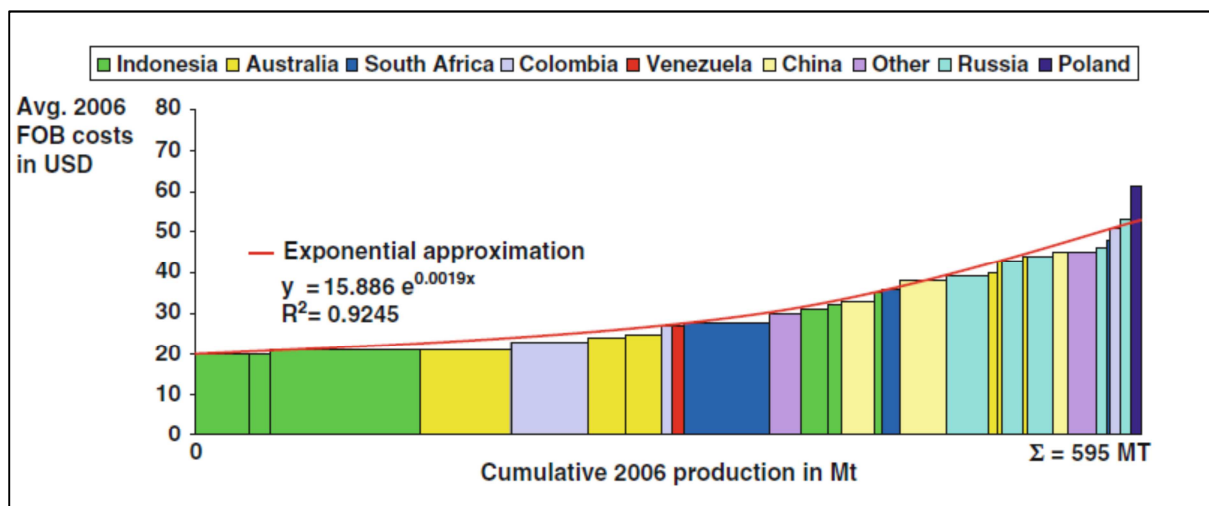


Figure 3: Supply FOB Cost curve per country (Schernikau, 2010)

Inland transportation remains relatively inexpensive, and with Richards Bay Coal Terminal, the marginal trans-shipment cost for the mining companies is very low.

1.2.2 Remaining reserves of economic interest in South Africa

According to the Energy Information Administration in the US (EIA) in 2012, South African coal reserves account for more than 90 percent of the coal resources of Africa. With the advent of major coal exploration campaigns in the rest of Africa, for instance Mozambique and Botswana, the reserves South Africa has as a percentage in Africa could be significantly less.

The coal reserves, but more importantly the quality of coal reserves in South Africa are steadily declining. This has major implications for the export market and profitability of the mining operations across South Africa. Another significant aspect is that the geographical location of the majority of the remaining coal reserves in South Africa lies within mainly arid regions with poor infrastructure, being quite a distance away from industrially developed areas. The Waterberg coalfield is a classic example as depicted in Figure 7 later in this section. According to Prevost (2004) the 1983 de Jager's 58.4 billion tons of recoverable coal reserves in the Waterberg were reduced to 55.3 billion tons by the Minerals Bureau's assessment in 2003 which included a reduction of the remaining reserves, to 28.9 billion tons. [NB: The most recent inventory of coal resources and reserves in South Africa was completed in 2013, but has not yet been published. For this reason, the numbers quoted above may change].

The market is further influenced by the supply and demand cycle illustrated in Figure 4. In Figure 4 (Thielemann, 2007), the effect of coal deposits with less favourable parameters are highlighted.

The challenges can be summarised as follows:

- The quality of the reserves, the proper characterisation and the predictability of beneficiation capacity of the reserves.
- The beneficiation requirements of the coal reserves with emphasis on additional resource requirement.
- The environmental impact of the levels of beneficiation (discussed in Section 10) on carbon footprint, discard and ash handling characteristics and emission factors (HAP (Hazardous Air Pollutants) and CO₂).

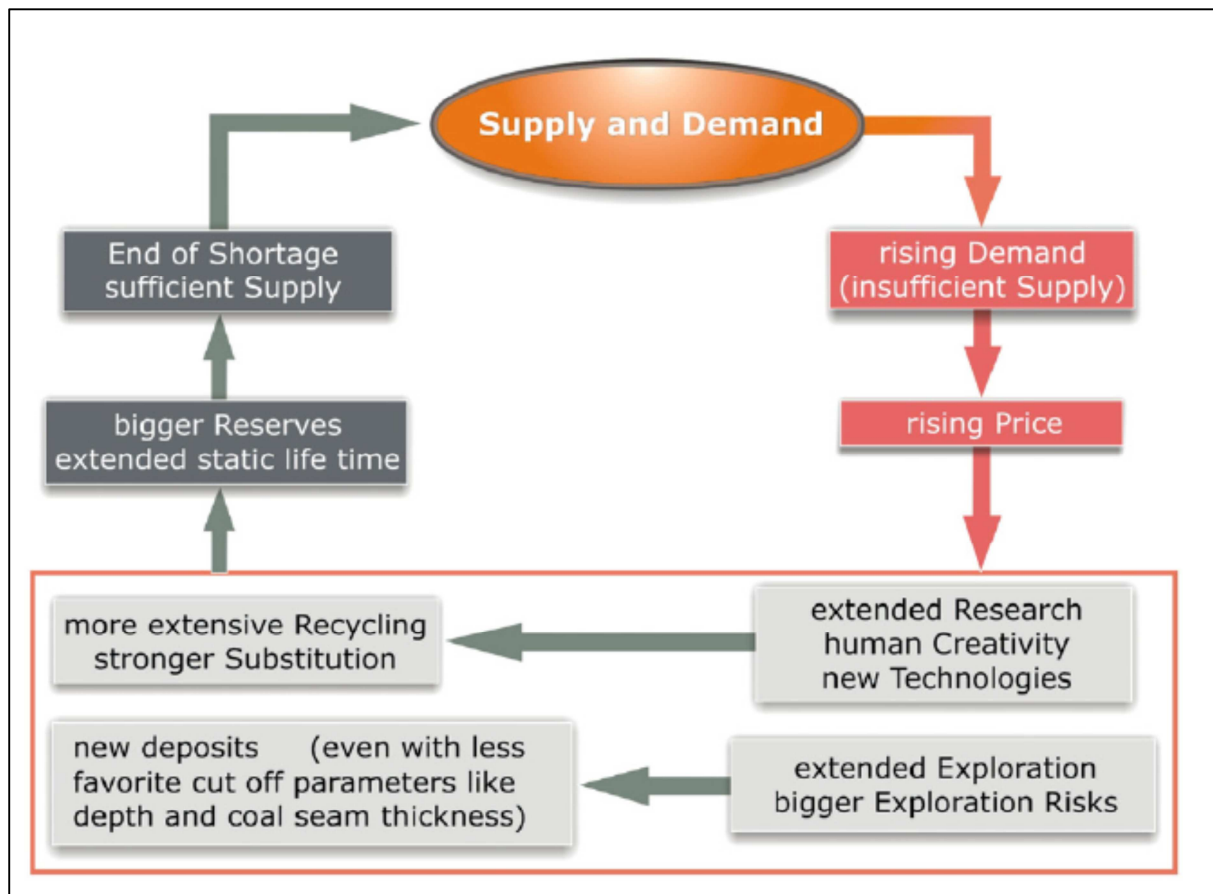


Figure 4: *Self-regulating cycle in (coal) raw-material supply; after: Thieleman et al. (2007).*

To mediate the current challenges in evaluating the economic exploitation potential of South African coal reserves, it is proposed that proper characterisation could give important information to the market that can be targeted by the evaluation of beneficiation capacity (via liberation and constitution) to obtain the greatest profit margin obtainable whilst taking into account resource availability and operating expenditure. The total influence of the identified effect on the carbon trading market also requires to be evaluated.

The accurate modelling and advanced characterisation of the remaining reserves in South Africa would allow coal export companies to obtain higher profit margins and maintain key requirements to sustain such operations.

The larger quantity of the remaining coal deposits in South Africa are distributed mainly within the Highveld and Witbank coalfields (Figure 5). According to the report by Prevost (2004), the Department of Minerals and Energy, the Highveld and Witbank coalfields account for approximately 66 % of the remaining coal reserves in South Africa. In the Witbank coalfield historically the No. 2 seam was of greater economic interest, but the No. 2 seam reserves have declined drastically over the last 2 decades which in turn promoted the No. 4 seam as the main source of export product. The Witbank coalfield No. 4 seam in essence is known as a high ash and inert seam or 'dirty' as described by Lurie (2000). This is extremely significant, and emphasises the fact that the 4 seam has to be cleaned or upgraded to yield an export grade product. In this instance the geological focus is to determine what the future geological composition of the coal deposits in R.S.A. will entail considering the impact that it will have on the marketability of that particular coal. A recent investigation into the existing coal reserves (Prevost 2004) for the Minerals Bureau painted a very bleak picture. In this particular report, against all expectations, the Waterberg reserves were estimated to be much lower than anticipated (2.96 % of the country's reserves). The report is not accepted by all. However, the estimations presented have one common factor; beneficiation must be optimised to counter quality (ash content) deterioration and difficulties in mining mechanisation.

Figure 6 indicates the changes in rank (maturity) in the coalfields in South Africa. Here higher rank coals are found to the east in the main Karoo Basin and in the northern basins bordering Zimbabwe. The major coal distribution lies in the Witbank, Highveld and Ermelo regions. From Figure 6 it may be noted that in these areas low to moderate rank coals exist. The Witbank region produces the highest percentage of thermal export coal followed by the Highveld and then Ermelo.

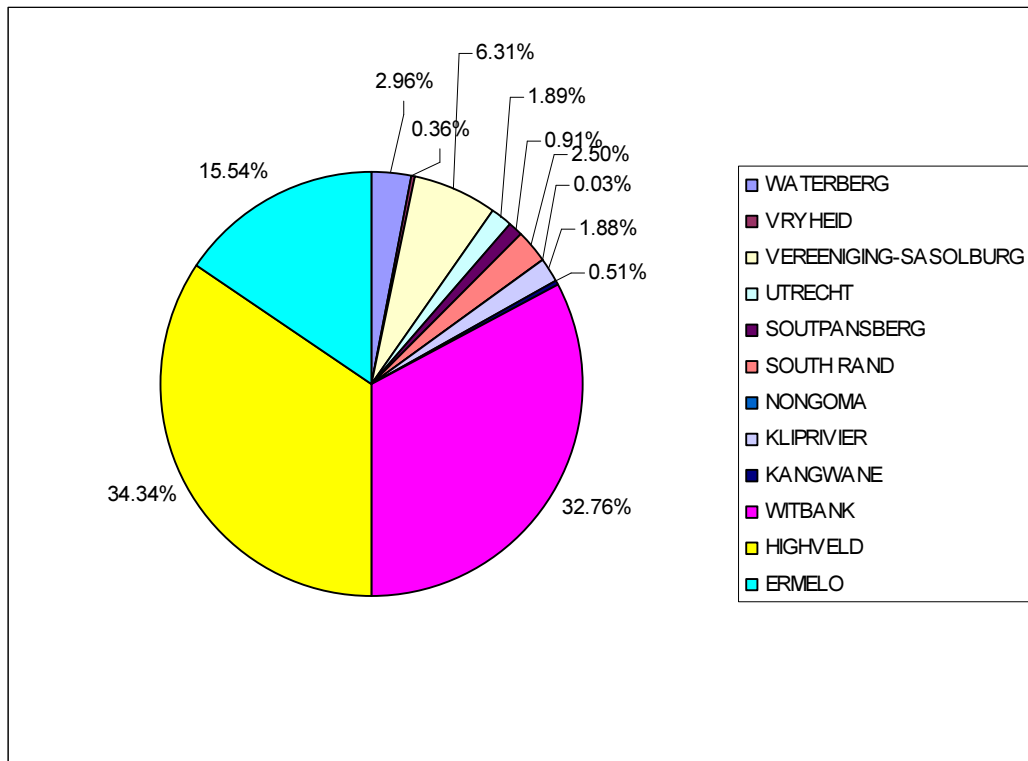


Figure 5: *Illustrating distribution of the remaining reserves in the R.S.A. (Spurr, 2006)*

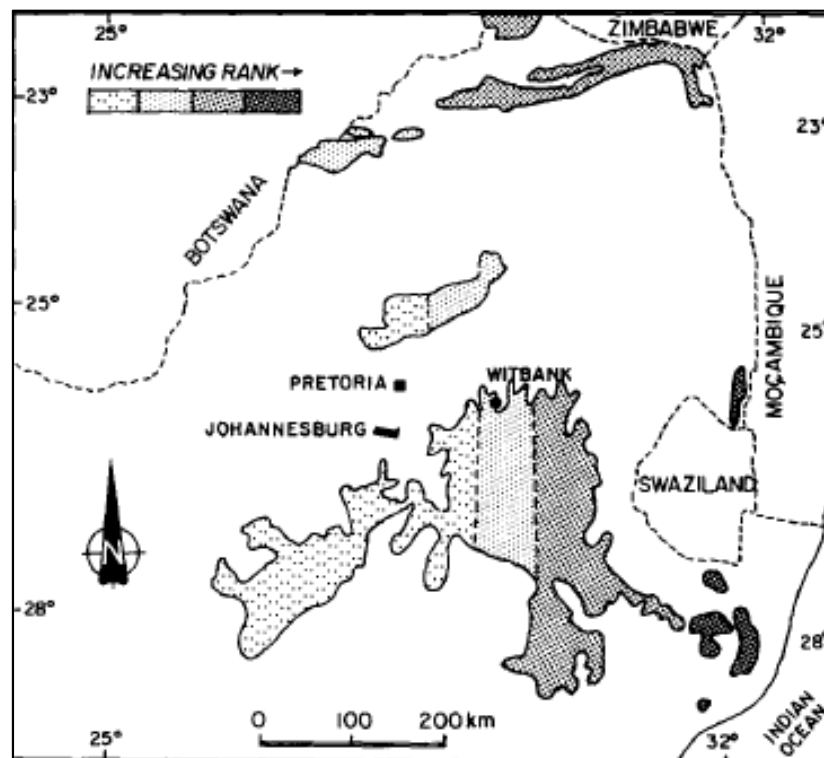


Figure 6: *Rank distribution in South Africa (after Snyman and Botha, 1993).*

When taking into account the distribution of coal operations and what reserves are exploited in South Africa at present (deducted from Figure 4 and 5), it could be envisaged that the quality of the remainder of the reserves will change, and in all likelihood, continue to decline in future. This means that the coal consumers and producers should prepare for coal quality predicaments in future, especially since mining mechanisation will expand into the poorer grade areas thereby producing greater tonnages of lower grade coals due to the expected increase in coal demand. It is difficult under these circumstances to lower the contamination levels caused through production in either the underground or open cast operations. The question now is whether coal consumers will adapt their operations to fit the poorer quality or whether the coal producers will try to improve beneficiation levels and ultimately the qualities. The determination of where the responsibility lies between with both coal producers and the local coal utilisation industry is not with one individual party, but rather with greater collaboration between both. One intriguing factor in balancing this equation is that of marketing, i.e. the situation in which overseas countries are willing to bid a higher price for South African lower quality coal which traditionally is only of domestic power generation value. This competition could ultimately threaten the health and sustainability of the power generation industry in South Africa. Government policy related to this matter could be imminent to curb the threat the low quality export market holds to on-going stable pricing for South Africa's power generation supplies.

Current and future recovery of coal will continue to come mainly from the Witbank and Highveld coalfields. Thermal coal obtained from the Witbank No. 4 Seam is exported mainly as power station smalls for pulverised fuel combustion. With the advent of new and improved technologies such as dry coal processing developments and expanding opportunities for exporting to foreign markets, and with the latest requirements from recent environmental legislation (for example the National Water Act (Act no. 36) of 1998 and National Environmental Management: Air Quality Act (Act No. 39) of 2004), enhanced characterisation methodologies need to be developed to adequately obtain the optimum value from the reserves.

It is envisaged that in future, extractions will move largely toward the Waterberg and Soutpansberg areas. In these areas the coal is of medium rank and grade and can, as in the case of Grooteegeluk be extracted and processed very successfully. Whilst

the Waterberg has been identified as a possible core South African Coal Reserve of the future, it must be realised however that infrastructure constraints could hinder progress in these areas, for example water availability, logistics (railway lines availability and capacity) and area of location (environmental impact). Relevant constraints in the development of reserves, especially in the Waterberg Coalfield as a thermal export reserve, are the lack of rail and industrial infrastructure, water scarcity and environmental sensitivity. Based on the Wood-Mackenzie (2012) cost reports, railage costs from the Waterberg are in the region of R269 per railed ton compared to R141 per railed ton from the Witbank Coalfield. This is due entirely to the distance to the Richard's Bay Coal Terminal, see Figure 7.

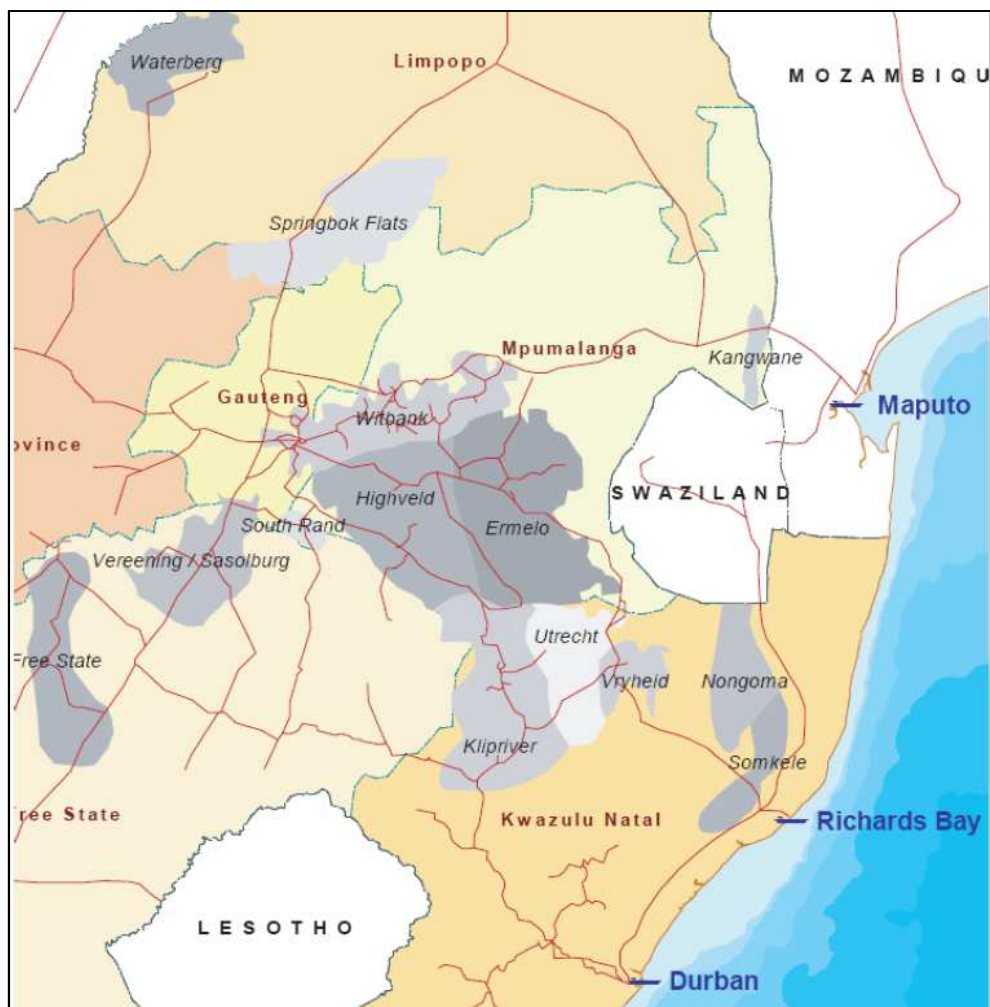


Figure 7: Logistical railway infrastructure within the coalfields of South Africa. Eberhard (2011). The red lines depict the railway lines.

In terms of rail and shipment capacity, South Africa operates the world's largest and most efficient coal export terminal – RBCT (Richards Bay Coal Terminal) – with a current capacity of 72 million tons. There is planned expansion from 72 to 91 million tons with an estimated completion time by 2014. The constraint currently is rail capacity and freight rail performance.

1.2.3 Role of coal preparation in the future coal industry in South Africa

Coal preparation can be defined as the process of the removal of mineral matter or ash constituents from raw ROM coal resulting in the upgrade of quality parameters in order to obtain products suitable, graded and consistent for the coal utilisation market. Osborne (1998) defined it as follows: "Coal preparation covers all aspects of preparing run-of-mine (ROM) coal for the market and can be broadly defined as the deliberate modification of the properties of the as-mined coal as it passes along the process from the mine to end-user, so as to meet end-use quality specifications and the constraints of the transportation and handling systems needs."

The most important part of the planning of mine activities is the need for accurate and reliable geological and compositional (mineral and maceral) data. The data has to be representative and as precise as possible. This is difficult to obtain with the requested high confidence levels. With the advent of many pollution control systems like the carbon credits, carbon footprint and greenhouse emission monitoring programmes, the production of "cleaner coal" is required throughout the world. For these reasons, the importance of coal beneficiation and preparation in the future is certain. The Grooteegeluk mine is an excellent example of maximum utilisation through careful planning. Various saleable coal products are produced from the Waterberg coalfield, which are semi-soft coking coal, high-ash steam coal (ESKOM), Corex coal, medium phosphorous PCI and sized steam coal. The use of sedimentology in conducting mine planning and evaluating budgetary requirements has to be of a high standard in these conditions. The question that arises is what data is required for designing a plant to produce saleable coal with such a wide range of properties.

Permian coals from South Africa have characteristically high ash and inertinite contents and therefore require further beneficiation. With the increase in environmental legislation the emphasis towards “clean coal” raises a concern in terms of the performance and marketability of export coal produced from South Africa’s remaining major reserves. The coalfields discussed in this thesis will in the future be economically significant and are still a viable source for export steam coal. Due to the nature and composition of the coalfields, coal beneficiation becomes essential in reducing the mineral and inert content to conform to quality specifications. Published washability characteristics of the Witbank No. 4 seam and Waterberg Upper Ecca coal indicate that coals are difficult to beneficiate.

The reserves discussed in this thesis could be earmarked for the traditional thermal coal export market (RB1), new lower grade export market (lower than 5500 kcal/kg NAR CV, RB3) and domestic thermal coal production. The latter product could be considered as the most prominent in future.

From a coal preparation and beneficiation perspective, the production of lower grade export and domestic thermal coal will entail the following in the case of the Witbank Coalfield No. 4 Seam and Waterberg Upper Ecca:

1. Higher Cutpoint Densities.
2. Higher Yields and Product Volumes.
3. Associated higher resources demand risk (water, magnetite and electricity).
4. Higher transport risk (rail and shipment).

As described by Osborne and Hughes-Narborough (1998), coal preparation provides economic and environmental benefits during transportation, utilisation, pollution control, and waste. Apart from this, Osborne and Hughes-Narborough (1998) identified that the main benefits of preparation come from greater unit energy content and lower emission levels per unit of energy, a direct result of lower mineral matter and sulphur contents in beneficiated coal.

In this thesis, the argument for, and against lower grade thermal coal export is investigated. One argument is that the production of product closer to raw ROM coal quality would entail an increase in overall energy recovery (Section 9.1), and that pollutant levels should not be considered simply as absolute volumes of carbon

dioxide or sulphur dioxide to be emitted/discharged, but rather the discharge/emitted volume per unit energy. Coal preparation could play an important role in the optimisation of product qualities to achieve optimum energy recovery levels with a calculated risk to the environment.

However, from a coal utilisation perspective the major combustion-related advantages accruing from the increased beneficiation of coal will be as follows (Osborne and Hughes-Narborough, 1998):

- Maximised availability of all plant components arising from consistent with increased thermal efficiency (lower carbon loss);
- Reduced equipment pulveriser wear and (in most cases) mill power needs;
- Reduced corrosion and erosion of boiler tubes;
- Significantly reduced quantity of ash requiring disposal.

1.2.4 Environmental concerns associated with the coal value chain in South Africa

As stated earlier, South African coals have high ash contents similar to other Gondwana coals, most of which require beneficiation to produce coals of acceptable quality for the world markets.

Bason *et al.* (2004) highlighted that the resultant discard dumps are responsible for some of the most serious environmental effects of coal mining, including land sterilisation and ground- water contamination. With the increased recovery through beneficiation, especially in the instance of low grade thermal coal export production, increased deleterious effects could be established in the arising discards through a decrease in the quality of the discards. On exposure to air and water, the pyrite oxidises to form sulphuric acid. The acid produced reacts with basic minerals in the rock to form salts, in the process of mobilising any heavy metals present (Bason *et al.*, 2004). The resultant acid mine drainage (AMD) contains elevated levels of salts (mainly calcium and magnesium sulphates) and metals (predominantly iron, manganese and aluminium). The higher pyrite levels in the discard dumps could also result in a higher propensity to spontaneous combustion. In order to minimise the possibility of spontaneous combustion, proper discard dump management through

compaction and height restriction is crucial. Modern day management includes the dry disposal of tailing slimes. The need for water treatment plants in coal complexes could also become mandatory as South Africa's water supply is under severe threat.

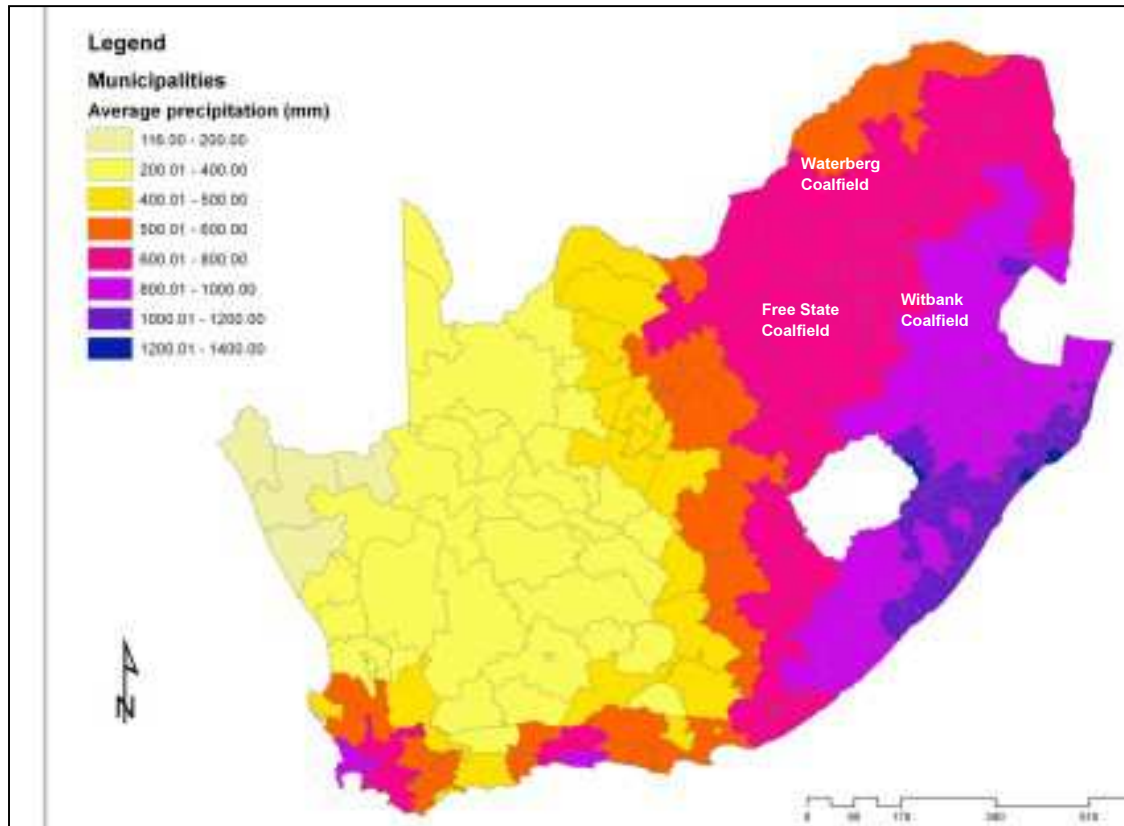


Figure 8: *Water precipitation and scarcity map in South Africa.*
www.globalsecurity.org (2012)

From a water quality perspective, the coalfields occur in the worst possible location (Basson *et al*, 2004), since most mines are situated in the vulnerable upper reaches of South Africa's major river systems, especially the Waterberg and Limpopo coalfields. Levels of rainfall are also shown in Figure 8.

The need for lower resource requirements in coal beneficiation, for instance water and energy, does not appear to have been recognised or widely adopted in the South African coal mining industry. This is most likely because of existing managerial, technological, and economical barriers. There are however major constraints in the planning and decision making process, as the strategies are often

based primarily on financial concerns, and budgets are often a limiting factor for new ventures (Basson *et al* , 2004).

The question now remains which strategies for the coal beneficiation industry are viable and best suited relative to the environmental constraints that exist today. The sustainability strategies fall into two categories namely:

1. Beneficiation with lower resource (water and power) requirement
2. Beneficiation to allow for lower emissions of air pollutants

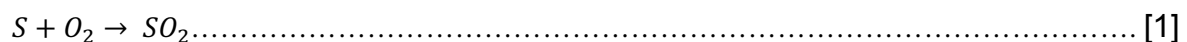
The thesis aims, as will be discussed in later sections, to identify trade off strategies for both categories. For water pollution reduction, dry processing is evaluated with estimated gains in environmental benefit.

In terms of emission reduction the following environmental aspects will be highlighted:

Sulphur Dioxide (SO_x)

The simplistic chemical reaction for sulphur dioxide formation is:

Equation 1: Formation of sulphur dioxide during combustion



Sulphur dioxide is considered a major contributor to acid rain. From a humanitarian perspective the health hazards of SO_x include asthma attacks, eye irritation, coughing, and chest pain, Denis (2007). Sulphur content, typically below 1 %, is required in virtually all internationally traded coal supply contracts. Northern hemisphere high CV coal and high sulphur coal is burnt only after blending with lower-sulphur coal (typically from South Africa and/or Indonesia) The equipment required during utilisation to limit the amount of SO_x released into the atmosphere is expensive and complex to operate.

Patwardhan and Chugh (2005) illustrated that it may be possible to increase the coal quality in terms of higher heating value and lower SO₂ generation, and while satisfying all current product quality constraints defined by contractual requirements while maintaining or even increasing the clean coal recovery. The test work by Patwardhan and Chugh (2005), in this instance, was conducted on Illinois (Carboniferous) coals which are inherently different compared to South Africa (Permian) coals.

Carbon Dioxide (CO₂)

The simplistic chemical reaction for carbon dioxide formation is:

Equation 2: Formation of carbon dioxide



Carbon emissions are identifiable with global warming concerns. The advent of carbon tax and carbon credits has now also served to incentivise the reduction of carbon footprints in industry. The cost of carbon dioxide abatement remains high as can be seen in Figure 9.

	R/t CO₂
Capture	160-320
Transport	8-40
Storage	8-16
Impact on Electricity Cost	16-24c/kWh
<i>Assuming Technology Advances</i>	
All up Cost	200
Impact on Electricity Cost	8-16

Figure 9: *Indicative carbon capture and storage costs according to the IEA (2012).*

From a coal mining perspective, carbon footprint management is of the utmost importance, despite the importance of producing products that could be issued with lower carbon tax.

Based on Equation 2, using stoichiometric calculations, Schernikau (2010) indicates from first principles, and assuming zero % unburnt carbon, that combusting 100 tons

of typical South African steam coal with 6,000 kcal/kg Nett As Received Calorific Value (NAR) or RB1 specification, at 25 % volatiles (AR), 11 % ash (AR), 0.7 % sulfur (AR), and 65 % fixed carbon content (AR) will result in 2.38 tons of CO₂ emitted per ton coal combusted.

Assuming power plant efficiency of $\omega = 0.38$, 1 MWh of coal power generated therefore emits 0.89 tons of CO₂.

Note that in the thesis, the calculations of predicted CO₂ levels are based on 860 grams of CO₂ emitted/kWh (according to NREL (2010)).

According to the NREL (2010), the most efficient way to reduce CO₂ is to increase the efficiency of coal-burning power plants. Each 1 % increase in average global coal-fired power plant efficiency would result in approximately 1 % less carbon dioxide emitted.

Nitrogen Oxide (NO_x)

Nitrogen oxides have been identified by the EIA (2012) as a contributor to global warming. While the concentration of nitrogen oxide is much lower than that of carbon oxide, the global warming potential of nitrogen oxides are considered to be 300 times greater than that of carbon oxides (Schernikau, 2010). Above standard nitrogen levels could have other adverse effects on human, animal, and plants. Nitrogen oxides, like sulfur oxides, also contribute to acid rain.

Davidson *et al* (1998) point out that it is difficult to predict the emissions of nitrogen oxides from coal combustion. The amount of nitrogen in coal, and the way in which it is bound into the coal structure, affects the amount and distribution of nitrogen oxide emissions. The relationship between nitrogen in coal and emissions of nitrogen oxides is an area in which further research is needed, especially if more effective in-furnace abatement techniques are to be developed. Some countries, especially the United States, already have strict NO_x limits that influence procurement of coal by

utilities. Other countries (e.g., in parts of Europe and Asia) have no such limits as yet in place (EIA, 2012).

Juniper (1995) states that the use of coal nitrogen content to evaluate NO_x emissions is not valid, as not only is there a poor correlation between NO_x emissions and coal nitrogen, the emissions are affected far more by the plant design and operation. NO_x emissions from a coal fired plant are affected by several factors including:

Coal Properties: - rank, volatile content, and nitrogen content.

Plant design: - type, number and geometry of burners, furnace size.

Operating Conditions: - furnace stoichiometry and combustion temperature.

In this thesis, further aspects regarding the relationship between coal constituents and rank and NO_x production are considered.

Trace Elements

Coal has distinctive properties and characteristics in terms of coal type which vary upon type of plant material and the conditions during formation, rank or the degree of metamorphism and grade or the degree of impurities which are predominantly ash constituting components.

All the distinct properties of coal play a role in the distribution of the trace elements within the seam. Firstly with a variation in the type of plant material a variance in the trace element will occur. It has been proven that maceral content have distinctive relationships with trace element content (Wenfeng, 2006). In essence a variation in vegetation from plant leaves and algae to tree barks at the time of deposition would mean a variation in trace element content. There are trace elements that have a higher organic affinity being associated with the maceral content in the coal. Many trace elements are essential for plant growth and their trace element profile is, to some extent, dependent on the composition of the soil in which they grow (Dale, 2003). Decaying plant material contains humic acid and many trace elements which

have an affinity to form chemical bonds with organic material are found at elevated levels in coal.

There are many instances where the release of specific trace elements has proven to have profound effects on the public health and the environment. Emissions of toxic trace elements such as mercury and arsenic from coal-burning power plants in Europe and Asia have been shown to cause severe health problems (Finkelman and Stanton, 1978). In China in particular some of the health problems are caused by trace elements emitted from domestic combustion. An improved understanding of the partitioning of trace elements in conjunction with the mineralogy and beneficiation and utilisation capabilities from specific deposits such as the Witbank coalfields No. 4 seam, Waterberg Upper Ecca and Free State coalfield would assist in reducing the possible emissions that result from combustion.

Trace elements from coal are classified into three classes in order of volatility (Figure 10). Mercury being highly volatile is one of the elements of greatest concern. Mercury in particular is known to cause neural and cardiovascular disease. Arsenic, which is less volatile, is known to be carcinogenic and to cause major harm to blood vessels and the human nervous system.

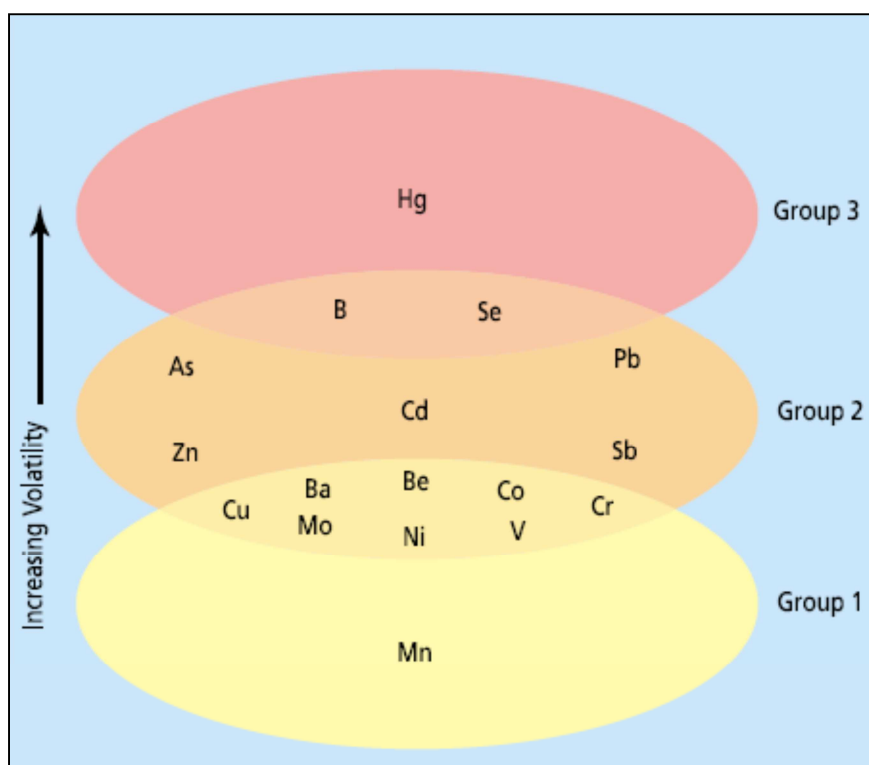


Figure 10: Classification of trace elements according to their behaviour during combustion or gasification (picture originally from Davidson and Clarke, 1993)

Toxic trace elements are not only dangerous via atmospheric emissions, but also leaching into ground water tables and other public water sources. Sufficient consumption via water could result in similar diseases to those associated with airborne trace elements.

In Section 2.4 the background associated to trace elements is described in more detail.

Ultra-fine particulate matter (PM₁₀'s and PM_{2.5}'s)

Although not covered in detail in this thesis, particulate matter (PM) is a dangerous pollutant considering that exposure to dust inhalation leads to possible silicosis. Particulate matter could also have other deleterious effects to humans and animals alike.

The fine particles having diameters of 10 microns or less (PM₁₀'s and PM_{2.5}'s) and smaller are classified separately. According to Juniper (1995), PM₁₀'s could travel

distances of 1 to 10 km and he regards these as predominantly oxides of the mineral constituents.

PM_{2.5}'s are generally formed by gas condensation of high temperature vapours during combustion (Bates, 1995). These particles could be rich in sulphate and nitrate compounds, including heavy trace metals (Cd, V, Zn, Mn and Fe).

1.3 Evaluation of thermal coal production & international markets

1.3.1 Thermal Coal Export Production, Cost and Demand

Steyn and Minnit (2010)^a explains that the geological setting of the reserves largely determines the characteristics of the coal product to be marketed, but the application of appropriate mining methods together with increasing levels of beneficiation can be applied to ensure that the product delivered meets and satisfies consumer specifications. This thesis aims to better quantify this characterisation as appropriate so as to predict and add value from the reserve. Steyn and Minnit (2010)^b continues that the principles of optimal resource use means that efficiency and profitability must be combined to extract value from deposits made up of multiple coal seams, for example the Waterberg coalfields with its multiple zones.

Steyn and Minnit (2010)^b on prices alludes to the fact that a number of factors, including the requirements of the IFRS system, the sophistication of customers, the nature of competition, attempts to increase market share, the elasticity of demand, and the involvement of agents and distributors, as well as other factors influence coal pricing. Stein also refers to the IFRS accounting policies and practices, which within the coal mining industry involve aspects such as depreciation, inventory valuation, fixed asset valuation, and impairment which affect costs and ultimately prices of the commodity.

A variety of macro-economic, environmental, and seasonal factors, for instance winter in Europe and eastern Asia, influence the demand and supply of coal, which could include forward prices. The major determinants of demand for coal are linked

principally to demand for energy, the intensity of coal use per capita income, and at a national level the state of economic and industrial development (Steyn *et al.*, 2010).

As described by Schernikau (2010), South Africa has a special position in the international steam coal business for the following reasons:

- South Africa runs the largest and most efficient coal export port globally, Richards Bay Coal Terminal;
- South Africa is a price trend setter for Europe; and
- The FOB South African price is quoted daily in the form of the API 4 Index, ensuring better market transparency.

In terms of cost, South Africa is one of the best performing coal producers and remains competitive. In Table 1 the distribution of the costs are illustrated. It should be noted that coal preparation only contributes on average 10 % to the total FOB cost, but it could be argued, it has the biggest influence on price and value that could be derived from the mined coal.

Table 1: *Distribution of costs for thermal coal export production, Wood-Mackenzie (2012)*

	Contribution to Total Thermal Export Cost
Mining	61%
Preparation	10%
Transport	19%
Port	3%
Overheads	6%
Royalty	1%

As a result of the global economic slowdown, the thermal coal price has undergone a significant decrease and was trending even lower than pre-2008 levels. The Wood-Mackenzie report which indicates a similar trend (Figure 11), a consistent coal price until 2014 with an increase in coal price trend mid-2014.

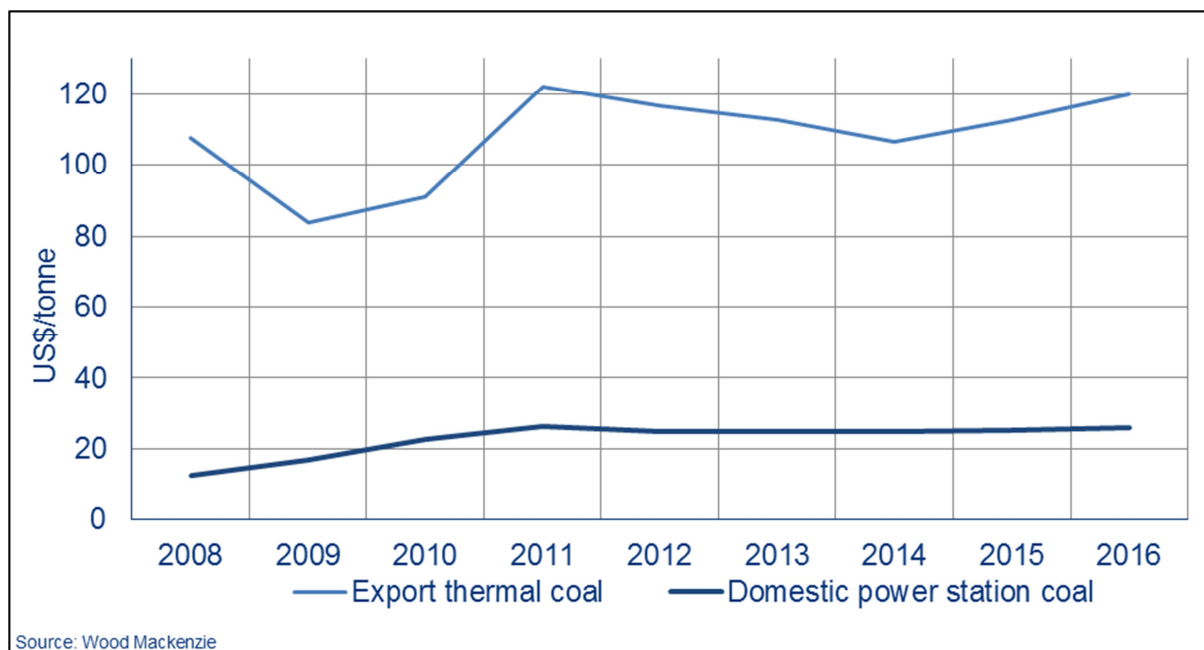


Figure 11: Thermal export and domestic coal price trends (Wood-Mackenzie 2012).

In Table 2 a summary of the production costs of two geographically different coalfields is shown. The Waterberg coalfield is considerably further from the bay loading terminals, both RBCT and Maputo. For this reason the transport costs which includes railings vastly exceeds that of the Witbank coalfield.

Table 2: Cost of production for thermal coal export per saleable ton, adapted from Wood-Mackenzie (2012)

	Mining	Preparation	Transport	Port	Overheads	Royalty
Witbank 4 seam	R 297.16	R 47.71	R 141.19	R 38.95	R 25.68	R 0.00
Waterberg	R 280.71	R 70.04	R 284.93	R 55.10	R 17.04	R 0.00

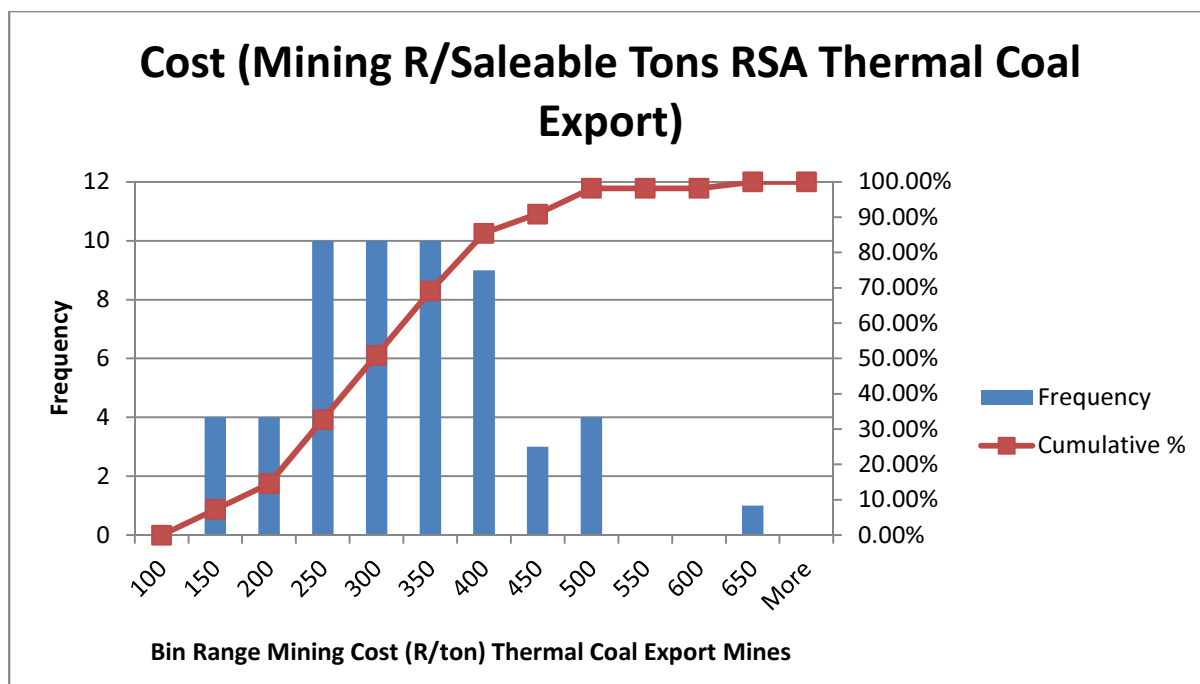


Figure 12: Bell distribution of mining costs of thermal export mines in South Africa. From Data Wood Mackenzie Operation Cost Report September 2012

The mining costs of South African export coal mines vary from R250-350/ton primarily as illustrated in the Bell distribution in Figure 12. It can be noted that the vast majority of coal preparation plants in South Africa employ dense medium processing having a weighted average cost of production of R45 per saleable ton (Wood-Mackenzie, 2012). The cost of coal preparation plants that operate primarily between R30 and R60 per saleable ton is illustrated in the Bell distribution curve in Figure 13.

Although the weighted average cost of coal preparation plants in South Africa is R45 per saleable ton (Figure 13), it is envisaged that the cost of coal preparation in South Africa will increase considerably in the near future as a result of the imminent rise in the price of electricity and magnetite.

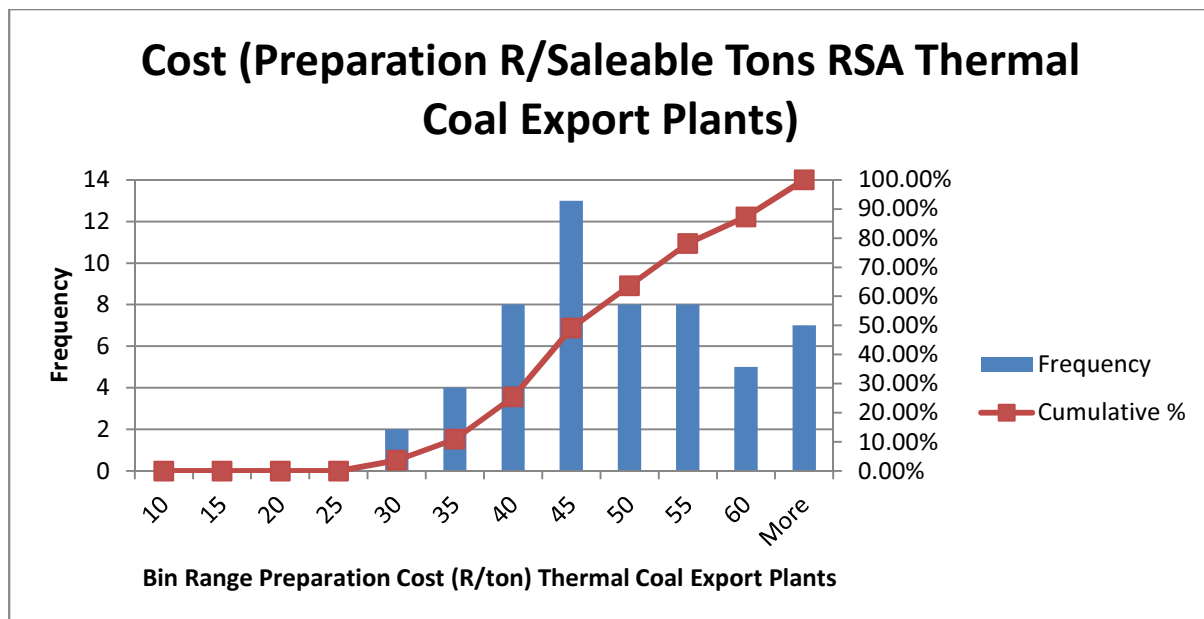


Figure 13: Bell distribution of costs of thermal export mines plant preparation production costs in South Africa. From Data: Wood Mackenzie Operation Cost Report September 2012

1.3.2 Lower Grade Thermal Coal Export Production

The shift in the demand patterns of global seaborne coal to the Asia Pacific region away from the Atlantic has also brought with it a shift in the quality that can be delivered. Presently there is a global general trend towards the production of lower CV coal (Schernikau, 2010) when considering international coal supplies. Indonesian export volumes have increased significantly and often are of lower CV content. South African exported coal products have also dropped in CV due to geological circumstances as well as decreased reserve quality in export coal mines. Lower CV requires an increase in volume of saleable production and hence increased capacity beneficiation plants. The plant capacity has to be increased to cater for increased product handling volumes. In the long term the higher saleable product volumes will increase the relative cost of transportation and also pose challenges for old and new power plants.

The product CV's of different lower quality products within the range of 4000-6000 NAR (kCal/kg) is illustrated in Table 3. The NAR CV of 4000 – 6000 kcal/kg and

corresponding calorific values will be evaluated in the thesis for the production of various lower quality products.

Table 3: *Calorific Value (MJ/kg on air dry basis) required to produce corresponding Net As Received (NAR) Product. [Note that these CV's are not sulphur corrected as it is anticipated that this is built into the model. The NAR CVs were calculated at 8% Total Moisture, 2.5% Inherent Moisture and 4.1% Hydrogen (db). CV kcal/kg Values indicate typical domestically required heating values.]*

NAR	CV	NAR	CV
Product	Required	Product	Required
(kCal/kg)	(MJ/kg adb)	(kCal/kg)	(MJ/kg adb)
6000	27.64	4900	22.57
5900	27.20	4800	22.13
5800	26.75	4700	21.69
5700	26.31	4600	21.25
5600	25.87	4500	20.81
5500	25.42	4400	20.37
5400	24.98	4300	19.93
5300	24.53	4200	19.49
5200	24.09	4100	19.05
5100	23.65	4000	18.61

Further advantages of producing and exporting of the lower quality coal to Asia can be summarised as follows:

- Increased yields and coal recoveries
- Higher coal saleable volume available for markets
- Reduced waste and thus environmental impact
- Longer life of mine and reserves
- Some uneconomical mining blocks/reserves will become feasible

The potential benefit and disadvantages are discussed in greater detail in Chapter 10 and 11 of this thesis.

1.4 Coal Resource Characterisation

Coal particles are inherently heterogeneous, and as a result several analytical techniques are needed to properly characterise the coal for beneficiation and subsequent conversion processes such as combustion, gasification, or liquefaction. Conventional analyses such as proximate analysis, ultimate analysis, ash analysis, and ash fusion temperatures provide the bulk analytical properties of the coal, but these cannot alone be used to predict the behaviour of coal particles in coal preparation, utilisation and the subsequent overall environmental impact. Additional special analyses are sometimes used to predict performance or diagnose problems in poor performance, namely mineral and maceral composition and rank using petrography and Computer-Controlled Scanning Electron Microscopy (CCSEM), and thermal tests including Thermogravimetric and drop tube equipment.

One particular aspect requiring attention is the prediction of ROM sizing. The sizing is important the liberation varies at different size fractions. In the case of borehole core sampling and even large borehole samples it is argued that the borehole core cannot give the correct accurate sizing information. Hence the accurate sizing of coal prior to excavation is impossible. Coal in the borehole core is brittle, and when the core is crushed or divided, replication of actual plant conditions is not possible. The best place possible to sample for sizing is at a coal seam, using guidelines of ISO14180 for such sampling. The condition of the coal at the seam face will also be critical. The core samples are mostly used for washability tests with specific analyses be done on each density fraction (See Figure 14).

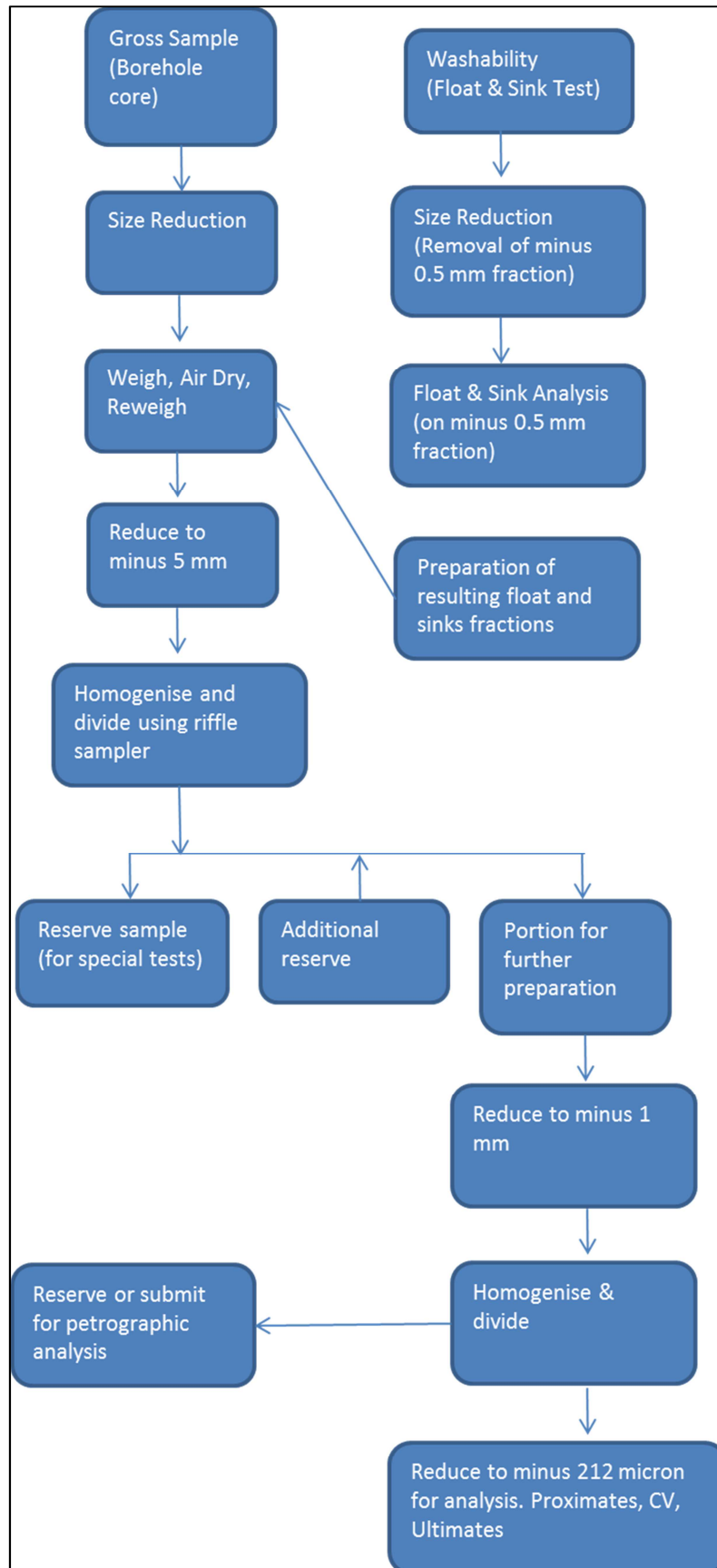


Figure 14: Division of core samples for analysis from SANS ISO 14180

In terms of generating sizing and washability data for design purposes, exploration has to endure a very comprehensive drilling program. The aim is to generate a large amount of applicable data that can be reduced to smaller sub-sets by taking into account the market specific factors identified. The continuous reconciliation of the operational factors in Figure 15 will improve clarity and confidence levels and is critical when predictions are made regarding washing plant parameters like cut-point density in the plant. The data is also critical in designing for plant operational flexibility, choice of equipment (modelling and sizing) and product or ROM handling sections.

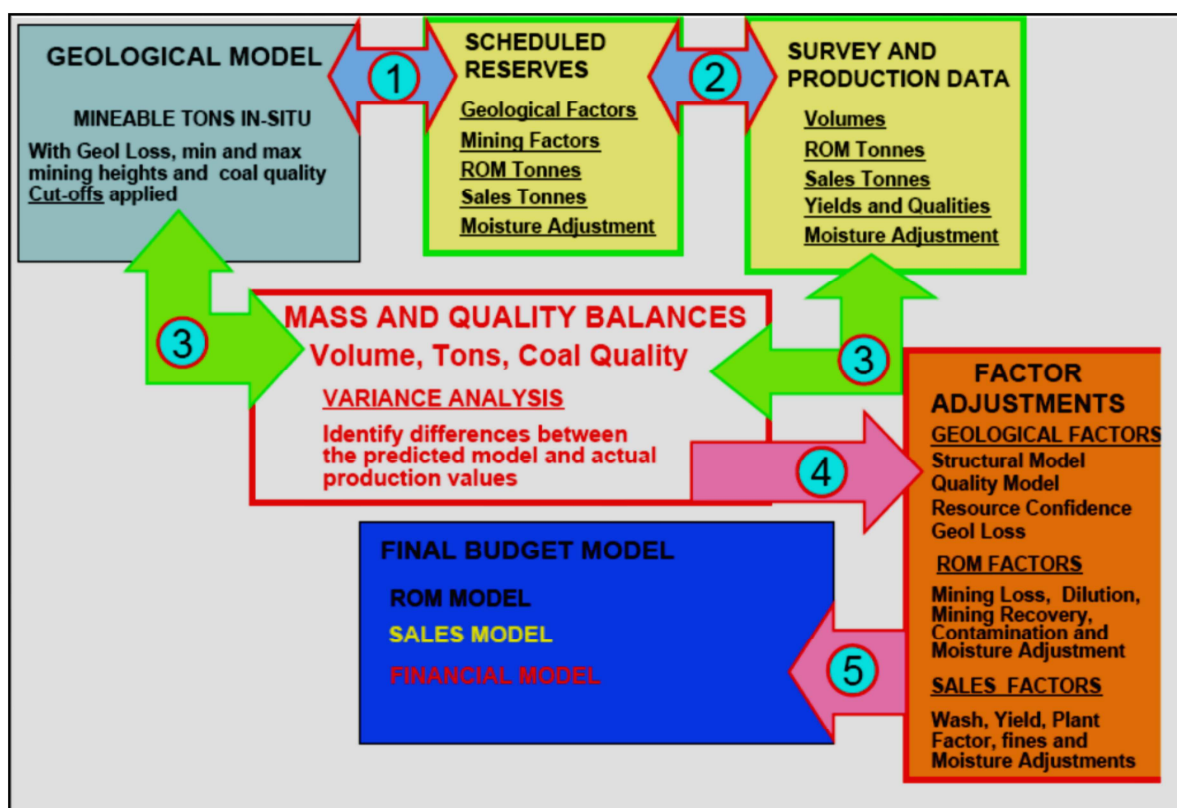


Figure 15: Continuous reconciliation of resources (de Klerk, 2006)

The simulation or modelling of plant performance goes hand in hand with the predictions made through geological modelling. On commissioning and production the organic efficiency percentage has to be as high as possible, i.e. having the theoretical geological predicted yield as close to the actual plant yield as possible. With the incorrect data this comparison will indicate poor correlation.

The modelling and simulation, however, cannot account for factors like clay and fine minerals in the coal matrix from sedimentation, contamination and dilution due to mining heights not adhered to or other factors beyond the predictable control of the geologist. The geological factors used to predict mass and quality balances will eventually affect the sales factors, budget planning and more importantly profit margins are most reliant on the accurate geological modelling of the scheduled reserves. Bed moisture which could be difficult to predict can also influence beneficiation and can create ROM handling problems.

For optimum beneficiation and accurate saleable predictions from borehole samples for reserve estimations the following can be done:

- Minimum and maximum cut-point densities can be obtained,
- Accurate washability tables can be drawn, borehole correlation factors for liberation can be obtained (organic efficiency),
- Possible fines loss and/or beneficiation can be estimated,
- Raw fines additions directly to product or discard can be regarded,
- Product moisture correction factors can be estimated.

These are but a few of the factors which can be evaluated to optimise production to obtain maximum process efficiency.