ASSESSING THE POTENTIAL ECONOMIC BENEFITS AND ENVIRONMENTAL IMPACTS OF EXTRACTING SHALE GAS IN THE KAROO, SOUTH AFRICA

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DECLARATION

I declare that this Research Report is my own, unaided work. It is being submitted for the Degree of Master of Science in Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

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(Signature of candidate)

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ABSTRACT

The decision to tap into the shale gas resources of the Karoo region in South Africa has become a topic of serious debate. Proponents highlight the significant potential economic gains and contribution to the energy mix. Adversely, there is great concern over the environmental risks involved, most importantly, the use and contamination of precious water resources. However, to not explore the opportunity any further due to environmental concerns is a decision that should be considered deeply. An early stage exploration programme, that does not include any fracking, could be of great benefit to understand the exact extent of the resource. If determined uneconomical, there is no longer a debate. However, if proven significant, a focus on the environmental risks will help assess the exact extent of the impact. Provided this new information, a more accurate cost-benefit analyses will be required to determine if fracking the Karoo will be worth it.

Fracking, South Africa, Karoo, economic benefits, economic costs, environmental risks.

To my dad.

1954 – 2017

ACKNOWLEDGEMENTS

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LIST OF ABBREVIATIONS

CBM	coal bed methane
CCGT	combined cycle gas turbine
CO_2	carbon dioxide
CGE	computable general equilibrium
CGS	Council for Geoscience
COGEH	Canadian Oil and Gas Evaluation Handbook
DMR	Department of Mineral Resources
ERR	economically recoverable resources
GDP	gross domestic product
GHG	greenhouse gas
GWP	global warming potential
KARIN	Karoo Research Initiative
LNG	liquid natural gas
NERSA	National Energy Regulator of South Africa
NMVOCs	non-methane volatile organic compounds
NO_x	nitrogen oxides
PASA	Petroleum Agency South Africa
PRMS	petroleum resources management system
R&D	research and development
SEA	strategic environmental assessment
Soekor	Southern Oil Exploration Corporation
TCP	technical cooperation permit
TOC	total organic carbon
TRR	technically recoverable resources
UCG	unconventional gas
UK	United Kingdom
US	United States

USEIA	United States Energy Information Administration
USEPA	United States Environmental Protection Agency

UNITS OF MEASUREMENT

Bar	100,000 Pa (pascal)
Bcf	billion cubic feet
boe	barrels of oil equivalent
GWh	gigawatt hour
ha	hectare
km^2	kilometre squared
kW	kilowatt
kWh	kilowatt hour
$m^3/km^2/a$	cubic metre per square kilometre per 1 inch of water
m^3s^{-1}	metres cubed per second
Ma	Million years ago
MMBtu	million British thermal unit
Mcf	thousand cubic feet
m	metres
md	millidarcy
mm	millimetres
MW	megawatts
Tcf	trillion cubic feet
tCO_2/MWh	tons of carbon dioxide per megawatt hour
toe	tonne of oil equivalent
TWh	terawatt hour
% Ro	percentage reflectance in oil

1 INTRODUCTION

Natural gas is a flammable gas, composed primarily of methane and other hydrocarbons, occurs naturally underground (often in association with petroleum) and can be used as a fuel (Econometrix, 2012). Natural gas is going through a golden age in the world (McGlade et al., 2013), emerging as a potential major energy source on a global level (Bilgen & Sarikaya, 2016).

Over the past decade, technological advancements, such as horizontal drilling and hydraulic fracturing (fracking) (de Wit, 2011), have led to a boom in the production of natural gas from shale formations, especially in the United States (US) and Canada (Altieri & Stone, 2016) who now account for over a quarter of global production (Speight, 2014). The boom in these areas has resulted in an abundant cheap energy source that produces less greenhouse gas (GHG) emissions than other fossil fuels such as coal (Alvarez et al., 2012; Brandt et al., 2014). As a result, shale gas has been dubbed the biggest energy story to emerge in the 21st century (Brooks, 2011; Economist, 2012; Chazan, 2012).

Shale gas is significant due to the wide distribution of shale formations throughout the world that are present to a greater or lesser extent in many countries (Lee & Sohn, 2014). The exploration and improvement of shale gas have attracted a lot of attention in many countries (Yingjie et al., 2015), particularly those containing potential shale gas resources who have been looking to exploit them (Melikoglu, 2014). It provides an opportunity to meet their ever-growing energy demand whilst reducing their dependence on imported fossil fuels (Wang et al., 2014a).

However, fracking is a controversial extraction process (Cronshaw & Quentin Grafton, 2016) with associated environmental concerns that have resulted in some countries and US states banning shale gas extraction until all potential risks have been sufficiently studied, e.g. France and New York (Kinnaman, 2011; Moore et al., 2014). These concerns include potential surface and groundwater contamination, local air quality degradation, fugitive GHG emissions, induced seismicity leading to earthquakes, ecosystem fragmentation and various community impacts (Jackson et al., 2014).

Recently, the potential to extract shale gas reserves in South Africa has become a topic of heated debate (Ingle & Atkinson, 2015). The Karoo Basin is the target area (Figure 1.1), with a specific focus on the carbon-rich units of the Ecca Group, a subgroup of the Karoo Supergroup (Rowsell & de Swardt, 1976). The basin covers approximately

300,000 km^2 of the country's interior and is estimated to contain 390 trillion cubic feet (Tcf) in technically unproved recoverable shale gas resources placing South Africa in the eighth position globally in volume (USEIA, 2013).

Figure 1.1: Main Karoo Basin in South Africa, the target area for shale gas development.

Source: *Map created using QGIS; base map from the ESRI plugin; shapefiles from PASA (2013), Stanford University (2017) and Natural Earth (2017). All items are open source and free to use.*

Supporters of fracking in the Karoo highlight the economic benefits involved, for example, economic growth and job creation (Econometrix, 2012; Wait & Rossouw, 2014). Beyond direct economic benefits, consumers can also benefit from shale gas as a source of energy used for home heating, electricity generation and production processes in multiple industries (Kinnaman, 2011). The use of natural gas for power generation could fill the energy supply gap in South Africa (PWC, 2012) and is a potential 'game changer' for a country facing an energy crisis (Hedden et al., 2013).

The local opposition argues the multiple environmental impact concerns involved with the exploration and extraction of shale gas. The primary concern is the utilisation and contamination of water sources, a scarce resource throughout the Karoo (Wait & Rossouw, 2014) which is a pristine semi-desert area (Vermeulen, 2012). Additionally, the current resource estimates have come under scrutiny as opponents highlight the limited amount of technical information available that forms the basis of the predictions (de Wit, 2011). There is also concern over the impact the dolerite dykes may have on the production of shale gas, a phenomenon unique to South Africa's case (Vermeulen, 2012; USEIA, 2013).

Thus, the benefits of fracking come with some very consequential disadvantages. Both need to be sufficiently determined prior to any decision on future proceedings. A great deal more research is required before it can be accurately determined whether shale gas is a viable energy option for South Africa; to date, this debate is a long way from being concluded (Wait & Rossouw, 2014).

1.1 Aim

Strong arguments from both parties emphasise the importance and need of an in-depth research study that not only covers the benefits involved but also focuses on the potential costs and environmental impacts. This report aims to provide an unbiased overview highlighting both the key potential benefits and costs associated with fracking in South Africa, as well as the potential profitability of extraction. Assessing these criteria can provide a deeper understanding of all aspects involved and can aid in future decisions regarding both the exploration and production of shale gas in the Karoo.

Four key questions need to be addressed:

1. Can shale gas development contribute positively to South Africa's economy?
2. Is the development of shale gas currently economically viable in South Africa?
3. What are the potential environmental risks and linked economic costs?
4. Based on the current state of shale gas development in South Africa, what should be done moving forward?

1.2 Method of research

The research analysis done in this report is based on open source literature of variable reliability. These may vary from books and peer-reviewed journal articles which exhibit high confidence to popular press articles and industry reports issuing a lower level of confidence and often a sense of bias.

The literature used throughout focuses on the relevant topics per section of the report, with material from a multitude of authors specialising on these topics. The literature was primarily collected from online sources. This included news articles, websites and mainly, e-journals. In addition, some hardcopy books were used from my personal library. These have all been referenced, both within the text as well as in the reference table at the end of this report.

The online e-journals were sourced from searching Google, Google Scholar and the Wits online library. Sources from the Wits library were then redirected to the specific journal website containing the article. These were downloaded as a pdf and sorted into a personal project library for continuous referencing throughout the report.

Where possible, the figures and tables in the report have been recreated from the original source. For figures, this was done using Adobe Illustrator, Microsoft PowerPoint and QGIS. QGIS was used for the creation of maps, where GIS data was sourced from multiple online sources, as well as from the Council for Geosciences through personal email conversations. In addition, a personal photo is used, this was taken on the Juriesfontein farm near Beaufort West. Tables were created from the original data when provided, this was done in Microsoft Excel.

Ultimately, the research focussed on highlighting the potential benefits as well as costs involved with fracking the Karoo. For the economic benefits, the research looked at both macroeconomic effects for South Africa, as well as local effects in the targeted areas. For the macroeconomic effects, the primary parameters used are contribution to GDP and job creation. For local effects, the focus is on the economic opportunities created from an influx of people to the area increasing its overall population size (even just temporarily). These values are sourced from a collection of articles that have used various methods to calculate their impacts. These are then compiled to present a dataset of comparable values to highlight similarities or contradictions.

In addition, a breakeven price is calculated for shale gas extraction in South Africa to determine whether extraction would be profitable in the current state of the South African gas market. This is done by using the work of Saussay (2018) that calculated a breakeven price for Europe by calibrating the calculation based on the differences it has from the US market. We look at whether South Africa exhibits the same differences to the US as Europe, allowing for the use of a similar breakeven price. This breakeven price is compared to the price paid by end consumers and the global price indices to determine possible profitability in South Africa.

For the environmental impacts and costs, a list of the primary environmental concerns is elaborated on. This does not provide quantitative costs; however, it does highlight how the qualitative negative impacts can lead to quantitative costs. For the economic costs to South Africa, the research focusses on the two main sectors in the area, agriculture and tourism. Again, no quantitative values are provided, instead, the idea is to highlight how the two largest economic contributors may be affected by shale gas extraction and the dire effects it may have on the long-term economic sustainability of the area.

Based on the provided potential benefits and negative impacts, an opinion is provided on what may be the best way to move forward on the shale gas debate in South Africa.

1.3 Structure of report

First, an in-depth literature review on shale gas is provided in Chapter 2. The review describes shale gas in its natural form and refers to the different types of reservoirs. The key technological advancements in the industry are highlighted, followed by the success story of fracking in the US. Previous work on the potential benefits and environmental concerns are then covered, and the review is concluded by work done specifically in South Africa.

Chapter 3 provides a brief description of the extraction processes involved with shale gas. This is followed by some key background information for shale gas extraction in South Africa, such as the geology, existing exploration and resource estimates and the recent activity around the debate over fracking in the Karoo in Chapter 4.

The background information in Chapters 3 and 4 acts as a foundation and provides insight to better understand the following chapters that focus on the potential economic benefits and viability, as well as the numerous environmental concerns and economic costs in Chapters 5 and 6 respectively. The report is finalised by a brief conclusion in Chapter 7 and future recommendations in Chapter 8.

2 SHALE GAS AS AN ENERGY RESOURCE

2.1 Chapter overview

This chapter provides background information on the topic of shale gas. It begins by describing the concept of petroleum and natural gas, the various reservoirs and natural gas types, as well as the global economic importance thereof. This is followed by the importance of technological advancements in the industry. Next, the focus is shifted to the US, the most advanced country in shale gas where the industry has boomed over recent years. Finally, a large amount of literature is covered based on the potential economic benefits and the environmental risks involved with shale gas globally and in South Africa.

2.2 Natural gas

2.2.1 Origin and types

By definition, petroleum, or its equivalent term crude oil, is a combination of gaseous, liquid and solid hydrocarbon compounds (Speight, 2000; Hsu & Robinson, 2006; Ancheyta & Speight, 2007; Gary et al., 2007) that is naturally occurring and usually in a liquid state (ASTM D4175, 2012). The word petroleum is derived from the Latin words *petra* and *oleum* which directly translates to rock oil, referring to hydrocarbons that occur in sedimentary rocks as a gas, liquid, semisolid or solid. It is a mixture of a wide range of constituents and proportions, resulting in significant variations in physical properties and colour, ranging from colourless to black (Speight, 2014).

A Total Petroleum System is an umbrella term incorporating all hydrocarbons and related reservoir types. The system has four main elements, the source rock, reservoir rock, seal rock and overburden rock. The system consists of two main processes, the trap formation and generation-migration-accumulation of hydrocarbons. All of these elements and processes must occur in the correct sequence and space for organic matter in the source rock to successfully be converted to an accumulation of petroleum and form a reservoir (Magoon & Beaumont, 2000).

The source rock, or source environment, is responsible for the origin of the petroleum. The majority of geologists believe that the origin of petroleum is organic, relating primarily to plants and animals that over time were altered by pressure, temperature and bacteria (Aguilera et al., 2014). These aquatic animals and plants died hundreds of millions of years ago and their remains mixed with mud and sand in layered deposits that over time formed sedimentary rock. The decomposition of the organic matter eventually forms petroleum which seeps from the source rock into more porous rocks such as sandstone and siltstone before becoming entrapped and forming the reservoir (Speight, 2014).

The source rock is usually in close proximity to the hydrocarbon reservoir suggesting that the petroleum was formed in the same area (Aguilera et al., 2014). Snider (1934) suggests that shale is the most important source rock for oil and gas, preceded by limestone. Shale is a fine-grained, laminated clastic sedimentary rock that is soft and easily split. It is compact with a low porosity and has an organic content range of 1% to 14% (Fakir, 2015).

Petroleum occurs underground at a range of pressures due to varying depths. The inherent pressure results in petroleum consisting of a large amount of natural gas in solution. The generic term natural gas refers to gases that are commonly associated with petroleum-containing geological formations (Speight, 2014). The primary constituent of natural gas is methane, but can also contain higher molecular weight hydrocarbons such as ethane, propane and butane, all of which are combustible. Carbon dioxide (CO_2) is also a common constituent of natural gas, with other non-hydrocarbon components such as helium and nitrogen in minor amounts. Similarly to hydrocarbons, the mixture of various constituents can vary greatly and two wells in the same field can produce gas of different composition (Speight, 1990).

The varying constituents have resulted in a few general definitions being applied to natural gas. These include dry or lean gas in which methane is the major constituent (Speight, 2014), at least 90% (de Wit, 2011). Wet gas contains a significant amount of the heavier molecular weight hydrocarbons (Speight, 2014) and is a more water-rich mixture (de Wit, 2011). Sour gas contains hydrogen sulphide, whereas sweet gas contains very little, or none. When the higher molecular weight hydrocarbons are removed from the natural gas you are left with residue gas, and casing head gas is derived from petroleum but is separated at the wellheads separation facility (Speight, 2014).

2.2.2 Reservoir types

Natural gas can also be classified by the mode in which it is present in a reservoir (Figure 2.1). Associated natural gas occurs either as free gas or in solution with the petroleum. The gas in solution is called dissolved gas, whereas the free gas in contact with petroleum is associated gas. Associated gas generally contains more of the heavy molecular weight constituents and less methane. Nonassociated natural gas occurs in reservoirs with no or very little petroleum. It is generally richer in methane and contains considerably less of the heavier weight constituents (Speight, 2014).

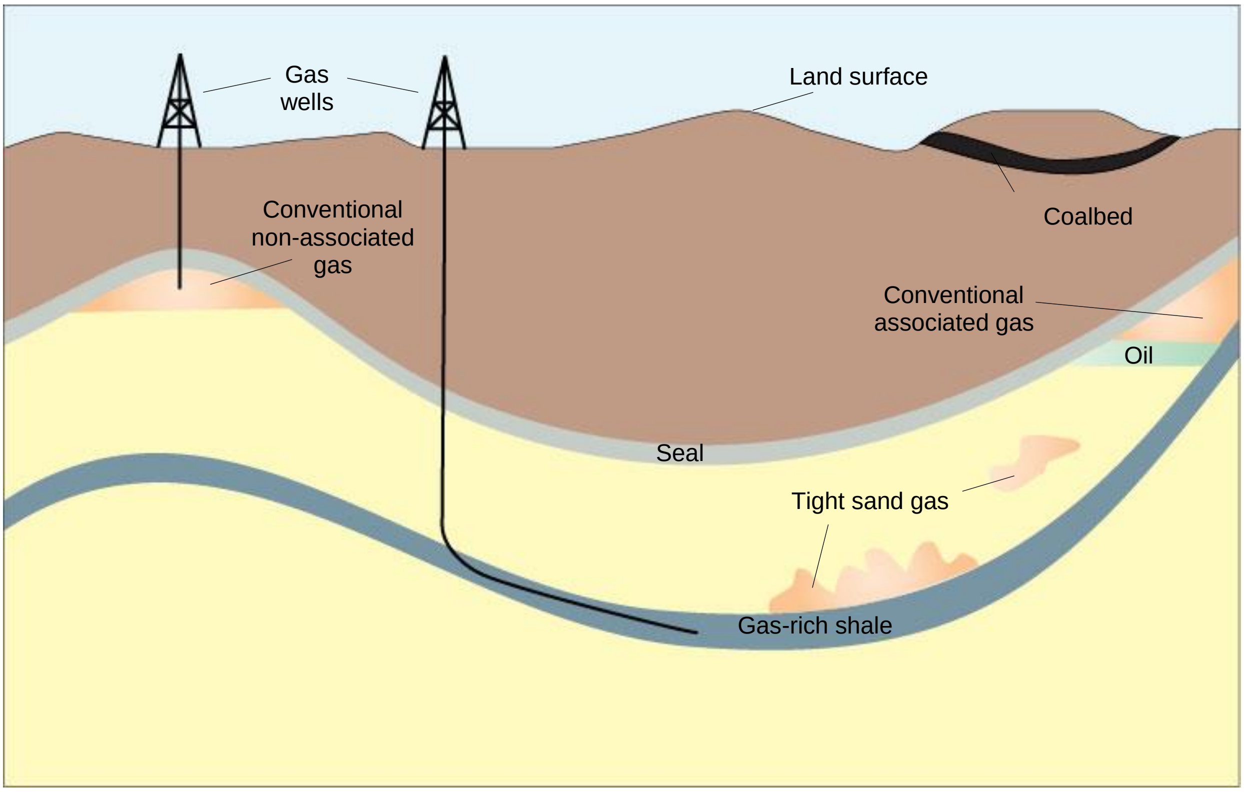

Figure 2.1: Schematic geology of natural gas resources and various reservoir types.

Source: *Modified from USEIA (2010a).*

There are two main gas reservoir categories, conventional and unconventional gas (UCG) reservoirs (EPA, 2015) (Figure 2.1). Conventional reservoirs primarily consist of sandstone and carbonate reservoirs (Aguilera et al. 2014) whereby oil and gas leak from the porous source rock and are trapped by impermeable rock barriers on the way to the surface. The barriers, form a natural seal and the resultant reservoir is usually shallow and easily accessible (Fakir, 2015). The most important seal type is shale, followed by carbonate rocks and the evaporites (Aguilera et al., 2014). This formation usually results in lower costs of extraction (Aguilera, 2014) whereby a vertical well is drilled into the reservoir and the gas flows to surface naturally without the need for much stimulation (Scholes et al., 2016a).

UCG reservoirs form in far more complex geological environments that limit the ability of the petroleum to migrate and therefore require different methods to extract (EPA, 2015). As a result, unconventional formations have generally been uneconomical to extract using vertical wells, and have required the use of horizontal drilling and multi-stage fracking to lower the costs and become viable (Aguilera, 2014). UCG consists of four primary types: Tight gas, natural gas hydrates, shale gas and Coal Bed Methane (CBM) (Figure 2.1) (Aguilera et al., 2014).

Tight gas forms when the gas moves from the source rock into a sandstone formation of low permeability, limiting its ability to continue to migrate to the surface (USEIA, 2010a). These reservoirs usually produce dry natural gas (Holdith, 2006). The dominance of sandstone as a host has led to the common term ‘tight sand gas’, but the term is misleading as lithology is not a key element to its formation and the key elements required can be found in other formations, e.g. carbonate reservoirs (Aguilera et al. 2014).

Natural gas hydrates, or methane hydrates, are a crystalline combination of methane and water, created under low temperature, high-pressure conditions under the ocean or within the permafrost (Dickens & Qunby-Hunt, 1994).

In shale gas formations, the natural gas is generated in the shale rock formation and trapped due to shales low porosity, with none, or only a minor amount able to escape to surrounding rock (e.g. to form a tight gas reservoir). In these formation types, the shale is both the source rock and the reservoir (Aguilera et al., 2014) and is composed primarily of dry gas (de Wit, 2011).

CBM does not originate from gas-rich shale but is generated during the transformation of organic matter to coal (USEIA, 2010a). The generated methane is trapped within the coal seam and is under pressure due to overlying rock formations (EPA, 2015). Similarly to the shale gas formation reservoir, the coal bed is both the source rock and the reservoir rock (Aguilera et al., 2014).

2.2.3 Uses

Petroleum is possibly the most important substance used in society today. It provides the raw materials for the majority of plastics and numerous other products, as well as the fuel for energy, industry, heating and transportation. From an energy perspective, the fuels generated from petroleum are responsible for over half of the worlds total energy supply. The fuel for modern-day automobiles, aircraft and ships are provided by gasoline, kerosene and diesel oil. Fuel oil and natural gas are used to heat homes and industrial buildings as well as to generate electricity. Basic materials produced from petroleum create the synthetic fibres that are used in a wide range of products such as plastics and paints. The use of the raw material from petroleum is a pivotal part of manufacturing in the current industry (Speight, 2014).

Fossil fuels have been the primary contributor to growth and trade since economies were reorganised for the purpose of manufacturing goods through industrialisation (O'Sullivan & Sheffrin, 2003). In 2014, the global total primary energy supply was dominated by fossil fuels, with renewables making up a minor portion. The three types of fossil fuels: natural gas, oil and coal provided 21.2%, 31.3% and 28.6% respectively. Renewable energy supplied only 14.1%, and the remaining 4.8% was provided by nuclear power (IEA, 2016a). These statistics indicate that we are still living in a world that is predominantly powered by fossil fuels (Walsh, 2011) with the current total primary energy supply gap between fossil fuels and renewables is too wide to close in the near future (Eaton, 2013) resulting from the reliance on fossil fuels for at least the next couple of decades (Ajanovic, 2013).

Of the three types of fossil fuels, natural gas is becoming increasingly important as it is a multipurpose fuel for electricity generation, heating and transportation (Melikoglu, 2014). The four main users of natural gas are 1) electric power generators, 2) industrial consumers, 3) commercial consumers and 4) residential consumers (Wang et al., 2014a). There has been a steady continuous increase in its usage in domestic households, industry and power plants around the world throughout the last 40 years (Correljé, 2013).

Reserve estimates of conventional natural gas have substantially outweighed that of unconventional plays (Rogers, 2011), and the global supply of natural gas has been dominated by conventional gas reservoirs. However, there has been an increase from unconventional sources following the shale gas boom in the US and development of CBM sources in Australia (Fakir, 2015).

2.3 Technological advancements

The increase in shale gas production is a result of improved gas extraction and drilling technological advancements that have allowed these previously uneconomical UCG reservoirs to become profitable. These technologies include a combination of horizontal drilling (first utilised for oil production in the early 1980’s (USEIA, 2011a)), hydraulic fracturing, 3D and 4D seismic imaging, coiled tubing, measurements whilst drilling and slim hole drilling that have enabled the economic extraction of natural gas from formations of low permeability (Cronshaw & Quentin Grafton, 2016).

Of these, the two main areas of development that have revolutionised the fracking of oil and gas are the modern refinements in the technology of horizontal drilling and fracking.

New drilling technology allows for the drill to turn corners at depth and continue horizontally within a narrow layer. The horizontal portion is easier to control and allows for the harvesting of shale gas along a much larger geographical area than a single vertical well. The use of horizontal drilling in multiple directions results in fewer well sites required and results in less construction (de Wit, 2011). Refinements in fracking technology have made it a very sophisticated engineering process whereby it is computerised to emplace predetermined fracture networks within a layer as thin as 1 m up to depths of around 500 m (USDoE, 2009).

Fracking is by far the most controversial of these technologies. Fracking is the injection of a fluid, usually about 95% water plus a proportion of certain chemicals, under high pressures to create fractures in the rock. There is an additional proppant (usually sand) that serves to keep the tiny fractures open (Cronshaw & Quentin Grafton, 2016). These pressurised fluids do the hard work of breaking open the rock, creating tiny fractures before being partly recovered through depressurization to allow the oil and gas to flow to the surface (de Wit, 2011). Although controversial, Aguilera et al. (2014) highlights that without fracking the extraction of natural gas from unconventional reservoirs will not be economical.

There is, however, a common misconception that producing natural gas from shale started only a few years ago. In fact, shale gas production goes as far back as 1821. In 1980 fracking had been used in North America for several years with thousands of shale vertical wells producing natural gas from the Appalachian Basin in the eastern US. These fracking methods included water fracturing, acid-methanol fracturing and even shooting with nitroglycerin. It is only in the last 15 years that the rapid technological advancements have truly allowed global production, in particular in the US, to increase dramatically (Aguilera et al., 2014).

As a result, from the year 2009 to 2015, global natural gas output grew by nearly a third, completely beyond previous predictions (IEA, 2016a). The UCG technologies have enabled the US, in 2013, to surpass Russia in natural gas production for the first time since 1982 (Young & McGarrity, 2013). This dramatic change in the US natural gas supply has resulted in numerous countries who also have large potential shale gas deposits such as China (Chang et al., 2012; Gunningham, 2014; Wang et al., 2014b); the United Kingdom (UK) (Selley, 2012; Young & McGarrity, 2013); European countries such as Germany (Klaver et al., 2012), Ukraine (Sachsenhofer & Koltun, 2012) and Poland (Gautier et al., 2012); Turkey (Kok & Merey, 2014; Coskun & Ergin, 2013); India

(Das, 2013); Australia (Warner, 2011) and South Africa (de Wit, 2011) looking to exploit their resources (Melikoglu, 2014).

2.4 Potential for shale gas extraction outside of the US

Some European countries, like Poland and the UK, want to move away from coal as an energy source and the need to import natural gas, as a result, they are considering shale gas as energy supply (Soeder, 2018). Germany (Uffman et al., 2014), and Hungary (Badics & Vető, 2012) have also been considering their shale gas options. However, environmental concerns over shale gas extraction have halted the development in many European countries, where green parties posses a lot of political influence (Kulkarni, 2011). In France, fracking is completely banned, and in Germany and some other countries, it has been put on hold (Lange et al., 2013). If the US manages to resolve the environmental uncertainty around shale gas, it could significantly increase the confidence of some of these nations to explore the prospect further (Soeder, 2018).

In Europe, Poland is experiencing the most shale gas activity (Bluestein et al., 2012) and has been exploring potential extraction from the Silurian black shales that have formed in the belt stretching from central Pomerania to the Lubin region (Konieczyńska et al., 2011). Environmental impact studies were done by the Polish Geological Institute and the Voivodeship Inspectorate for Environmental Protection in 2011 on the Lebien LE-2H shale gas well, one of the first such prospective studies ever done (Soeder, 2018). The study focused on the environmental impact of the well, monitoring the air, water, groundwater, ecosystems and landscape impacts from the well. The study concluded that if done properly, and the correct construction processes are followed, the impacts can be managed and are minimal (Konieczyńska et al., 2011).

The UK has been considering and investigating shale gas potential since development started in the US (Selley, 2012; Stephenson, 2015). Since ‘Brexit’, this has become increasingly more urgent as the separation from the European Union instils concerns over the ease of access to energy imports (Soeder, 2018). The British Geological Survey is assessing the Jurassic-age shales in the Wessex and Weald Basins in the south of England, Bowland Basin shales in central Britain, Cambrian-age shale in Wales, and Carboniferous shales of the Midland Valley of Scotland. Some of the results have high potential, such as the estimates done by the British Geological Survey on recoverable shale gas in the Bowland Basin ranging from 822 to 2281 tcf (British Geological Survey, 2018).

In India, the push for shale gas extraction results from the rise in energy demand across the country, as well as the energy security concerns. There is currently no shale gas production, and the industry is still in a very early development stage, with the first exploration hole only being drilled in January 2011 (US USEIA, 2011b). However, the need to increase local production of shale gas has been prioritized by the Indian government (Vaid, 2017), and the exploration of basin resources and well development technologies are underway (Bluestein et al., 2012). However, environmental concerns are resulting in delays, primarily the contamination of groundwater and the acquisition of land in such a densely populated country (Vaid, 2017),

Outside of the US, China is one of the major nations planning to move forward on its shale gas development. The country aims to substitute toe use of coal with natural gas in multiple areas (Yu, 2017). Currently, coal is still widely utilised as an energy source for multiple uses such as domestic heating and cooking, as well as electricity production. This has contributed to the high levels of air pollution in major cities such as Beijing. Yet China has a large potential for shale gas development as resources occur in multiple basins across the country (Soeder, 2018).

The organic-rich shales in the Qiongzhusi Formation and Longmaxi Formation in the Sichuan Basin in south-central China are favoured for development, they are both rich in gas and close to many of the major cities in China (Dong et al., 2016). The natural gas transport infrastructure is underdeveloped in China, and the proximity of the resource to major cities is important. The Ordos Basin may also be favourable for shale gas development even though the area is better known for the production of CBM. Near the Mongolian border in the west, the large Tarim Basin also indicates large potential; but is far from populated areas in the eastern part of the country and is under-explored (Soeder, 2018).

2.5 US shale gas

The discovery of new UCG reservoirs has greatly increased the natural gas technically recoverable resources (TRR) for the US (USDoE, 2009; IEA, 2011; USEIA, 2012a). As of 1 January 2015, the US has an estimated 2,355.0 Tcf of total TRR dry natural gas resources, of which shale gas makes up 1,024.8 Tcf, approximately 43% of the total (USEIA, 2017a). Proved reserves at year-end 2015 was a total 324.3 Tcf, with shale gas accounting for 175.6 Tcf, about 54%. The same year-end saw shale gas account for 15.2 Tcf in production, around 51% of the total 29.3 Tcf (USEIA, 2016a).

The state of Pennsylvania had the highest amount of proved natural gas reserves from shale in 2015, followed by Texas, West Virginia, Oklahoma, Ohio, Louisiana and Arkansas in descending order. At the end of 2015, seven shale plays accounted for 91% of total shale gas proved reserves. The Marcellus shale play is the largest (72.7 Tcf) with the Eagle Ford play coming in second (19.6 Tcf), followed by the Woodford, Barnett, Haynesville/Bossier, Utica/Point Pleasant and Fayetteville plays in descending order (Figure 2.2) (USEIA, 2016a).

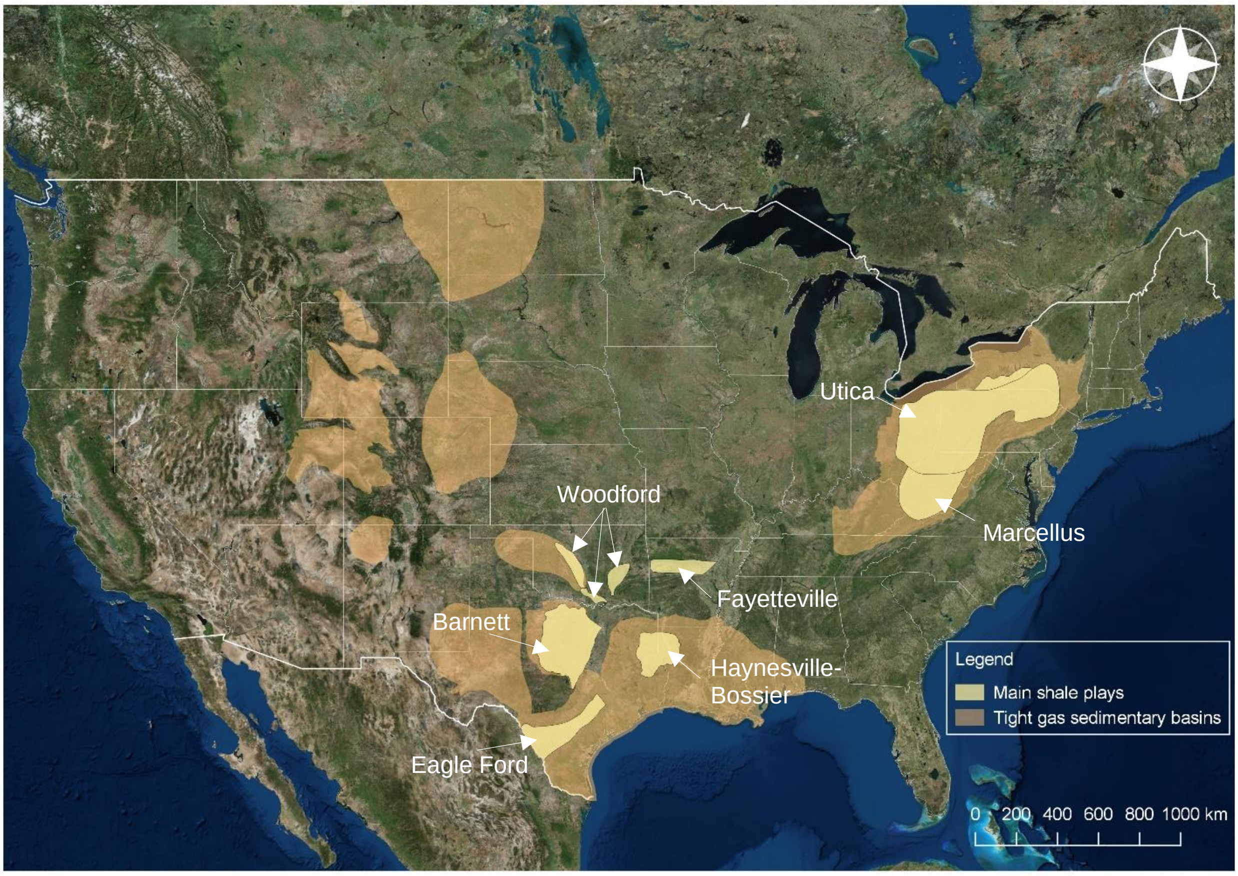

Figure 2.2: Map of US shale oil and gas plays in the lower 48 states.

Source: *Map created using QGIS; base map from the ESRI plugin; shapefiles from USEIA (2016b), Natural Earth (2017) and ArcGIS (2012). All items are open source and free to use.*

Wang et al. (2014a) provide a comprehensive overview of the evolution of the US shale gas boom, together with the opportunities and challenges of production. Constructed around the changing oil price, the paper breaks down the history of shale gas development in the US into 3 specific eras, the infant, large demonstration and industrial-scale periods.

2.5.1 Infant period

The first era is termed the ‘infant period’, from 1821 to the 1970’s, before the 1970’s oil crisis (Wang et al., 2014a). The start date is a result of the first ever shale gas well drilled in the US in 1981, in the Devonian Dunkirk Shale in the Chautauqua County, New York. The gas was produced, transported and sold in Fredonia (Peebles, 1980; Hill & Lombardi, 2004). This discovery initiated the development of hundreds of new wells drilled on the Lake Erie shoreline and the establishment of multiple shale gas fields southeastward of the lake in the late 1800’s (Hill & Lombardi, 2004).

However, even with these establishments, the exploitation of shale gas was discouraged as it was easier to produce natural gas from conventional reservoirs such as from the Drake well, developed in 1859 (Peebles, 1980). There were three primary stages from 1860 to 1970’s, including the discovery of shale gas reservoirs in western Kentucky in 1863, West Virginia in 1920’s and the first use of the fracking method in the 1940’s (Wang et al., 2014a).

2.5.2 Large demonstration period

The second era is the ‘large demonstration period’ from the 1970’s to the 2000’s (Wang et al., 2014a). The oil crisis of 1973 and 1979 had led the US to search for alternative energy sources to solve energy deficiencies and the increasing price of oil. It encouraged the US government to invest in and drive research and development (R&D) in alternative energy, including shale gas, throughout the entire value chain. The high oil prices also encouraged private enterprises to increase investment in UCG reservoirs (Montgomery et al., 2005; Cleveland, 2005; Bowker, 2007; Henriques & Sadorsky, 2008).

This investment from government resulted in the US Department of Energy establishing projects such as the Eastern Gas Shale Project in the late 1970’s. The EGSP aimed to work coherently with industry to research new technology to improve the development of the Devonian shale gas (Schrider & Wise, 1980). Additionally, the Gas Research Institute was established in 1977, and the National Energy Technology Laboratory in the late 1990’s, both served to provide further R&D within the shale gas industry. In 2000, the GRI merged with the R&D laboratory for the gas distribution industry, the Institute of Gas Technology, to create the Gas Technology Institute (Biederman et al., 2007).

During this time, multiple companies on the forefront of the oil and gas industry had been trying to economically improve shale gas extraction by combining larger fracture designs, highly detailed reservoir characterization, horizontal drilling and lower cost approaches (Kvenvolden, 1993; Montgomery et al., 2005; USEIA, 2011a).

The main pioneering company was Mitchell Energy and Development Corporation who invested over a quarter billion dollars and underwent multiple experiments in the 1980's and 1990's in the Barnett Shale in North-Central Texas to unlock its hydrocarbon reserves. The company managed to use fracking techniques to profitably extract the natural gas from deep shale reservoirs, establishing confidence in other companies to pursue these types of reservoirs. The success of the fracking techniques by Mitchell Energy and Development Corporation revolutionised the oil and gas industry (USEIA, 2011a; Pickett, 2010; Kutchin, 2001; Becchetti et al., 2008; Zuckerman, 2013). The success of fracking was then combined with horizontal drilling by Devon Energy in 2003, taking the monumental breakthrough of fracking even further (Yergin, 2011).

These combined efforts by the US government and industry contributed significantly to the extensive growth in shale gas output. Between 1979 and 2000 the US experienced a seven-fold increase in its shale gas output (USEIA, 1998).

2.5.3 Industrial-scale period

The final era is the 'industrial-scale period' since the 2000's when the period of cheap oil appears to have come to an end. Throughout this period three key factors have contributed to the confidence of oil and gas companies to tap into shale gas reserves (Wang et al., 2014a). First, and primarily, is the advancement of drilling techniques and that of horizontal drilling in particular. Horizontal drilling together with fracking has greatly increased the chances of exploiting these reservoirs profitably (Kutchin, 2001; Bowker, 2007; USEIA, 2011a; de Wit, 2011; Cronshaw & Quentin Grafton, 2016).

Second, the increasing price of oil since 2003 has made shale gas more economically attractive than ever before (Owen et al., 2010; Heinberg & Fridley, 2010). From the mid-1980's to 2003, the price of crude oil was usually under $30/barrel (BP, 2011). In 2003, the price increased above $30/barrel, to $60/barrel in 2005, beyond $75/barrel in 2006, almost $100/barrel in 2007, and reached a high of $140/barrel in 2008 (Kilian & Lewis, 2011; Wang, 2011). This is a clear indication of how new technology can allow for demand to shift toward a cheaper substitute (Gordon & Tilton, 2008).

The third and final key factor is the decrease in local natural gas production from conventional sources since 2000. This slow and steady decline over the next few years resulted in the expectation of higher US gas prices in response to the tightening market supply (The Perryman Group, 2007; Rogers, 2011).

The resultant increase in confidence has resulted in upstream oil and gas companies aggressively entering the shale gas market. Independent energy companies like Devon Energy, Goodrich Petroleum and XTO Energy have substantially increased their drilling for gas (The Perryman Group, 2007; Jarvie et al., 2007; Bowker, 2007). This abundance of activity within the industry enabled the US to go from producing just under 0.4 Tcf of dry natural shale gas in 2000 (USEIA, 2011b), 1.2 Tcf in 2007, to a substantial increase of an estimated 15.2 Tcf in 2015 (Figure 2.3) (USEIA, 2016c).

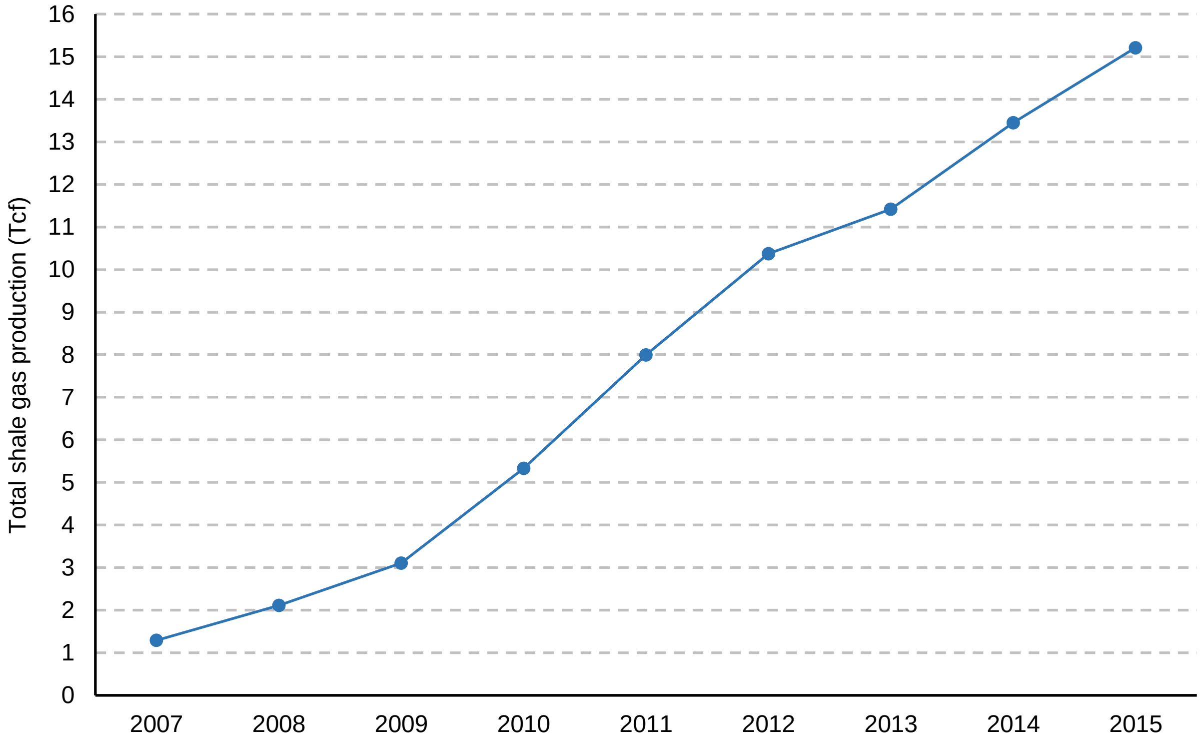

Figure 2.3: US shale gas production from 2007 to 2015.

Source: *Data from USEIA (2016c).*

The US is now the worlds leading natural gas producer, and together with Canada are responsible for more than 25% of global production (Speight, 2013). It is estimated that natural gas will account for 40% of US energy production by 2040 (USEIA, 2017b), with production from shale gas and tight oil plays to increase from 50% of total natural gas production in 2015 to 69% in 2040, a total of 29.0 Tcf (USEIA, 2016d).

2.5.4 US natural gas price

The high levels of domestic shale gas production have contributed substantially to the decrease in the price of US natural gas, reaching a 10 year low in 2012 (USEIA, 2012b). The lack of sufficient export capacity with the new influx of production has led to lower prices compared to the pre-shale gas era (Oglend et al., 2015). The price has been at or below US$4/MMBtu over the past few years. In relevant energy terms, this is the same as an oil price of approximately $25/barrel (Cronshaw & Quentin Grafton, 2016). Cronshaw & Quentin Grafton (2016) continue to use a price of US$2/MMBtu at the time of the report (USEIA, 2016e) to demonstrate a comparative price at the time to oil of US$40/barrel, highlighting natural gas as being much cheaper. The 2016 Annual Energy Outlook report by the US Energy Information Administration (USEIA) estimates the price to average at around US$5/MMBtu to 2040 (USEIA, 2016d).

Prior to the shale gas boom, the US oil and natural gas prices were integrated (Bachmeier & Griffin, 2006; Villar & Joutz, 2006; Neumann, 2009; Erdős, 2012), although the relationship was often weak and a large portion of the natural gas price was unaccounted for by the oil price (Parsons & Ramberg, 2012). Nonetheless, the issue of ‘the end of cheap oil’ (Kunstler, 2006; Tsoskounoglou et al., 2008; Wang, 2011) questions if the age of cheap natural gas in the US will also diminish, to which shale gas has now played a substantial contradictory role. Therefore, the boom has not only contributed to an era of cheaper natural gas, but also to the decoupling of the US natural gas price from the price of crude oil. This effect has a substantial impact on the world’s gas pricing system (Wang et al., 2014a).

Without the local production, the US would need to import much more expensive liquid natural gas (LNG) resulting in gas prices closer to those in the UK and Europe that have been about $4-5/MMBtu more expensive than in the US. With the resultant natural gas price’s effect on the price of wholesale electricity, households can expect cheaper electricity as a direct result of cheaper natural gas in the US (Bonakdarpour & Larson, 2012).

The resounding success of shale gas production in the US has transformed the country’s energy scenario, moving from one of the largest gas importers to becoming self-sufficient and getting ready to export excess resources (Wang et al., 2014a). Calculations indicate that primarily due to shale gas, the US may become completely self-supporting in fossil fuels; this will be for the first time since the 1970’s when the Middle East, Mexico, South America and Africa became its primary suppliers (de Wit, 2011).

2.5.5 Key success factors

It should be noted that the success of shale gas production in the US seems to be unique and may not be applicable everywhere else (Fakir, 2015). The well-known oil and gas expert Leonardo Maugeri emphasises this point (Maugeri, 2013), and goes as far as to say that the shale gas experience of the US is bound to stay in the US (The Guardian, 2014). The US is considered a well-developed and mature oil and gas industry (Brown & Yücel, 2013), in light of this, Fakir (2015) lists 8 key elements in the success of the US shale gas industry:

1. Technological advancements and innovations were primarily developed by minor players and entrepreneurs who were willing to take risks and hedge their bets. Once successful, these innovations spread rapidly through the industry as a result of the geographic proximity of players in the shale gas industry.
2. An already well-established oil and gas industry, with well-established relevant engineering capabilities and knowledge of the geology and resource base.
3. Highly specialised local equipment manufacturing, such as by companies like Halliburton, KBR, Schlumberger and Baker Hughes. This has allowed for cheaper goods and services to the local shale gas industry.
4. The mineral rights are privately owned, whereas in most other countries they are owned by the state. These private owners are often willing to earn extra income by leasing the land to the oil and gas companies, enhancing the ease of access for the companies.
5. There is good existing oil and gas infrastructure throughout the value chain in most of the shale gas plays areas.
6. A well-developed gas use market whereby the wellhead prices (the producer's all-inclusive price for the natural gas before transportation costs (USEIA, 2017c) are controlled at the producer’s end using the Henry Hub price, resulting in easy clearance and trade of gas.
7. Most of the horizontal drilling rigs in the US are focused on shale plays.
8. A well-established financial sector that is experienced in dealing with the oil and gas sector, in all areas of the value chain (Fakir, 2015).

Experts like Maugeri and others insist that the lack of these endowments in other countries will lead to more expensive exploitation of their shale gas reserves, as these endowments will lower the costs, especially if already in place and is just an extension of an already existing system (McMahon, 2013).

2.6 Economic and energy benefits

Logically, the economic benefits of a growing gas industry, amplified by a shale gas boom, should outweigh the costs involved. These benefits will depend on the gas/inter-industry linkages with other domains in the economy; especially increased employment, income, government revenue and economic growth are expected (Wait & Rossouw, 2014). However, there is still a lack of a complete understanding of the potential size and impacts of the benefits and costs, leading to a mixed public response. As a result, in an attempt to enhance public policy making, the natural gas industry has sponsored several research reports that estimate the potential economic benefits of shale gas extraction (Kinnaman, 2011).

These reports are often authored by private consulting firms, or by research economists associated with well-known universities who serve as private consultants to industry. These types of reports are not published in academic journals and lack the credibility generated by journals through the peer-review process which exists to ensure fairness, promote the honest exchange of ideas and often improve the quality of the work (Kinnaman, 2011). These type of reports are often referred to as ‘grey literature’ (Hoy et al., 2017).

Examples include Considine et al. (2009, 2010) that were both funded by the Marcellus Shale Coalition (Pennsylvania’s shale gas extraction industry), and a report by CBER (2008) sponsored by four gas extraction companies. Although funded by industry, all these reports feature the logo of well-known universities, Penn State on the former two and the University of Arkansas logo on the latter (Kinnaman, 2011).

2.6.1 Macroeconomic benefits

Using an IMPLAN input-output model, Considine et al. (2009) assessed the economic effect the Marcellus shale gas industry has had on Pennsylvania during 2008 and 2009. The calculated estimates for 2008 are an economic output of US$2.3 billion (value added), the generation of over 29,000 jobs and US$240 million in state and local taxes. Estimates for 2009 indicate an economic output of US$3.8 billion, over 48,000 jobs created and tax revenue in excess of US$400 million (Considine et al., 2009). The follow-up study in 2010 estimates an impact on gross output of US$7.17 billion, value added of US$3.87 billion and an increase in jobs to 44,098 (Considine et al., 2010). In a review of several studies estimating the economic impact of shale gas extraction, Kinnaman (2011) suggests that the assumptions made regarding the spending behaviour and drilling activity are very optimistic and make the results of Considine et al. (2009 and 2010) questionable.

The CBER (2008) report presents a similar study, using the IMPLAN model to estimate the economic output and employment impacts from extracting shale gas from the Fayetteville shale reserves for the state of Arkansas. Estimated impacts include the gross output of US$2.6 billion and the development of 9,533 jobs in the year 2007.

Industry-generated reports not affiliated with any academic institution include examples such as Scott (2009), The Perryman Group (2009) and Weinstein & Clower (2009). The report by Scott (2009) estimates an economic impact of US$2.6 billion in revenue and creation of 9,533 jobs for the state of Lousiana by extracting from the Haynesville shale play in the year 2008. The Perryman Group (2009) focused on the impact on the Dallas-Fort Worth regional economy from the Barnett shale play and estimates an impact of US$11 billion in revenue and 111,131 jobs in the year 2008. The Weinstein & Clower (2009) report estimates the impact on Broome County, New York, from the Marcellus Shale. Estimates are over a 10 year period based on the drilling of 2,000 wells. Results show a generation of US$2.06 billion in an average year over a ten-year period and support 2,200 jobs each year.

The literature review by Kinnaman (2011) concludes that due to the various questionable assumptions used to generate the estimated values, the industry-sponsored reports listed above, both affiliated and non-affiliated with prestigious academic institutions, are probably overstated. Both Weber (2012) and Barth (2013) are in agreement, stating that the models rely too heavily on assumptions about economic multipliers and the resultant estimates may vary heavily from actual effects.

Another industry-sponsored study by Thomas et al. (2012) looked at the economic impact on the state of Ohio from developing the Utica Shale. An input-output model was used to estimate the economic impact of shale gas extraction to the year 2014. Results for 2014 include a total value added of US$4.9 billion and a total 65,680 jobs created.

Kinnaman (2011), Barth (2013) and Hoy et al. (2017) highlight the shortfall and need for more peer-reviewed academic studies on the economic impacts of shale gas. A literature review by Barth (2013) therefore focused on peer-reviewed studies on the general economic impacts of extractive industries, relating to that of shale gas. The study looked at key elements such as the resource curse phenomena, the need to analyse both boom and bust cycles, as well as the socioeconomic impacts. The report concludes that each extractive industry and its effects on a particular area need to be analysed on a case-by-case basis. Further research is required before any definitive estimates can be drawn on the short- and long-term effects on the local and state economies (Barth, 2013).

A report by Hoy et al. (2017) addressed the key issues and criticisms made by Kinnaman (2011) on the assumptions made by industry-sponsored input-output model reports. The report used detailed county records and results from a survey to directly address the assumption issues by being more conservative to reflect real-world spending patterns and create a more accurate estimate. The aim was to compare their results to those of Considine et al. (2009 and 2010) on the impact of the Marcellus Shale exploitation on the economy of Pennsylvania for 2009. Results indicate that the industry will support up to 23,884 jobs and generate a total value-add of at least US$1.86 billion. These results are approximately 52% of those from the prior studies, confirming that some of the industry-sponsored ex-ante studies use assumptions that lead to gross overestimates of the potential economic impact (Hoy et al., 2017).

A peer-reviewed report by Weber (2012) systematically documented the magnitude income and employment impacts, as well as its distribution amongst the local population, in states that experienced a natural gas boom in the United States. They used empirical estimates to measure the changes in economic outcomes over several years in the states of Colorado, Texas and Wyoming. Differentiating from the reports listed above, instead of using an ex-ante input-output model, Weber (2012) did an ex-post assessment using an OLS and IV regression analyses.

The results indicate that the booming regions experience a higher growth in employment and labour income, determining that every million dollars in gas production create 2.35 jobs. The report analysed the effect this will have on both the Marcellus shale play on Pennsylvania’s economy and the Fayetteville shale reserves on the economy of Arkansas, comparing results to Considine et al. (2010) and CBER (2008) respectively. For Pennsylvania, Considine et al. (2010) estimate a total job creation of 44,098 compared to the 2,183 estimated in the report. CBER (2008) estimates a total of 9,533 jobs generated in Arkansas, compared to 1,377 estimated in the report (Weber, 2012).

A key difference between the reports is that the input-output models estimated jobs across the entire state, where the ex-post assessment only considered the impact on the county in which production occurs, ignoring spill-over job creation in other counties across the state. Nonetheless, for the spillover effects to make up the difference in each state, it will have to be around 85% in Arkansas and 95% in Pennsylvania (Weber, 2012).

The empirical approach determines a large increase in the value of gas production leading to modest increases in employment, wage and salary income, and median household income. However, although results are more modest and significantly smaller than those estimated by input-output models, the estimated effects are certainly not negligible. An employment and wage and salary income growth of 1.5% and 2.6% are important economic gains that cannot be ignored (Weber, 2012).

Lee (2015) highlights that the conventional input-output model used for ‘impact’ studies for a particular region has been subject to criticism in academic literature. He attempts to empirically investigate the regional economic impact of oil and gas extraction in Texas during the recent shale oil boom using a spatial regression model. Extraction from gas well generate a larger economic impact than for oil wells, and the initial drilling phase results in comparable estimations. He notes that estimates of economic impacts are greater when using a dynamic spatial model that allows for spillover effects across local economies as well as over time.

A summary of the economic impacts estimated by the various reports is presented in Table 2.1 below:

Table 2.1: Summary of US economic impact studies of shale gas development.

Author	Year assessed	US shale play	US State/region impacted	Value added (US$bn)	Jobs created
Considine et al. (2009)	2008	Marcellus	Pennsylvania	2.3	29,000
	2009	Marcellus	Pennsylvania	3.8	48,000
	2010	Marcellus	Pennsylvania	3.9	44,098
Hoy et al. (2017)	2009	Marcellus	Pennsylvania	1.86	23,884
CBER (2008)	2007	Fayetteville	Arkansas	2.6	9,533
Weber (2012)	2010	Marcellus	Pennsylvania		2,183
	2007	Fayetteville	Arkansas		1,377
Scott (2009)	2008	Haynesville	Lousiana	2.6	9,533
The Perryman Group (2009)	2008	Barnett	Dallas-Fort Worth	11.0	111,131
Weinstein & Clower (2009)	Estimated over a 10 year period	Marcellus	Broome County, New York	2.06, average over 10 year period	2,200 per year

Thomas et al. (2012)	2014	Utica	Ohio	4.9	65,680

Source: *Values from CBER (2008)***,** *Considine et al. (2009,) Scott (2009), The Perryman Group (2009), Weinstein & Clower (2009), Thomas et al. (2012), Weber (2012) and Hoy et al. (2017).*

2.6.2 Energy benefits

Beyond the benefits of employment, fiscal revenue and economic growth, people can benefit from shale gas as a source of energy used for home heating, electricity generation and production processes in multiple industries (Kinnaman, 2011). Hence the biggest energy story to emerge in the 21st century has been the extraction of natural gas from shale rock formations in the US (Brooks, 2011; Economist, 2012; Chazan, 2012).

Outside of the US, many countries seeking to exploit their shale gas reserves are trying to meet the ever-growing energy demand whilst reducing their dependence on imported fossil fuels (Wang et al., 2014a). This trend is anticipated to spread globally and shale gas investments will increase exponentially over the second half of this decade (Melikoglu, 2014). Some believe shale gas may produce more fossil fuel energy than the world's oil and coal combined (de Wit, 2011).

A study by Melikoglu (2014) on the effect of shale gas on the global energy market concludes that without utilising the available shale gas resources, the world will need to consume around 66% of the worlds total natural gas reserves by the year 2040 in order to meet the energy demand. This would result in most countries becoming natural gas importers, and the price would skyrocket. Shale gas is therefore not an option, but a must for the further development of the global energy market and economy (Melikoglu, 2014).

Shale gas is considered the cleanest fossil fuel (Nature, 2009; Bluestein et al., 2012) and many authors believe that it can act as a transitional fuel, allowing the continuous reliance on fossil fuels for energy whilst reducing the total GHG emissions compared to oil and coal combustion (Pacala & Socolow, 2004; Kinnaman, 2011; Deutch, 2011; Melikoglu, 2013;). The concentration of GHG emissions in the atmosphere is one of the main contributors to climate change, from which average temperatures have increased by 0.2°C per decade over the last 50 years (RSA, 2010). Weitzman (2011) highlights that the exact significance of such extreme climate change levels are unknown, and it is highly probable that they will be overwhelmingly negative.

Many believe that the burning of coal in power plants is one of the major contributors to climate change due to the high concentration of GHG emissions (Wolde-Rufael, 2006). According to Olivier et al. (2016), coal combustion was responsible for 46% of global CO_2 emissions, with 31% being emitted from coal-fired power plants for electricity generation. The combustion of shale gas produces less CO_2 than coal and is hoped to reduce the GHG footprint from the electric power sector (USEIA, 2011c).

However, there is a growing objection to this belief (Wang et al., 2011), as methane, the primary component of shale gas, is also a powerful GHG, with a greater global warming impact than CO_2. The effective time frames of these two gases are also important as they have different impacts over the short- and long-term (Howarth et al., 2011a).

Howarth et al. (2011a and 2012) suggest that the life-cycle GHG footprint of shale gas will be worse than that of coal. The studies state that due to the excessive methane leakage during operations, the impact of shale gas is significantly greater over the short-term and comparable in the long-term to coal. However, Cathles et al. (2012) argue that Howarth et al. (2011a) base their results on heat generation instead of electricity which is the main purpose of coal. If more rational leakage rates and base levels of comparison are applied, the GHG footprint of shale gas is half, or even up to a third, of that of coal (Cathles et al., 2012).

Proponents of shale gas, such as Jaramillo et al. (2007), compared the GHG lifecycle emissions of electricity generated using natural gas and coal. The aim was to determine how using coal compared to natural gas presents different advantages and disadvantages. The study concludes that when factoring in all GHG emissions during the entire life cycles of coal and natural gas, natural gas has lower GHG emissions (Jaramillo et al., 2007).

Wang et al. (2011) determine that if the higher power generation efficiency of shale gas is considered, shale gas has less of an impact than coal over the long-run. In the short-term, shale gas emissions can be lowered to the same level as coal if existing technologies are utilized to minimize the methane emissions.

Stephenson et al. (2011) modelled the emissions of gas production, placing the results into a context of power generation. The study concludes that in all the cases considered, the emissions from shale gas are significantly lower than those of coal. Focusing primarily on the electricity generating sector, Hultman et al. (2011) show that the GHG impacts of shale gas are only 56% of that of coal when using standard assumptions.

Jiang et al. (2011) suggest that natural gas from the Marcellus shale generally has lower life-cycle GHG emissions than coal for electricity production. Without any effective carbon capture and storage processes, emissions are reduced by 20-50% depending on plant efficiencies and the variability of natural gas emissions. A report by Burnham et al. (2012) establishes a 33% reduction in shale gas life-cycle emissions when compared to coal. Also in agreement, Jenner & Lamadrid (2013) states that shale gas is most likely to have a smaller GHG than that of coal.

Globally, energy-related CO_2 emissions from fuel combustion have been flat for a third straight year in 2016 (Figure 2.4). These statistics are a result of increasing power generation from renewable energy, a switch from coal to natural gas, improvements in energy efficiency and structural changes in the global economy. The US experiences the biggest decrease due to a boom in shale gas supplies which have become a cheaper power source, as well as a more attractive renewable power that has replaced coal (IEA, 2017a).

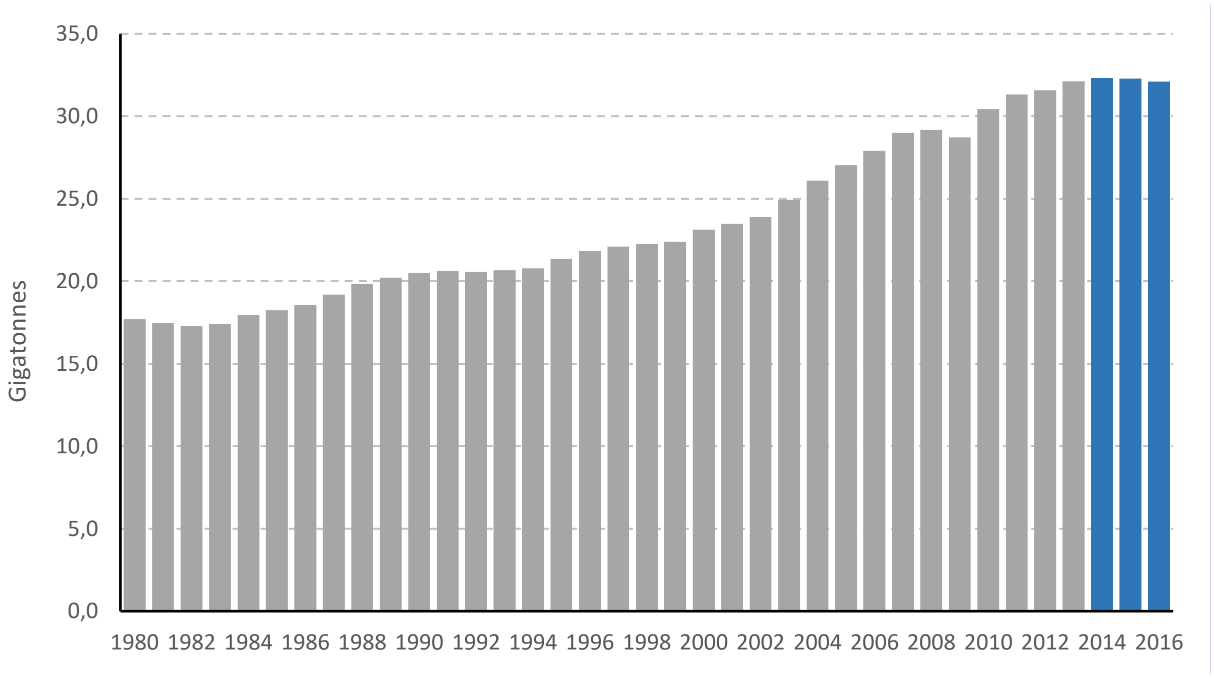

Figure 2.4: Global CO_2 emissions from fuel combustion, 1980 to 2016.

Source: *Created from free statistical data downloaded from* IEA (2017b) *containing values from 1980 to 2015, the value for 2016 was obtained from IEA (2017a).*

In 2015, CO_2 emissions from the US decreased by a considerable 2.6%, caused mainly by a large drop in coal consumption of 13% which is the largest decrease of any fossil fuel usage in the US over the past five decades. For the first time, the total (kilowatt hour) kWh produced by gas-fired plants was nearly equal to those produced by coal. Over the last 10 years, the 12% decrease in energy-related CO_2 emissions was mainly in the power sector as a result of natural gas replacing coal for electricity production, even though the demand for electricity has remained constant since 2005 (Olivier et al., 2016).

Hence, the discovery of natural gas is one of the most important energy revolutions of this age, transforming the global energy marketplace (Curtis, 2002; Arthur et al., 2008; Deutch, 2011; Boersma & Johnson, 2012; Hughes, 2013; Wang et al., 2014a; Murphy, 2016; Wang & Li, 2016a) with the potential to strengthen energy security whilst reducing harmful GHG emissions (Boersma & Johnson, 2012; Hughes, 2013; Malakoff, 2014; Wang, 2014; Wang & Chen, 2015; Wang & Li, 2016b). This revelation, as with most emerging technologies, has attracted huge attention from researchers and resulted in somewhat of a virtual information explosion (Bilgen & Sarikaya, 2016; González, 2016). For more on the development and trends in shale gas research, see the study by Wang & Li (2017).

2.7 Environmental concerns and economic costs

Many believe that shale gas extraction will be extremely beneficial to the state and local economies containing the reserves, but the negative externalities and resultant overall economic impacts are often overlooked in economic impact studies (Barth, 2013). The negative concerns are primarily environmental costs that require a full understanding and the industry is to be sufficiently regulated by the government (Wait & Rossouw, 2014). These concerns include potential groundwater and surface-water contamination, local air quality degradation, fugitive GHG emissions, induced seismicity, ecosystem fragmentation and various community impacts (Jackson et al., 2014).

These issues create a varied public response (Kinnaman, 2011) with protesters arguing (Howarth et al., 2011b) that the environmental costs of using fracking to extract shale gas are too high when considering the risks of methane leakage and water contamination. Opponents also believe that the benefits of reducing CO_2 emissions by replacing coal and oil consumption with natural gas are not enough to offset the environmental risks (Dongxiao & Tingyun, 2015). The environmental concerns have resulted in states like New York issuing a moratorium on shale gas extraction until all the environmental risks have been sufficiently studied (Kinnaman, 2011).

Over 20,000 shale gas wells have been drilled in the US from 2001 to 2011, most of which have had good environmental assessment results (Moniz et al., 2011). However, some studies put forward that shale gas exploitation could lead to water contamination (Dongxiao & Tingyun, 2015).

2.7.1 Water quality

Vengosh et al. (2014) provide a comprehensive survey of the literature on potential risks that shale gas poses to water sources, both surface and groundwater. The analysis of published data indicates evidence of stray gas contamination, impacts on surface water in areas of large development and the concentration of radium isotopes in some of the waste disposal and spill sites. They do highlight, however, that it is still very controversial whether the direct contamination of shallow groundwater is from fracking fluids and contamination of deep natural water is the result of fracking itself (Vengosh et al., 2014).

Osborn et al. (2011) examined the quality of the drinking-water relating to shale gas extraction in the Marcellus region. The focus was on the potential contamination by stray or fugitive gas, metal-rich formation brines and flowback fluids to the shallow drinking-water aquifers. They discover an increase in the concentrations of methane, ethane and propane with thermogenic isotopic signature in shallow water wells within a 1 km radius of a shale gas well. The contamination is most likely a result of poor well integrity. These results suggest environmental risks that accompany the exploration of shale gas globally, and that greater supervision, data and possibly regulation is needed to ensure sustainable extraction of shale gas in the future (Osborn et al., 2011).

Following the study by Osborn et al. (2011), Jackson et al. (2013a) present a more extensive dataset for the presence of natural gas in shallow drinking-water wells in northeastern Pennsylvania. The study compared the data with sources of thermogenic methane, biogenically derived methane and methane found in natural seeps. The distance to gas wells was the most significant factor for methane contamination and the only factor for ethane concentrations. In conclusion, the data set confirms that some homeowners living within a 1 km radius of shale gas extraction wells have drinking water contaminated with stray gases (Jackson et al., 2013a).

Similarly, Darrah et al. (2014) analysed data from the Marcellus and Barnett shales finding evidence of fugitive gas contamination in clusters of groundwater wells near shale gas drill sites. They conclude that the fugitive gas contamination is most likely a result of poor well integrity associated with casing or cementing issues.

However, these results have not been consistent in all areas as some studies show no evidence of significant migration or contamination due to fracking processes (Molofsky et al., 2011; Warner et al., 2012; Warner et al., 2013a; Kolesar Kohl et al., 2015; Nelson et al., 2015), with others presenting indecisive results (Hildenbrand et al., 2015; Alawattegama et al., 2015).

Myers (2012) characterises the risk factors involved with vertical contaminant transport from the fractured shale to near-surface aquifers through natural pathways. Although the various complexities involved in the contaminant transport to surface make estimations highly uncertain, a range of interpretive simulations indicates that the transport times may decrease from lengthy geological time scales from thousands to hundreds, or even tens of years as a result of fracking. Natural pre-existing faults or fracture zones, such as in the Marcellus shale region, could reduce these timelines even further (Myers, 2012).

Contamination of aquifers through the injection and extraction of fluids during the fracking process is not the only type of major contamination, but there is also a high possibility of accidental spills or flaws during well construction (Brantley et al., 2014; USEPA, 2015). Manda et al. (2014) highlight how the evolution from single well pads to multi-well pads has led to less accidental spills per well.

Warner et al. (2013b) focused on the impact of wastewater disposal from shale gas development on the quality of water in affected areas of Pennsylvania, where wastewater is usually passed through brine treatment facilities and released into local streams. They conclude that the discharge of effluent from a treatment facility increased the downstream concentrations of chloride and bromide beyond those of normal background levels. Radium levels were approximately 200 times greater at the point of discharge compared to upstream and background sediments. These levels are above the radioactive waste disposal threshold regulations and pose a risk of radium bioaccumulation in areas directly affected by the wastewater disposal (Warner et al., 2013b).

A study by Shih et al. (2015) analysed a comprehensive data set of 160 samples containing flowback, produced water and drilling wastes from the Marcellus shale play for 84 different chemicals. They compared the wastewater characteristics to permitted effluent limits and the surrounding monitoring limits and capacity. Results indicated the majority of the samples exceed the water quality thresholds, generally by 2 to 3 orders of magnitude, highlighting the need for substantial treatment before released into the environment (Shih et al., 2015).

Annevelink et al. (2016) analysed the risks posed to water concentrations by separating the risks into two main categories: 1) those posed during the production processes; and 2) during the wastewater treatment. The study concludes that a lack of aquatic field data prevents the ability to properly perform an ecological risk assessment predicting ecotoxic effects resulting from elevated chemical concentrations. However, it is expected that the insufficient treatment and disposal of wastewater poses the largest threat to the environment, especially to the areas in close proximity to the shale gas wells (Annevelink et al., 2016).

Harkness et al. (2017) examined the geochemical variations of groundwater and surface water prior, during and post-fracking in relation to various geospatial parameters in an area of shale gas exploitation in West Virginia, US. The results indicate that the saline groundwater resulted from natural processes, probably from the natural migration of deeper methane-rich brines that interacted with coal lithologies. These observations were consistent with the absence of changes to drinking water quality in the wells after the development of shale gas wells nearby, suggesting anthropogenic contamination. In contrast to these results, the composition of surface water in areas of known spills or leaks show direct evidence of contamination from water fluid accidentally released from nearby shale gas wells and wastewater disposal (Harkness et al., 2017).

2.7.2 Water quantity

In addition to potential water contamination, the volume of water used is of key concern (Jackson et al., 2013b; Vidic et al., 2013) as fracking processes require large amounts of water to be pumped into the shale formations. These requirements put pressure on nearby water resources (Costa et al., 2017). Differing views on how much water is used during the fracking process can be found in various sources such as Abdalla & Drohan (2010) and Chang et al. (2014). Clark et al. (2013) indicate that from a life-cycle perspective, the amount of water required per energy generated varies between each shale gas play evaluated.

2.7.3 Air quality

Shale gas development in densely populated areas has created concern over the effect it may have on air quality, both on a local and regional scale (Costa et al., 2017). Associated sources of air pollution include emissions from diesel engines, natural gas leakage during extraction processes and transport and the volatile compounds from surface storage ponds (Vidic et al., 2013). These emissions may result in direct negative physical impacts on health, infrastructure, agriculture and ecosystems (Litovitz et al., 2013).

Combustion or fugitive emissions from equipment can be considered a major source of air pollution from shale development, Rutter et al. (2015) highlights a variety of such equipment. Through combustion, a range of equipment used in exploration and production processes run on diesel engines releasing multiple air pollutants (Rutter et al., 2015).

Walter et al. (2012) examined the potential for radon emissions into the atmosphere from the disposal of drill cuttings and wastewater in landfill sites. The study concludes that some of the landfill and off-site atmospheric activities are above the allowed radon emission levels allowed for uranium mill tailings. The actual level of radon emissions depends on the place of the waste, construction of the landfill cover and the nature of the landfill gas control system.

Whether the air pollution generated may be a health risk to nearby communities remains a controversial issue (Costa et al., 2017). A study by Bunch et al. (2014) indicates that the volatile organic compound (VOC) levels created by fracking did not expose surrounding communities to excessive risk; whereas McCawley (2015) indicates a connection between air contaminants causing respiratory problems and fracking, as well as to the increase in overall traffic. In the UK, Reap (2015) estimates an increase in health risks resulting from the inhalation of hydrocarbons from air emissions resulting from the operations.

Concerning the direct impact on workers, Rosenman (2014) investigated the risk of silicosis resulting from large amounts of sands used during extraction. Results from air samples show that the majority of silica levels at well sites exceeded the Occupational Safety and Health Administration allowable standard. These levels of exposure put workers at the risk of silicosis and other silica-related conditions. Rosenman (2014) highlights that because fracking did not become widely used until the 2000's, it may still be years before healthcare providers begin to notice the effects.

Other studies focusing on the impacts on communities and workers show differing results (Costa et al., 2017). Bunch et al. (2014), Ethridge et al. (2015) and Goetz et al. (2015) show results that vary between low and no major risks resulting from exposure for either of the groups; whereas Colborn et al. (2014) and Paulik et al. (2015) suggest potential risks. In summary, Costa et al. (2017) suggest that the differing result of all these studies may result from different compounds being monitored. This issue remains highly uncertain, this could be a result of the high costs and difficulties involved in trying to monitor air pollution generated from shale gas development (Costa et al., 2017). When taking the large potential risks into account, more studies are required as direct measurements of air pollutants over a long period of time in a specific area are very rare (Roy et al. 2014; Goetz et al. 2015).

2.7.4 Climate change

Another fiercely debated environmental issue is climate change (Sovacool, 2014), as the development of shale gas has not only increased fossil fuel production in the US but also introduced the design of new energy systems around the world. These issues raise questions regarding how countries may meet their future GHG reduction targets (Ciplet et al., 2015). Proponents and opponents hold different views on the relationship between shale gas extraction in the US and climate change mitigation (Partridge et al., 2017).

Proponents highlight that shale gas extraction not only produces large economic benefits but has decreased GHG emissions by reducing the reliance on coal (Stern et al., 2014), with multiple authors describing it as a bridging fuel to meet global emission reduction goals (Levi, 2013; Sovacool, 2014). However, recent studies have questioned this assumption due to the high global warming potential (GWP) of methane and the variable estimates of methane leakage and emissions from fracking processes (Brandt et al., 2014; Schneising et al., 2014).

Some reports suggest that the recent reduction in US emissions are not a result of shale gas replacing coal, but instead has been driven by the economic recession (Feng et al., 2015). Another argument is that shale development increases the effects of climate change due to an increase in overall fossil fuel production and dependence (Broderick & Anderson, 2012; Stern et al., 2014) potentially delaying the shift to renewable energy sources and a reduction in overall consumption (Broderick et al., 2011; McGlade et al., 2016).

2.7.5 Seismicity

Induced seismicity resulting from high-volume fracking and energy extraction has become a topic of considerable attention in the US, and especially, in the UK (Jackson et al., 2014). Costa et al. (2017) determine that between 2010 and 2015 a disproportionate amount of studies compared to existing exploration in Europe focused on induced seismicity from fracking, suggesting that regulatory bodies and researchers are taking the issue very seriously.

To date, induced seismicity from fracking has been considered relatively mild when compared to other anthropogenic seismic triggers, as they usually cause very small magnitude earthquakes only. Although approaches to mitigating the risk have been proposed (Brodylo et al., 2011; Green et al., 2012), one cannot rule out the potential that the reactivation of pre-existing faults can induce felt seismicity (Davies et al., 2013).

There are multiple good examples of fracking causing fault or fracture reactivation (Warpinski et al., 1998; Wolhart et al., 2006; Vulgamore et al., 2007; Maxwell et al., 2008; Cipolla et al., 2012), however, the seismicity is generally of very low magnitude and not recorded above the noise level by traditional seismometer networks. After thousands of fracking operations, only three examples of felt seismicity have been documented (Davies et al., 2013). These were in the Etsho and Kiwigana fields, Canada, in 2009, 2010 and 2011 (BC Oil and Gas Commission, 2012), the Eola Field, Oklahoma, the US in 2011 (Holland, 2011) and Lancashire, the UK in 2011 (de Pater & Baisch, 2011). Even though the chances of fracking resulting in felt induced seismicity is extremely low, it cannot be ruled out (Davies et al., 2013).

2.7.6 Land use and biodiversity

The effects fracking may have on land use and the long-term ecological effects on landscape-level ecosystem functions are of high concern (Moran et al., 2015). The development of shale gas involves a variety of activities that can all have a negative impact on land use causing issues such as habitat disruption, erosion and increased noise pollution (Drohan et al., 2012; Olmstead et al., 2012; Moran et al., 2015).

In evaluating the damage to ecosystems, Kiviat (2013) and Latta et al. (2015) highlight that most of the impacts caused is a result of bad management and handling of chemicals, spills, wastewater and other materials. Shank & Stauffer (2015) and Latta et al. (2015) establish comparable results in their studies on the effects on biodiversity. Negative impacts are not always the norm throughout studies, as Shank & Stauffer (2015) find limited impacts, whereas Stearman et al. (2015) discover no relationship between the abundance of the analyzed species and shale gas development.

2.7.7 Cost implications of the environmental impacts

These potential negative environmental impacts of fracking cannot be ignored and must be incorporated into any discussion of potential benefits (Wait & Rossouw, 2014), as in the study by Ames et al. (2013) who performed a basic cost-benefit analysis of shale gas extraction in the US. The economic benefits were measured as a consumer surplus that is estimated using the natural gas price reduction as a result of a boom. The environmental cost was estimated based on the clean-up costs of potential accidents. The outcome of their comparison indicates that the overall benefits outweigh the costs 400-to-1, and results in approximately US$25.6 billion in consumer surplus for the US economy over one year. Wait & Rossouw (2014) mention that these results are highly dependent on the author's assumptions regarding the benefits and costs; and that it is questionable whether the costs and benefits used are an accurate reflection of those occurring in shale gas extraction.

Sovacool (2014) reviewed over 100 studies, mostly peer-reviewed, on the topic of shale gas to determine the overall technical, economic, environmental and social costs and benefits of fracking. The review finds that if done properly, fracking can bring about a wide range of benefits, however, if done poorly, it can result in more net economic costs than benefits. In a similar review, Mehany & Guggemos (2015) provide six categories of environmental impacts and three economic effects. No comparative assessment is made, but they stress that these positives and negatives need to be fairly assessed using the right tool. Hausman & Kellogg (2015) and Mason et al. (2015) both highlight that the potential market benefits from fracking are large, but further research is required to put a value on the environmental costs.

Loomis & Haefele (2017) highlight the misconception that the fracking debate is a choice between economic benefits and environmental quality, stating that environmental quality can produce its own economic benefits that can be compared to the economic benefits flowing to society from fracking. They reviewed the existing grey and published literature to calculate the monetary values of the environmental costs of fracking. The biggest economic gain is that of consumer surplus, resulting in a gain of US$75 billion per year, whilst the biggest cost was that of air emissions valued at US$17.5 billion per year. The study concludes that there is still insufficient data available to definitively determine whether the economic benefits of fracking outweigh the environmental costs (Loomis & Haefele, 2017).

2.8 Hydraulic fracturing in South Africa

Recently, South Africa was placed eighth in the world for shale gas resources with an estimated 390 Tcf (USEIA, 2013), resulting in fracking in the Karoo becoming a topic of heated debate. Supporters highlight the enormous economic benefits, whilst opponents argue the huge environmental risks involved (Wait & Rossouw, 2014).

A report by Econometrix (2012) conducted on behalf of Royal Dutch Shell plc (Shell), indicates the economic benefits available from a large gas find in South Africa's Karoo. It states that shale gas exploitation could boost South Africa's economy and ultimately create a multitude of jobs. The report concludes that successful exploration of shale gas in the Karoo could deliver positive effects on the countries Gross Domestic Product (GDP), increased government revenues, sustainable job creation and an increase in South Africa's energy security (Econometrix, 2012).

Wait & Rossouw (2014) highlights that the report by Econometrix is an industry-sponsored report, suggesting a biased approach that has been criticised and results questioned. Their study estimated the economic impacts by means of a Computable General Equilibrium (CGE), an economy-wide impact modelling methodology. The focus was to accommodate both benefits and costs, and numerous scenarios were used in determining a variety of results. The results generated were compared to those of the Econometrix report and indicate similar GDP outcome results, however, this is not the case for employment, where results show much lower gains (Wait & Rossouw, 2014).

On a regional scale in the Karoo, Toerien (2015) attempts to quantify the economic impacts of a large shale gas development. The main aim of the study was to determine if economic, demographic and entrepreneurial proportionalities are present in the Karoo towns that might be affected by the development; and if these proportionalities are present, to use them to predict the extent of potential future development impacts on the local economies of affected Karoo towns.

Results show that there is a relationship between the different proportionalities and that they pose a predictive power. The modelled predictions show that shale gas development can result in a large influx of people into the towns and could have a major impact in terms of economic expansion, infrastructure requirements and the need to provide sufficient municipal services. There would be significant new as well as existing entrepreneurial opportunities. This would benefit the towns as services that were not there before would now be present (Toerien, 2015).

From an energy perspective, Pollett et al. (2015) provides an outlook on South Africa's energy situation and highlights the current and future policies that are being planned or put in place by the government. South Africa is currently faced with big challenges in its energy sector, and the failure to generate efficient supply is resulting in planned and unplanned power outages that have been a major cost to the economy over the years (Pollett et al., 2015). Andersen & Dalgaard (2013) further elaborate on how power outages across Africa have had a substantial negative impact on the growth of economies.

A search for solutions to the energy crisis in South Africa has lead to energy schemes such as the Grand Inga Hydroelectric project on the Congo River in the Democratic Republic of Congo. It is designed to be the world's largest hydroelectricity project and is anticipated to provide electricity to half the African Continent (Green et al., 2015). South Africa is designated to be the principal buyer with more than half the total estimated capacity contracted to the South African market (Taliotis et al., 2014).

The project has been foreseeable since the early 1950's, but continuous political instability and the civil war have hindered its progress (International Rivers, 2014). Most recently, in May 2016 it seemed that construction would start in just a few months, however, in July 2016, the World Bank suspended its disbursements due to disagreement with the local government (GCR, 2016). At present, the availability of a market, the necessary funding and unresolved social impacts are hindering the construction of the project (Bank Track, 2017).

A local supply of shale gas has the potential to fill the energy supply gap in South Africa (PWC, 2012). The burning of natural gas will provide a cleaner source of energy with less GHG emissions compared to coal, which is currently South Africa's main source of energy (Jaramillo et al., 2007; Wang et al., 2011; Cathles et al., 2012; Cohen & Winkler, 2014). As a cleaner source, it has the potential to act as a bridging energy during the country's shift from carbon-intensive coal to renewable energy (de Wit, 2011; Jenner & Lamadrid, 2013; Hedden et al., 2013). In terms of a shift to nuclear power, gas power plants have a substantially lower cost per kilowatt (kW) output and lead time compared to nuclear alternatives (EPRI, 2010).

Vermeulen (2012) highlights that there are still numerous questions that need to be addressed before development can get underway in the Karoo. Are the predicted resources correct? Will there be enough water available, or will there be a need to transport water from other areas? After such an increase in activities, will the Karoo be able to be rehabilitated?

An initial shale gas resource estimate was done by the USEIA in April 2011, with adjustments made in 2013 to total 390 Tcf (USEIA, 2011a; 2013). The USEIA resource estimate was used by Decker & Marot (2012) to calculate high-, medium- and low-case alternative resource estimates. The only other known resource estimate was done by Cole (2011) that was presented at the Geosynthesis Conference in Cape Town.

The initial estimate by USEIA (2011) is based on the exploration work done by the Southern Oil Exploration Corporation (Soekor) in the 1960’s (Vermeulen, 2012). This has been the only substantial exploration work done, with only a few minor studies such as those by Geel et al. (2013), and the Karoo Research Initiative (KARIN) in de Kock et al. (2016). The limited exploration work has resulted in doubts over the accuracy of the resource estimations, with the need for more exploration being highly emphasised (de Wit, 2011; Vermeulen, 2012; PWC, 2012; Decker & Marot, 2012; Hedden et al., 2013).

This lack of accuracy in the resource estimation is emphasised by de Kock et al. (2017) who highlight that the range of resource estimates vary from 13 to 390 Tcf. The study also states that these estimates are not based on any measurements of available gas content in the shale. Two boreholes were drilled during the study, and available gas measurements were taken. The results indicated that there is little to no desorbed and residual gas, despite high total organic carbon (TOC) values. As a result, it is more likely that the lower 13 Tcf is the most reasonable, however, even if this amount is available, it is still a large resource with developmental potential for South Africa’s economy.

A major concern is an availability and access to the large amounts of water required for the fracking process in the drought-prone Karoo, and the possibility of contaminating the limited amount of drinkable water (de Wit, 2011). De Wit (2011) elaborates on the huge amounts of water required for the drilling operations even in simple fracking during an exploration phase, and how access, sharing and contamination of this scarce resource raise genuine concerns to the Karoo farmers and municipalities.

The Karoo’s unique geology is of great importance as it differs from other shale gas hosting deposits around the world. In particular, the presence of dolerite dykes and sills and how lessons learnt around the world might not be applicable in South Africa, adding to the level of uncertainty. Not much is certain about the continuation and orientation of these intrusions at greater depths beyond the reach of usual borehole depths (Vermeulen, 2012).

Evidence suggests the potential for large economic benefits, but these cannot be maximised without fully weighing the potential environmental and economic costs (Wait & Rossouw, 2014). From their modelling exercise, Wait & Rossouw (2014) conclude the potential costs of fracking are: 1) redirection of resources from other industries to be the shale gas industry, 2) substitution of agriculture, 3) nuisance, noise and loss of privacy for landowners and 4) potential irreparable damage to the environment.

2.9 Chapter summary

The various natural gas types and reservoirs highlight the importance of distinguishing between them and knowing the different challenges involved with extraction. The case of shale gas in the US can be considered an economic and energy success story. However, its success cannot simply be predicted for all countries, as the US already had a very advanced natural gas industry. The literature review on the benefits and costs indicate that there is a wide variety of differing opinions on the subject matter and that no simple conclusions should be made. There is also very little work done on the subject relating specifically to South Africa and it seems to be under-researched.

3 SHALE GAS EXTRACTION

3.1 Chapter overview

This chapter highlights the importance of technological advancements in the shale gas industry, and how horizontal drilling and fracking have allowed for economical extraction. The chapter concludes by summarising the stages of extraction, laying a foundation for the chapters that follow.

3.2 Importance of technology

Extraction of natural gas from conventional reservoirs is usually by vertical wells (Schaffer et al., 2013) whereby the gas flows to surface without the need for much stimulation (Scholes et al., 2016a). Generally, this method results in lower costs of extraction when compared to methods required for UCG reservoirs (Aguilera, 2014). However, recent technological advancements have allowed previously uneconomical UCG reservoirs to become profitable (Cronshaw & Quentin Grafton, 2016). Improvements in technology have reduced the costs of producing UCG so much that at times it is cheaper than producing from conventional reservoirs (Aguilera, 2014).

Technology has become the most critical factor affecting the shale gas competitive market. These technological advancements affect not only the extraction cost but also the actual production capabilities (Bilgen & Sarikaya, 2016). These technologies include a combination of horizontal drilling, fracking, 3D and 4D seismic imaging, coiled tubing, measurements whilst drilling and slim hole drilling that have enabled the economic extraction of natural gas from formations of low permeability (Cronshaw & Quentin Grafton, 2016).

The two main areas of development that have revolutionised shale gas extraction are the modern refinements in the technology of horizontal drilling and fracking (de Wit, 2011). These innovative developments have contributed significantly to making trillions of cubic feet of shale gas both technically and economically feasible to extract, where once it was not (Bilgen & Sarikaya, 2016; Estrata & Bhamidimarri, 2016). Figure 3.1 below provides an illustration of the processes involved in extracting UCG from shale (Jackson et al., 2013b).

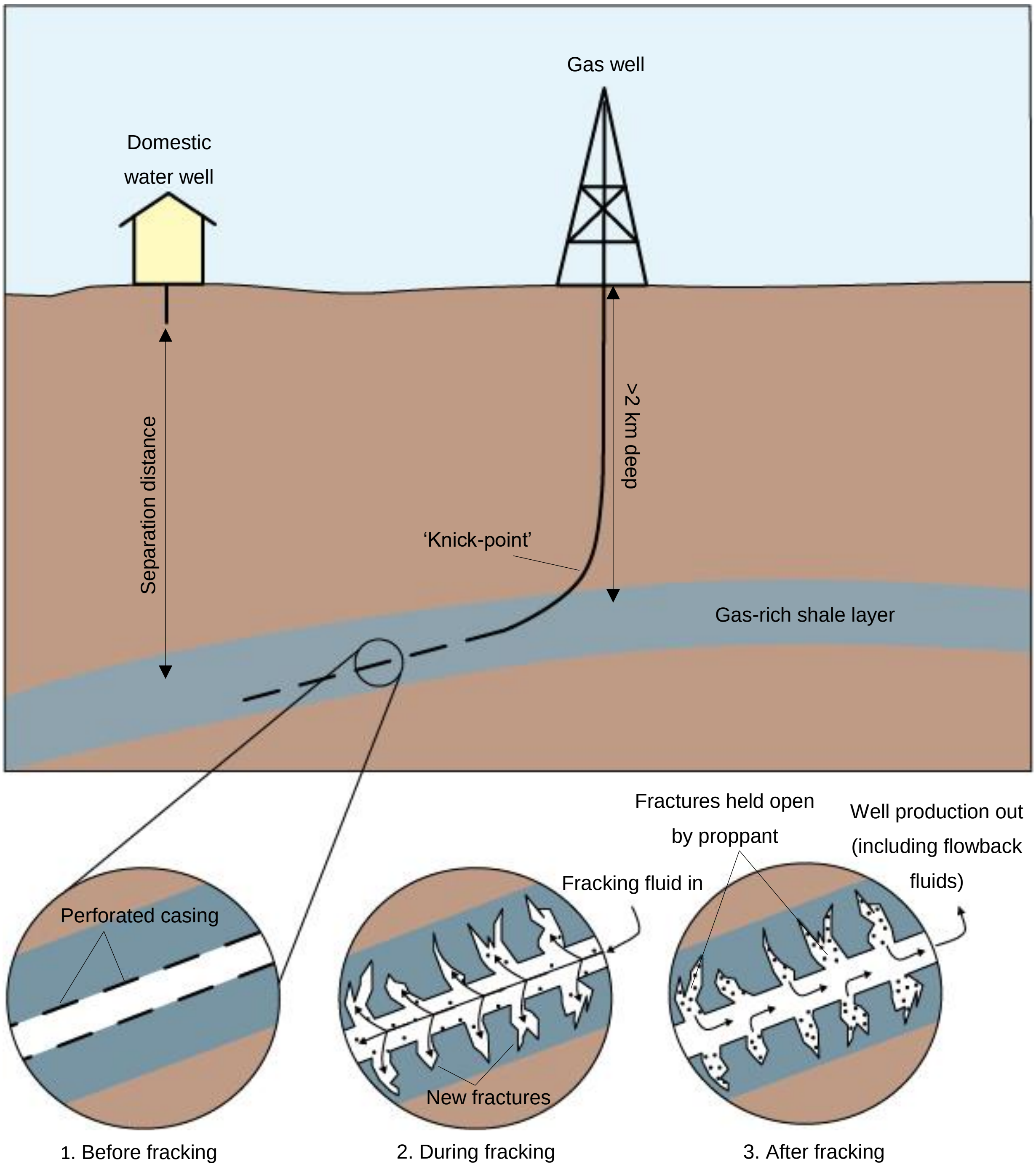

Figure 3.1: Illustration of horizontal drilling and fracking processes involved in shale gas extraction (not to scale).

Source: *Modified from Bickle et al. (2012) and Jackson et al. (2013b).*

3.3 Horizontal drilling

Shale formations are established kilometres below the surface and usually form a very thin, pressed layer that is nearly horizontal. As a result, to be commercial, extraction of gas from such a formation requires the drilling of not only a conventional vertical well but additional horizontal wells (Kotsakis, 2012). The technique of horizontal wells started in the US in in the 1940's but remained borderline until the 1970's and 1980's when the first 'modern' horizontal wells were drilled (Pendleton, 1991).

The technique involves drilling a conventional vertical well that upon the intersection of the designated shale layer (usually thousands of metres deep), diverts at an angle to move into the horizontal layer where the natural gas is located (Figure 3.1). The horizontal well maximises the area of contact with the target layer so that gas may be extracted from thousands of metres of shale, as opposed to a few tens or hundreds of metres accessed by a vertical well (Vidic et al., 2013).

One or more horizontal wells can be produced from a single vertical well (Figure 3.2) (Joshi, 1987). Nowadays, multiple wells are usually drilled from a single surface site with each of them including horizontal sections, this arrangement is commonly called ‘multi-well pad’ and allows the recovery of gas from approximately 1 km^2, minimizing the land requirements at the surface (Broderick et al., 2011).

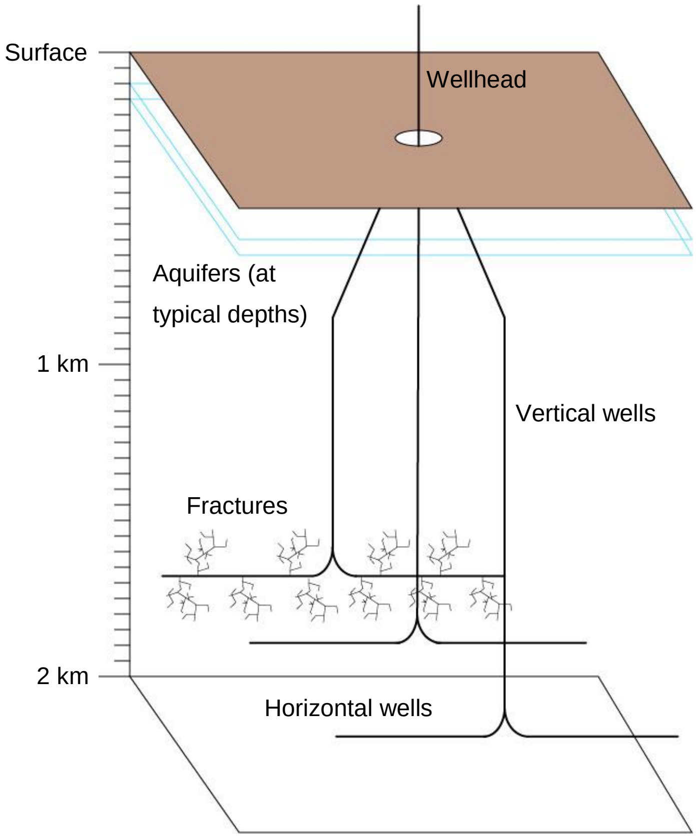

Figure 3.2: Schematic representation of a multi-well pad shale gas extraction process.

Source: *Modified from Estrata & Bhamidimarri (2016).*

The wells are separated and protected from the environment by a protective casing that is usually multi-layered armour shielding of hollow steel pipe and cement (Broderick et al., 2011). Multiple consecutive holes of decreasing diameter and increasing depth are drilled and lined with steel casing; these are joined together to form continuous ‘strings’ of casing (Figure 3.3) (Bickle et al., 2012). There can be as many as four protective layers inserted between the well and ground to ensure no leakage of gas and liquid pollutants (Broderick et al., 2011), this is referred to as ‘well integrity’ (API, 2009).

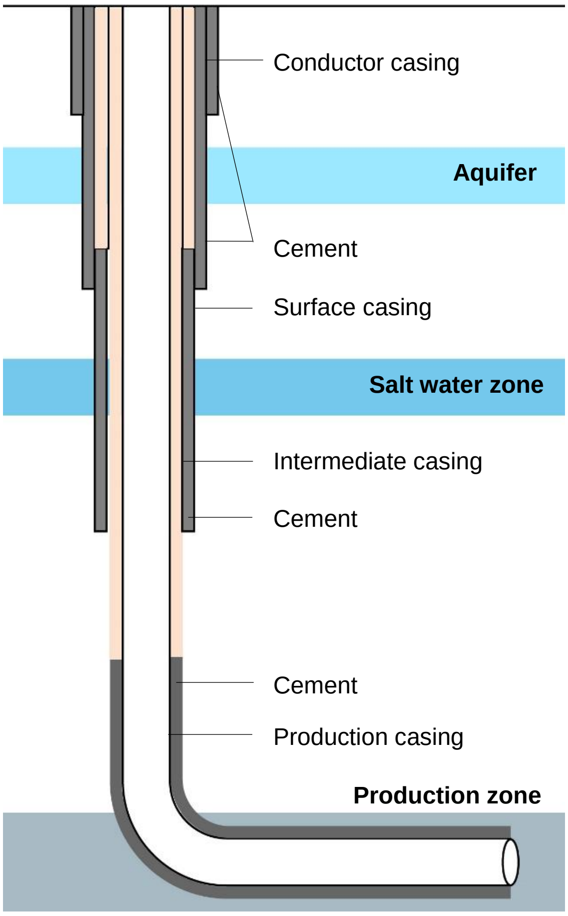

Figure 3.3: Shale gas well design with associated protective casings.

Source: *Modified from DoE (2009).*

The four layers are the conductor, surface, intermediate and production casings. The conductor casing serves as a foundation for the well and prevents the surface soils from caving in, it is usually up to about 30 m. The next hole is drilled to below the freshwater zone where the surface casing is installed, and cement is pumped down the hole and up between the casing and rock until it reaches the surface. A new hole is drilled to beyond the non-freshwater or salt water zone and the intermediate casing is installed. Cement is pumped up to the bottom of the surface casing, or all the way to surface again. The final hole is drilled into the target or production zone, the shale layer containing the gas, and lined with the production casing. Cement is pumped again until a safe height above the target layer, the bottom of the intermediate layer, or all the way to surface (Bickle et al., 2012). Some states also require the additional use of well tubing inserted inside the casings, this is usually also a steel casing but is not cemented into the well (Broderick et al., 2011).

Poor well integrity may lead to well failure resulting from a blowout, annular leak or radial leak. A blowout is any sudden escape of fluids from the well to the surface. Annular leaks result from poor cementation and allow for fluids to move vertically either between the different casings or between the casings and the wall rock. Casing failures may lead to fluids migrating horizontally into the surrounding wall rock, these are radial leaks (Bickle et al., 2012).

3.4 Hydraulic fracturing (fracking)

Horizontal drilling alone cannot create enough natural flow from the shale formation to the well as the permeability of the shale layers is too low. Therefore, fracking is required to extract shale gas (Vidic et al., 2013) and is nearly always present in the extraction programme of a UCG reservoir, except for some CBM reservoirs (Aguilera, 2014).

During the fracking operations, a fluid of about 95 % water and a proportion of other chemical agents together with a proppant (usually sand) (Cronshaw & Quentin Grafton, 2016) is pumped into a well at high pressures to fracture the reservoir rocks (Figure 3.1) (Barbot et al., 2013; Engle & Rowan, 2014). In order to fracture the rock, the fluid must be pumped at such a rate to create enough pressure to overcome the fracture gradient/pressure gradient of the surrounding rock (Wang et al., 2014a). Injection rates are up to 0.3 m^3s^{-1} reaching high pressures of 480 to 680 bar (Barbot et al., 2013; Al-Muntasheri, 2014).

Once these fractures are created, the drill operator tries to maintain fracture width by adding a proppant to the fracking fluid that will prevent fracture closure once the pumping stops and pressure are reduced (Wang et al., 2014a). The fractures that are created increase the permeability of the bulk formation through shear failure (Zoback et al., 2012) allowing the hydrocarbon gases to flow back to the production well (Jackson et al., 2013b). Once fracking is complete, the injected fluid is allowed to flow back to surface relieving the downhole pressure and allowing natural gas migration from the formation to the well at the surface (Barbot et al., 2013).

Fracking is not a continuous process, wells are fractured once after drilling and the process is performed in stages with about 8 to 10 single fracturing stages per well (Gregory et al., 2011). The rapid increase in technology has led to stage spacing decreasing continuously from 200 m to 100 m and more recently to 50 m. Stages are moving into more than 60 stages of fracking per well (Aguilera et al., 2014). As production may decline toward the end of the wells lifetime, the process may be repeated for re-stimulation (Gregory et al., 2011).

3.5 Stages of extraction

Shale gas extraction consists of a few primary stages: exploration, pre-production, production and abandonment (Broderick et al., 2011; Bickle et al., 2012).

3.5.1 Exploration

Before any exploratory drilling is allowed, the potential shale gas formations need to be identified, and permits, legislations and drill rights must be granted (Annevelink et al., 2016). During the initial exploration phase, various geophysical surveys are performed to identify the physical properties of the target zone (shale layers), including the depth, thickness and orientation. Surveys such as seismicity, induced polarisation and magnetotellurics can be used to create a 3D image or model of the area's subsurface (Esterhuyse et al., 2014).

However, these geophysical survey techniques cannot determine if there is tight gas present in shales. To evaluate this potential, rock samples need to be brought to the surface through regular drilling (de Wit, 2011). The drilling locations will be based on the best potential areas identified from the geophysical data obtained. Both chip and core drilling are usually performed, and the samples are sent to the laboratory for gas testing (Esterhuyse et al., 2014). No fracking is required for this early stage of exploration and drilling (de Wit, 2011).

The final stages of exploration must determine if the gas can be freed and economically extracted from depth, this requires the breaking up of the shale *in situ* using the fracking process (de Wit, 2011). During this phase, the rocks are fractured to determine how the rock will fracture under its specific conditions at depth and how much gas the wells will be able to produce. This also allows for the determination of the best drilling techniques for each specific area, as every drilling area has its own specific features. The well production tests are performed over several weeks and ultimately determine the technical behaviour and potential profitability of the wells. Once a sufficient area has been tested, a feasibility study is done, if the results are encouraging, the extraction phase will commence (Binnion, 2012; Broomfield, 2012).

3.5.2 Pre-production

First, boreholes are planned at a density that will optimise the extraction of gas from the target layer (Esterhuyse et al., 2014). The process begins with building the necessary site infrastructure including the well construction (Wang et al., 2014a). Each pad requires sufficient space to accommodate fluid storage and equipment associated with the high-volume fracking operations as well as the larger associated equipment. The activities that follow are vertical drilling with a smaller rig, horizontal drilling, hydraulic fracturing procedure, fluid return and treatment, waste disposal and well clean-up and testing (Broderick et al., 2011).

3.5.3 Production

Once the drilling and fracking operations are complete, a production wellhead is put in place to collect and transfer gas for subsequent processing via a pipeline. Production from a well on a given well pad may begin before the other wells have been completed (Broderick et al., 2011).

3.5.4 Abandonment

As with any other well, a shale gas well is abandoned once production is complete. Sections of the well are filled with cement to prevent gas from flowing into water-bearing zones or up to the surface. A cap is then welded into place and then buried (Bickle et al., 2012). The quality of the plugging process is critical to protecting the surrounding environment (Broderick et al., 2011); and if the well is properly abandoned, there is little to no chance of contaminating freshwater aquifers (King, 2012).

3.6 Chapter summary

Technological advancements have and continue to revolutionise the shale gas industry. Research and development can be considered a primary factor in the success of shale gas and should not be taken lightly by countries wishing to utilise their resources. The various stages of extraction have different processes and challenges. These are important to recognise, as each stage will have a different impact on the economy and environment. A primary example is early stage exploration not requiring any fracking, and hence has less of a potential contamination on aquifers compared to late-stage exploration.

4 SHALE GAS IN SOUTH AFRICA

4.1 Chapter overview

The focus is now on South Africa, with the chapter starting with the geological background of the country and which geological formations are important for shale gas. This is followed by the primary exploration targets as well as existing exploration work done. Exploration leads to a resource and reserve estimate, the importance thereof is briefly described, as well as the different classification types. The existing estimations for the Karoo Basin are highlighted in detail as well as a few important implications affecting the estimations. The chapter concludes by providing a summary of how the issue of shale gas extraction has developed over time and recent activity in South Africa.

4.2 Geological background

The Karoo Basin of South Africa is one of many intracratonic basins in southwestern Gondwana that became active in the Permo-Carboniferous era, 280 Ma, and continued to accumulate sediments until the earliest Jurassic period 100 million years later. Today, the outcrop represents approximately 300,000 km^2 and has a maximum thickness of around 8,000 m (Smith et al., 1993). The basin is underlain primarily by the Kaapvaal Craton and the Namaqua-Natal Metamorphic belt. To the south, it is bounded by the Cape Fold Belt, a large fold-thrust belt, and along the east by a monoclinical downwarp, the Natal Trough (Johnson et al., 1997).

The basin is filled with clastic sediments and subordinate igneous rocks that are all part of the Karoo Supergroup (Johnson et al., 1997). The Karoo Supergroup is divided into multiple Groups, named in stratigraphic succession, the Dwyka, Ecca, Beaufort, Stormberg and Drakensberg Groups (Figure 4.1 and Figure 4.2) (Catuneanu et al., 2005). The basal Dwyka Group consists of diamictite and other glacial related rock types deposited during the Late Carboniferous and Early Permian (Johnson et al., 1997). Above the Dwyka Group, the Ecca Group occupies the majority of the Permian time slot. It is essentially a clastic sequence of organic-rich mudstone, siltstone, sandstone, minor conglomerate and coal (in places) and outcrops extensively throughout South Africa (SACS, 1980; Cairncross, 1987; Johnson et al., 1996; Johnson et al., 1997).

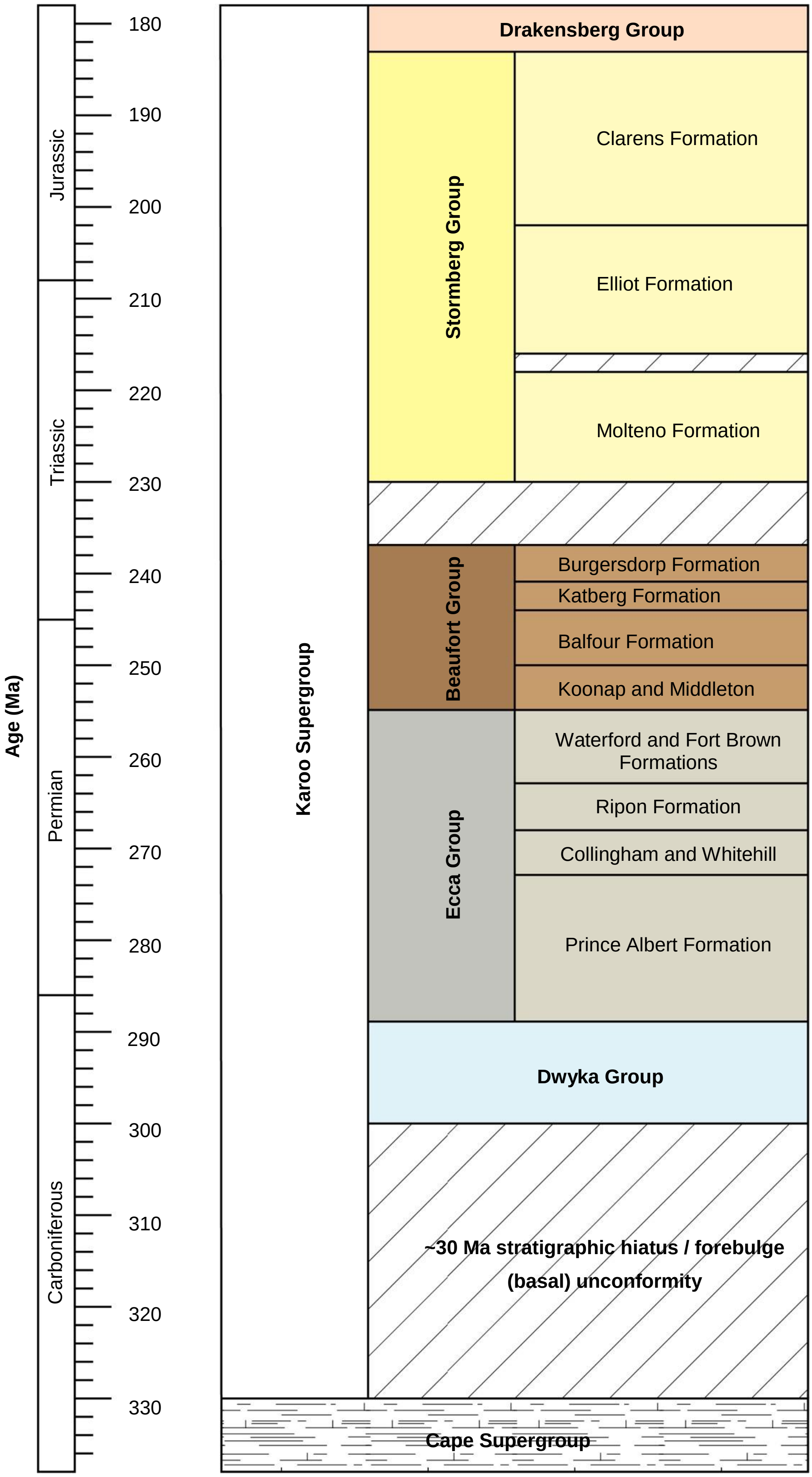

Figure 4.1: A stratigraphic column of the Karoo Supergroup in South Africa.

Source: *Modified from Catuneanu et al. (2005).*

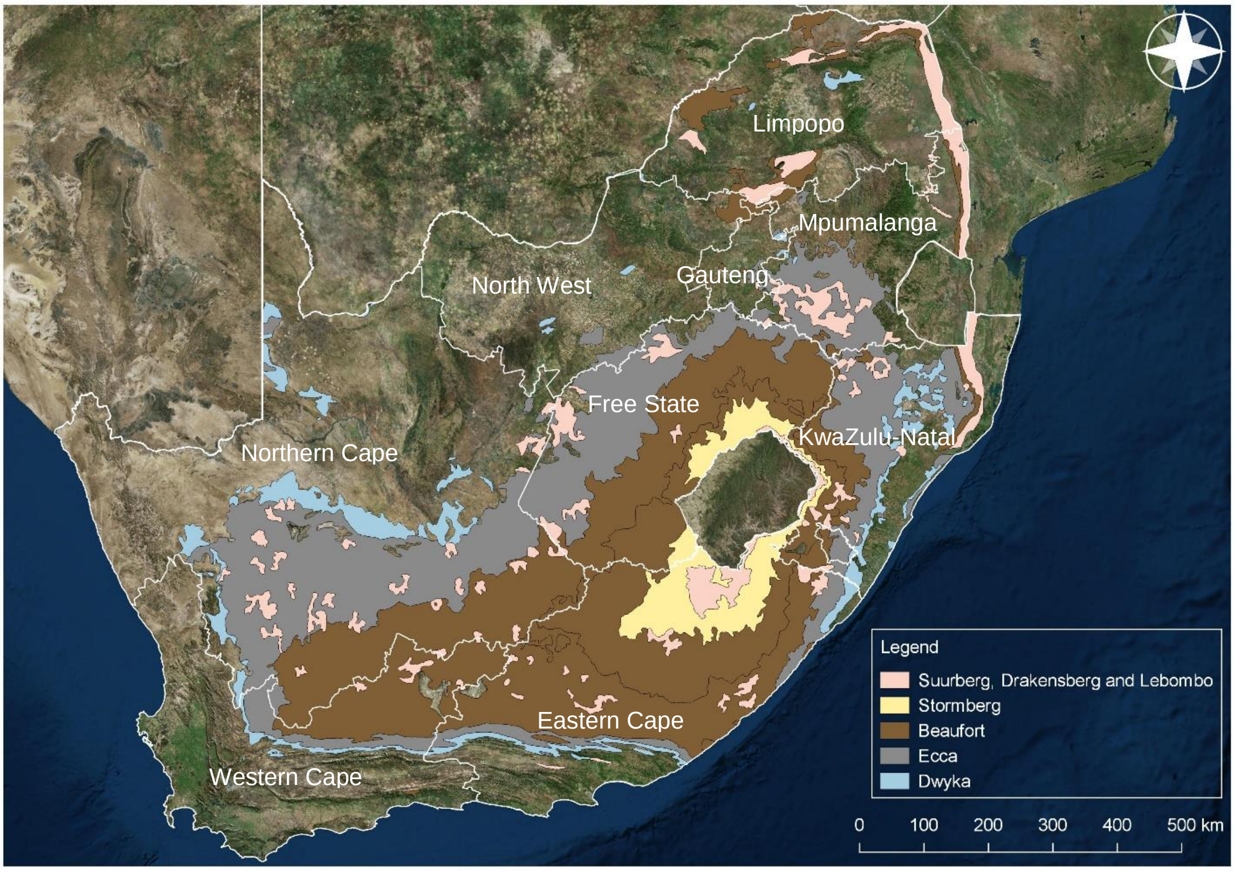

Figure 4.2: Geological map of the subgroups of the Karoo Supergroup in South Africa.

Source: *Map created using QGIS; base map from the ESRI plugin; shapefiles from Stanford University (2017), Natural Earth (2017) and Council for Geoscience via SANSA (2017). All items are open source and free to use.*

During the Late Permian and Triassic, after the Ecca Group, the Beaufort Group was deposited by a variety of fluvial systems. The strata are predominantly made up of mudstones, siltstones and sandstones that covers an approximate 200,000 km^2, making up around 20% of South Africa's total surface area (Johnson et al., 1997; Catuneanu et al., 2005). The same fluvial deposition events formed the Molteno and Elliot Formations in the Stormberg Group. Later fine-grained aeolian sand and silt and playa lake mud formed the Clarens Formation during desert conditions in the Early Jurassic, completing the Stormberg Group. Filling of the Karoo Basin in South Africa was finally completed by the outpouring of at least 1,400 m of basaltic lava, named the Drakensberg Group (Johnson et al., 1997). The lava flooding began in the Late Triassic, interrupting the deposition of the Clarens Formation (Duncan et al., 1997), and continued into the early Cretaceous as a result of the breakup of Gondwana (Eales et al., 1984).

In South Africa, organic rich-shales are confined to the Ecca Group in the main Karoo Basin, some smaller basins in the northern section of South Africa and the Bokkeveld

Group in the most southern portion of South Africa (Rowsell & de Swardt, 1976). The muds become buried and lithified over millions of years and generate various types of hydrocarbons as the depth of burial increases resulting in increased temperatures. Burial depths between 2 to 4 km produce oil, between 4 to 5 km produces wet gas and between 5 to 6 km results in dry gas (shale gas' primary type (de Wit, 2011)) including methane. Burial beyond 6 km deep ends up in low-grade metamorphism, terminating the formation of hydrocarbons and forms graphite instead (Steyl & van Tonder, 2013).

The Bokkeveld shales have undergone this low-grade metamorphism and therefore are not eligible for hydrocarbon generation (Steyl & van Tonder, 2013). In the northern portion of South Africa, the shales are not buried deep enough for gas, but instead have the potential for oil, except for areas of dolerite intrusions that increased the local temperatures within the surrounding rocks and can lead to the generation of dry gas (Rowsell & de Swardt, 1976). The northern portion of the Ecca Group's organic-rich shales has not been buried deep enough to reach a level of thermal maturity capable of generating dry gas. Therefore, only the Ecca Group shales that are south of the latitude 29°S have the potential to generate dry gas (Rowsell & de Swardt, 1976; Steyl et al., 2012).

4.3 Exploration

The organic-rich units of the Ecca Group are the primary target for the exploration of shale gas in the Karoo Supergroup (Rowsell & de Swardt, 1976). The larger Ecca Group is made up of an upper and lower Ecca Group. The upper Ecca Group consists of the Fort Brown and Waterford Formations, whilst the lower contains Prince Albert, Whitehill and Collingham Formations (USEIA, 2015).

The shale gas project in South Africa initially aimed to target the Whitehill formation of the lower Ecca, which is a carbonaceous shale unit characterised by its unique white weathering outcrop. However, the distribution of the Whitehill Formation with its marine setting resulted in additional studies into the dynamics of the Karoo Basin and similar types of formations in search of more potential target zones (Steyl et al., 2012). The revised target zones now include the carbonaceous shales of the lower and upper Ecca Group as well as increased attention in the Dwyka Shales (Figure 4.3). The formations now include the following:

- Whitehill Formation (Cape region)
- Prince Albert Formation (Cape region)

- Vryheid Formation (Free State and KwaZulu-Natal regions)
- Volksrust Formation (Free State and KwaZulu-Natal regions)
- Pietermaritzburg Formation (Natal region)
- Dwyka Shales (all regions that are shallow enough) (Steyl & van Tonder, 2013).

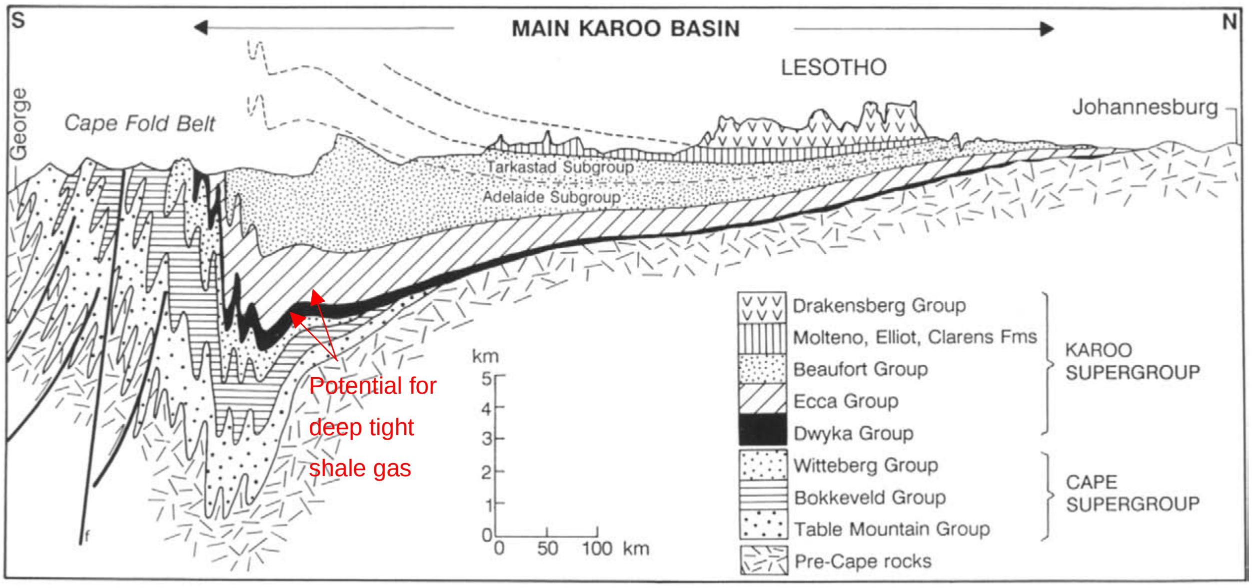

Figure 4.3: North-south cross-section of the Karoo Basin.

Source: *Cross-section from Johnson et al. (1997), red text insert from* Chevallier (2012).

To date, the earliest and most abundant exploration done was by Soekor from 1965 to 1975 during their exploration for oil and gas in the Karoo. The zones targeted were the carbon-rich units of the Ecca Group of the Karoo Supergroup, especially the Whitehill and Collingham Formations. Geophysical exploration techniques were used together with the drilling of 24 deep wells. Analysis of results allowed for a good understanding of the depth and thickness of targeted zones (Rowsell & de Swardt, 1976).

The Soekor work has been the only substantial exploration work to date, with only minor efforts since, such as those by Geel et al. (2013) and de Kock et al. (2016). Geel et al. (2013) focused on a small particular area and included geological mapping on a scale of 1:50000, sedimentary and structural evaluation, core drilling together with a relevant analysis of the core samples. The core drilling included two boreholes, the first SFT1 to a depth of 100 m and the second, SFT2 to 300 m (Geel et al., 2013).

The Karoo Research Initiative (KARIN) group’s main aim is to investigate the southern part of the Main Karoo Basin by means of deep drill holes. To date, two boreholes have been drilled, one in the Tankwa Karoo near Ceres in the Western Cape (KZF-01) to a depth of 671 m and the other near Willowvale in the Eastern Cape (KWV-1) to a depth of 2,353 m; these were both analysed in 2015 (de Kock et al., 2016). Currently, a research initiative from the Council for Geoscience (CGS) plans to drill a 3,500 m borehole near Beaufort West as part of the Karoo deep drilling and geo-environmental baseline programme (Council for Geoscience, 2018).

The deep wells drilled by Soekor indicate the occurrence of natural gas at the surface as well as in intervals at depth. The core samples from the Ecca Group underwent a desorbed gas analysis and show varying quantities of gas (Rowsell & de Swardt, 1976). An important parameter within the shale is the TOC due to its linear relationship with the gas content, as demonstrated in the Barnett Shale. Thickness of the shale layer is also important, as most areas of extraction have layers that are 90 to 183 m thick (Hayden & Pursell, 2005), however, in recent times it has been technically possible to extract gas from layers that are as thin as 10 to 15 m (de Wit, 2011).

The study by Rowsell & de Swardt (1976) determined that only the lower Ecca Group shales within the dry gas window south of 29°S have a TOC that is comparable to shales that are producing gas elsewhere in the US (Table 4.1) (Steyl & van Tonder, 2013). The upper Ecca Group shales, namely the Tierberg Formation (Viljoen, 2005), average only 1.2% TOC (Cole & McLachlan, 1994) which is much lower than the 3 to 12% range of producing shales (Steyl & van Tonder, 2013). The Dwyka Group also contains black shales, but the range is only between 0.1 and 4.3% TOC, averaging 1.9% (Cole & Christie, 1994; Cole & McLachlan, 1994). The Dwyka Group shales are also narrow and restricted as they are interbedded with diamictite and sandstone layers (Steyl & van Tonder, 2013).

Table 4.1: TOC and thickness of Karoo Basin shale layers compared to producing shale formations in the US.

Unit or formation	Percentage organic carbon (%)	Thickness (m)
Marcellus Shale (US)	0.3-20.0	12-270
Barnett Shale (US)	0.5-13.0	15-300
Whitehill Formation	0.5-14.7	0.4-72
Prince Albert Formation	0.3-12.4	30-500
Pietermaritzburg Formation	0.3-11.6	0.8-420
Tierberg Formation	0.3-5.2	400-1,300
Volksrust Formation	0.3-5.9	250-415
Dwyka Group	0.1-4.1	0-58

***Source:** Steyl & van Tonder (2012).*

4.4 Resource and reserve estimates

4.4.1 Background importance

It is important to understand and distinguish between resources and reserves. Resources are the total volume of gas that is estimated to be present in the ground, regardless of whether it is economically recoverable. Reserves are the resources that are expected to be economically recoverable from known deposits starting at a specific date (PWC, 2008).

The resource and reserve estimations need to be very dependable as it is essential to any mining operation, regardless of commodity and size (Dominy et al., 2002). Mining is associated with numerous risk factors of which the main one is the orebody itself (Snowden et al., 2002). A significant difference in mining compared to other businesses is that the product is based primarily on estimates, which naturally have a level of uncertainty. Volatile and cyclical commodity prices and exchange rates play a big role in determining and continuously changing estimated revenue. Managing risk is the key to efficient mining of an orebody, and the correct management of the resource estimation is vital in achieving this (Dominy et al., 2002).

Reserves ultimately determine the profitability of production and are the essence of the upstream petroleum industry (McMichael & Young, 2001). A firm’s total resource is its most important economic asset and the strength of the firm is dependent on the size and quality of the resource it has the rights to, serving as the source of future cash inflows and provides the basis for raising equity finance (PWC, 2011).

It is, therefore, essential that the classification is by a first-class interpretation based on high-quality data. However, these estimations carry potential errors that lead to uncertainty and risk that need to be made aware of (Dominy et al., 2002). Estimations of technically recoverable gas resources remain highly uncertain, even in regions that are experienced and well developed in shale gas production (McGlade et al., 2013).

These potential uncertainties and errors have resulted in multiple regulatory bodies, technical organisations and financial institutions introducing efforts of global standardisation for reserves classification (McMichael, 2011). This resulted in the development of the Canadian Oil and Gas Evaluation Handbook (COGEH) and the Petroleum Resources Management System (PRMS) global resource classification systems (SAMOG, 2015).

4.4.2 Classifying a petroleum resource and reserve

Establishing a consistent and integrated resource reporting system is a critical component of any country or company who aim to successfully document their resource base and/or adopt portfolio management systems (Ross, 2001). The estimate should be done by a competent person (CP), usually, a geologist or petroleum reservoir engineer, based on the information gathered from exploration and evaluation techniques (PWC, 2011). Current classifications are based on geological assurance, data quality, technical feasibility and economic viability in today's cost and price systems (Stephenson, 2000; Stephenson & Stoker, 2001).

Ultimately, the estimation is up to the CP, however, there are minimum requirements to be followed set out by specific reporting codes that ensure that the process is clear and transparent (Dominy et al., 2002). In South Africa, public reporting of oil and gas resource estimations should follow the South African Oil and Gas (SAMOG) code, prepared by the SAMREC/SAMVAL Committee. These are not a separate set of rules, however, but rather a depiction of the position status of the SAMREC/SAMVAL Committee regarding the recognition of international standards set out by the COGEH and the PRMS (SAMOG, 2015).

The PRMS and COGEH define major recoverable resources into different classes, including Production, Reserves, Contingent Resources, Prospective Resources and Unrecoverable petroleum, all with varying degrees of commerciality and uncertainty (Figure 4.4) (SPE, 2007). Prospective resources are the volumes potentially recoverable that need to be discovered. Contingent resources are the potentially recoverable quantities that have been discovered but do not yet satisfy the requirements for commerciality (Ross, 2001).

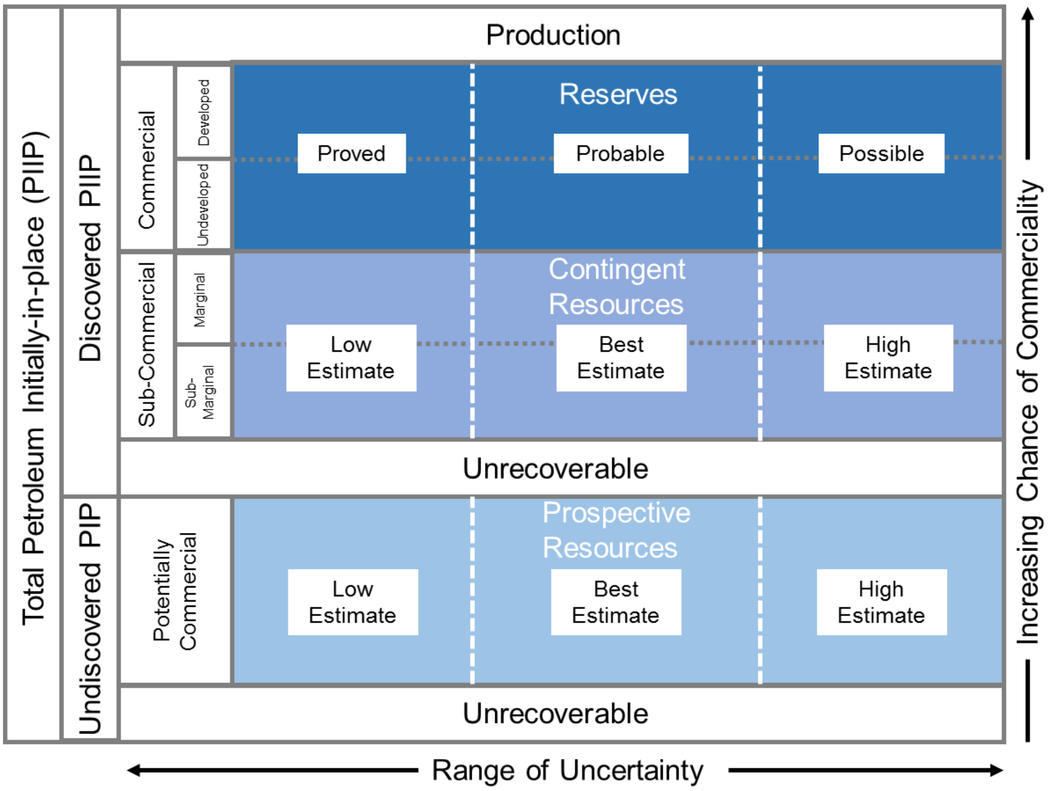

Figure 4.4: PRMS resource classification framework.

Source: *Modified from SAMOG (2015) and Ross (2001).*

The range of uncertainty indicates a range of estimated potentially recoverable volumes for a project. In the case of reserves, the range of uncertainty descends from proved, probable and possible. The resource equivalent is categorised as Low Estimate, Best Estimate and High Estimate (Ross, 2001).

Additionally, the USEIA indicates that due to multiple factors, a shale gas resource is usefully classified into four categories:

- Remaining oil and gas in-place
- Technically recoverable resources (TRR)
- Economically recoverable resources (ERR)
- Proved reserves

The categories display varying degrees of certainty, and as a result, the size of the estimate decreases with increased certainty (Figure 4.5). The lower the level of certainty, the more the estimate is based on assumptions and less on facts, whereas the highest degree of certainty estimation is based on facts and fewer assumptions (USEIA, 2015).

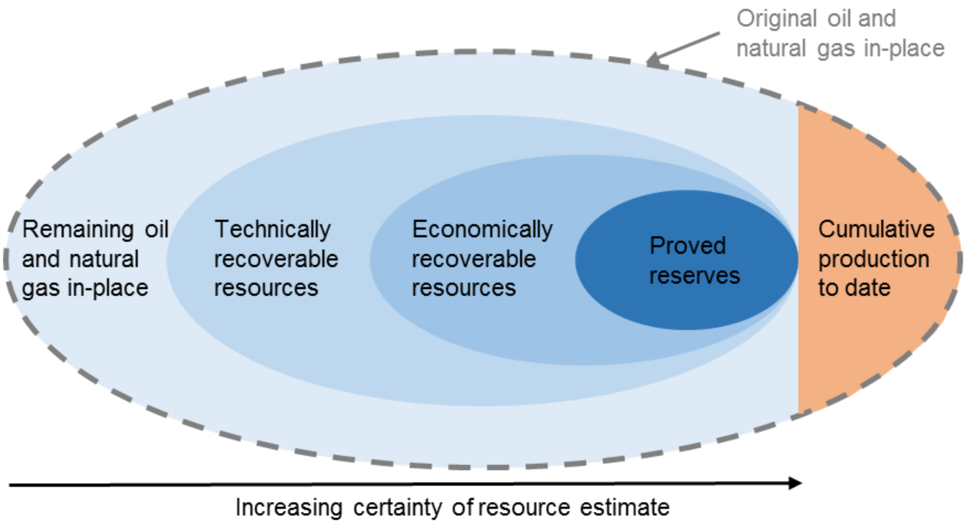

Figure 4.5: Four categories of resource estimation used by the USEIA.

Source: Modified from USEIA (2015).

The remaining oil and gas in-place is the total volume before the start of any production, it is the original untapped volume. As natural gas is produced, the amount of gas inseparable from the rocks is the remaining oil and gas in-place. This has the biggest volume and displays the highest level of uncertainty. TRR is the next largest volume of gas in the ground and is the total gas that can be produced using existing geological knowledge, industry practices and technological advancements. As these factors improve, the amount of TRR will expand. ERR is the portion of TRR that can be produced profitably. These volumes are determined by the oil or gas prices and the inclusive capital and operating costs of production (USEIA, 2015).

The U.S. government agencies, the USEIA included, tend to report resource estimates of TRR rather than ERR as any estimate of ERR is tied to a specific set of prices and costs. This results in difficulties when comparing to other estimates made that are based on different assumptions. Another issue is the volatility of costs and market prices, these can result in an estimation that is made quickly becoming irrelevant (USEIA, 2015).

Proved reserves is the resource category with the highest level of certainty and will have the smallest volume. The proved reserve is the volume of oil or gas that geologists and engineers are relatively certain can be extracted from known deposits under current economic and operating environments. Like ERR, proved reserves decrease or increase as prices and costs of extraction change (USEIA, 2015).

4.4.3 Resource estimates for the Karoo Basin

The three lower Ecca formations were used for the initial resource estimate by the USEIA in 2011 and 2013 in collaboration with Petroleum Agency South Africa (PASA) based on its organic-rich source rocks (USEIA, 2011d; USEIA, 2013; USEIA, 2015). An initial resource estimation for shale gas resources in the Karoo region was done by the USEIA in 2011, this was subsequently revised, and a new estimate produced in 2013 (USEIA, 2013). The CP used open source data and existing literature (USEIA, 2015), primarily information from the exploration work done by Soekor in the 1960's (Vermeulen, 2012). The information was used to estimate the 'risked oil and natural gas in-place', followed by the estimation of an unproved TRR (USEIA, 2015).

The risked oil and natural gas in-place estimates are determined by estimating the volume of in-situ gas in a basin, and then factoring in a success factor as well as a recovery factor. The success factor is the likelihood that a section of the formation should have good oil and natural gas flow rates. The recovery factor depends on the current technological capabilities of extracting the resource, determined by comparing to those used for deposits of similar geophysical characteristics. The resultant values are used to calculate a TRR for the basin (USEIA, 2015).

The initial USEIA estimate in 2011 classified a total 1,834 Tcf of risked gas in-place, and an unproven TRR of 485 Tcf (USEIA, 2011d). The revised 2013 USEIA estimates a total 1,559 Tcf of risked gas in-place, with an unproven TRR of 390 Tcf. This reduction was due to the presence and potential impact of dolerite igneous intrusions on the *in situ* gas. The new value in 2013 has placed South Africa in 8th position globally in terms of unproven TRR (Table 4.2) (USEIA, 2013).

Table 4.2: Shale gas TRR of the top 10 countries in the world.

Rank	Country	Shale gas TRR (Tcf)
1	China	1,115
2	Argentina	802
3	Algeria	707
4	US	665
5	Canada	573
6	Mexico	545
7	Australia	437
8	South Africa	390
9	Russia	285

10	Brazil	245
	World total	7,299

Source: *Modified from USEIA (2013).*

The three primary shale plays in the Karoo Basin are Prince Albert, Whitehill and Collingham Formations. The upper Ecca shales were excluded from the resource assessment as their TOC falls below the 2% standard used in the resource assessment study. A summary of the reservoir properties and resources estimated by the USEIA are presented in Table 4.3 below (USEIA, 2015).

Table 4.3: Karoo Basin shale gas reservoir properties and resource estimate by the USEIA.

Shale formation		Prince Albert	Whitehill	Collingham
Physical extent				
Prospective area (km^2)		96,850	96,850	96,850
Thickness (m)	**Organically rich**	122	61	61
	Net	37	30	24
Depth (m)	**Interval**	1,829-3,200	1676-3048	1585-2957
	Average	2591	2438	2377
Reservoir properties				
Reservoir pressure		Moderately overpressured	Moderately overpressured	Moderately overpressured
Average TOC (wt. %)		2.5%	6.0%	4.0%
Thermal maturity (% Ro)		3.00%	3.00%	3.00%
Clay content		Low	Low	Low
Resource				
Gas phase		Dry gas	Dry gas	Dry gas
Gas in-place concentration (Bcf/mi^2)		42.7	58.5	36.3
Risked gas in-place (Tcf)		385.3	845.4	327.9
Risked recoverable (Tcf)		96.3	211.3	82.0
Total (Tcf)		389.6		

Source: *Modified from USEIA (2015).*

In addition to the initial estimation by the USEIA, three different resource estimation scenarios are developed by Decker & Marot (2012) in a report for the Department of Mineral Resources (DMR). The TRR of 485 Tcf by USEIA (2011) is used as a high-case scenario. The calculations are modified to develop two smaller-case scenarios, a middle- and low-case scenario, with TRR values of 377 and 32 Tcf respectively (Decker & Marot, 2012). An inferred resource estimate of 243 Tcf was presented by Cole (2011) at the Geosynthesis conference in Cape Town and is the only other known resource estimate. The existing resource estimates are summarised in Table 4.4 below:

Table 4.4: Existing shale gas resource estimates for the Karoo Basin.

Author		Resource estimate (Tcf)	Estimate type
USEIA (2011)		485	TRR
USEIA (2013)		390	TRR
Decker & Marot (2012)	High	485	TRR
	Middle	377	
	Low	32	
Cole (2011)		243	Inferred resource

Source: *Values from USEIA (2011), USEIA (2013), Decker & Marot (2012) and Cole (2011).*

Decker & Marot (2012) highlight that their values are not inclined to have any statistical importance, and are not necessarily a representation of the range of shale gas resource estimates for the Karoo region. Instead, they serve to indicate that the initial resource estimates have a high level of uncertainty, resulting from a lack of geo-scientific information. It does, however, point out that even an intentionally conservative scenario, such as the 32 Tcf lower-case, still proposes a significant amount of recoverable shale gas (Decker & Marot, 2012). To put the lower-case scenario into a South African perspective, the country’s only gas project is Mossgas which was based on a reserve of only 3 Tcf (Vermeulen, 2012).

4.4.4 Key implications

One of the main issues highlighted by proponents is the lack of certainty on just how much gas there is underneath the Karoo (de Wit, 2011). The holes drilled by Soekor have provided a very limited amount of information and simply present tentative clues to the presence of shale gas in the Karoo (Steyl & van Tonder, 2013). Ultimately, a limited amount of resource estimation work has been done, and results show a wide range of values from 32 to 485 Tcf (USEIA, 2013; Decker & Marot, 2012; Cole, 2011). These values have come under scrutiny and opponents have expressed doubts regarding the extent of determined resources (PWC, 2012).

Additionally, the existence of dolerite dykes and sills throughout the Karoo is a major concern when estimating the shale gas resource (Figure 4.6). The intrusions are unique to South African shale gas and pose a different scenario compared to other shale gas areas in the world. Generally, borehole depths in the Karoo are not very great, and as a result, not much is certain about the continuation and orientation of these intrusions deep below the surface (Vermeulen, 2012). The dolerite has shown its significance by playing a major role in the reduction of the 2011 resource estimate by the USEIA in 2013. The intrusions may impact the quality of the shale resource, restrict the usage of seismic imaging and increase the risk of shale gas exploration in the basin (USEIA, 2013).

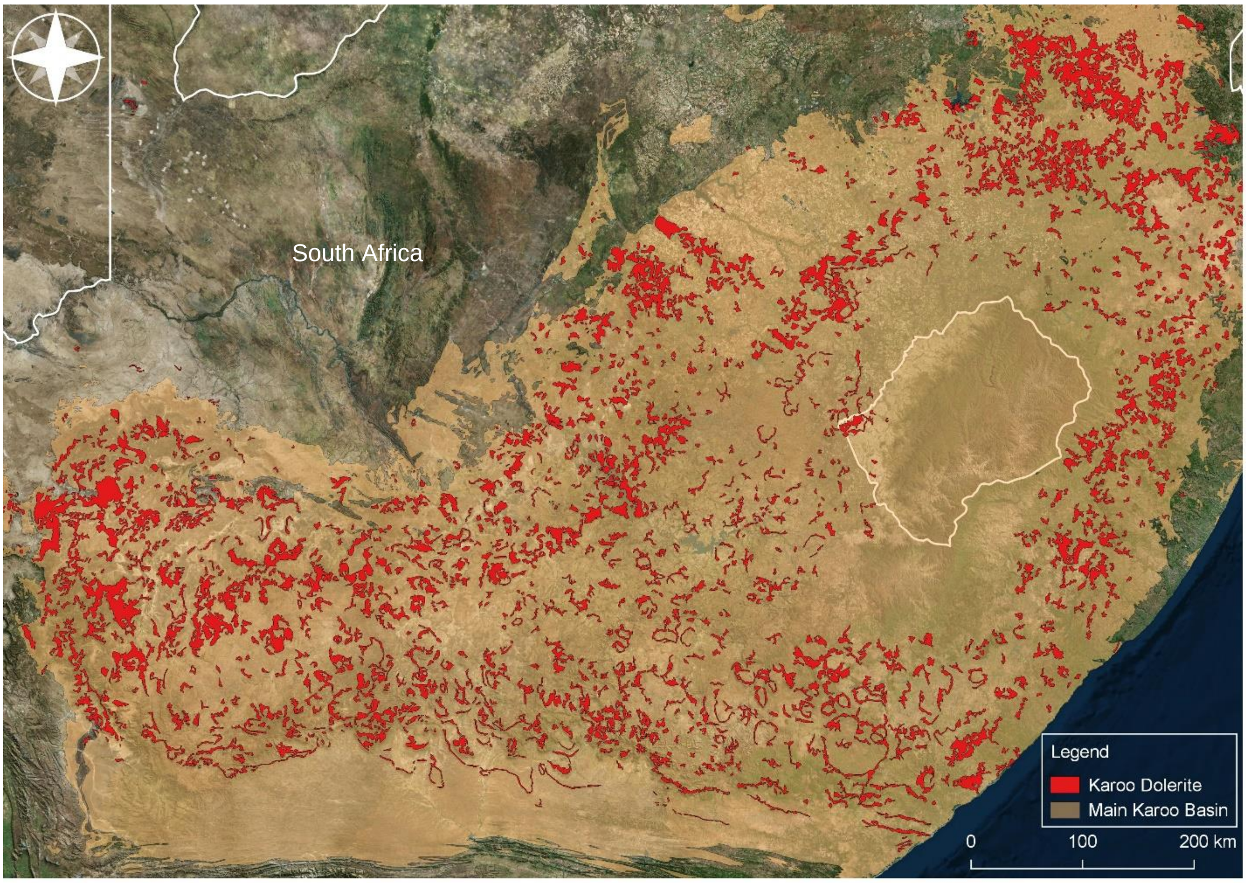

Figure 4.6: Map of the Karoo Dolerite intrusions throughout the Main Karoo Basin.

Source: *Map created using QGIS; base map from the ESRI plugin; shapefiles from PASA (2017), Natural Earth (2017) and Council for Geoscience (2017). All items are open source and free to use.*

The variation and uncertainty of the resource estimates, together with the dolerite intrusions further encourage the need for more exploration in the Karoo area for natural gas. The true extent of the shale gas resource that is economical to extract remains unknown until further drilling of wells and technical studies are done (De Wit, 2011; Vermeulen, 2012; PWC, 2012; Decker & Marot, 2012; Hedden et al., 2013). The gas companies need to perform an adequate exploration and confirmation programme that may go on for about 3 to 6 years depending on the geological complexity of the target areas. Thereafter, it should be followed up by a pilot study to determine the characteristics of the reservoirs; this can be done simultaneously on different sites and can take over 2 to 4 years. If the *in situ* gas resource is determined sufficient, then the development and production of the shale gas could commence lasting for approximately 30 to 100 years depending on the gas price and available resources (Steyl & van Tonder, 2013).

4.5 Fracking the Karoo - Recent activity

The central Karoo is an arid, extensive landscape with a unique biodiversity (de Wit, 2011), experienced by many as a sanctuary of harsh but captivating beauty (Scholes et al., 2016b). However, it is sparsely populated with very little industrial activity (Altieri & Stone, 2016) and most people that live in the area are poor, with the region exhibiting high levels of unemployment and inequality. South Africa is investigating the chance to introduce more natural gas into the country's energy mix by fracking the Central Karoo region. Thus, the development of shale gas presents both economic and energy security opportunities, but at the same time potential social and environmental risks to the targeted area (Scholes et al., 2016b).

The issue of Karoo shale gas began in late 2009 (Steyl & van Tonder, 2013) when Shell was awarded a Technical Cooperation Permit (TCP) for a one-year study to determine the Karoo's natural gas potential (Shell, 2017). After Shell, multiple companies have applied to the DMR for licenses to explore using the fracking technique (News24, 2011).

The granting of the applications was met by strong opposition from all facets, such as environmental groups including Treasure the Karoo Action Group, the Centre for Environmental Rights, Sustainable Alternatives to Fracking and Exploration Alliance, the Southern Cape Land Committee and landowners (van Wyk, 2014). All the uncertainties and controversies led to the DMR placing a moratorium in March 2010 on licenses to frack in the Karoo. A month later the minister assembled a Task Team to investigate the impact of fracking for shale gas on the Karoo, with the report released in 2012. The Working Group of the Task Team was chaired by the chief executive officer of PASA at the time and was comprised of representatives from multiple government departments and institutions (DMR, 2012).

The report points out the key issues such as the need to use large amounts of water, potential water contamination, need to treat wastewater and the potential 'footprint' of any development as well as the concerns around the socio-economic impacts.

Nonetheless, the proposed implementation plan based on the study recommended projects proceed with normal exploration but no actual fracking may take place under the existing regulatory framework (DMR, 2012).

The report aimed to constitute a monitoring committee to ensure comprehensive and co-ordinated augmentation of the regulatory framework and supervision of operations. Importantly, it was proposed that the current regulatory framework at the time be augmented with an establishment of the appropriate regulations, controls and coordinate systems; this was expected to take 6 to 12 months. Upon completion of these actions, they aim to authorise fracking but with the monitoring committee providing stern supervision (DMR, 2012). In September 2012, the Minister of Mineral Resources removed the moratorium on the development of shale gas (Steyl & van Tonder, 2013; van Wyk, 2014).

To address the lack of critically evaluated information regarding shale gas development, a Strategic Environmental Assessment (SEA) was commissioned in February 2015 by South Africa’s Department of Environmental Affairs, with the support of the National Department of Energy, Mineral Resources, Water Affairs and Sanitation, Science and Technology and Agriculture, Forestry and Fisheries. Additionally, there was support from the Provincial Departments of the Eastern, Western and Northern Cape Governments (Scholes et al., 2016b).

The SEA was coordinated by the Council for Scientific and Industrial Research together with the South African National Biodiversity Institute and the CGS. The SEA includes 146 independent authors contributing to the 18 chapters in the assessment. The chapters have been independently reviewed by 25 local and 46 international peer review experts, as well as by multiple stakeholders involved (Scholes et al., 2016b).

The mission statement of the SEA is to provide an integrated assessment and decision-making framework to enable South Africa to establish an effective policy, legislation and sustainability conditions relating to shale gas development. The key objective is to develop a better understanding of the opportunities and risks involved to guide decision-making processes, e.g. requirements of an Environmental Impact Assessment. The development of the SEA included three phases, first a preparation phase, followed by a scientific assessment phase where information was accumulated and organised by the authors. The third and final phase translated the scientific assessment into an operational Decision-Making Framework, this was completed in June 2017 (Scholes et al., 2016b; Snyman-Van der Walt, 2017).

In June 2015, the DMR published Regulations for Petroleum Exploration and Production which introduced guidelines covering onshore fracking to be read in line with the Mineral and Petroleum Resources Development Act of 2002. Exploration and production of shale gas will now be subject to the additional requirements that are set out in the Regulations for Petroleum Exploration and Production, such as the areas including environmental impact assessments; well design and construction; management of water, waste and air quality; pollution incidents and decommissioning activities (Jones, 2016).

The Karoo shale gas has already attracted some major players in terms of license applications (AOP, 2016), with a number of companies lining up to explore for shale gas (Fig, 2012). In South Africa, shale gas exploration begins with a TCP, which can lead to an Exploration Permit and eventually to a contract to start production (USEIA, 2015). In October 2014, the DMR minister was quoted in parliament as saying *(*CSIR, 2016):

> *“There are currently five applications to explore for shale gas in the Karoo area. Applications were received from Falcon (x1), Bundu (x1) and Shell (x3). The applications have not been assessed and therefore no applications have been approved or refused.”*

There were additional TCP applications submitted to PASA in the last few years for desktop studies, but many of these have expired. At the commencement date of the SEA, the Exploration Right applications by Bundu Gas and Oil Exploration (Pty) Ltd (Bundu), Shell and Falcon Oil and Gas Ltd (Falcon) were the only ones that had been accepted by PASA, with the applications still under consideration (Figure 4.7) (Scholes et al., 2016b; CSIR, 2016).

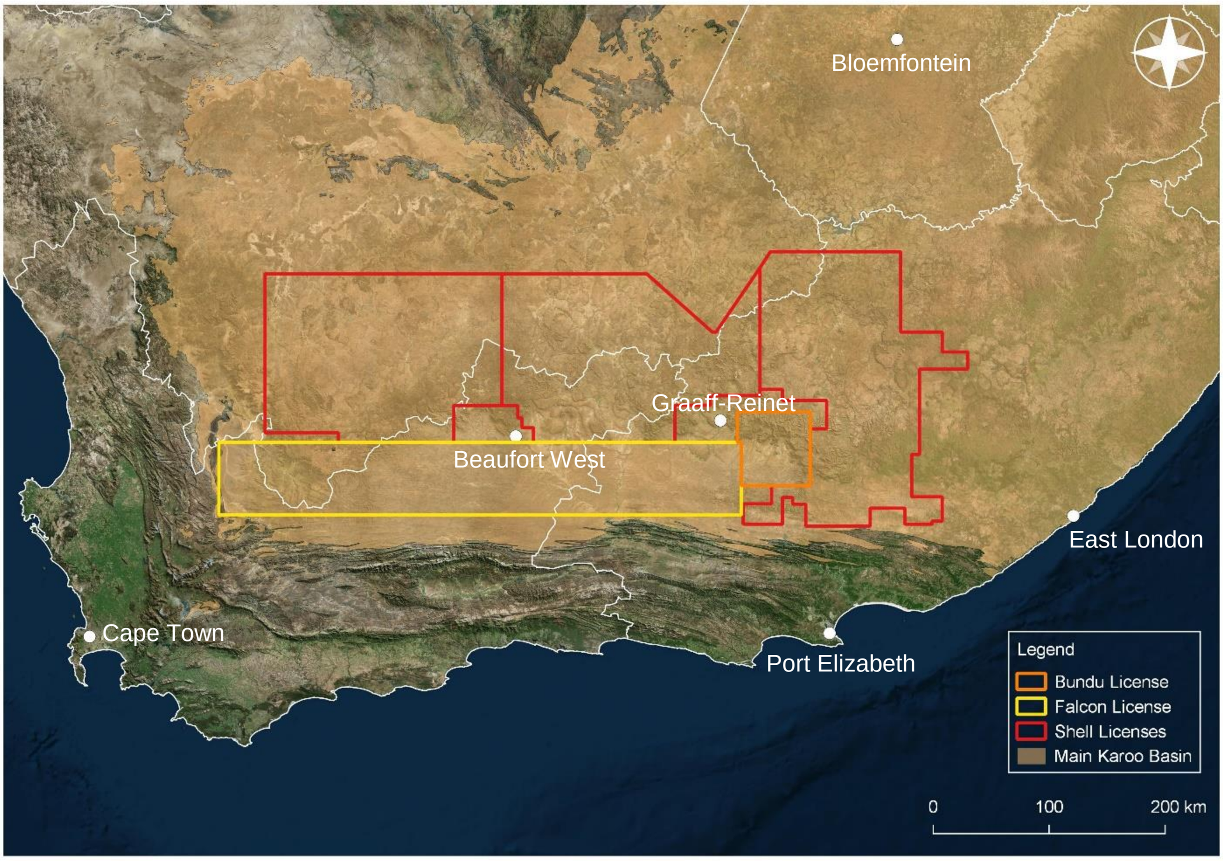

Figure 4.7: Current shale gas exploration license boundaries under application.

Source: *Map created using QGIS; base map from the ESRI plugin; shapefiles from PASA (2013) and Stanford University (2017).*

All the companies with applications under review are foreign: Shell, Falcon from America and Bundu from Australia. Shell aims to extract gas from 90,000 km^2. This is an area as large as KwaZulu-Natal and stretches from Bedford in the east to Sutherland in the west. Falcon has a permit to explore 30,327 km^2 for gas, an area one and a half times the size of the Kruger National Park. It includes the mohair capital of Jansenville, as well as Aberdeen, Rietbron, Merweville and Leeu Gamka. Bundu has about 3,200 km^2, including Pearston and areas around Graaff-Reinet (Econometrix, 2012; USEIA, 2015; Shell, 2017; Falcon Oil and Gas, 2017; Challenger Energy, 2017).

However, based purely on theoretical grounds, the institutional framework in South Africa is still inadequate to sufficiently regulate the exploration and mining of shale gas. In South Africa, it is very important that the ‘rules of the game’ make the situation as clear and democratic as possible (Chapman et al., 2016). The Mineral and Petroleum Resources Development Act 28 of 2002 does not provide enough clarity to instil policy stability that would contribute in attracting sufficient private investment, and at the same time provides for excessive ministerial discretion (Harvey, 2014).

Recently, in October of 2017, the court ruled that the current petroleum regulations in place are invalid. This court order would likely shift the granting of the exploration licenses for fracking beyond the initially planned date of 2019, as current permits only allow for seismic and exploratory drilling, not fracking. However, the government remains committed to shale gas exploration and are deciding on a possible appeal, but if unsuccessful the regulations will have to be redrafted and could cause additional delays (Mathews, 2017; Groenewald, 2017; Reuters, 2017).

With all this being said, while the practical application of South African oil and gas legislation may be weak, the laws themselves, when compared to the loopholes that exist in the US framework, are actually well written and have a lot of potential. South Africa can learn from existing regulatory frameworks used in other more mature regulatory environments around the world. If exploration and production are to proceed, effective regulation and the enforcement thereof are paramount (Chapman et al., 2016).

4.6 Chapter summary

Geologically, the most important formations for shale gas are the organic-rich shale layers of the Ecca Group, however, there is an increasing interest in the shale layers of the Dwyka Group. To date, there is very little exploration work done for shale gas in South Africa, with only about 28 boreholes drilled in total. When considering the importance of an accurate resource and reserve estimation, the lack of data presents a clear implication. The various assumptions used by different authors have resulted in a wide distribution of estimation results from 32 Tcf to 485 Tcf. An additional problem is the lack of understanding of the impact the dolerite dykes may have on shale gas in the Karoo. Based on recent activity surrounding the topic of shale gas in South Africa, the political framework is still a major issue that needs to be addressed.

5 SHALE GAS CONTRIBUTION TO THE SOUTH AFRICAN ECONOMY

5.1 Chapter overview

This chapter provides an overview of the potential economic contribution of shale gas in South Africa, including the macro, local and regional impacts. Additionally, it focuses on the potential influence shale gas could have on South Africa's energy mix, a key component to the economic growth of the country. A cost-driven approach is then used to determine whether, in its current state, shale gas development in South Africa will be profitable.

5.2 Macroeconomic impacts

International evidence, primarily from the US (e.g. CBER, 2008; Considine et al, 2009, 2010; Scott, 2009; The Perryman Group, 2009; Weinstein & Clower, 2009; Thomas et al., 2012; Weber, 2012; Hoy et al., 2017), shows that development of shale gas, like any other mining-related activities, has the potential for significant economic opportunities (Van Zyl et al., 2016). The economic gains from a growing gas industry, greatly influenced by shale gas development, will rely on the linkages between the gas and other industries in the various sectors of the economy. There is a noticeable expectation for an increase in employment, income, government revenue and economic growth (Wait & Rossouw, 2014).

Due to the shale gas scenario in South Africa being relatively new, the exact level of shale gas resource is not well-known and needs to be established through further exploration studies. As a result, the current economic impact studies need to be ex-ante or predictive assessments (Wait & Rossouw, 2014). Existing studies on economic benefits in South Africa have focused primarily on the macroeconomic opportunities, such as the reports by Econometrix (2012), Wait & Rossouw (2014), Leke et al., (2015) and Van Zyl et al. (2016).

The Econometrix report was done on behalf of Shell in order to indicate the potential economic benefits of extracting the shale gas resource in the Karoo. The report identifies five primary uses for natural gas in South Africa, namely, the use of gas as an energy source for domestic, commercial and industrial applications, the exporting of gas, development of automotive fuels, power generation and in the fertiliser sector as an energy input (Econometrix, 2012).

The study used a relatively static model, principally Keynesian in design. The model assumes shale gas production will start in 2020 and estimates the potential economic impact over a 25 year period (2020 to 2045). It uses two scenarios of varying resource sizes, scenario A uses a resource of 20 Tcf, whereas scenario B uses 50 Tcf; and is standardized to constant 2010 prices. Scenario A and B both use a wellhead price of US$8/mcf and US Dollar exchange rate of R7.303/$ for the conversion to Rand values (Econometrix, 2012).

Results for the modelling of Scenario A indicate a combined turnover (upstream and downstream benefits) of R4.031 trillion, a total value add (contribution to GDP) of R2.006 trillion, R887 billion earned in government revenue and a maximum job creation of 355,817. Scenario B modelled a combined turnover of R9.520, a total value add of R5.015 trillion, a total R2.223 trillion contributed to government revenue and the creation of 854,757 jobs (Econometrix, 2012). The report does highlight and indicates with modelled results, that the amount of gas that will be exported has a significant effect on the potential economic impacts (Econometrix, 2012).

Wait & Rossouw (2014) suggest that economic impacts will vary greatly based on the assumptions of resource size and wellhead gas price. They mention that the Econometrix report is an industry-sponsored one resulting in criticism and doubt with respect to the predicted values. Such as Fakir (2012) who criticises the use of a single wellhead price, suggesting that a range of prices is required to incorporate the unique characteristics of existing gas market in South Africa. He mentions that the report is biased as it supports Shell’s and industry’s overall position to promote shale gas extraction.

In the DMR report of 2012, Leiman (2012) provides a comment on the Econometrix report. He states that the report is very straightforward, and could only be a representation of a large shale gas find in South Africa if the economy remained structurally unaffected and prices did not change. This, of course, is highly unlikely. However, the authors of the Econometrix report do go out of their way to make this clear and indicate that their estimate is a conservative one. Leiman (2012) concurs with their statements.

A similar static model is used by Leke et al. (2015) in a study by the McKinsey Global Institute, although limited details on the exact approach are provided. They calculate that a combined potential economic impact of domestic gas production, power production and downstream petrochemical production can lead to an increase in South

Africa’s GDP by R138 to R251 billion per year by 2030, creating up to 328,000 jobs. The rand values are quoted in 2010 prices.

A peer-reviewed academic study by Wait & Rossouw (2014) bases their results on a CGE model that assumes capacity constraints within the economy. The study discusses the various benefit and cost considerations but does not provide an actual cost-benefit analysis. Instead, it focuses on quantifying macroeconomic impacts in terms of contribution to GDP and employment.

They create short- and long-run estimates using 4 different scenarios. The study utilises the same resource estimates of 20 Tcf and 50 Tcf used by Econometrix and creates a comparison to the report. The first two scenarios use the two resource estimates over a short time frame of 2 to 3 years, whereas the third and fourth scenarios use the resource estimates for a longer time frame of more than 10 years. The scenarios estimate an annual GDP contribution of R26, R52, R32 and R77 billion respectively, showing similar results to that of the Econometrix report. However, the CGE model predicts much lower permanent employment opportunities for 1,441 and 2,471 jobs for scenario 1 and 2. The long-run scenario employment is not provided as it is assumed exogenous to the model (Wait & Rossouw, 2014).

Due to the similar parameters used by Econometrix (2012) and Wait & Rossouw (2014), the results can be summarised (as is done by Chapman et al. (2016)) and compared to the 2016 GDP contributions of various industries in South Africa to provide an understanding of the size of the potential contributions (Table 5.1 and Figure 5.1).

Table 5.1: Comparative estimates of potential economic impacts of shale gas development on South Africa.

Category	**Econometrix (2012)**		**Wait & Rossouw (2014)**	
	20 Tcf	**50 Tcf**	**Scenario 1**	**Scenario 2**
Potential life of resource (years)	25	25	25	25
Potential contribution to GDP (%)	3.3	9.6	3.5	6.9
Potential contribution to GDP (ZAR bn)	35	90	26	52

Source: *Values from Econometrix (2012) and Wait & Rossouw (2014).*

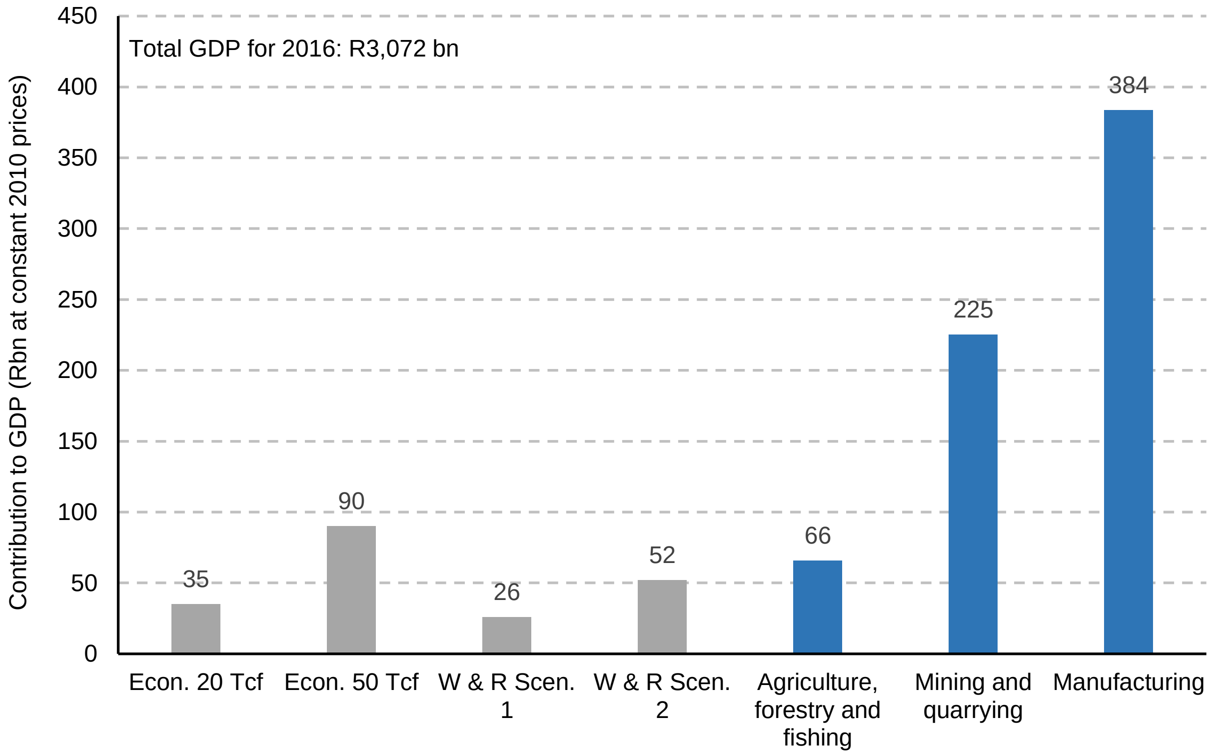

Figure 5.1: Comparative representation of the potential annual contribution of shale gas to national GDP and the contribution of various industries in 2016. Values are at constant 2010 prices.

Source: *Values from Econometrix (2012), Wait & Rossouw (2014) and* STATS SA (2017a).

Van Zyl et al. (2016) used a basic calculation to determine the magnitude of the revenue that can result from developing shale gas. The calculation used an annual production (total production per scenario smooth over 60 years) multiplied by a gas price range of US$3 and US$6/MMBtu and a rand-dollar exchange rate of 14:1. They use two scenarios, a Small Gas scenario that has an estimated resource size of 5 Tcf, and a Big Gas scenario of 20 Tcf. Results for the Small Gas indicate a value of revenue/turnover that could reach between R3.5 and R7 billion per year, with a Big Gas scenario reaching between R14 and R28 billion. In terms of employment, the calculations estimate a total 420 job opportunities for the Small Gas, and 2,575 for the Big Gas scenarios.

They put these numbers into perspective by highlighting that for the year 2015, the annual current account deficit was R174 billion. Thus, the total gas revenue could meet between 8% and 16% of the current account deficit. Therefore, one can conclude that shale gas could play a big role in reducing the country's current account deficit, with increasing significance as the resource of natural gas increases. It can be argued that the revenue from natural gas can offset imports such as oil, whilst allowing other fuels that are being produced locally to be exported, e.g. coal (Van Zyl et al., 2016).

It is important to highlight that the Karoo is an area in which skilled labour is relatively scarce. It is likely that the jobs designated to the local people will be unskilled and semi-skilled positions such as truck drivers and maintenance workers. However, local participation could increase as the industry matures and local skill levels rise (Van Zyl et al., 2016). As a result, Van Zyl et al. (2016) uses a tentative estimation of 15 to 35% of the jobs being awarded locally, reducing the predictions for the Small Gas scenario jobs from 420 to a range of 60 to 145, and for the Big Gas scenario from 2,575 to a range of 390 to 900.

To summarise the predicted employment opportunities of shale gas extraction from the various reports, Table 5.2 indicates the author, resource estimate used and resultant calculated job opportunities of each report. To put these numbers into perspective, Figure 5.2 illustrates the calculated employment opportunities compared to the contributions made by the agriculture, mining and manufacturing sectors in South Africa in 2017.

Table 5.2: Summary of calculated job opportunities by the various reports.

Author	Resource estimate used (Tcf)	Jobs created
Van Zyl et al. (2016)	5	420
	20	2,575
Wait & Rossouw (2014)	20	1,441
	50	2,471
Leke et al. (2015)	Not stated	328,000
Econometrix (2012)	20	355,817
	50	854,757

Source: *Values from Econometrix (2012), Wait & Rossouw (2014), Leke et al. (2015) and Van Zyl et al. (2016).*

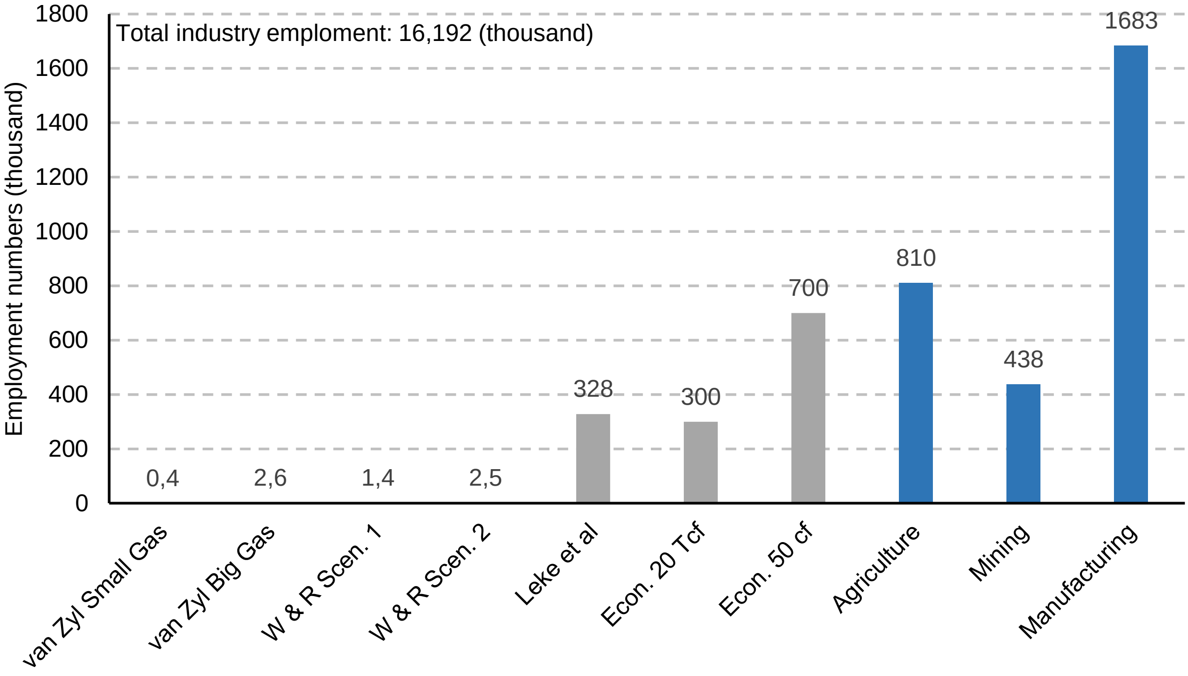

Figure 5.2: Representation of the estimated employment numbers from shale gas development from the various reports compared to the total employment contributions from other sectors in 2017.

Source: *Values from Econometrix (2012), Wait & Rossouw (2014), Leke et al. (2015), van Zyl et al. (2016) and STATS SA (2017b).*

5.3 Local and regional economic impacts

The Karoo region is a place of intense poverty, with a high rate of unemployment and some of the biggest gaps between the rich landowners and the previously disadvantaged (Toerien, 2015). Toerien (2015) is the only South African study that partially quantifies the impact of developing shale gas at a regional scale in the Karoo. He uses information from shale gas development in the US combined with quantified relationships between economic value added, population sizes and enterprise structures of Karoo towns to make the economic predictions. Using these relationships, the study primarily looks at the impact of worker spending in the area.

He takes a conservative approach, using a figure of 30 rigs per municipality, each with 50 workers, meaning that at any point in time, there are 1,500 workers involved in shale gas extraction in a local municipality. During the period of gas extraction, if each worker spends R300 a day on accommodation and food, it would inject an addition R162 million per year into the local economy. In a town experiencing shale gas extraction, the influx would result in the population of the town growing by about 4,300 people (Toerien, 2015).

An influx of this many people would have a major impact on the small Karoo towns, not only from an economic expansion perspective but there would be an increase in infrastructure requirements (both general and gas-specific) and the need to provide sufficient municipal services, e.g. water and electricity. The population increase would result in between 37 and 41 additional enterprises, which would grow the enterprise structures of most small Karoo towns significantly. There would thus be a host of new, as well as existing entrepreneurial opportunities, some of which would be associated with services in new business sectors. This would benefit the towns as services that did not use to exist will now be present (Toerien, 2015).

5.4 Contribution to South Africa’s energy mix

Shale gas could be an alternative source of electricity supply and energy (Cohen & Winkler, 2014); with natural gas becoming increasingly important in the global energy market (Melikoglu, 2014). For South Africa, a country facing a current energy crisis (PWC, 2012) with an emerging energy supply gap after 2020 (Leke et al., 2015), this is a potential ‘game changer’ (Hedden et al., 2013).

Beyond the energy supply-gap, the dependence of South Africa on coal as its primary source of electricity has it searching for alternatives to decrease the levels of GHG emissions from its energy supply (Cohen & Winkler, 2014). This is crucial for South Africa to reach the strict 2020 carbon emission target it set to reduce its carbon footprint (de Wit, 2011), in accordance with the important environmental challenge facing the globe (Menyah & Wolde-Rufael, 2010).

South Africa has a high energy-intensive economy that is dominated by raw material extraction and primary stage processing. Energy demand is expected to grow and continue to be of fundamental importance to economic growth in RSA (Nkomo, 2005). Electricity plays a pivotal role in any economy, acting as one of the main drivers for economic growth (Blignaut, 2009). The ability to generate, supply and distribute and the ease of access to electricity provides an opportunity for economic development in a country (Inglesi-Lotz & Blignaut, 2011).

South Africa’s electricity sector has undergone a lack of investment, resulting in an increase in price and a struggle to meet the necessary demand. This has caused rationing of power and unplanned blackouts (Pollett et al., 2015). The supply limitation results in a negative impact on the economy (Wait & Rossouw, 2014), and has been earmarked by the South African government as one of the main hindrances to economic growth. In 2015, the South African government established the so-called ‘Energy War Room’ in response to the national energy crisis to implement the ‘5-Point Energy Plan’. One of the main points is the need to introduce gas-to-power technologies (Pollett et al., 2015).

5.4.1 South Africa’s energy landscape

Globally, South Africa is one of the most carbon-intensive economies (Alton et al., 2014); coal is responsible for approximately 70% of its main energy supply, with 93% of electricity generation produced by coal-fired power stations (World Bank, 2008). Many believe that the burning of coal in power plants is one of the major contributors to climate change due to the high concentration of GHG emissions (Wolde-Rufael, 2006).

Approximately 48% of the country’s CO_2 emissions are produced by the electricity sector (Figure 5.3), making it the largest contributor (Devarajan et al., 2011; RSA, 2010). In comparison to other developed and developing countries, South Africa is amongst the top ranked in terms of GHG emissions per capita and per unit of GDP (Winkler, 2007; World Bank, 2008). South Africa is in the top 20 in non-annex 1 developing countries for absolute CO_2 emissions (RSA, 2010).

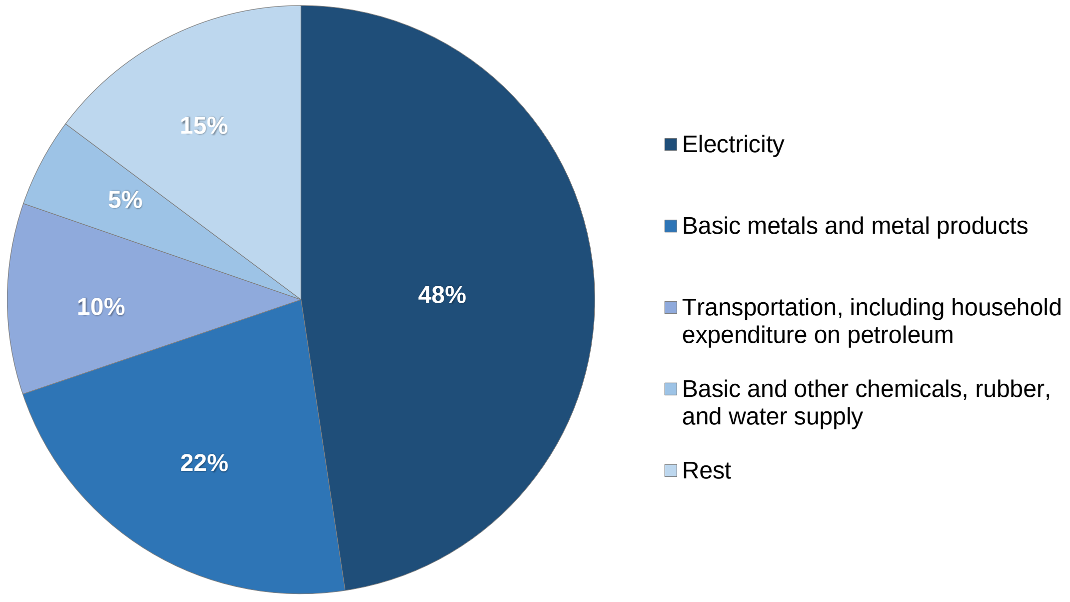

Figure 5.3: CO_2 emissions per economic sector in South Africa.

Source: *Modified from Devarajan et al. (2011).*

Average temperatures have increased by 0.2°C per decade over the last 50 years (RSA, 2010). Weitzman (2011) highlights that the exact significance of such extreme climate change levels are unknown, yet it is highly probable that they will be overwhelmingly negative.

Concerns over climate change have induced the need for international response and national efforts to reduce GHG emissions into the atmosphere. The United Nations Framework Convention on Climate Change (UNFCCC) is the main response to global climate change. The Kyoto protocol classifies countries based on their level of industrialisation and commits certain countries to GHG emission reductions. During the 2009 Copenhagen climate change negotiations, South Africa voluntarily committed to reducing its GHG emissions by 34% by 2020 and by 42% by 2025 (RSA, 2010).

Thus, the country is faced with the issue of trying to reduce its GHG emissions, whilst at the same time needing to increase coal production to satisfy energy requirements. Amplifying the situation is the increased coal price in comparison to other energy sources, as well as the exhaustion of non-renewable coal reserves. To address these problems, South Africa needs to diversify its electricity sector and lower the reliance on coal-generated electricity (Menyah & Wolde-Rufael, 2010). The Government has stated that an increased use of available natural gas is a way of potentially addressing the GHG emission from electricity generation (Peters, 2010).

5.4.2 Role of energy in South Africa’s economy

South Africa’s economy is extremely energy intensive (Nkomo, 2005), recording an energy intensity of approximately 0.4 tonne of oil equivalent (toe) per thousand dollars of GDP in 2012 (Figure 5.4). This is a result of coal's dominance in its energy production, and the outdated and inefficient infrastructure, particularly for electricity generation. In terms of emerging countries, India is the only country that requires more energy per unit of GDP output (IEA, 2015).

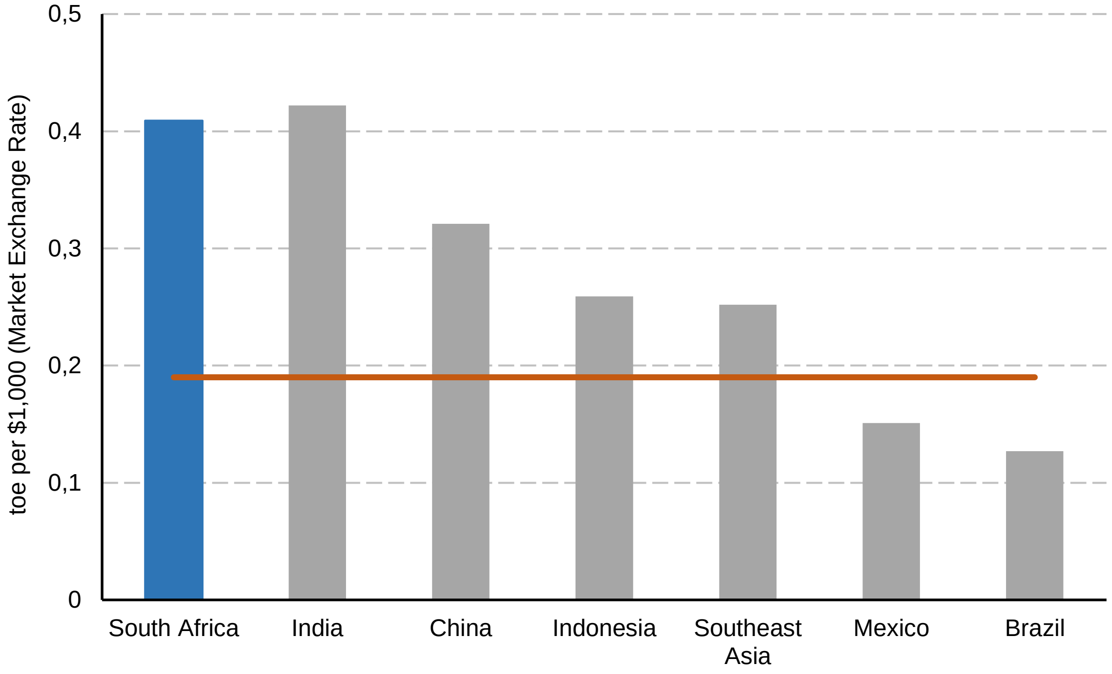

Figure 5.4: Energy intensity of selected countries (2012).

Source: *Modified from IEA (2015).*

From a sectoral approach, industry dominates, accounting for over a third of total energy consumption (Figure 5.5) (Pollett et al., 2015). The industry itself is dominated by mining and primary aluminium manufacturing, making up about a third of total electricity requirements (IEA, 2015). Mining counts for approximately 18% contribution of the GDP, both directly and indirectly (Eskom, 2010).

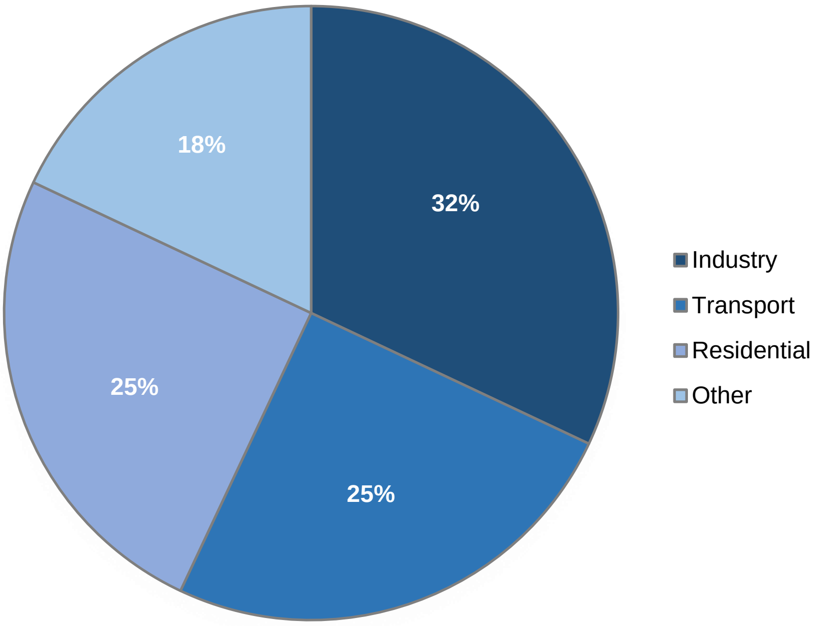

Figure 5.5: Energy usage per sector in RSA (2009).

Source: *Modified from DoE (2013).*

The energy mix in RSA is made up of coal, crude oil, renewable, nuclear power, natural gas and hydro-electrical power (Figure 5.6) (Lin & Wesseh Jr, 2014). Coal and nuclear power provide a stable base; however, the variable nature of renewables creates security and supply concerns that result in failure to consistently meet the daily cumulative demand (Figure 5.7) (PWC, 2012).

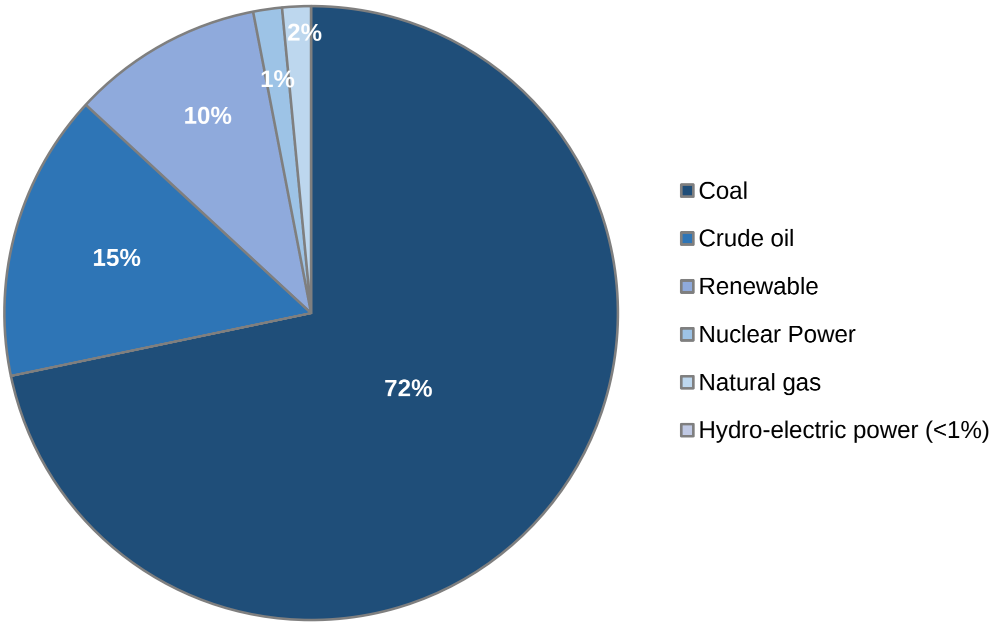

Figure 5.6: Distribution of primary energy supply in RSA (2014).

Source: *Created from data in Lin & Wesseh Jr (2014).*

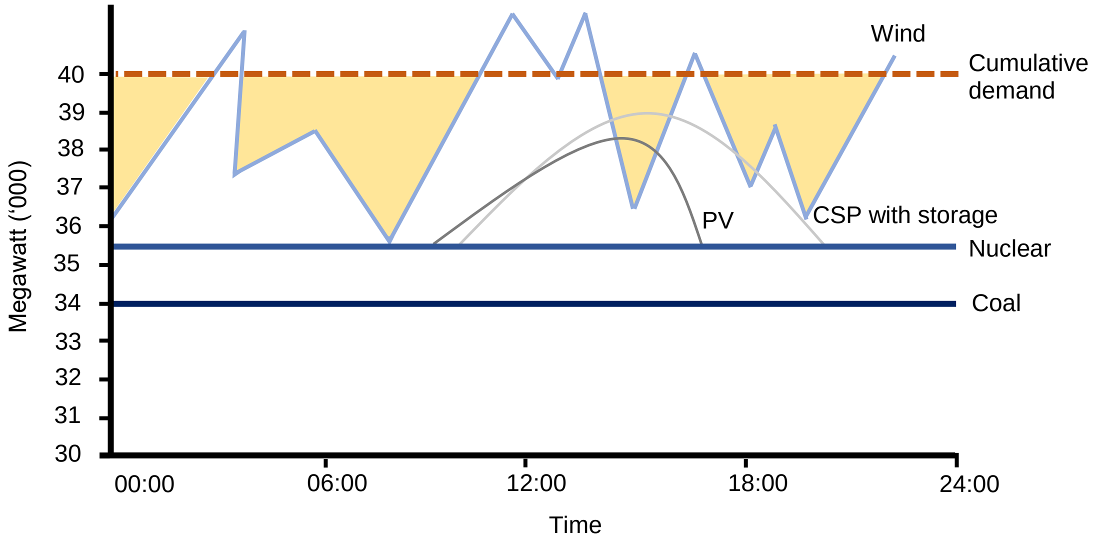

Figure 5.7: South Africa's daily energy supply gap.

Note: Photovoltaic (PV); concentrated solar power (CSP).

***Source:** Modified from PWC (2012).*

The failure to meet demand has left South Africa facing an energy crisis with the need to add and diversify electricity sources to meet future demand (Hedden et al., 2013). In 2013, the Department of Energy released a revised Integrated Resource Plan predicting future electricity demand from 2010 to 2030. Based on economic indicators and measured electricity demand, moderate and low forecasts of about 622 terrawatt hour (TWh) and 441 TWh are predicted by 2050 (Figure 5.8) (DoE, 2013). Figure 5.8 includes the amount of electricity made available for distribution in South Africa from 2010 to 2016 (STATS SA, 2017c). As can be seen, the amount made available is well below the predicted levels of demand.

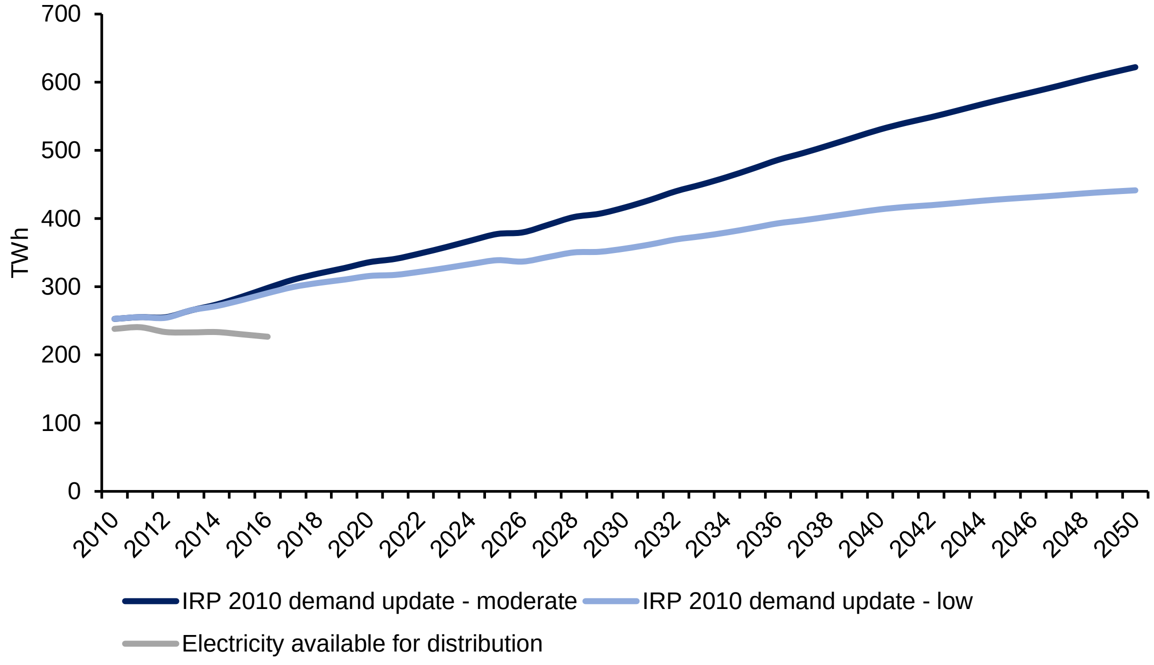

Figure 5.8: Electricity demand forecast and available for distribution.

Source: *Data sourced from DoE (2013) and STATS SA (2017c).*

5.4.3 Potential contribution from shale gas

Using a large-scale, long-term, extremely integrated modelling software, known as International Futures (IFs), Hedden et al. (2013) created 3 different energy scenarios for South Africa by 2050 (Figure 5.9).

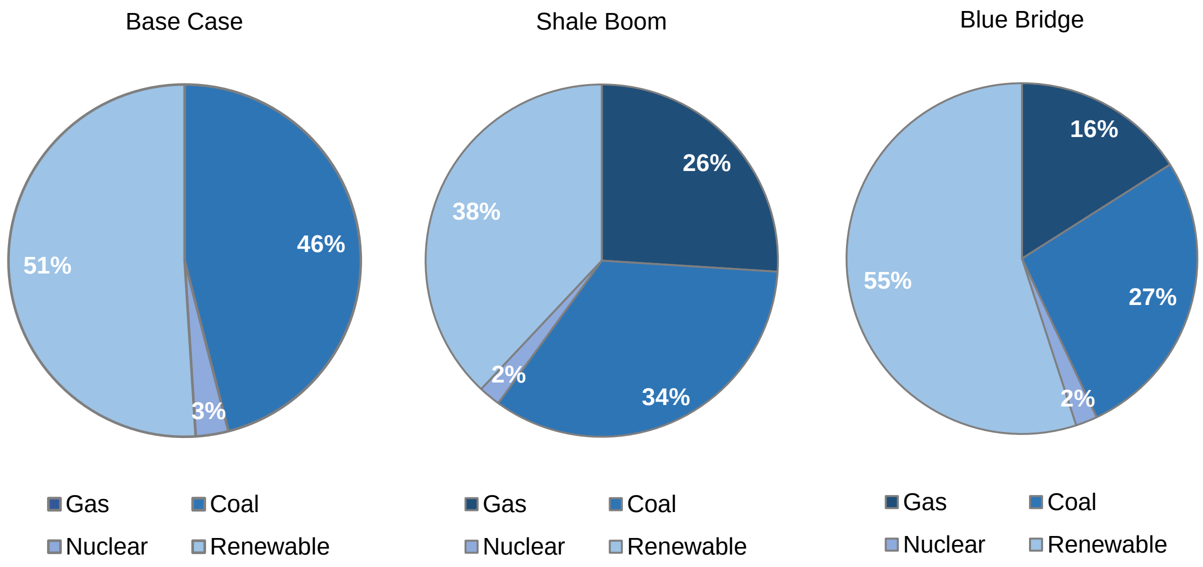

Figure 5.9: Three possible energy scenarios for South Africa by 2050.

Source: *Modified from Hedden et al. (2013).*

The first scenario, the Base Case, predicts the potential energy output without tapping into any shale gas. The Shale Boom scenario maximises the potential of shale gas and sees South Africa's natural gas production reach 644 million barrel of oil equivalent (boe) by 2050. To put this in perspective, it matches the same level of coal production at the end of the Apartheid era. Finally, the Blue Bridge scenario makes use of the economic gains from a shale boom to invest in renewable energy for long-term sustainability (Hedden et al., 2013). Energy production and carbon emission results from all scenarios are presented in Table 5.3 below:

Table 5.3: Energy production and carbon emissions per 2050 scenario.

Energy Scenario	Total energy production (billion boe)	Total carbon emissions (billion tonnes)
Base Case	1,88	5,36
Shale Boom	2,52	5,35
Blue Bridge	2,94	5,11

Source: *Modified from Hedden et al. (2013).*

The Base Case is forecast purely on historical trends and current policies being implemented. It should be noted that the investment and future of renewable energy are very optimistic and has a significant impact on the analysis (Hedden et al., 2013).

Compared to the Base Case, the large gains from the Shale Boom scenario are apparent. It does, however, present the chance of a large increase in natural gas exports and an increase in the country's currency exchange. This results in the non-extractive exporting sectors struggling to remain competitive, a phenomenon termed the 'Dutch Disease' (Hedden et al., 2013).

The Blue Bridge scenario agrees with de Wit (2011), shale gas can play a role as a cleaner bridging energy from coal towards the more sustainable, and inevitable need for renewable energy. This scenario also contributes the most to achieving the strict GHG emission reduction goals that were voluntarily set out by South Africa (RSA, 2010; Hedden et al., 2013).

The potential for shale gas to contribute to South Africa's electricity supply is presented in numerous scenarios in the 2013 revised Integrated Resource Plan presented by the Department of Energy (Figure 5.10). The majority of the scenarios provide little exposure to new gas-fired combined cycle gas turbine (CCGT) capacity. However, the main outlier is the 'Big Gas' scenario, which maximises the use of potential shale gas reserves, and is estimated to account for 62,480 MW of CCGT capacity by 2050 (DoE, 2013). This alone is beyond the current 40,000 MW demand presented in Figure 5.7 by PWC (2012).

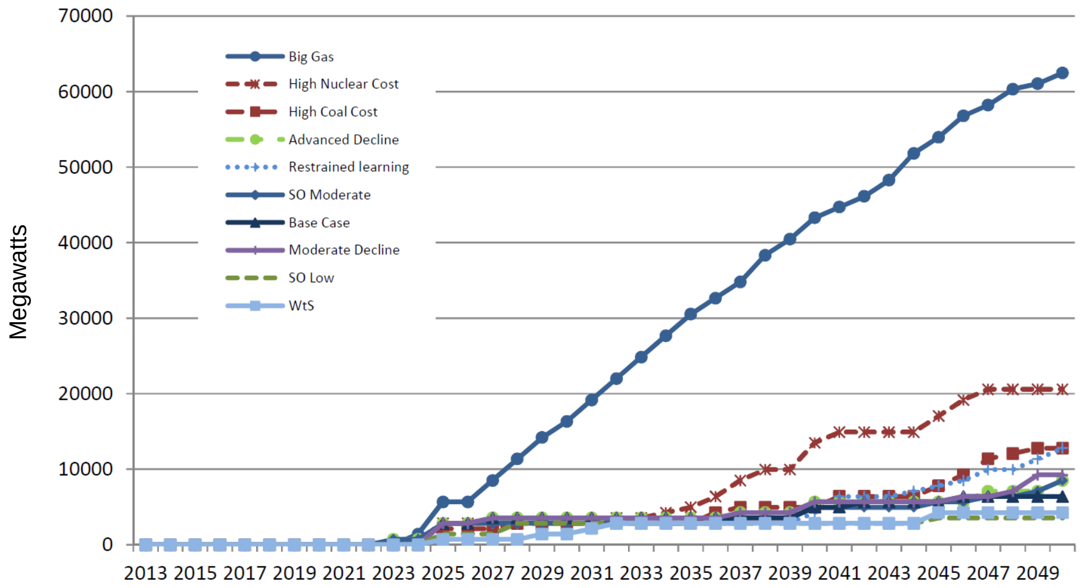

Figure 5.10: Various potential natural gas CCGT capacity scenarios by 2050.

Source: *DoE (2013).*

5.4.4 Shale gas as a cleaner source of energy

In terms of electricity generation, overwhelming evidence based on the analysis of numerous studies indicate that electricity production from shale gas has lower GHG emissions than that from coal. Electricity from shale gas will have a specific emissions intensity between 0.31 tCO_2/MWh and 0.59 tCO_2/MWh, versus approximately 1.06 tCO_2/MWh for coal-fired electricity in South Africa (Cohen & Winkler, 2014). Throughout the combustion process, as well as the full life-cycle of coal and natural gas, the latter has the lower GHG emissions for electricity production, when considering the traditional coal technologies (Figure 5.11). Figure 5.11 provides a high and low scenario of total emissions, together with a midpoint value. The midpoint values for natural gas are lower for both combustion and total life-cycle emissions (PWC, 2012). When converted to tons, the results coincide with the findings presented by Cohen & Winkler (2014).

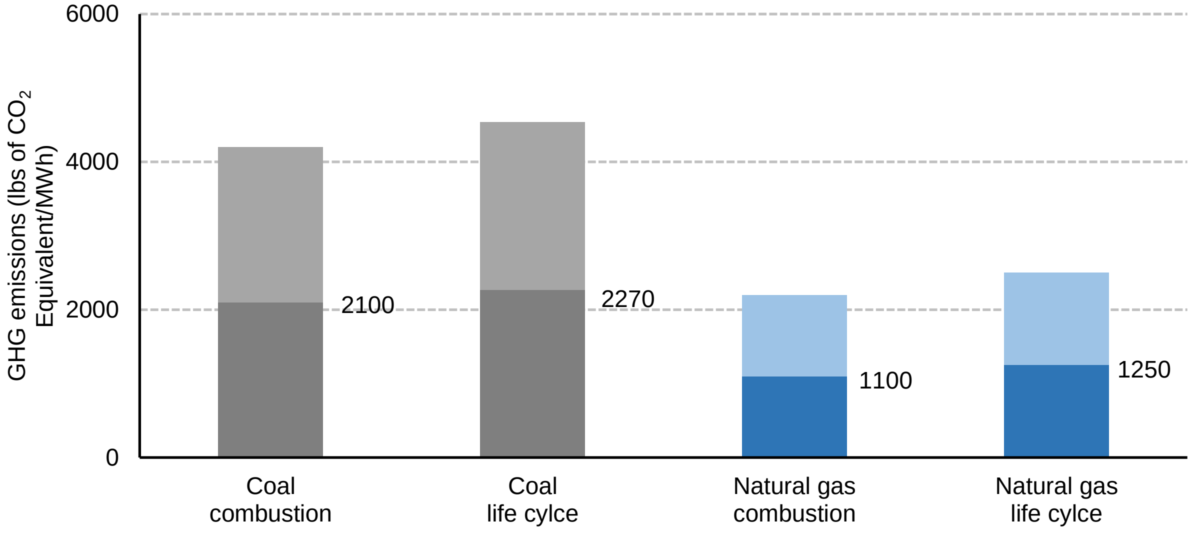

Figure 5.11: Combustion and life-cycle CO_2 emissions of coal and natural gas used for electricity generation.

Source: *Modified from Jaramillo et al. (2007).*

Using the newer technologies, such as the efficient carbon capture and storage techniques, both coal and natural gas GHG emissions are reduced substantially, but natural gas remains lower. These results and conclusions are further backed up by numerous studies, such as the National Energy Technology Laboratory (Skone et al., 2011), the National Renewable Energy Laboratory (Spath & Mann, 2000), and The Centre for Liquefied Natural Gas (Pace Global, 2009) (PWC, 2012).

5.4.5 The efficiency of shale gas electricity generation

If gas is available at competitive prices, the use of CCGT for shale gas is the favourable option. It has proved to be a method of high efficiency, with the top natural gas-fired CCGTs running at about 60% (Sims et al., 2003). In operating power plants across the United States, coal runs at an efficiency range between 30% and 37%, whilst natural gas power plants run between 28% and 58%; indicating a significantly higher level of efficiency (Jaramillo et al., 2007).

5.4.6 Cost of electricity generation from shale gas

Efficiency and GHG emissions are not the only issues to consider, as they would be irrelevant if the costs associated with electricity generation from shale gas were not competitive. Issues such as capital costs, lead times of plant construction, fuel costs and the economic life of the plant need to be weighed against that of coal (PWC, 2012). Table 5.4 displays a final Levelised Cost of Electricity, determined from the various costs and issues. From a Levelised Cost of Electricity point of view, the CCGT is lower than pulverized coal with values of R460/MWh and R553/MWh respectively. These values suggest gas-fired CCGT is the cheaper source of electricity production for South Africa (PWC, 2012).

Table 5.4: Electricity cost of pulverised coal and CCGT.

	Pulverised coal	CCGT
Total plant cost per kW (ZAR)	16,880	5,780
Lead time (years)	5	3
Fuel cost per GJ (ZAR)	15	42.1
Economic life (years)	30	30
LCOE (ZAR//MWh)	553	460

Source: Modified from (EPRI, 2010).

5.4.7 Importance of energy to economic growth

Numerous empirical data analysis studies on various countries, spanning from 1978 to 2009, are reviewed by Ozturk (2010). The review concludes that although there are differing and conflicting results, the majority of the studies indicate a uni-directional relationship whereby energy/electricity consumption is required for economic growth, and a lack thereof will have negative consequences (Ozturk, 2010).

Electricity plays an important role in economic growth (Blignaut, 2009). The ease of access to electricity, as well as amount allowed to be consumed, are the two most important factors that indicate the level of contribution by the energy sector to national economic growth. There is a close relationship between electricity consumption and economic development, and growth cannot occur without a step up in the electricity sector (Castellano et al., 2015).

Figure 5.12, generated by Castellano et al. (2015), demonstrates this relationship by indicating the effect of electricity consumption on a country’s GDP per capita. South Africa, which is the continent’s main electricity producer (Inglesi-Lotz & Blignaut, 2011), also has the highest overall GDP per capita of all sub-Saharan countries. There is a general upward trend indicating an increase in GDP per capita as electricity consumption increases.

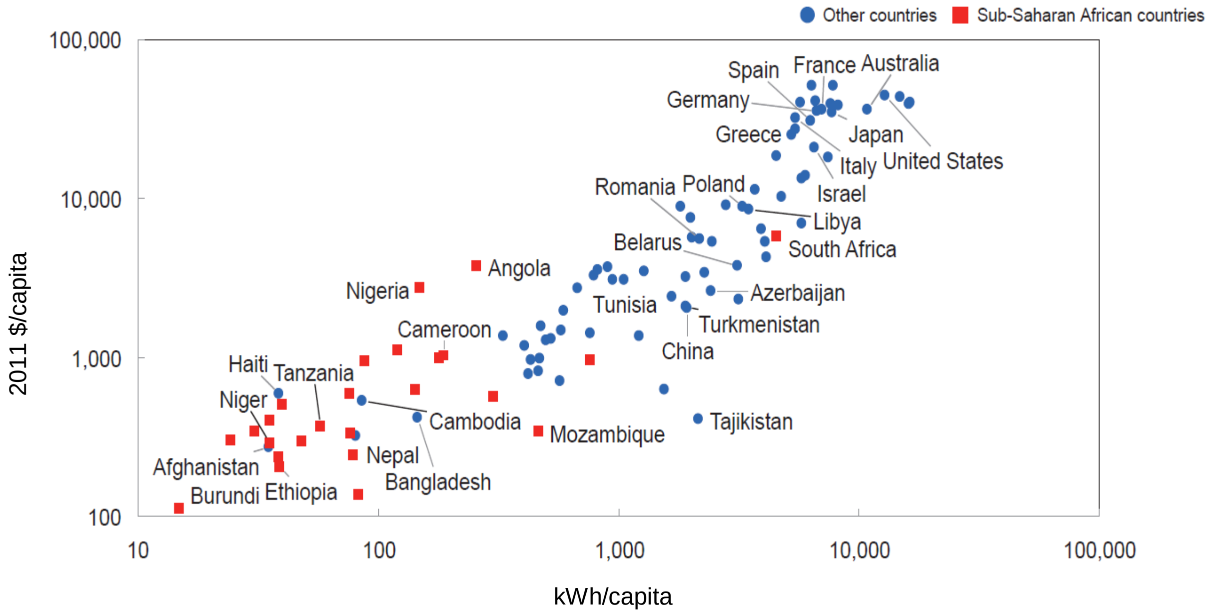

Figure 5.12: GDP/capita and electricity consumption relationship (2011).

Note: 1 Base 10 logarithmic scale.

Source: *Castellano et al. (2015).*

The link between electricity and economic growth explains why the RSA government considered electricity production pivotal to the country's growth and development. As a result, the demand for electricity has tracked the country's economic growth over the years (Figure 5.13) (Inglesi-Lotz & Blignaut, 2011).

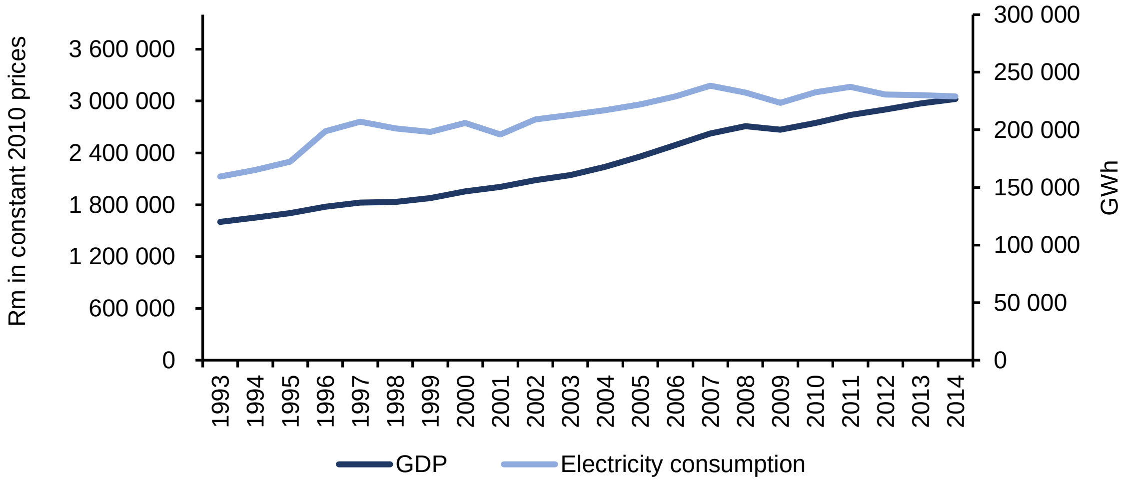

Figure 5.13: GDP and electricity consumption in RSA, 1993 to 2014.

Note: Electricity consumption = gross production + imports – exports – losses.

Source: *Data sourced from STATS SA (2016) and USEIA (2014).*

5.5 Assessing the economic viability of shale gas in South Africa

5.5.1 South Africa’s natural gas supply and pricing system

In South Africa, the use of natural gas as an energy source dates to 1892. The South African gas distribution company, now Sasol Gas, was formed in 1966 to market and distribute gas via pipelines on a broader scale. Initially, gas was sourced from industrial coal-to-gas processes, but in 2004 the first natural gas arrived in Secunda via the 856 km pipeline from the Temane and Pande gas fields in Mozambique (DoE, 2017). This remains the only source of imported natural gas to South Africa, with Sasol being the sole importer (PWC, 2012).

In terms of South Africa’s total gas supply, the imports from Mozambique account for nearly all of South Africa’s natural gas requirements, the only other source is a very small amount produced by PetroSA in the offshore Bredasdorp Basin, all of which is consumed as feedstock in their gas-to-liquid refinery plant (PWC, 2012; Oberholzer & Davidson, 2017). The majority of Sasol's imported natural gas is used in their gas-to-liquid and chemicals plant in Secunda; whilst the remaining portion is distributed to commercial and industrial customers via a pipeline of approximately 2,000 km to the Free State, Gauteng, Mpumalanga and KwaZulu Natal (Sasol, 2010). Of the seven gas traders in South Africa, Sasol is by far the largest, and according to their 2015 Annual Report, they accounted for 94% of the gas sales to end customers (Modliwa & Roberts, 2017).

The price that Sasol sells its gas to the market is made up of the sum of four components: the price of the gas molecule, transmission tariffs, distribution tariff and a trading margin. Due to their market dominance and a lack of competition, the National Energy Regulator of South Africa (NERSA) is mandated to approve a maximum gas price for all classes of customers (based on customer usage, Gigajoule (GJ) per annum) of piped-gas and prevent discrimination. As a result, since April 2014, a maximum gas price exists, enforced by NERSA, that Sasol and other traders may not exceed (Modliwa & Roberts, 2017).

5.5.2 Shale gas production profitability factors

Ultimately, shale gas production is only profitable if the natural gas price is offset against the cost of production, i.e. the breakeven price is below the market price (Le, 2018). This requires that the inputs, the capital and operating costs, are lower than the outputs, the revenues generated as a result of gas production and wellhead price (Yuan et al., 2015). The wellhead costs guide the pricing of shale gas before it enters into the domestic or international market. The pricing not only needs to cover the costs but must be enough to ensure private investment is able to see a return (Fakir, 2015).

The capital costs include the drilling costs, fracturing treatment costs and facility costs. The operating costs are associated with the expenses of production and operation (Yuan et al., 2015). The drilling costs are the most important consideration as it usually makes up for the majority of the input costs (Yuan et al., 2015); this can be as much as 40 to 60% of the total cost (Bonakdarpour et al., 2011).

In terms of revenue, the production rate of a gas well declines rapidly over time and struggles to maintain stable production rates. This makes it difficult to accurately predict shale gas production over time and can have large impacts on the predicted economic values (Yuan et al., 2015).

The gas price will have a significant effect on the revenue generated and economic margin of producing shale gas (Yuan et al., 2015). The big drop in the price of natural gas over the past decade, from a weekly average of 14.49 $/MMBtu in December 2005 to a low of 1.86 $/MMBtu in April 2012, has been one of the most significant consequences of the boom of shale gas in the US. Unlike other commodities, particularly crude oil, natural gas prices are not the same globally but instead is fragmented into several regional markets. Therefore, the price of natural gas differs in the US, Europe and East Asia. As a result, the decrease in gas price due to the natural gas boom in the US has remained localised (Saussay, 2018).

5.5.3 Determining a breakeven price for shale production in South Africa

The study by Fakir (2015) highlights the need to develop a base economic model for shale gas production in South Africa. They propose the use of a sensitivity model which can be used for different cost and revenue variables that could be modified to suit local South African conditions. Developing such a model would allow for the estimation of breakeven costs that could be used to guide appropriate prices for shale gas, royalty rates and environmental levies that can be determined for a specific well (Fakir, 2015).

However, the application of a base economic model in South Africa is limited due to the insufficient data and exploration information. A large amount of work still needs to be done on the geological and other aspects of local shale gas development (DMR, 2012; Hedden et al., 2013; Fakir, 2015). Therefore, this study draws upon the work of Saussay (2018) in order to assign a potential breakeven price for South African shale gas extraction, and ultimately, whether it would be profitable in the current state of South Africa’s gas market.

Saussay (2018) determines whether the US shale gas boom can be replicated in Europe, with a specific focus on France, Germany, Denmark and the Netherlands. The study uses a techno-economic model of shale gas production amenable to direct estimation of historical production data to analyse the primary factors for shale gas wells and plays profitability. An in-depth analysis is done on a large production dataset covering 40,000 wells which account for nearly 90% of total shale gas production in the US from 2004 to 2014. They calibrate their model to suit Europe by establishing the main differences between the US and European contexts before doing Monte-Carlo simulations. This allows for the determination of an average breakeven price for shale gas extraction in continental Europe.

This study will utilise the work done by Saussay (2018), particularly the differences between the European and US context that allowed for the calibration resulting in a European average breakeven price. We will determine whether South Africa shows similar differences to the US, if so, the calculated breakeven price by Saussay (2018) could potentially be applied to South Africa. This breakeven price can then be compared to the price paid by end consumers and the global price indices to determine possible profitability.

According to the calculations done by Saussay (2018), a shale gas wells breakeven price is determined by the initial production rate, decline rates over time, and drilling and completion costs.

By analysing the large dataset of wells in the US, Saussay (2018) created a full distribution of initial well production rates in the six largest shale plays in the US. The study noticed that due to technological advancements, the initial production rates per well increased over time before stabilising. Assuming Europe would make use of these technological advancements, the probability distribution of the initial production rates is taken from the time of stabilisation for the relevant wells (Saussay, 2018). In terms of decline rates, Saussay (2018) found that decline rates were stable across drilling years.

As in Europe, these technological advancements will need to be taken advantage of and will be especially important in the early stages of shale gas development in South Africa (Fakir, 2015).

The drilling cost is the primary factor contributing to the profitability of the well (Yuan et al., 2015), and is largely a factor of the depth of the well and its horizontal length (Pulsipher, 2007). The average drilling costs in the six main shale plays in the US is presented in Table 5.5 below (Saussay, 2018).

Table 5.5: Average drilling costs per well and depth of the main US shale plays

	Fayetteville	Marcellus	Barnett	Haynesville	Woodford
Average drilling costs (million USD/well)	2.8	5.3	3.5	9.9	8.5
Average depth (m)	1,100	1,900	2,400	3,700	4,000

Source: *Berman & Pittinger (2011), Nickelson (2013), Kaiser & Yu (2015).*

As is evident, the most expensive drilling costs are associated with the deepest deposits, indicating the relationship of increased drilling costs with increased depths (Saussay, 2018). According to USEIA (2013), the French resources are found at depths about 3,050 and 4,250 m, German between 3,500 and 4,400 m and the Netherlands at 3,300 and 3,800 m. As a result, the average drilling costs in Europe can be estimated to be like the drilling costs in the Haynesville shale play, approximately $10 million per well (Saussay, 2018).

However, due to the contextual differences to the US, specifically, the lack of available drilling equipment, infrastructure and experience, the drilling costs are expected to be higher, at least in the first few years of production. As a result, Saussey (2018) uses a mean cost hypothesis of 50% higher, reaching a total estimate of $15 million average cost per well (Saussay, 2018). It is worth noting, that this is still lower than the $17 million average cost per well calculated for the UK by Wood Mackenzie (2012).

From a South African perspective, the targeted formations for shale gas development are between 3,000 and 5,000 m below the surface (Vermeulen, 2012), like those in the European examples and Haynesville shale play. In addition, South Africa also lacks the infrastructure, equipment and relevant experience associated with shale gas drilling (Fakir, 2015). As a result, it is logical to suggest that the same average drilling cost assumptions can be made to those applied to continental Europe by Saussey (2018).

It is important to note that drilling costs are not only affected by depth, but numerous factors, such as the geometry of the rock, formation type or fracking fluid to be used are all important factors of total drilling costs. However, due to the lack of experimental drilling in potential shale gas plays in continental Europe, it is impossible to calibrate these other factors (Saussay, 2018). The same lack of drilling and information is applicable in South Africa (De Wit, 2011; Vermeulen, 2012; PWC, 2012; Decker & Marot, 2012; Hedden et al., 2013).

These calibrated input factors led Saussey (2018) to calculate an average breakeven price (before taxes and royalties) of 10.1 $/MMBtu for European shale gas production. Due to the similarities between the European and South African contexts, this study will assume the same can be used as a potential average breakeven price for South Africa. To put this price into perspective, in the US, decreases in both capital and operating costs (primarily due to technological advancements) reduced production costs to 3.2 to 3.6 $/MMBtu in 2014 and 2.8 to 3.4 $/MMBtu in 2015 (USEIA, 2016).

5.5.4 Potential profitability of shale gas production in South Africa

To determine profitability, the breakeven price will need to be below the current and predicted future price index. However, currently, no price index exists for South Africa (Fakir, 2015). However, Gqada (2012) suggests that in the future, LNG or piped gas from Mozambique could provide an index price for South Africa's domestic natural gas prices.

Using this suggestion, a comparison can be made between the breakeven price and the price Sasol charges its end customers. Table 5.6 presents the prices charged by Sasol to its end customers since the introduction of the maximum price by NERSA in April 2014.

Table 5.6: Average Sasol prices charged to end customers since introduction the of the NERSA maximum price ($/MMBtu).

Year	Maximum Price	Class 1 (33 GJ)	Class 2 (333 GJ)	Class 3 (3,333 GJ)	Class 4 (33,33 GJ)	Class 5 (333,333 GJ)
2014	11,07	8,23	7,41	6,17	4,11	3,70
2015	10,96	8,15	7,34	6,11	4,08	3,67
2016	11,04	8,21	7,39	6,16	4,11	3,69

Note: Values converted from R/GJ to $/MMBtu, the exchange rate on 24/07/2018.

***Source:** Data from DoE (2015), DoE (2016), DoE (2017).*

Since 2014, the price of gas in South Africa has not gone above the potential breakeven price of 10,1 $/MMBtu, even for the highest paying customers in Class 1. This indicates, that in its current state, based on prices charged by Sasol to its customers, it is still cheaper to continue importing natural gas from Mozambique than to start producing it locally through shale gas development. This may change if import costs rise or future production costs decrease.

In addition, the potential breakeven price for South Africa can be plotted against major natural gas price indices from different regions (Figure 5.14). Included, is the US and European natural gas spot prices, as well as the Japan liquified natural gas price for the last two decades.

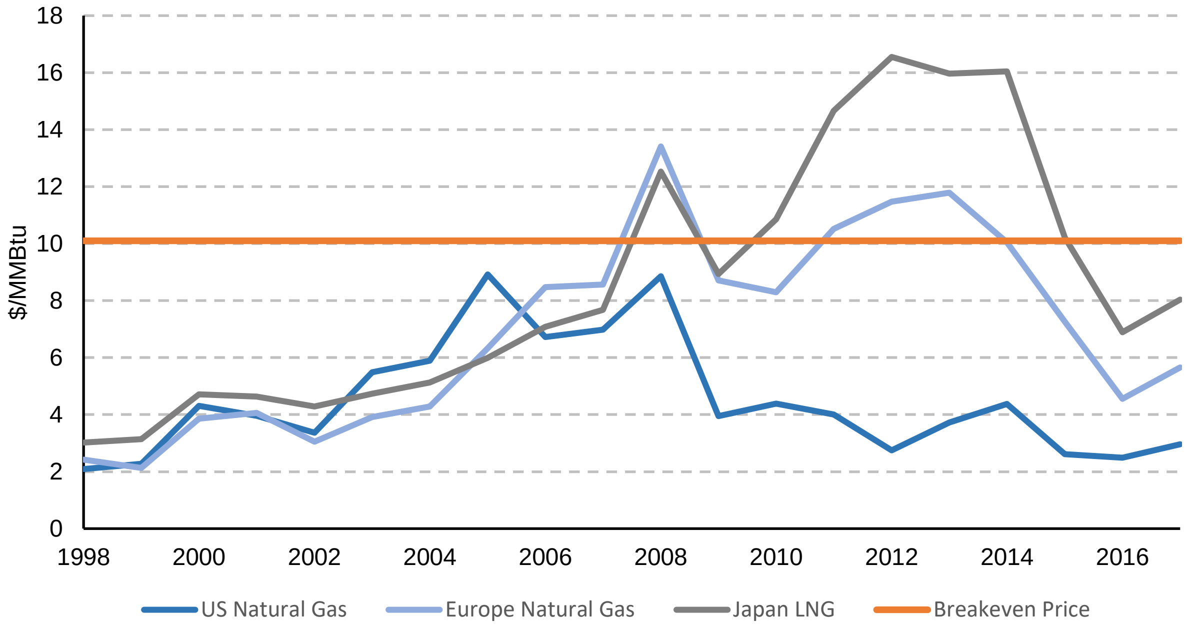

Figure 5.14: South African natural gas breakeven price vs global price indices.

Source: *Data from South Africa Data Portal (2018).*

The mechanisms of gas price formations differ between the major markets. In the US, the gas price is set by gas-on-gas competition and the interplay of supply and demand determines the price (USEIA, 2011d). Hence, when the production rate of local shale gas grew rapidly it changed the balance of the local supply and demand immediately, whereby supply outgrew demand and resulted in a large drop in prices (Saussay, 2018).

In Europe, the price formation follows a different mechanism, whereby the natural gas supplies have been priced through a mix of long-term contracts with producing countries and spot market pricing. The long-term contracts are usually priced using a mechanism called oil price escalation, where the gas price is linked, usually through a base price and escalation clause, to the price of competing fuels, usually crude oil (International Gas Union, 2012). This pricing structure makes the market less reactive to supply and demand, and whilst an increase in local production can improve the European bargaining power, the effect on price from introducing small volumes of domestic shale gas production remains unclear (Saussay, 2018).

The Japan LNG is noticeably higher compared to the US and Europe, but this is a result of the transportation and regasification costs of LNG adding upwards of $2 per Mcf to the cost of supplying natural gas (Mokhatab et al., 2013).

When compared to these different regional price indices, since 2015, the average price per annum for all three price indices have been below the potential breakeven price. These results suggest that when compared to these global indices, the chance of profitable shale gas extraction in South Africa in its current state is unlikely.

However, these conclusions assume that South Africa can be assigned a breakeven price like that of continental Europe, due to the contextual similarities when compared to the US. The reality is that South Africa does not have a well-developed and sizeable domestic gas market, and price determination for new gas extraction is something which must evolve once shale gas reserves are proven to be economically viable. The process of pricing and integration of the shale gas into a domestic and international market is known as monetisation. Since this involves identifying a fair price, it would require an accurate estimation of the breakeven price for shale gas extraction. The exact method for monetisation is still to be determined (Fakir, 2015).

5.6 Chapter summary

From the existing economic studies, there is great potential for a positive macroeconomic impact. Similar values of a substantial impact on national GDP is seen across all the studies, however, the contribution to employment varies significantly. From a regional and local perspective, the large influx of people to the small towns in the target area can result in an increase in entrepreneurial opportunities, as well as an upgrade to the local services provided by these towns.

Energy is a key factor to the economic growth of a country. This is particularly true for South Africa, one of the most energy-intensive economies in the world. The various scenarios and predictions provided suggest that shale gas has the potential to contribute significantly to South Africa’s energy mix, enabling economic growth as well as aiding in the shift towards renewable energy.

Based on contextual similarities between South Africa and Europe when compared to the US, a breakeven price of 10.1 $/MMBtu determine by Saussay (2018) for European shale gas development was used for South Africa’s case. When compared to the current prices paid by Sasol’s end customers, and three different global gas price indices, the breakeven price was too high. This suggests that it is still cheaper to import natural gas from Mozambique than to produce it locally; and if South Africa’s natural gas index was to be like that of the US, European or Japanese LNG Natural gas indices, production would not currently be profitable.

6 ENVIRONMENTAL IMPACTS AND ECONOMIC COSTS

6.1 Chapter overview

The focus of this chapter is on the environmental risks associated with fracking for shale gas, as well as the key potential economic costs. It starts by providing background information on the biome and geohydrology of the Karoo, this is key for a better understanding of the environmental risks involved. The risks highlighted are water contamination and usage, air pollution, impact on climate change, induced seismicity and land use. From an economic perspective, the two main sectors that may be affected are agriculture and tourism, both are briefly described.

6.2 Environmental concerns

Though the potential benefits from shale gas development are significant, they are associated with a significant amount of potential costs that include contaminating the surface and groundwater, consuming freshwater resources and increasing stress on water supplies, polluting the air, fugitive GHG emissions affecting climate change, enhancing the risk of earthquakes and seismic events, land use and ecosystem fragmentation, as well as negative impacts on socio-economic environments (Sovacool, 2014; Jackson et al., 2014; Dongxiao & Tingyun, 2015; Esterhuyse et al., 2016; Costa et al., 2017).

The size of the environmental impact has become the most fiercely contested part of the fracking debate (Sovacool, 2014). Uncertainties surrounding the exact size of the environmental cost has led to a mixed response from the public regarding the extraction of shale gas. Areas familiar with the natural gas industry such as central Texas and western Pennsylvania have applied existing environmental and safety regulations to the new extraction methods. Whereas some countries and US states have put a ban on shale gas extraction until all potential risks have been sufficiently studied, e.g. France and New York (Kinnaman, 2011; Moore et al., 2014). In the Karoo, neither exploration nor extraction has yet commenced, however, the risks involved have resulted in a fierce debate and resistance from opponents (Ingle & Atkinson, 2015).

6.2.1 The Karoo biome and geohydrology

The climate of the Karoo is arid to semi-arid which is characterised by extremes in temperatures and great variability in both the amount and timing of rainfall. As a result, it can be separated into different rainfall areas. The western part of the Karoo receives more than 60% of its rain from cyclonic fronts in winter. Along the coast, dry season precipitation is a result of fog. In areas of even rainfall, the rain may fall at any time in the year. The large north-eastern section of the Karoo receives primarily summer rainfall in the form of thunderstorms. Reliability on rainfall is highest in the southern and eastern parts of the Karoo and lowest in the western and northern parts of the Karoo (Cowling, 1986).

Mean rainfall varies from 100 mm in the west to more than 400 mm in the east annually, but for most of the biome, it seldom reaches above 250 mm. In winter, snow is often recorded in the high areas of the escarpment. Mean annual temperatures vary from around 22.5°C in the north-west to 15°C on the escarpment (Cowling, 1986).

The vegetation in the Karoo is characterised by dwarf open shrubland. In the Great Karoo, succulents are less prominent, and dwarf deciduous shrubs predominate. Grasses may be common and even dominant, depending on soil, rainfall and grazing intensity (Cowling, 1986).

The Karoo vegetation is a result of the low rainfall in the region, this combined with the characteristic dry river beds and limited presence of dams depicts an image of an area without water (Vermeulen, 2012). However, metres below the surface, groundwater aquifers which remain under-utilised. Studies and previous exploration indicate the aquifers have a harvest potential that ranges from 5,000 $m^3/km^2/a$ to more than 25,000 $m^3/km^2/a$ (Baron et al., 1998). These groundwater aquifers are used as a water supply to surrounding towns, irrigation and drinking water for livestock (Vermeulen, 2012).

The aquifers are secondary in character with fracturing, faulting, weathering and dolerite sills and dykes that all affect the storage and transmission capabilities. As a result, the properties of an aquifer can vary greatly over short distances. A dual porosity model can be assigned to these systems, suggesting most of the groundwater is present in the matrix and the movement occurs in the secondary fractures and joints (Vermeulen, 2012).

It is important to note that hydrogeological studies of the Karoo aquifers are generally confined to about 100 m below surface. Technological advancements in water drilling equipment allowed for depths of up to 150 m, however, not many holes are drilled beyond 300 m (Vermeulen, 2012). Golder Associates (2011a) extracted and presented data from the National Groundwater Data Base in 2008 and indicated that of the 2,323 boreholes drilled, only 4% were drilled beyond 100 m. Woodford & Chevallier (2002a, 2002b) report comparable results. They analysed 67 borehole logs that totalled 13,799 m (at an average depth of 206 m) in the area of Victoria West. The results show that 73% of the water interceptions were shallower than 80 m deep.

Kent (1949) assessed some of the thermal springs throughout South Africa and found that 12 of the 74 springs analysed were associated with the Karoo Supergroup. Eight of these springs are situated in the designated shale gas development area and are determined to be warm springs. Most of the springs migrate up the dolerite dykes and originate from depths of approximately 600 to 1,300 m below surface. Although originating from a relatively shallow depth, the springs do suggest that the deeper underground waters are far more saline than the aquifers within the first 150 m (Kent, 1949). Recent magnetotelluric studies located these large saltwater reservoirs (brackwater) in the Karoo at a depth greater 1 km (de Wit, 2011).

6.2.2 Water contamination

To date, the processes involved in fracking have seen only a few accidents (USDoE, 2009; Zoback et al., 2010). In the US, less than 1% of wells has caused detectable fracture fluid leakage or contamination (de Wit, 2011). From 2001 to 2011, more than 20,000 shale gas wells were drilled in the US with the majority having good environmental assessment results (Moniz et al., 2011). But there have been worrying incidents (Urbina, 2011), with some studies (Osborn et al., 2011; Jackson et al., 2013a; Warner et al., 2013b) suggesting that shale gas production can lead to surface and groundwater contamination. This has become the most severe and controversial issue among the potential environmental concerns of shale gas development (Dongxiao & Tingyun, 2015).

There are three main classifications of wastewater generated during the extraction of shale gas and are defined by the different processes and operation periods (Costa et al., 2017). The first type is drilling fluid, which is wastewater created during the initial hole that is drilled prior to any fracking or extraction of gas occurs. Drilling fluid is used as a lubricant as well as to clean the rock cuttings and cool the drill bit when drilling the borehole (Lutz et al., 2013).

The second type is primarily known as flowback water but is also referred to as flowback brine or fracturing water flowback (Costa et al., 2017). It is the first flow of wastewater directly after fracking and is a mixture of the fracking fluid and the natural existing fluids. It mainly resembles the fracking fluid as it contains organic compounds. It is predicted that 10 to 40% of the water pumped into the well returns as flowback water back to surface. Flowback fluid is mainly present in the first 7 to 10 days but has shown to occur up to 4 weeks after fracking (Barbot et al., 2013; Haluszczak et al., 2013). It can represent an average of 32.3% of the total wastewater produced during the lifespan of a well (Lutz et al., 2013).

The third and final type is water produced. This is the recovery of the natural fluids that already exist within the shale formations mixed with a minor amount of fracking fluid and is present from the beginning until the end of the wells lifespan. Neither flowback fluid nor produced water has a standard definition, and the two are often grouped together as distinguishing between the two is often very difficult. This has resulted in multiple authors suggesting another term, transitional water, to help differentiate between the two terms (Bai et al., 2015).

The fracking fluid is generally made up of around 95% water together with a proportion of certain chemicals and the additional proppant that is usually sand (Cronshaw & Quentin Grafton, 2016). The chemistry is designed according to the geological characteristics of each site and the chemistry of the water supply used (Barbot et al., 2013). The added chemical components usually contain acids (e.g. hydrochloric acid), additives to adjust viscosity (guar gum, borate compounds), viscosity reducers (ammonium persulphate), corrosion inhibitors (isopropanol, acetaldehyde), iron precipitation control (citric acid), biocides (glutaraldehyde), oxygen scavengers (ammonium bisulphite), scale inhibitors (e.g. acrylic and carboxylic polymers) and friction reducers (surfactants, ethylene glycol, polyacrylamide (Gregory et al., 2011; Struchtemeyer & Elshahed, 2012; Struchtemeyer et al., 2012; Vidic et al., 2013; Jackson et al., 2013b).

Although some of the chemicals used are generally harmless (USEPA, 2011a; Jackson et al., 2011), multiple are considered toxic and are known carcinogens (Arthur et al., 2009). The occurrence of these genotoxic and carcinogenic chemicals in the aquatic environment has increased the regulatory attention on the matter across the globe as it can lead to both short- and long-term survival of natural biota as well as being potentially dangerous to human health (Jha, 2004; Jha, 2008). Whilst the potentially harmful additives are only a minor percentage of the mixture, it can add up to thousands of litres entering the ground (Schmidt, 2011; Broderick et al., 2011). These amounts are sufficient to threaten drinking water if they were to contaminate aquifers or surface water (BCWA, 2010; Griffiths, 2007).

Yet companies have generally been unwilling to reveal the exact combinations of chemicals they use in their fracking fluid, however, this is now considered counterproductive (de Wit, 2011). In the US, companies can voluntarily provide their additives online by using websites such as FracFocus (de Wit, 2011; FracFocus, 2017). In the case of the Karoo, Shell has promised to reveal all of the additives they will use in their operations and that they will not use any unacceptable additives (Golder Associates, 2011b). The full list of chemicals that should not be used for fracking in South Africa is in the Mineral and Petroleum Resources Development Act No.28 of 2002 (Government Gazette, 2015).

However, the pumping and removal of fracking fluids in and out of the ground are not the only possible cause of contamination, but can also result from accidental spills or faults in the well construction and integrity (Costa et al., 2017). The US Environmental Protection Agency (USEPA) recently published results of a review of spills that are related to shale gas across 10 states in the US from 2006 to 2011. There were approximately 36,000 spills identified, of these, 33% are disregarded from having an association with fracking and only less than 1.3% were caused by fracking. Of this small total, flowback and produced water were responsible for 50%, whereas 20% were from the fracking fluid. Additionally, nearly half of the spills were from the storage systems and were mostly a result of human error. However, the number of spills increased three-fold from 2006 to 2011 and nearly 70% of the spilt material was not able to be recovered (USEPA, 2015).

Another contamination source may result from the migration of methane from the natural gas in shales, and salts from the deeper saline brines to the shallower groundwater resulting from the fractures created at depth (Osborn et al., 2011; Jackson et al., 2013a; Heilweil et al., 2015; Dongxiao & Tingyun, 2015). The primary problem with methane in shallow aquifers is that it poses both an explosion and asphyxiation (confined spaces) hazard either during well water extraction or by escaping and accumulating in basements, well pits, etc. (Jackson et al., 2013b). Elevated levels of methane in shallow drinking water wells pose a potential flammability or explosion hazard to homes with private domestic wells (Figure 6.1) (Vengosh et al., 2014).

Figure 6.1: Tap leading from artesian borehole SA 1/66 drilled by Soekor. Warm water containing methane and a total dissolved salts value of 8,100 mg/l flowed from it once the tap was opened (van Tonder et al., 2013).

Source: *Photo from Unearthed (2012).*

The migration of stray gas in shallow aquifers is possible by the release of hydrocarbons (in gas phase) as a result of leaking through faulty casings or along the well annulus, poorly abandoned wells, faulty cementing, or via natural joints, fractures and faults (Kissinger et al., 2013; Jackson et al., 2013a) in the target or adjacent geological formations following drilling and fracking (Osborn et al., 2011). The borehole in Figure 6.1 is 1 of 5 boreholes drilled by Soekor in the Karoo that are leaking fluids to the surface (Unearthed, 2012).

In addition to these contamination sources, a major concern is the treatment of the recovered wastewater (Warner et al., 2013b; Lutz et al., 2013; Skalak et al., 2014; Kassotis et al., 2014; Pancras et al., 2015; Getzinger et al., 2015; Bowen et al., 2015). The highly contaminated produced water volumes are either stored in large reservoirs, recycled on site, treated and discharged by large industrial wastewater treatment plants or are re-injected deep into the ground (Lutz et al., 2013). Before the wastewater can be reused or discharged into the environment it needs to be treated properly, if not, the toxic components could pose risks to the environment and human health (Ferrar et al., 2013; Warner et al., 2013b; Hladik et al., 2014).

The literature review by Vengosh et al. (2014) summarises these potential water risks into four main styles of contamination:

1. Shallow aquifers contaminated from fugitive/stray gas resulting from poor well integrity, possibly followed by water contamination from fracking fluids and/or from the deep saline formation waters.
2. The contamination of surface water through spills, leaks and the inadequate disposal of wastewater into the surrounding environment.
3. An accumulation of toxic and radioactive elements in the soil and sediments of rivers that have come into contact with wastewater or fluids used for fracking.
4. The large water requirements can cause an overuse of what is naturally available resulting in competition among other water users in water-stressed environments (Vengosh et al. 2014).

These are illustrated schematically in Figure 6.2 below, followed by a relevant description of each label on the diagram:

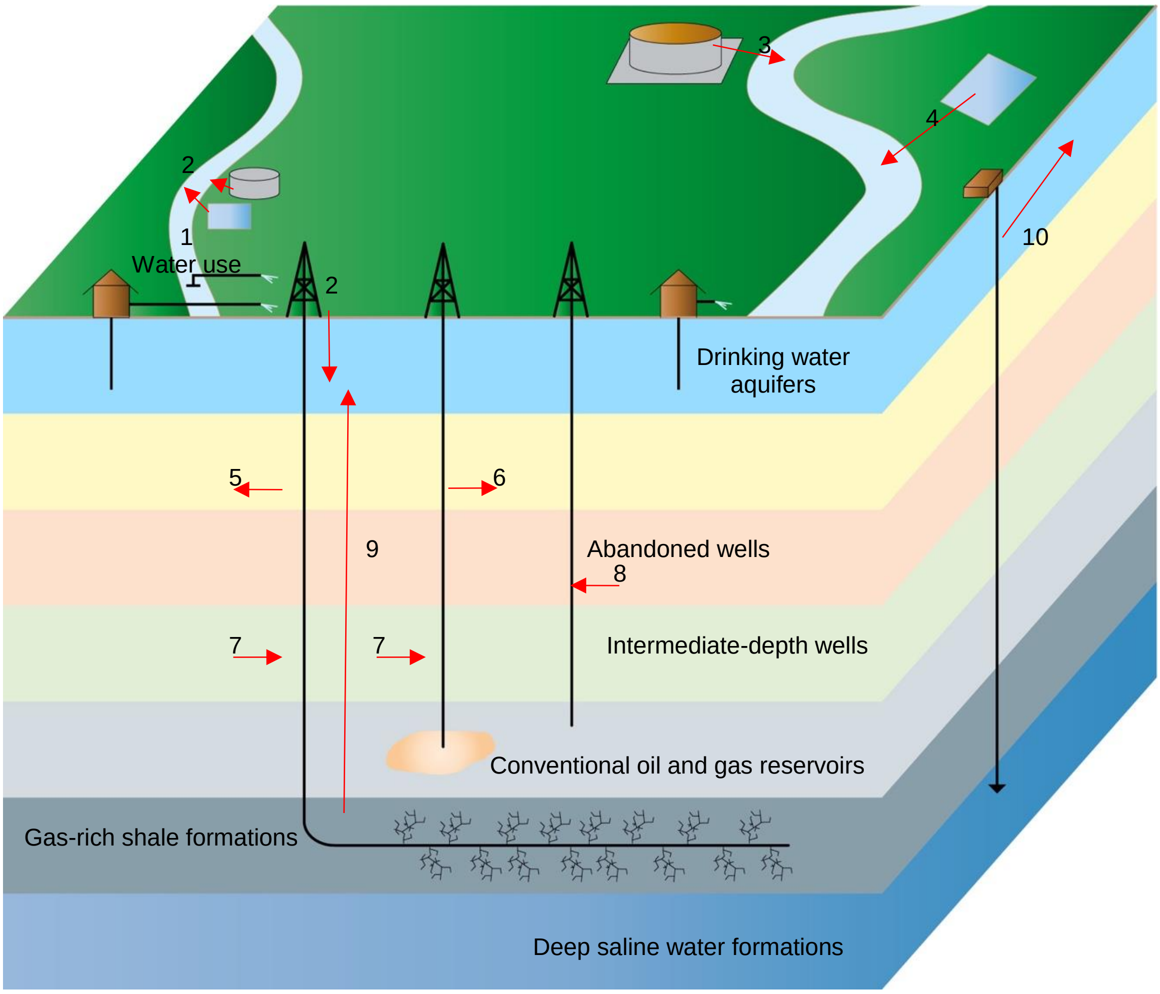

Figure 6.2: Potential water risks and modes of contamination (not to scale).

Source: *Modified from Vengosh et al. (2014).*

1. Overuse of water in water-scarce areas leading to depletion and quality degradation, as well as competition between industries.
2. A drilling site may have on-site wastewater storage and open pits that may leak and contaminate the surrounding surface and groundwater.
3. Disposal of poorly treated wastewater and the concentration of contaminant residues in disposal sites.
4. Storage ponds used for deep well injection may leak (as a form of wastewater storage underground).
5. Contamination of shallow aquifers from the stray gas originating from target shale layers as a result of leaking casings and poor well integrity. Additionally, this may be compounded by salt and chemical contamination from fracking fluids and/or the deep saline formation waters.
6. Stray gas contamination from leaking casing in the conventional well system.
7. Annulus leakage resulting in the migration of stray gas from the intermediate geological formations, this may contaminate shallow aquifers.
8. Poorly abandoned wells may contaminate the shallow aquifers.
9. The direct flow of gas and deep saline water to shallow aquifers.
10. Underground injection wells used for wastewater storage may leak and contaminate shallow aquifers (Vengosh et al. 2014).

Additionally, due to the distinguishing geological feature of dolerite dykes and sills in the Karoo, a big concern is whether the dykes will behave as vertical conduits for the groundwater and fracking fluids. The primary mechanism of groundwater flow at depth and around dykes is by sub-horizontal fractures. The fractures are not interlinked and the collection of water is from the surrounding matrix (Steyl & van Tonder, 2013). Various studies indicate that the permeability of the dolerite dykes is too low for a large amount of water to flow within the dykes themselves (Murray et al., 2012). Therefore, dolerite dykes seem to have a very limited impact on the vertical migration of groundwater at depth. Yet, there is a lack of available data, and therefore this possibility cannot be omitted (Steyl & van Tonder, 2013). Additionally, the warm springs that are present in the Karoo Basin suggest clear evidence of a natural connection between the groundwater at depth and the surface (Kent, 1949).

6.2.3 Water usage

When water is used for the drilling and fracking of a horizontal, multidirectional shale gas well, the required amounts are estimated between 10 and 20 million litres of water (equivalent to about 150 domestic swimming pools; the Vaal Dam holds around 25 trillion litres), most of it staying underground once used (de Wit, 2011). Reports on water consumption from fracking operations in the Marcellus (Lutz et al., 2013), Barnett, Haynesville, Eagle Ford (Nicot & Scanlon, 2012), Woodford Shale (Murray, 2013) and Horn River in British Columbia (Johnson & Johnson, 2012; Jackson et al., 2013b; Rivard et al., 2014) showed varying water usage from 800 thousand to 100 million litres of water per unconventional shale gas well (Vengosh et al., 2014). This key implication can make it very difficult to produce shale gas in an area where water is scarce (Sovacool, 2014).

Most of the water is used in the beginning stages of well life (Jackson et al., 2014), with approximately 80% of the water used during the fracturing stage (Dongxiao & Tingyun, 2015). Additional uses of water are commonly related to drilling, extraction and proppant (sand) mining (Nicot & Scanlon, 2012). Aquifers in close proximity may become stressed (Costa et al., 2017) and the increased use of local water resources could decrease the base flow in streams (Nicot & Scanlon, 2012), create changes in the aquatic ecology (Gallegos et al., 2015) and create conflict between industries that rely on the same water source, such as agriculture (Goodwin, 2014).

However, to put these claims of excess water requirements into the Karoo’s perspective, Vermeulen (2012) provides the following:

- Approximately 5 million litres of water is required to irrigate 1 hectare of crops in the Karoo, therefore, the water requirements to frack one well is equivalent to the irrigation of 4 hectares of land. A key difference is that the irrigation of crops is done over 3 to 4 months, whereas in the fracking process it is all applied within 5 days.
- On average, a Karoo towns water consumption per day (e.g. Beaufort West) is 8.5 million litres, thus the fracking of one well is equivalent to the use of the average town in 2.5 days. Here, the timeframe is about half of that for fracking, which is over about 5 days.

Nonetheless, in the US, in geographic areas with drier climates such as Texas, Colorado and California, groundwater exploitation for hydraulic fracturing can lead to local water shortages (Nicot & Scanlon, 2012) and resultant degradation of water quality (Vengosh et al., 2014). Even in wet areas, large water withdrawals for fracking can change stream flows and result in a water shortage (Mitchell et al., 2013). In small to moderate streams in the Susquehanna River Basin of northern Appalachian Basin, in the US, extraction of water needed for fracking can surpass the natural flows, especially during low-flow periods (Rahm & Riha, 2012). Similarly, in southern Alberta, Canada, water use for fracking has become limited as the water has already been designated to other users, whilst in other areas in British Columbia, changes in stream discharge restrict the water withdrawals needed for fracking (Rivard et al., 2014).

Currently, South Africa is a water-stressed country, meaning the population has access to below 1.7 million litres/person/annum. The country is predicted to face a water scarcity by 2025, meaning access to less than 1 million litres/person/annum (DWA, 2011). By 2010, the various users of water had already allocated 80% of the country's surface water and 40% of its groundwater resources (DWA, 2010). The use of large amounts of surface water will not only impact those who rely on its availability but can affect the hydrology and hydrodynamics of the water sources. Consequences can result in streams changing their flow regime by altering their flow depth, velocity and temperature (Zorn et al., 2012) and a reduction in the overall dilution effect (Esterhuyse et al., 2016).

If the sand from river banks is appropriate to be used as the proppant in the fracking fluid, its removal can negatively impact the alluvial aquifers present in some of the rivers. This is a water-intensive activity as the removal and processing of this sand require large amounts of water and would be a threat to the temporary waters in the semi-arid Karoo (Esterhuyse et al., 2016).

Additionally, an important consideration is that surface and groundwater are hydraulically connected (Winter et al., 1998; Parsons, 2004) and the altering of one source will affect the other (Esterhuyse et al., 2016). The construction of roads and stream crossings can result in erosion, sediment transport and increased salinity, all of which may impact the receiving rivers (Rahm & Riha, 2012). Access to, negative impacts and the equal sharing of this scarce and precious resource is a legitimate concern in the drought-prone Karoo. The gas companies need to learn to be more aware and appreciative of the public concerns over the threatening water crisis in South Africa. The local farmers and municipalities throughout the Karoo are correct in being extra aware and defensive over their water rights (de Wit, 2011).

However, fracking technology has come a long way over just a few years, and less water is now needed than ever before (de Wit, 2011). The industry is constantly looking for ways to decrease the overall water usage per well in shale gas extraction (Nicot et al., 2014) and alternative options for water sources have become available. These include the use of municipal or tap water that does not require extensive pretreatment before it can be used for fracking. Acid mine drainage is another alternative water use. This reduces the demand for fresh water but ultimately requires treatment prior to use (Abdalla & Drohan, 2010; Rodriguez & Soeder, 2015). Brine groundwater and seawater have both successfully been used in onshore and offshore fracking (Rodriguez & Soeder, 2015). These may be a possibility for onshore shale gas projects in water-stressed regions (Costa et al., 2017).

In the Karoo, the provision for enough water for fracking is an essential consideration, and a few potential sources of water exist:

- The use of local groundwater supplies, including the utilisation of the 4,000 breccia plugs in the western Karoo, and the fracking of the underground aquifers in the Karoo.
- Bringing in surface water from somewhere else, this will, however, require a large amount of transport by either road, rail or pipeline and will put extra strain on the infrastructure and roads.
- The use of seawater or desalinated seawater from the coast. For this to be a realistic option, the water will need to be purified and transported via a pipeline which can prove to be expensive.
- The Orange River could be a large water source; however, excess water has already been designated for the agricultural sector (Vermeulen, 2012).

Transporting freshwater and seawater has a range of limitations and therefore must be open to additional studies to adequately assess this option (Vermeulen, 2012). Regarding the use and amount of local groundwater, Van der Voort (2001) used geological core samples from various Karoo formation to established the porosity values for fractured sedimentary rocks that are within a depth of 100 m. Results indicate values from between 3 and 15%, averaging about 8%. This suggests that, on average, each m^3 of rock contains around 0.08 m^3 of water, about 80 litres. A hectare of land thus contains about 80,000 litres for every 1 m of saturated thickness. When considering a saturated thickness of 80 m (using an average water level from 20 to 100 m deep), an amount of 6.4 million litres is stored within 1 hectare. The recharge rate of the groundwater ranges from 1 to 5% of the annual rainfall, averaging 3% if the annual rainfall is 480 mm. Therefore, 144,000 litres/hectare will be the annual recharge, or

2.25% of all the groundwater stored within the first 100 m (Van der Voort, 2001; Vermeulen, 2012).

The original thickness of the overburden can be deducted from the porosity of sandstones and shales (Vermeulen, 2012) as is indicated by a study by Maxwell (1964) who indicates that the main processes responsible for porosity are compaction and cementation, with a minor contribution from the temperature gradient. Additionally, however, Rumeau & Sourisse (1972) suggests that porosity of shale is highly affected by the sediments age, i.e. the duration of burial.

The boreholes drilled by Soekor in the 1960's provide the only estimations of porosity from 100 to 3,000 m in depth. The results indicate a porosity between 0.1 and 8%, averaging 2.5%. The permeability (hydraulic conductivity) is extremely low (less than 10 to 11 md) and fracking will be required to allow water to move freely. Therefore, non-chemical fracking can be used in the shallower formations to increase the permeability of the rock. The groundwater at greater depth (e.g. from 300 to 700 m) can be the water source for the fracking of the shale gas formations (Vermeulen, 2012).

Importantly, the geological target formations for shale gas extraction are between 3,000 and 5,000 m below the surface (Figure 4.3). This means that a large barrier exists between the shallower aquifers of the Karoo and the deeper target zones intended for fracking. Provided the low permeabilities reported in the study Rowsell & de Swardt (1976), and the generally accepted aquifer thickness in the Karoo, it is very difficult to imagine any serious connection between the two bodies. However, the integrity of this barrier is absolutely paramount, as poor well integrity can compromise this 'safety net' by leaking casings. Sufficient monitoring and rehabilitation of the wells are of vital importance to ensure the aquifers are protected (Vermeulen, 2012).

The fracking process for the shallow depths will not use any harmful chemicals, but only water and sand, making it a safe and feasible option. If the deeper groundwater is going to be used for fracking the shale targets, the question will be what impact that will have on the shallower fresh groundwater aquifers. From practical experience in the Karoo, at the Mooikraal Underground Coal Colliery, the mined-out area is deeper than 100 m below the surface and a shallower water table is still present (Vermeulen, 2012).

A detailed study is needed to determine whether supplying water for fracking the Karoo is a viable option. Target zones include dolerite contact zones, breccia plugs and localised fracture zones. The key to successful utilisation of any resource is proper development and management. Therefore, sufficient exploration, testing and management of groundwater resources is needed if groundwater resources will be used. Advisably, only a few test wells should be drilled to see if it is possible to extract the required amount of water without depleting the aquifers. If such an operation is successful, it will ease a large amount of concern within the public, as clean, drinkable groundwater has become the lifeline of the Karoo (Vermeulen, 2012).

It is worth noting, that from an energy perspective, surprisingly, given all the attention shale gas extraction and processing receives for water use, it is less water intensive than most of the energy extraction processes. Exceptions are conventional wells and some renewable energy types such as wind or solar as these require nearly no water. Coal, nuclear and oil extraction processes have water intensities that are nearly 2, 3 and 10 times more than that of shale gas, respectively. The process of corn ethanol, due to the evapotranspiration of the plants, uses nearly 1,000 times more water than shale gas if the plants are irrigated (Jackson et al., 2014).

When considering electricity production, a larger amount of water is needed for cooling requirements than is required to produce the fuel. From this perspective, shale gas is better than most other fossil fuels as well as nuclear energy. The technologies used has a large impact on the amount of water required and a natural gas combined cycle plant, such as the CCGT, consumes only a half or a third of the water compared to a nuclear or pulverised coal power plant. This is attributed to methane gas having a higher energy content per carbon atom as well as gas power plants having a higher efficiency. This relative difference diminishes or disappears when the power plant uses dry-cooling. Biofuels, particularly irrigated crops, and concentrated solar power are more water intensive than natural gas, coal and nuclear. Alternatively, renewables such as wind and photovoltaics use 100 times less water for electricity production than other sources (Jackson et al., 2014).

6.2.4 Air pollution

The exploration, production and development of shale gas results in many relatively small sources of air pollutants spread out over a potentially vast geographical area such as the Karoo (Altieri & Stone, 2016). Sources of air pollution resulting from shale gas extraction include pollutant emissions from diesel engines, natural gas leakage during extraction and transport and the volatile compounds from surface storage ponds (Dongxiao & Tingyun, 2015).

Most of the shale gas wells rely on diesel-powered pumps to inject and manage water, leading to dangerous levels of volatile hydrocarbons, ground-level ozone and particulate pollution associated with drills, compressors and other machinery (Sovacool, 2014). In addition, thousands of trucks are required to deliver water to well sites and haul wastewater away for disposal, as well as the use of venting techniques to maximise production efficiency (Argetsinger, 2011).

The main pollutants include nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs) and fine particulate matter (Altieri & Stone, 2016). NO_x and NMVOCs are precursors to ozone which can lead to large regional effects on air quality as increased ozone is linked to asthma, decreased lung function and premature mortality (Levy et al., 2001). An increase in particulate matter has been identified as the cause for numerous health effects such as increased hospital admissions, respiratory symptoms, exacerbation of chronic respiratory and cardiovascular diseases, decreased lung function and premature mortality (Samoli et al., 2008; Halonen et al., 2009; Guaita et al., 2011; Perez et al., 2012). The total combined emissions from multiple small sources can thus be significant for local health and regional air quality, especially regarding the ozone production (Altieri & Stone, 2016). Therefore, before the commencement of any exploration or production, it is vital to gather air quality measurements to best determine the exact impact shale gas extraction has had on the surrounding air quality (Costa et al., 2017).

Currently, there is no air quality management plan and no ambient air quality monitoring in the Karoo region (Altieri & Stone, 2016). However, the work by Altieri & Stone (2016) developed an air pollutant emissions inventory associated with the potential shale gas development for the Karoo region, with the main focus on NO_x, NMVOCs and particulate matter. Results indicate that NO_x and NMVOCs emissions will be more than all the other sources of emissions in the region. These could be big contributors to regional ozone and local air quality, especially when considering the current lack of industrial activity in the region. Particulate matter emissions will contribute to local air quality and will be of a similar impact as the typical vehicle and industrial emissions from a large South African city. The inventory created in the study will provide the necessary information for regulatory authorities to identify opportunities to reduce emissions using existing technologies and decide on the best methods to monitor proceedings (Altieri & Stone, 2016).

6.2.5 Climate change

Based on the reports by the Intergovernmental Panel on Climate Change (IPCC, 1997; IPCC, 2006), the general acceptance is that if used in efficient power plants, natural gas will release approximately half the amount of carbon when compared to coal. Official reports on carbon emission from fossil fuel combustion, such as by the USEIA (USEIA, 2010b), USEPA (USEPA, 2011b) and IEA (IEA, 2012a; IEA, 2016b) are based on this consensus. Additionally, the same consensus is used by multiple academic research papers regarding carbon emission (Jaramillo et al., 2007; Raupach et al., 2007; Le Quéré et al., 2009; Peters et al., 2012).

However, if based on the entire life-cycle GHG emission, the ‘carbon footprint’ (Wiedmann & Minx, 2008; Matthews et al., 2008), shale gas’ contribution to climate change has become more controversial, particularly due to the concerns of fugitive methane leakage (Howarth et al., 2011a; Wigley, 2011; Howarth et al., 2012; Cathles et al., 2012; Townsend-Small et al., 2012; Schrag, 2012; Cokar et al., 2013). Different end uses for shale gas, such as heating or electricity production, have different factors in play and end-results (Howarth et al., 2012; Cathles et al., 2012). For example Howarth et al. (2011a) states that when used for heating, shale gas produces more GHG emissions than coal; whereas when utilised for electricity production, shale gas produces far less than coal, producing up to 38 to 50% less GHG emissions (Stephenson et al., 2011; Jiang et al., 2011; Chang et al., 2015).

Methane is a very powerful GHG, although it only remains in the atmosphere for a tenth of the time of CO_2. Methane has a GWP that is 72 times greater than CO_2 when viewed over a 20 year period and 33 times greater when viewed over a 100 year period (USEPA, 2010). Nonetheless, partially due to different estimations of entire life-cycle methane emissions from shale gas, recent studies (Jiang et al., 2011; Wigley, 2011; Stephenson et al., 2011; Ridley, 2011; Howarth et al., 2011a; Fulton et al., 2011; Skone, 2011; Pétron et al., 2012; Burnham et al., 2012; Weber & Clavin, 2012; Tollefson, 2012; Alvarez et al., 2012; Cathles et al., 2012; Howarth et al., 2012; Hou et al., 2012) have developed complex and differing conclusions on whether shale gas would be better for climate change compared to oil or coal (Wang et al., 2014a).

6.2.6 Induced seismicity

Induced seismicity refers to earthquakes that are a result of stresses that have been introduced through human activity (Rubinstein & Mahani, 2015). There is a wide range of human activities linked to induced seismicity, including reservoir impoundment, conventional oil and gas field depletion, fluid injection for geothermal energy recovery and wastewater injections that modify the stress and/or pore pressure (Figure 6.3) (Davies et al., 2013; Ellsworth, 2013; Rubinstein & Mahani, 2015).

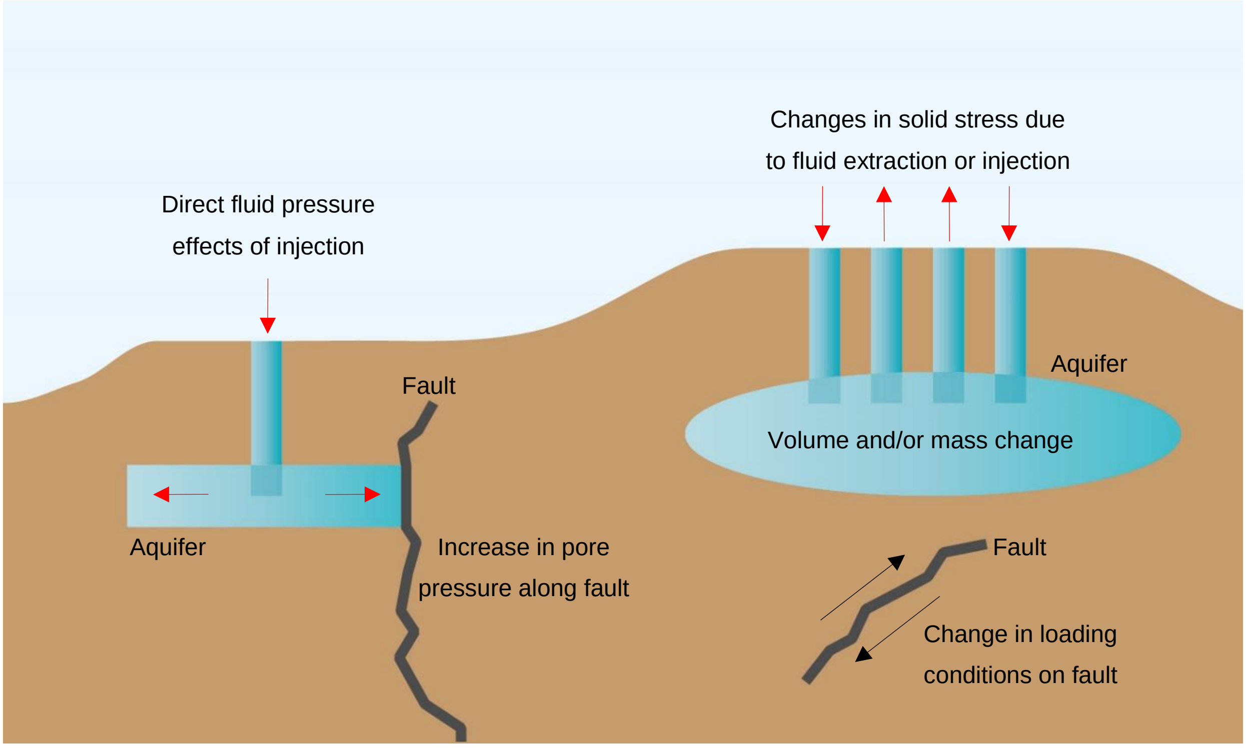

Figure 6.3: Mechanisms of induced seismicity.

Source: *Modified from Ellsworth (2013).*

In shale gas exploration and production, the two main sources of induced seismicity are fracking and the deep well injection of wastewater (Costa et al., 2017). The case of wastewater injection is associated with all of the largest injection-induced earthquakes (Horton, 2012; Frohlich et al., 2014; Keranen et al., 2014; Rubinstein et al., 2014), with many reported cases in the past few years in the US alone (Frohlich et al., 2011, 2014, Frohlich, 2012; Justinic et al., 2013; Kim, 2013; Block et al., 2014; Keranen et al., 2014), yet there are only around 35,000 wastewater disposal wells that are active in the US (Rubinstein & Mahani, 2015). In contrast, fracking is far more common than wastewater disposal wells, yet there are only a few reported cases of fracking-induced earthquakes in the US (Holland, 2013; Friberg et al., 2014; Skoumal et al., 2015) and worldwide (BC Oil and Gas Commission, 2012, 2014; Green et al., 2012; Farahbod et al., 2015).

The induced seismicity resulting from fracking activities are non-destructive micro-earthquakes below 2 in magnitude on the Richter scale, with the vast majority being below 1 in magnitude (Dongxiao & Tingyun, 2015) and are imperceptible to humans (Durrheim et al., 2016). The earthquakes of more than 3 in magnitude caused by fracking that was reported in British Columbia (Green et al., 2012) and Canada (BC Oil and Gas Commission, 2012) were most likely related to unknown pre-existing faults in the area (Ellsworth, 2013). It must be emphasised that the induced earthquakes from fracking are more of an annoyance than major catastrophic earthquakes (Sovacool, 2014). Whereas seismicity induced by wastewater injection has shown to repeatedly cause ‘disturbingly strong earthquakes’ registering 4 or 5 on the Richter scale which have rattled local populations, shut down clean energy projects and initialising a host of new regulations (Kerr, 2012).

Currently, the disposal of wastewater by injection into underground aquifers is forbidden in the South African legislation (Durrheim et al., 2016), and with the evidence suggesting that earthquakes induced by fracking are small in magnitude and below the damage threshold (Ellsworth, 2013), it is considered unlikely to cause a damaging event in the relatively stable Karoo (de Wit, 2011; Durrheim et al., 2016). Although each extraction operation will be site-specific, generally, current evidence suggests that the chances of a damaging seismic event from fracking the Karoo is very low. With good management and monitoring, induced seismicity should not be considered a hindrance to the shale gas development (Chevallier et al., 2012).

However, the possibility that a shallow event of more than 5 on the Richter scale may be induced cannot be entirely excluded (Durrheim et al., 2016); and Dongxiao & Tingyun (2015) highlight that there are uncertainties in reservoir description before fracking and the development of fractures is still difficult to predict. The mechanisms of fractures cracking and propagating and the impacts of injecting wastewater on the *in situ* stress and seismic events need to be investigated further (Dongxiao & Tingyun, 2015).

6.2.7 Land use

Land use is one of the primary concerns in densely populated areas and is often considered one of the biggest limiting factors in Europe (Costa et al., 2017), however, the Karoo is a sparsely populated large area that has low levels of industrial activity (Altieri & Stone, 2016). Nonetheless, shale gas development involves a multitude of building activities in the targeted area and has large potential land use impacts (Moran et al., 2015; Costa et al., 2017). Negative land use effects from the construction of well pads involve noticeable impacts such the clearance of soil and vegetation. Additionally, there are the clear impacts caused by the transport, handling and storage of chemicals and other materials that are required for the construction of pipelines, water extraction structures and multiple other facilities needed for operations. These activities all have the potential to impact land use and cause a disruption to the surrounding habitat, cause erosion and increase noise pollution (Drohan et al., 2012; Olmstead et al., 2012; Moran et al., 2015).

The activities can fragment, modify and degrade landscapes (Johnson, 2010; Entrekin et al., 2011; Beckmann et al., 2012; Walton & Woocay, 2013; Souther et al., 2014) in ways that may reduce population sizes or change the behaviour of many species (Bayne et al., 2008; Sawyer et al., 2009; Beckmann et al., 2012; Blickley et al., 2012). The fragmentation of habitat is a particularly severe potential impact, as shale gas development is often widely spaced and occurs in rural areas with substantial ecological value (Moran et al., 2015), such as the Karoo (de Wit, 2011; Scholes et al., 2016b).

The actual land use and area occupied depends on multiple factors such as the well pad size, number of wells per pad and the distance between pads (Baranzelli et al., 2015). Well densities are usually greater than one per km^2, and the operations can take up an area ranging from 100,000 to 300,000 km^2. Each well site, which includes the drilling rigs, associated equipment and the pits to store drilling fluids and waste (Figure 6.4), generally takes up an area of around 10 km^2 (IEA, 2012b).

Figure 6.4: A shale gas well site in Pennsylvania, US.

Source: *Sheppard (2014). Photographer: Andrew Harrer/Bloomberg.*

Horizontal drilling has resulted in one well pad being able to support up to 50 drilled wells (IEA, 2012b), but although a high number of wells per pad decreases the overall area covered by the pad as the supporting structures are more concentrated, it does result in a larger spacing between pads. This can impact the road and pipeline construction requirements as well as intensify the environmental impacts locally (Baranzelli et al., 2015). When considering land use allocation, the spacing between wells is dependent on both legal requirements and technical issues regarding horizontal well extraction (Costa et al., 2017). While these parameters can be reasonably measured and estimated, it is far more complex and difficult to measure the indirect impact on land use from associated industries (Moran et al., 2015).

Ultimately, the main concerns are the risks to biodiversity resulting from the direct impact on habitat fragmentation and pollution dispersion. The amount of literature covering these risks is still rather poor, perhaps as a result of the long timeframes required to observe these types of impacts on the environment. More research on land use impacts is required, especially in the more densely populated areas where the potential conflict between parties needs to be resolved (Costa et al., 2017).

6.2.8 Socio-economic impacts

Recently, the relationship between the environmental and socio-economic impacts have become essential in establishing sustainable human development (O'Riordan, 2007; Morton et al., 2009; UNFPA, 2012; DSD, 2015). Society and the environment are linked in many ways, and these necessitate the need to research the potential impacts exploiting shale gas will have on the biophysical and socio-economic sphere; and how the effects may be linked. A good understanding of the potential negative social impacts is required and these need to be prevented wherever feasible (Esterhuyse et al., 2016).

These potential impacts include: disturbance of social unity; conflict regarding the use of available water resources between the gas extraction companies and the current lawful water users in the Karoo; the ability to secure access to water and sanitation for the previously disadvantaged communities in the already challenging water scenario; some communities are already vulnerable to health risks and not enough water and satisfactory sanitation may amplify their risks; and an increase in the population density in an area that has a very sensitive ecology and is already water-stressed (Kargbo et al., 2010; Beemster & Beemster, 2011; Broderick et al., 2011; Dolesh, 2011; Brasier et al., 2011; Warren, 2013; Schafft et al., 2013). One could even argue the social-economic benefit of job creation since there is no guarantee that these new jobs will not detract from the job opportunities in other sectors, such as agriculture, and can result in people being displaced (Kargbo et al., 2010; Dolesh, 2011; Warren, 2013; Schafft et al., 2013).

Therefore, it is important that the potential effects of shale gas extraction on the socio-economics within the area are identified, especially in the areas that are more vulnerable as a result of the current water situation. Additionally, these impacts should be related to the wider developmental and environmental concerns (Esterhuyse et al., 2016).

6.3 Potential negative economic impacts in the region

From a sectoral perspective, the two main industries that are at risk are agriculture, the dominant sector in the target area, and tourism which continues to grow in importance (Van Zyl et al., 2016).

6.3.1 Agriculture

In 2014, the value of agricultural production in South Africa was R218,045 million and contributed approximately R69,423 million to national GDP. Since 1970, the primary agriculture sector has grown by an average of 11.8% per annum compared to the total economy growth of 14.9% per annum over the same period, resulting in a decline in agriculture's share in the total GDP from 7.1% in 1970 to 2.0% in 2013 (Lindeque et al., 2016).

However, agricultures prominent, indirect role in the economy is through the backward and forward linkages with the other sectors of the economy. Purchases of goods such as fertilisers, chemicals and implements indicate a form of backward linkages to the manufacturing sector, while forward linkages involve supplying raw materials to the manufacturing industry. Around 70% of agricultural output is utilised in other industries as the intermediate products, thus contributing much more to the total national GDP than is apparent from the statistics. Agriculture is a crucial sector and an important engine of growth for the rest of South Africa’s economy (DAFF, 2014).

Agriculture is the dominant land use in the Karoo region and is a key contributor to its economy. The sector provides a direct source of income to approximately 38,000 people and considering the average size of families in the area is around 4.5, the income supports the livelihoods of about 133,000 people. Underpinning the Karoo’s economy is its 7 million sheep and approximately 1 million goats. The region has long been a producer of fibre, contributing 13 million kg of South Africa’s annual 44 million kg of wool. It also produces all South Africa’s 2.4 million kg of mohair annually, around

60% of the world’s production, from about 670,000 angora goats. Most of this wool and mohair is exported and brings in billions in foreign revenue for South Africa (Lindeque et al., 2016).

The main grazing capacity in the Karoo is very low, with a carrying capacity that varies between 41 and 80 hectares per animal unit. The area has a vast species diversity, but is of low to medium grazing quality, therefore the area is best suited for the farming of livestock with conservation of the indigenous plant species (Pekeur, 2012). The agriculture sector in the Karoo is extremely dependant on water, especially from underground aquifers as surface water resources are very limited. Windpumps, or windmills, were first introduced in 1874 (Figure 6.5) and made permanent farms and towns in the Karoo possible by providing access to underground water (Lindeque et al., 2016).

Figure 6.5: Photo of a windmill on Juriesfontein farm near Beaufort West.

Source: *Own photo.*

This groundwater is essential for human and livestock consumption, with surface water also used for livestock and irrigation purposes. In the central, drier areas of the shale gas development area, the farming communities rely completely on boreholes as a water source for both humans and livestock. This is a result of the unreliable and limited rainfall in the area and high evapotranspiration rates, resulting in very little surface water. Therefore, the biggest risk of shale gas development to agriculture in the region is the potential contamination and use of large quantities of water (Lindeque et al.,

2016) as well as the environment on which agriculture relies so heavily on (Wait & Rossouw, 2014).

6.3.2 Tourism

Tourism and mining are important sectors of South Africa’s economy but inevitably result in conflict with each other (de Klerk & Heath, 2015; McLennan et al., 2015). Such evidence suggests that shale gas development will create various risks for the tourism sector in the area (Toerien et al., 2016).

Tourism in the study area is important, with three broad groups of tourists that will visit the area: 1) Those seeking unique experiences such as ‘getting away from it all’, adventures, agri-tourism, hunting, heritage sites, Karoo food, festivals, etc.; 2) Those travelling through; and 3) Business travellers visiting towns for business reasons and people visiting friends and relatives (Toerien et al., 2016).

In 2016, tourism housed 830 enterprises, the most of any business sector. It employed between 10,100 and 16,400 people and annually adds between R2.3 billion and R2.7 billion (2010 Rand) to the regional gross value added. The sector has diversified dramatically over recent years, which has dispersed tourism activities throughout the area, also into the rural areas. Some towns have particularly strong tourism sectors and will be impacted more than others (Toerien et al., 2016).

Expected impacts resulting from shale gas development on tourism are: large numbers of slow-moving trucks on roads leading to and crisscrossing the study area and hindering tourist access, causing road degradation and resulting in noise pollution; reduction of the scenic beauty of the Karoo and its mountainous access routes; replacement of the Karoo brand as ‘a place to get away from it all’ with an industrial image; crowding out of regular tourists by the shale gas personnel using tourism facilities; problems with basic services such as safe water provision; increased complexity of the integrated management of tourism activities; and exposure to earthquakes (Toerien et al., 2016).

The main risk is the overall reduction in tourists visiting the area, reducing the gross value added by tourism to the region. It could result in a loss of jobs in the tourism sector, which involves semi-skilled workers and is well represented by female employees. These impacts may become progressively worse the further the development and size of the shale gas project. However, the early exploration stages, that do not involve any fracking procedures, will not have any significant impacts on tourism in the area (Toerien et al., 2016).

6.4 Chapter summary

The main concern from an environmental perspective is the impact on water, a scarce resource in the Karoo. Studies and statistics indicate that the primary risk to near-surface aquifers is that of human error and poor well integrity, not the design of the fracking process itself. The natural migration of chemicals and brine from depth seems unlikely due to the large distance between the shale layers and the aquifers, highlighting the importance of good well construction, abandonment and monitoring. Additionally, the role of dolerite dykes and sills may play is still relatively unknown and further studies are required. As indicated, there are multiple ways in which aquifers may be contaminated, showing just how risky the fracking process may be. Water usage is a grave concern, and an adequate supply will need to be sourced without negatively impacting the availability to the current water users.

Due to the vast open landscape and geological stability within the Karoo region, air pollution, land use and induced seismicity are less of a worry. As for climate change, literature suggesting a positive contribution seems to outweigh those suggesting a negative one, whose main concern is that of the full life-cycle impact of shale gas.

Ultimately, the environmental risks involved, especially in South Africa, is under-researched and a lot more studies are needed to better understand the various potential impacts involved. Additionally, it is vital that studies acquire good data before any operations commence to provide base values that will allow for accurate impact measurements in the future should fracking commence.

In terms of economic costs, water usage and contamination could have dire consequences for the agricultural sector, a key contributor to the regional economy. Shale gas development may also have a negative impact on the tourism industry by reducing the number of tourists interested in coming to the Karoo. A dangerous knock-on effect is the potential loss of jobs in the industry which is counterproductive to the potential job creation of shale gas.

7 CONCLUSION

Based on the existing literature, there are substantial potential economic benefits of fracking in South Africa. This includes a large contribution to economic growth by increases in national GDP and government revenue. Comparative studies suggest that the contribution to GDP can range from R25 to R90 billion per annum, an amount comparable to the contribution from the industry of agriculture, forestry and fishing. Importantly, it has the potential to create an abundance of new jobs, a key concern in South Africa and the Karoo. However, economic impact studies indicate extremely variable results due to the uncertainty of the impact of South Africa's low skilled labour force. There are also large potential benefits on a regional scale and can provide an opportunity for an increase in entrepreneurial activity as well as grow the overall services within the small towns.

Additionally, there is the potential for a significant contribution to the struggling energy and electricity sectors of South Africa. The availability of energy and electricity plays an important role in economic growth and shale gas has the potential to provide a vast amount of natural gas into the country's energy equation. Additionally, many consider it a cleaner source of energy when used for electricity production, this can aid in the country's goal to reduce its substantial carbon footprint created by the electricity sector. Therefore, in agreement with De Wit (2011), Jenner & Lamadrid (2013) and Hedden et al. (2013), shale gas has the potential to act as a cleaner bridging energy source between coal and the inevitable need to shift to renewable energy.

Yet, clearly, these benefits do not come without substantial potential costs. These can be in both economic and environmental terms. Environmental impacts include issues such as air pollution, the effect on South Africa's contribution to climate change, induced seismicity leading to earthquakes, land use and socio-economic effects. Most importantly, however, is the concern over the use and contamination of the water resources in the Karoo. Water is already a scarce resource and has been described as the lifeblood of the Karoo. Therefore, any negative impact on the water resources may have dire consequences and the local people have every right to be gravely concerned.

From an economic perspective, the two key sectors that will be affected in the region are agriculture and tourism. Agriculture has become the dominant land use in the area and plays a significant role in both the local and South Africa's economy. The availability of water is a key contributor to the success of the agricultural sector, and the reduction and/or contamination of the water resources could negatively impact the sector significantly. Tourism is increasing in importance, and a negative impact on the surrounding environment can reduce its contribution to the economy.

Beyond the potential economic impacts and environmental concerns, it is important to determine the profitability of shale gas development in South Africa’s current state. A cost-driven approach is adopted, whereby a similar breakeven price estimated by Saussay (2018) for Europe of 10.1 $/MMBtu is used. The breakeven price is then compared to the current prices paid by Sasol’s end customers as well as three different global indices, proving to be too high on both accounts. This suggests that it is still cheaper to import gas from Mozambique than produce it locally from shale gas. South Africa does not have a natural gas price index, but if it had to follow that of the US, European or Japan LNG natural gas price indices, production would currently not be profitable.

There is concern around the long-term impacts that have not yet been realised. There is debate around whether, when considering the entire life-cycle of shale gas extraction, the long-term impacts truly are beneficial to South Africa. An example is highlighted in the debate around the GHG emissions from a life-cycle used for heating versus electricity. In addition to envrionmental impacts, this holds true for economic costs as well, where benefits realised over the short-term during extraction may result in long-term economic unsustainability due to the negative impacts it has on other contributing sectors. The long-term effects need to be considered.

Ultimately, it is evident that there is still a lack of research and understanding of the exact extent of the potential profitability, benefits and costs of fracking in South Africa. More unbiased academic studies based on good quality data are needed to create a platform of information that can assist future decision makers to best decide on how to move forward on the Karoo shale gas debate. It is vital that any future decisions made are not one-sided and that both the benefits and costs are accurately measured and weighed to get a true representation of how fracking will impact South Africa. There is a clear opportunity to enhance the development of South Africa but simultaneously a risk of creating irreparable damage that should not be taken lightly.

8 RECOMMENDATIONS

It is important to be open-minded about the fracking debate, and to factor in both benefits and costs. To completely shut down the thought of fracking in the Karoo due to environmental threats is something that should be avoided, as there is true potential to aid in the overall development and economic success of South Africa. The reality is that South Africa has been designated a significant potential shale gas resource and to not explore this potential any further would be a disservice.

A key factor in the whole debate that should not be underestimated is the lack of exploration that has contributed to the current low confidence resource estimations. The resource estimates form the base and guideline for the economic benefit predictions, and one of such low confidence simply does not allow for accurate enough estimations. In addition, the lack of information prevents the development of an economic model which could allow for the establishment of a more accurate breakeven price and associated market price, ultimately leading to profitability determinations.

Therefore, it is recommended that large early phase exploration programmes such as geophysical surveys and early-stage drilling, no fracking, is initiated to develop a higher confidence resource estimate that can allow for better economic benefit predictions.

However, this will be a costly undertaking, and it is unlikely that companies would be willing to invest in early stage exploration programmes without the insurance that if successful, fracking stage exploration and ultimately production of shale gas will be allowed. Perhaps, like the CGS Karoo deep drilling programme near Beaufort West, the government should look at investing in more early stage exploration themselves, removing the reliance on private companies to take all the risk with the potential of no rewards.

Currently, late stage exploration and production are being held back by the environmental impact concerns. Yet, if the early exploration yields uneconomical results, there is no need to take the debate any further. However, if the resource proves to be significant, there is a genuine opportunity for the country to utilise a large shale gas resource. Provided a large resource, it is essential that further in-depth studies on fracking’s negative impacts are done to understand the exact environmental consequences of fracking in South Africa. Using this newly provided data, an adequate and accurate cost-benefit analysis is recommended to determine the exact impact shale gas development will have in South Africa.

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