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South African Power Market

A full-cost analysis of future technology options for electricity generation

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Abstract

The aim of this research is to facilitate informed decision making for an optimal allocation of future electricity generation resources in South Africa. Such a study is important in order to find out which technologies are economically favorable from a long-term perspective for a growing and emission-intensive emerging economy that bases its energy production predominantly on the depletion of its domestic fossil coal resources. The research approach adopted in this dissertation is based on a profound review of literature on South Africa's electricity market, coupled with the development of a full-cost approach based on levelized cost of electricity. This approach is used to empirically evaluate the performance of new-build technologies including coal, nuclear, natural gas, solar PV, CSP and wind with regard to economic, environmental and social criteria. The findings from this research provide evidence that coal power stations are not the optimal option for electricity generation in South Africa and that wind, CSP, PV and nuclear are to be preferred for new investments. The main conclusion drawn from this study is that the inclusion of indirect costs and non-monetary aspects of electricity generation makes technologies competitive in South Africa that seem expensive from a pure-economic point of view. The dissertation recommends that the structure of the South African electricity market should be improved to facilitate the accommodation of higher shares of renewable energy.

Preface

This master thesis was written as part of the requirements to obtain a double degree from the Norwegian School of Economics (NHH) with the major MSc. in Energy, Natural Resources and the Environment, and from the University of Mannheim with the major MSc. in Management. It was written in Bergen and constitutes a workload of 30 ECTS.

The idea and motivation for this work emerged from a lecture at NHH called “Alternative Energy Systems in Physical, Environmental and Economical Perspectives”. South Africa, the country of analysis, was insofar of special interest to me as it belongs to the emerging countries whose economic development is heavily based on the depletion of fossil resources. Given today’s carbon-constrained world, it was especially interesting to evaluate the competitiveness of alternative energy sources in such a setting.

The research wouldn’t have been possible without the valuable professional, moral and financial support from others. First and foremost, I want to thank my supervisor Endre Bjørndal for his academic guidance and constructive feedback in our meetings. A special thank you goes to Patrick-André Narbel, lecturer in Alternative Energy Systems at NHH, for the valuable and inspiring brain-storming and discussions we had together, which eventually helped me to find this interesting topic. I am also very grateful to Grant McDermott, who shared his personal views and knowledge about the South African energy market with me. Moreover, I have to thank Dania Petrik, Marlett Balmer, Rögnvaldur Hannesson, Dick Berlijn and Melita Steele for sharing information with me and for pointing me to literature. During my study visit in Norway, I had the privilege to benefit from the E.ON Ruhrgas Scholarship for Economics, which allowed me focus on my research.

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Bergen, June 2013

Jan Eberbach

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List of Acronyms

ANC	African National Congress
BAU	Business as usual
c.f.	Compare
CCGT	Combined-Cycle Gas Turbine
CEF	Central Energy Fund
CEO	Chief Executive Officer
CO_2	Carbon Dioxide
COP15	Copenhagen Climate Change Conference
CSP	Concentrating Solar Power
CTL	Coal-to-liquid
DME	Department of Minerals and Energy
DMR	Department of Mineral Resources
DNI	Direct Normal Irradiation
DoE	Department of Energy
DPE	Department of Public Enterprises
e.g.	For example
EAF	Energy Availability Factor
ECB	Electricity Supply Board
EDI	Electricity Distribution Industry
EDIH	Electricity Distribution Holding
EIUG	Energy-intensive User Group
ERC	Energy Research Centre, University of Cape Town
ESCOM	Electricity Supply Commission
ESI	Electricity Supply Industry
et al.	And others
ETS	European Emissions Trading Scheme
FGD	Flue Gas Desulphurization
FMA	Financial Model Approach
Gen.	Generation
GHG	Greenhouse gas
IAEA	International Atomic Energy Agency
IDM	Integrated Demand Management
IEP	Integrated Energy Plan
INEP	Integrated National Electrification Programme
IPCC	International Panel on Climate Change
IPP	Independent Power Producer
IRP	Integrated Resource Plan
ISMO	Independent System and Market Operator
LCOE	Levelized Cost of Electricity
Lib.	Liberalization
MYPD	Multi-Year Price Determination
NECSA	South African Nuclear Energy Corporation

NER	National Electricity Regulator
NERSA	National Energy Regulator of South Africa
NG BL	Natural Gas Base Load
NG IM	Natural Gas Intermediate Load
NG Peak	Natural Gas Peak Load
NMR	Net marginal revenues
NNR	National Nuclear Regulator
No.	Number
NO_x	Nitrogen oxide
O&M	Operation and Maintenance
OCGT	Open-Cycle Gas Turbine
OECD	Organisation for Economic Co-operation and Development
PetroSA	South Africa’s National Oil Company
PPA	Purchasing Power Agreement
PPI	Producer Power Parity
PPP	Purchasing Price Index
PV	Photovoltaic
RE	Renewable Energy
REBID	Renewable Energy Bidding Programme
RED	Regional Electricity Distributor
REFIT	Renewable Energy Feed-In Tariff
REIPPP	Renewable Energy Independent Power Producer Procurement Programme
RES	Renewable Energy Sources
RRT	Residential roof-top
RUS	Rural utility-scale
SABRE	South African Bulk Renewable Energy
SADC	Southern African Development Community
SANEDI	South African National Energy Development Institute
SANERI	South African National Energy Research Institute Pty (Ltd)
SAPP	Southern African Power Pool
SBO	Single buyer office
SC	Super critical coal
SHS	Solar home system
sLCOE	Simplified Levelized Cost of Electricity
SO_2	Sulfur dioxide
SOC	State-owned company
SOE	State-owned entity
TCP	Technical Cooperation Permit
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
US	United States of America
WASA	Wind Atlas of South Africa
WPEP	White Paper on Energy Policy
WPRE	White Paper on Renewable Energy

List of Units

c	Cents
c_f	Fuel costs
c_{fom}	Fixed operation and maintenance costs
CO_2-eq.	CO_2-equivalent
c_p	Plant costs
CRF	Capital Recovery Factor
c_{vom}	Variable operation and maintenance costs
DC_{GHG}	Damage Costs from greenhouse gas emissions
e	Price escalation rate
E_{BC}	Estimate Value Benchmark Country
EI_{rt}	Emission Intensity Factor
$\bar{E}_{SA}$	Estimate Value South Africa
EX_{GHG}	Externalities from greenhouse gas emissions
EX_{net}	Net externalities
f	Capacity factor
GJ	Gigajoule
GW	Gigawatt
GWh	Gigawatt hours
H	Hours of the year
I_{BC}	Per Capita Income Benchmark Country
intl. $	International Dollars
I_{SA}	Per Capita Income South Africa
$J_{c,t}$	Job Creation Potential in Construction Sector
JCP_t	Job Creation Potential
$J_{fp,t}$	Job Creation Potential in Fuel Processing Sector
$J_{in,t}$	Job Creation Potential in Installation Sector
$J_{mf,t}$	Job Creation Potential in Manufacturing Sector
$J_{mn,t}$	Job Creation Potential in Maintenance Sector
$J_{o,t}$	Job Creation Potential in Operations Sector
kg	Kilogramme
KW	Kilowatt
KWh	Kilowatt hours
kWp-y	Kilowattpeak per year
kW-y	Kilowatt-year
l	Levelization Factor
l_f	Levelization Factor Fuel
l_{om}	Levelization Factor Operation and Maintenance
m	Meter
m/s	Meter per second
m^2	Square Meter
m^3	Cubic Meter
MC_P	Private Marginal Cost

MC_S	Social Marginal Cost
mm	Millimeter
Mt	Megaton
Mtoe	Megatons of oil equivalents
MW	Megawatt
MWh	Megawatt hours
mZAR	Million South African Rand
n	Number of observations
P*	Equilibrium Price
P_m	Monopoly Price
PPP	Purchasing Power Parity
Q	Income Elasticity for Environmental Quality
Q*	Equilibrium Quantity
Q_m	Monopoly Quantity
r	Discount rate
t	Tons, Technology
T	Time in years
TWh	Terrawatt hours
USD	US Dollar
ZAR	South African Rand
η	Ratio of Energy Input to Energy Output

1. Introduction

1.1 Background

According to Griffin (2009), a smart energy policy must fulfill three main goals: “energy should be cheap, clean and secure”. For most developing and emerging economies this is an ambitious target, and normally they cannot satisfy all three requirements at the same time. Their first priority is access to cheap energy, followed by securing the availability of energy supplies. The third goal of a smart energy policy, the provision of clean energy, becomes only relevant after the two other objectives have been satisfied.

This kind of situation can be observed in South Africa, a country which Okonjo-Iweala (2012) counted as one of the most progressive emerging economies in the world. South Africa is very rich in fossil energy resources, namely coal, and in consequence has built up an infrastructure to harness the energy contained in their domestic resource stock. In fact, there is no other major economy that uses coal as extensively as South Africa in its energy mix. As Burnard and Bhattacharya (2011) attested, the share of coal in electricity generation reached an unparalleled 93% in 2011 and coal was responsible for almost 70% of total South African primary energy supply. This might not be surprising given that South African coal export prices range amongst the cheapest in the world (IEA, 2012b).

South Africa is one the most sophisticated economies in Africa. As Griffin (2009) pointed out, the more affluent a society becomes, the more importance will be given to clean energy supply and to energy security issues. Despite the fact that competitive industries such as mining, automotive, agriculture, food processing, manufacturing and a flourishing service sector have developed in South Africa, both energy security and clean energy supply still represent a big hurdle for the country. External effects from air pollution, use of scarce water resources and CO_2 emissions from the extensive burning of hydrocarbons are a tremendous issue, especially in the Mpumalanga region, where coal power plants with a capacity of 30 GW are installed (Eskom, 2012a).

In addition to environmental degradation, energy supply issues are problems that can be observed regularly. Power outages happen frequently throughout the country at times of peak demand and both generation and transmission systems are almost constantly under their maximum stress (Eskom, 2012c, McGreal, 2008). The given power system is not yet managed sustainably and the infrastructure continues to wear out as maintenance times are reduced in order to keep the lights on. To manage peak demand and the burden on the system, Eskom (2013h), the national and monopolistic energy supplier in South Africa, provides the end customer with live system alerts. The actual stress on transmission and regional distribution grids is published and advices which devices should be turned off in order to avoid a bigger system collapses are given to the public.

The South African government has recognized the need for a cleaner and more reliable energy system for its society and economy. In 2003, the Department of Minerals and Energy (DME), predecessor of today's Department of Energy (DoE), has created a road-map for future energy planning. This road-map was called the Integrated Energy Plan (IEP). It constitutes South Africa's principal policy documents for energy planning. The Integrated Resource Plan (IRP) is embedded in the IEP and takes care of electricity generation and transmission capacity planning. It is constantly reviewed, latest in 2010, according to new technological and cost developments. The following statement from the DoE (2012a) depicts the governments' point of view on energy politics in a nutshell:

"Energy is one of the key elements in production processes. A lack or shortage of energy has a serious effect on the economy and gross domestic growth. By virtue of its size and economic importance, the energy sector periodically requires considerable investments in new and replacement supply capacity. Historically, such decisions were primarily driven by concerns regarding maintaining supply security, without giving full consideration to the economic, environmental and social impacts of all alternatives. As a consequence, the tendency has been towards the construction of large-scale capital-intensive supply facilities and the neglect of alternatives that might have been more cost effective in the long term, and had greater employment benefits and more favourable environmental impacts."

It seems as if the government actually favors a process of planning and renewing the energy sector with a stronger focus on long-term benefits. The potential role of alternative energy sources is recognized, and also the need to consider environmental and social impacts from the energy system.

1.2 Research Focus

As demonstrated in the background chapter, South Africa’s DoE focused mainly on cheap energy supply in the past, followed by concerns about energy security, but without caring much about clean energy at all. Coal, the main resource for electricity generation in South Africa, is mainly a cheap fossil fuel but it also comes with considerable drawbacks: greenhouse gas (GHG) and particulates emissions and quality issues with mined coal make this source of energy a dirty and less secure one. Clearly, as long as these aspects are not taken into account in an economic evaluation of the technology, coal fires a trade-off between the three goals of a smart energy policy.

Obviously, the government is aware of this and has recognized the need for a more sustainable energy pathway. A major contribution to move towards the goals of clean energy and energy security is expected to come from renewable energy sources (RES). Although this transformation has been planned for more than one decade, the government has not yet managed to remove persisting obstacles to the deployment of RES. Some of these barriers will be outlined subsequently.

One such example that illustrates the challenge with increasing the share of RES is the government’s target to deploy a fixed quantity of RES by 2013. In the White Paper on Renewable Energies (WPRE), the government committed itself in 2003 to an additional yearly primary energy supply of 10,000 GWh in 2013 (which equals about 0,6 % of South Africa’s primary energy consumption in 2010) to be produced from new installed RES (Shabangu, 2003). Now, in 2013, there is little information that this target has been reached and an official monitoring and evaluation program from the DoE is not accessible. Therefore, it is appropriate to argue that a major discrepancy exists between what has been planned and what has been realized.

Yet the reasons for this discrepancy are not fully evident and might be diverging. Authors like Sebitosi & Pillay (2008a) have pointed out that especially “high capital costs, though declining rapidly, have been a significant barrier against the deployment of renewable energies.” Other authors such as Krupa & Burch (2011) adduced that mainly poor policy documents lacking concrete and workable targets, together with slow innovation and sustainability entrepreneurship represent one major flaw to the development of RES. They also added that corruption, graft and a general lack of transparency in South African politics and businesses jeopardize a systematic change. Furthermore, the obstructive development of market conditions is blamed by authors such as Pegels (2010) as one major reason that impeded investments into RES. A highly monopolized market structure, regulations that have been changed a couple of times such as the Renewable Energy Feed-In Tariff (REFIT), or the abortive restructuring of the electricity distribution industry into Regional Electricity Distributors (REDs), are perfect examples that may be able to explain, why the investment climate for renewable energy projects was not very favorable.

Another reason for the slow deployment of RES is the low prices for electricity in South Africa, which are kept low artificially. Although real prices increased by a factor of 2.3 since 2003, the current level of prices still prevents alternative technologies from entering the market. Amusa (2009) pointed out that on an aggregate level, electricity demand is rather insensitive to price changes in South Africa. Prices which reflect the true cost of electricity provision would be possible from this point of view. Amusa (2009) argues, that resource allocation and efficiency could then be boosted. But he also acknowledges that this was especially difficult in South Africa, where a high percentage of the population lives below the poverty line. To these people, electricity price increases would be a major threat to get access to energy. Another impediment which was mentioned by Yelland (2012) is that discrepancies about the calculation of levelized cost of electricity (LCOE) for current and future electricity generation technologies exist.

These examples highlighted some of the major barriers to investments into renewable energy projects. The electricity industry in South Africa is not yet a level playing field for all generation technologies. One should also bear in mind that commitments into new fossil power stations are sunk investments for decades to come. This will have a severe impact on South Africa’s CO_2 future emission trajectories.

The rationale behind this research is to verify, whether RES are cost-effective in a smart energy policy of an emerging economy.

Therefore, the major focus of this thesis is to concentrate on the three goals of a smart energy policy for South Africa. This implies an integrated and comprehensive analysis looking at South Africa’s electricity sector from an economic, social and environmental perspective. The research focuses on full-cost calculations for all technologies that are considered to be relevant for South Africa’s future energy supply. These include coal, nuclear, natural gas, concentrating solar power, photovoltaic and wind.

Such a multi-dimensional approach intends to make different technology options comparable between each other. Investment decisions makers are enabled to broader their views, because traditional models of costing energy generation so far seem to favor only the use of fossil energy, as Sebitosi & Pillay (2008a) acquiesced. An approach that considers the true economic costs of electricity does not exist or is communicated for South Africa. Thus, research in this area is necessary and justified. This was also requested by Worthington (2012, in (Fakir, 2012):

> *"We need a transparent decision making process informed by consideration of the full range of costs and benefits to society as a whole and comparative analysis of the economic, social and environmental merits of competing investment options and energy development pathways."*

From this statement, the overall research aim of this thesis can be derived.

1.3 Overall Research Aim and Individual Research Objectives

The overall aim of this research is to facilitate informed decision making regarding competing investment options in South Africa’s electricity market, based on the principle of a smart energy policy. In order to reach this overall research aim, it is helpful to develop sub-objectives as proxies that provide the reader with the necessary background knowledge about the specific South African case. Hence, to allow for a sound conclusion in the end, a step-wise approach is applied and the following three sub-objectives will be integral parts of this thesis.

The first sub-objective of this thesis is to explore the very unique structure in which South Africa’s energy market evolved to what it is today. This is a necessary element to be able to understand the context for future investment decisions. Specifically, the aim is to advance an understanding about the historical development, different actors and stakeholders on the market that will be affected by decisions, on current market structure, as well as on future policy plans that will guide investment decisions.

The second sub-objective of this research is to introduce and evaluate critically a common method to compare the costs of different technologies. This is ought to be an evaluation of the levelized cost of electricity (LCOE) approach and an evaluation of its shortfalls. Based on this, lacking aspects should be incorporated into a more comprehensive framework that comprises environmental and social dimensions to arrive at a full-cost analysis.

The third sub-objective of this research is to exert the framework developed in the second step empirically into practice and apply it for the case of South Africa. As an outcome, different technology choices should be made comparable between each other.

The last sub-objective is to conclude on future investment options that are favorable to overcome the trade-off between cheap, clean and secure energy in a sustainable manner.

The research strategy for this thesis can be best described as a stepwise approach, providing first the background, then a methodology and finally the application of that methodology on the case of a specific country. In this work, relevant research subjects are in the end the citizen of South Africa, as they are the ones affected by the outcome of the analysis. In principle, this research will be carried out using literature review of primary and secondary data as the main data collection techniques.

1.4 Value of this Research

This research adds value to the research community in several dimensions. First, through its literature review it reduces complexity in a very fragmented and complicated political environment that has developed a certain level of institutional inertia which seems difficult to overcome. Thus, the thesis provides a clear overview to potential investors who are not very familiar with the structure of the South African market on what stakeholders, laws and policies are important for their investment decisions.

Furthermore, the research contributes in that it tries to provide a comprehensive approach to measure the full costs of electricity generation by including social and environmental factors as decision criteria. The need for such a comprehensive analysis was stipulated by Sebitosi & Pillay (2008a), who claimed that RES must be reevaluated given the likely emergence of carbon markets and the omission of environmental aspects and human well-being in traditional models for costing energy generation.

In addition, the outcome of this research provides the reader with an up-to-date cost analysis in 2012 ZAR currency values. At the same time it is clear that the empirical outcome will certainly be subject to change rather sooner than later in a quickly developing energy market. Costs are affected strongly by varying input factors such as fuel costs, learning rates, economies of scale, and these can be higher for some technologies than for others. Thus, the outcomes obtained in this thesis are under a constant need for verification regarding the accuracy of the input data used for cost calculations.

Last but not least, this research fits well into a period, where the pressure on the power sectors of emerging economies is rising from various perspectives. Be it the request of the international community to contribute to climate change abatement or, at the other side, be it internal pressure from a steadily growing demand for electricity, emerging economies all face similar investment decision problems regarding their power sectors. A methodology that includes the internalization of externalities into the LCOE, displayed through the example of South Africa is thus a valuable exercise for the research community as results might be transferable to similar countries.

1.5 Outline Structure

Chapter 1: Introduction

The first chapter provides the reader with the necessary background on the South African energy market and includes a description of the impediments to renewable energy deployment. Based on this, the research focus is explained, the overall research aim is derived and individual sub-objectives are identified. Chapter 1 also includes a description of the value of this research.

Chapter 2: Structure of the South African Power Market

In the second chapter, the evolution of the South African power market is described based on a broad literature review. The market transformation, regulations and relevant stakeholders are described. Socio-economic aspects including market size, technology mix, externalities and access to power are covered. The chapter ends with an illumination of current policies that will guide the future development of the market.

Chapter 3: Research Methods

Chapter 3 introduces the Levelized Cost of Electricity approach to the reader and provides a discussion of its benefits and flaws. The framework is extended with an inclusion of indirect costs of electricity generation and of non-monetary aspects of energy planning to allow for a full cost comparison between different generation technologies.

Chapter 4: Economic, environmental and social analysis of technologies

In this chapter, relevant generation technologies for the South African electricity market are individually assessed, based on the methodology developed in chapter 3. Research findings are presented, contrasted and discussed. Subsequently, the stability of the obtained results is tested through a sensitivity analysis with regard to selected parameters.

Chapter 5: Conclusion

In the last chapter, conclusions are drawn and outlined based on the context and results obtained from the previous chapters. From that, recommendations for the stakeholders in the market are derived and introduced. Finally, this chapter also includes a critical self-reflection and provides suggestions for further research that emerged throughout the research process.

2. Structure of the South African Power Market

2.1 Evolution

The South African power market has evolved over more than 130 years and is today Africa’s largest and most dominant electricity market. Consequently, the sector was subject to a variety of changing legislations and regulations, which became especially evident during the past 20 years after the official end of the apartheid regime. Since then, market conditions in the electricity supply and demand markets have changed substantially. Therefore, it is helpful to give an overview on the historical evolvement of the South African power market and its institutional inertia to be able to understand the current picture and variety of stakeholder interests in the market. This is followed by a description of socio-economic market characteristics, and of new developments and policies guiding the market.

2.1.1 Historical market development before 1994

The history of electricity supply and demand in South Africa dates back as far as 1881. In that year, the first electric lights were installed in Cape Town in the British Cape Colony, only two years after Thomas Edison had invented them in the United States. The advantages that electricity would bring were recognized soon and the use of electricity quickly spread to the inner part of the then Boer-ruled South African Republic. The main beneficiary was the gold mining industry. As early as 1895, first small hydro- and steam-powered electricity power plants were in operation in the main cities of Cape Town, Johannesburg and Pretoria (Eberhard, 2003).

Likewise, the gold mining industry was the driving force behind the development of further power stations. In the years around 1900, the mining industry recognized that existing power plants where too small in capacity and that more energy was needed for their mining processes. This proved to be the beginning of the idea of “larger and centralized power plants” in South Africa, which provide cheap and reliable electricity supply to the industry. Soon, several mining companies bundled their forces and gave concessions to newly founded electricity companies that would provide them with the necessary electricity. Coal was then introduced for electricity generation in thermal power plants (Kolb, 2009). Subsequently, both private companies and municipalities started to produce electricity from a variety of technologies and under a variety of municipal laws and regulations in order to cover the increasing electricity demand (Eberhard, 2003).

To bundle new individual power stations into a network and to deliver power to railroads and nearby cities, the Electricity Supply Commission (ESCOM) was created in the government's Electricity Act of 1922, with a mandate to supply electricity at the least cost possible. Likewise, a first regulatory body, the Electricity Control Board (ECB) was installed. New licenses to private companies and municipalities were issued at a limited scope by the ECB and preference was given to ESCOM's own electricity generation projects. Large investments were made into coal-fired power stations fuelled by cheap domestic low-grade sub-bituminous coal. In this way, the state secured more and more influence in the electricity sector and was able to suppress competition, which was seen to be wasteful at that time, as Eberhard (2003) explains. The main political purpose of this strategy was to allow for world competitive resources and mining sectors that were very energy-intensive (Renfrew, 1984). As a result, South Africa soon possessed one of the cheapest sources for electricity in the world.

In 1948, the National Party took over and eventually installed the apartheid regime which lasted until 1994. This time period was also crucial to how the electricity sector developed, as power stations brought online during that time are still running in many cases. In addition, energy politics from the National Party had a huge impact on the availability of electricity throughout the country and authors such as Renfrew (1984) and Steyn (1995) claim that it was also used by the white government as a means for social control of the suppressed Black population.

Around 1950, ESCOM had cemented its position as a vertically integrated monopoly by taking ownership over the national transmission grid and parts of the distribution grid. As in many other developing countries, high economic growth rates implied the need for capacity enlargements in electricity generation. Starting from the 1960s, state-guaranteed investments into a number of base load coal power plants were made through ESCOM and these were mainly located next to coal mines in the Mpumalanga Province. Table 1 shows a list of coal power stations build:

Table 1: Electricity generation capacity enlargements with coal power plants

Name of power plant	Year(s) grid integration First unit – last unit	Installed net capacity in MW	Location
Komati*	1961 – 1966	940	Middleburg, Mpumalanga
Camden*	1966 – 1969	1510	Ermelo, Mpumalanga
Grootvlei*	1969 – 1977	1200	Balfour, Mpumalanga
Hendrina	1970 – 1977	1965	Hendrina, Mpumalanga
Arnot	1971 – 1975	2352	Middleburg, Mpumalanga
Kriel	1976 – 1979	3000	Kriel, Mpumalanga
Matla	1979 – 1983	3600	Kriel, Mpumalanga
Duvha	1980 – 1984	3600	Witbank, Mpumalanga
Tutuka	1984 – 1990	3654	Standerton, Mpumalanga
Lethabo	1985 – 1990	3708	Sasolburg, Free State
Matimba	1987 – 1991	3990	Lephalale, Limpopo
Kendal	1988 – 1993	4116	Witbank, Mpumalanga
Majuba	1992 – 2001	4110	Volksrust, Mpumalanga
Cumulated installed net capacity in MW		37745	

Sources:(Eskom, 2012a, Eskom, 2013g)

** These power stations have been mothballed between 1980 and 1990 and were re-commissioned between 2005 and 2008.*

With the oil crisis in 1973, South Africa’s economy shifted towards a substitution of oil with electricity and consequently peak demand growth rates skyrocketed with demand increases of 6 – 16 % per year from 1972 to 1982 (Eberhard, 2003). This situation induced yet more commitments for capacity increases and the fear of power shortages was permanent at that time. The capacity increases were not used to electrify rural areas. Instead, the electricity supply was concentrated to major cities, industries and the farms of white farmers (Steyn, 1995). Increasing costs and poor financial management with capacity enlargements triggered a government enquiry in 1983, where ESCOM was accused of questionable investment decisions, accounting principles and forecasting methods from the De Villiers government. Out of this trial originated a new Electricity Act in 1987. ESCOM was forced to undergo an organizational restructuring process and was renamed in Eskom (Bekker et al., 2008). Eskom’s new mandate was described by Gentle (2009) in providing “the system by which the electricity needs of the consumer may be satisfied in the most cost-effective manner, subject to resource constraints and the national interest”.

After the Electricity Act was passed, Eskom was no longer subject to price regulations and licensing through the ECB, leading Steyn (1995) to assert that the role of the ECB was literally marginalized. As Eberhard (2003) points out, since then electricity retail prices are controlled by the Electricity Council, and are subject to government review and approval.

The political end of the apartheid regime came in 1994 and things have changed dramatically since then in South Africa's electricity sector. The following section summarizes the more recent developments.

2.1.2 Restructuring process after 1994

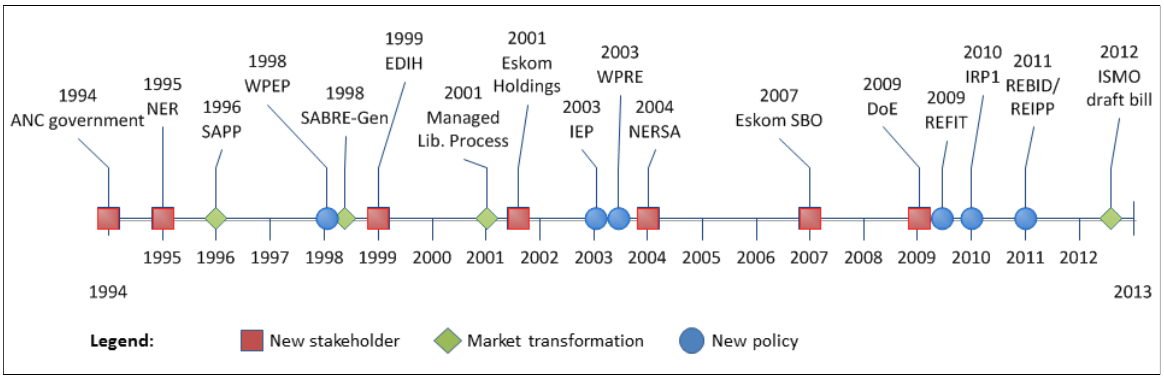
With the African National Congress (ANC) coming into power in 1994, Bekker et al. (2008) allude that the years between 1994 and 1999 represented a period of transition where *"...apartheid frameworks and policies were dismantled or reformed, a new constitution was adopted, new government institutions were created at national, regional and local levels, and other institutional reforms were carried out…"*. They also comment that as an outcome of this transition period, most of the institutions that had been created after the political change started to work effectively from the year 2000. Eberhard (2007) concurs that a major achievement of ANC's policy reforms was the shift away from the state-centered orientation advocated by the National Party, towards a more market-oriented economy and tendencies of liberalization.

If this was true for other sectors, for the electricity sector, however, liberalization and deregulation have not been implemented completely and the worldwide trend throughout the past 20 years to unbundle state-owned electricity utilities has thus not fully materialized in South Africa. Even in the year 2013, Eskom still remains a state-controlled utility, though in the legal form of a holding, with business operations in electricity generation, transmission, trading and distribution (DPE, 2013). Galen (1998) derived a main reason for the lack of competition from his assessment that two out of three drivers for more competition did not exist in South Africa during the last decade of the 20th century. He specified a lack in cost and price drivers and in service quality, while he saw that adequacy of supply was an existing driver for more competition in the market.

Nevertheless, the new government has started a restructuring process for the electricity sector, which proved to be a very complex undertaking. This was manifested in a variety of new policies, stakeholders and transformations of the market. In retrospect, it proves difficult to identify a continuous and straightforward strategy of the government. This view is also supported by Sebitosi & Pillay (2008b) who have disclosed "…uncoordinated and at times conflicting approaches by various arms of the government…". In more than one case, a decision has been dismissed and an opposite action has been followed later. This was for instance the case with the Renewable Energy Feed-In-Tariff (REFIT) program or the introduction of Regional Electricity Distributors (REDs) which were both revised short time after being implemented. Another shortfall was mentioned by Fakir (2012) who criticized the introduction of an Integrated Resource Plan for Electricity (IRP) before the broader energy concept, the Integrated Energy Plan (IEP) was introduced. He added that this has led to negative effects on overall carbon emissions.

To keep track of all the new stakeholders, market transformations and policies, which have been implemented since 1994, an illustration might be useful. Figure 1 provides a chronological overview of the most important new elements in South Africa’s power sector reform after 1994. A description of the main new policies and market transformations follows below, while new stakeholder bodies will be described separately in Chapter 2.1.3.

Figure 1: Chronological schema of power sector reform in South Africa after 1994



Source: Own illustration.

ANC government

The overall new strategy of the new ANC government in 1994 was to address existing inequalities and injustices and to transform society and economy accordingly. Broken down to a transformation of the electricity sector, this implied four main aspects: One major focus was put on countrywide electrification, with the aim of overcoming the massive prevailing back-lock in grid connection of many rural and urban black South Africans. Simultaneously, a focus was put on the economic and political empowerment of large parts of the marginalized black population. A third focus was put on the restructuring of state-owned enterprises, including the energy utility Eskom. Restructuring plans from the ANC also included a focus on the optimization of new investments into the electricity supply industry to make the electricity system more accessible and efficient (Eberhard, 2007, Turkson and Wohlgemuth, 2000).

Southern African Power Pool (SAPP)

In 1996, the Southern African Power Pool (SAPP) was introduced as a market for electricity exchange with the goal to make reliable and economical electricity available to all member countries. As Sebitosi (2010) argues, the main advantages with the creation of a regional SAPP market were seen in cost reductions, optimized use of large-scale generation units, improved system reliability and security of supply, as well as risk pooling. Today, the SAPP is a day-ahead market and has 16 member parties from 12 countries in the Southern African Development Community (SADC) region.[1] As Graeber et al. (2005) pointed out, the SAPP takes an important role in balancing the market during peak demand periods. The actual monthly volume in electricity traded ranged between 39 MWh and 4953 MWh at average monthly system prices between 270.85 and 722.34 ZAR/MWh during the year 2012. Matched sales and buy bids were always higher, but transmission constraints regularly made a good proportion of matched sales impossible for actual exchange (SAPP, 2012). The South African utility Eskom is by far the biggest participant in the SAPP and accounted for almost 79% of the installed capacity in 2010 (SAPP, 2010).

South African Bulk Renewable Energy Generation Program (SABRE-Gen)

The SABRE-Gen program was established in 1998 and is an in-house program from the state utility Eskom. It was introduced to obtain scientific evaluations of potentially viable utility-scale electricity supply technologies and projects for South Africa. The program includes research and feasibility studies on bio-energy, wind power, concentrating solar power (CSP) and wave power (Eskom, 2006).

White Paper on Energy Policy (WPEP)

The WPEP was released in 1998 as the centerpiece for South Africa’s future energy policy during the next decade and it represents “the basic direction for energy service delivery strategies and their implementation towards achieving the national goals.” (Ziramba, 2008) As mentioned by Maleka et al. (2010), these include increased access to affordable energy services, improved energy governance, stimulation of economic development,

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[1] The member parties are: Botswana Power Cooperation, Copperbelt Energy Cooperation (Zambia), Electricity Supply Commission of Malawi, Eskom (South Africa), Electricidade de Mozambique, HCB (Mozambique), Lesotho Electricity Corporation, Nam Power (Namibia), Societe National d' Electricite (Democratic Republic of Congo), Swaziland Electricity Company, Tanzania Electric Supply Company Limited, Zimbabwe Electricity Supply Authority, Zambia Electricity Supply Corporation Limited, MOTRACO (Mozambique), Lunsemfwa Hydro Power Company (Zambia) and Empresa Nacional de Electricidade (Angola).

management of energy-related environmental and health-effects and increased security of supply through diversification. With this new strategy paper, South Africa formally started to express a paradigm shift in its energy policy. The times of mere focus on security of supply, for instance expressed through the costly build-up of overcapacities on the supply side, the nuclear power program with only one nuclear power station or the synthetic fuels program during times of the political embargo against the Apartheid regime came then formally to an end. A new orientation towards the attraction of new private investment into the energy sector and improved efficiency through competition was advanced. As Sebitosi & Pillay (2008b) pointed out, the WPEP can also be seen as the document that has set energy politics into a broader context, by recognizing that everybody in South Africa should have the right to a peaceful and intact environment in the present and in the future. Thus, the authors advocate that legislation has to be adapted in a way that prevents from pollution and ecological degradation and that ensures conservation and sustainable development while promoting economic and social development. The former Minister of Minerals and Energy, Penuell Maduna, has also emphasized in his ministerial foreword to the White Paper (DME, 1998), that in addition to that, energy should be available to all citizen at an affordable cost.

Managed liberalization process

Following the WPEP, the South African Cabinet approved proposals for a reform of the Electricity Supply Industry (ESI) and the Electricity Distribution Industry (EDI) in May 2001. According to Eberhard (2007), main points brought forward concerning the restructuring of the ESI consisted in a break of Eskom’s supply monopoly with a limitation of its share in electricity supply to 70%, leaving 30 % to Independent Power Producers (IPPs). The Cabinet also decided to establish a separate and state-owned transmission company. Furthermore, it agreed on changing the market structure into a multi-market model electricity market framework, allowing for transactions on a power exchange, for balancing mechanisms and bilateral delivery contracts. In addition, the Cabinet agreed to develop a new regulatory framework to ensure the market participation of IPPs. In terms of the EDI, an equally important decision was taken: to unbundle distribution, EDI Holdings Company was scheduled to be incorporated and the Eskom-managed electricity distribution grid was supposed to be divided between six new Regional Electricity Distributors (REDs) (Cassim et al., 2003).

Integrated Energy Plan (IEP)

The IEP is a macro-economic policy roadmap and planning framework and includes all aspects of the energy planning process for the Republic of South Africa. Its ultimate aim is to guide and provide a vision on future energy infrastructure investments, by modeling different scenarios. The compilation of an IEP was scheduled in the White Paper on Energy Policy of 1998 and subsequently a first IEP was issued in 2003 (DoE, 2012a). According to the Energy Act of 2008, the Minister of Energy has a mandate to review and publish the IEP on an annual basis. An updated IEP was initially scheduled for 2012, but is still under development and according to McLaughlin (2012), the final draft for the cabinet can be estimated in mid-2013. The IRP will be incorporated as a sub-part of the next IEP.

White paper on Renewable Energy (WPRE)

The WPRE was published by the DME in November 2003 and complements the WPEP from 1998. It was brought forward in the spirit of the World Summit on Sustainable Development, which was held in Johannesburg in 2002 (Maleka et al., 2010). The main goals of this policy document are to ensure that RES will help to diversify and secure the energy supply by gaining a foothold in the South African energy mix, and that they are developed optimally, given their vast resource potential in the country. Suitable RE technologies mentioned in the WPRE are wind, biomass, hydropower, solar, wave energy, ocean currents and energy from waste. The government committed to encourage the deployment of RES by facilitating private investments into the market and through the introduction of independent power producers (IPPs). As former Deputy Minister of Minerals and Energy, Susan Shabangu, has suggested in her foreword to the WPRE (DME, 2003), the development of the RE sector should also contribute to the further electrification of disadvantaged communities, the development of human capacity building programs, and to the stimulation and commercialization of local manufacturing of RE systems. To make progress on RES deployment measureable, the DME (2003) has set itself the following target:

"10 000 GWh (0.8 Mtoe) renewable energy contribution to final energy consumption by 2013, to be produced mainly from biomass, wind, solar and small-scale hydro. The renewable energy is to be utilised for power generation and non-electric technologies such as solar water heating and bio-fuels. This is approximately 4% (1667 MW) of the projected electricity demand for 2013 (41539 MW). This is equivalent to replacing two (2x 660 MW) units of Eskom's combined coal fired power stations. This is in addition to the estimated

existing (in 2000) renewable energy contribution of 115 278 GWh/annum (mainly from fuelwood and waste).”

The WPRE lists a number of potential barriers to the deployment of RES. These include a lack of non-discriminatory open access to the national electricity grid, the fact that RES remain expensive compared to coal because they account for higher capital costs, and last but not least, legal, regulatory and organizational barriers (DME, 2003).

Renewable Energy Feed-In Tariff (REFIT)

The REFIT was introduced in March 2009 by the National Energy Regulator of South Africa (NERSA). With the introduction of this feed-in tariff scheme, the NERSA followed the international trend of establishing support mechanisms for RES to trigger much needed environmentally friendly capacity enlargements for electricity generation. The main benefit of the REFIT was seen in the creation of investment incentives for private RE projects. Hence, the support scheme was designed such that it guaranteed power producers a fixed rate of income over 20 years for each KWh fed into the national power grid, a rate that should allow potential investors to cover their full costs and gain a reasonable premium. NERSA calculated the rates based on the LCOE methodology and these were subject to a review every year (NERSA, 2009). In phase I, feed-in tariffs for wind, CSP, small hydro and landfill gas were introduced. In phase II, large PV, biomass and biogas were added and the tariffs for CSP were revised. Table 2 lists the fixed purchase prices for electricity generated from these technologies, as guaranteed by the REFIT phase I and phase II.

Table 2: REFIT compensation scheme

Technology	**Compensation in ZAR/KWh**
REFIT Phase I	
Wind	1.25
CSP through with 6 hour storage	2.10
Small hydro (<10 MW)	0.94
Landfill gas	0.90
REFIT Phase II	
CSP through without storage	3.14
Large scale grid connected PV (≥1 MW)	3.94
Biomass solid	1.18
Biogas	0.96
CSP tower with 6 hours storage	2.31

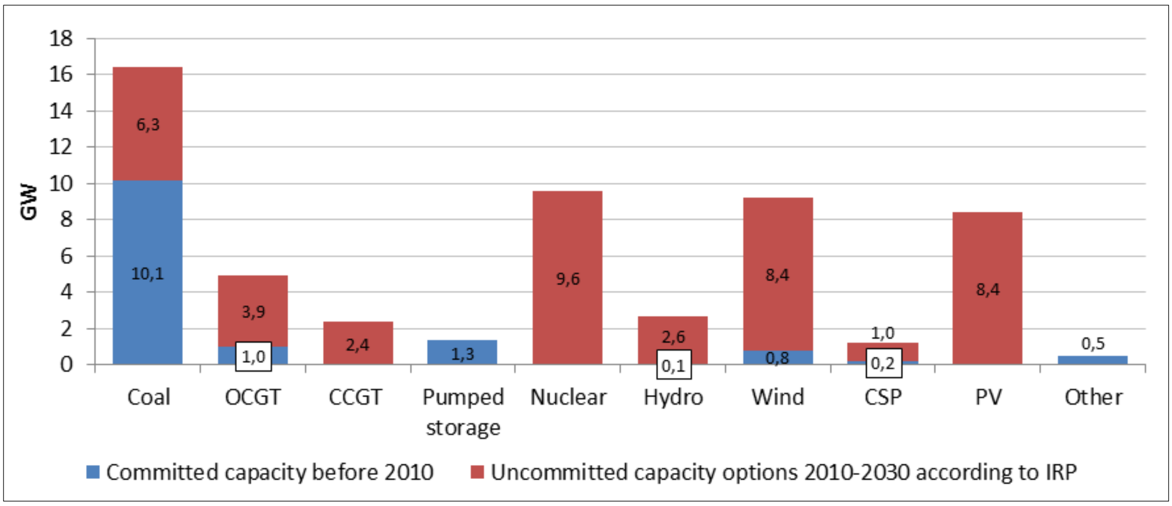
Sources: (Mbatha, 2011, Pegels, 2010)

To bring renewable electricity into the public grid, a power purchase agreement (PPA) had to be signed, between a power producer and Eskom. In retrospect, this proved to be the weak point of the REFIT program as no PPA had been made available by Eskom, even two years after the program started (Kernan, 2013). Thus, the DoE announced in July 2011, that a competitive element should be included in the distribution of PPAs. In the end, the REFIT program as initially planned was given up due to barriers in its implementation stemming from instability in political support and without that one single MW of RE capacity had been installed under its tariff (Pegels, 2012). As Pienaar (2011) pointed out, it was even believed to be unconstitutional by some stakeholders, given that fairness, equitability, transparence, competitiveness and cost-efficiency of the tariff were perceived questionable.

Integrated Resource Plan (IRP)

The IRP is the long-term policy document for South Africa's electricity strategy between 2010 and 2030. It was introduced by the DoE in October 2010 with the purpose to identify required investments for the electricity supply sector which are most beneficial to South Africa's national interest, given technical, economic and social constraints as well as externalities[2] (DoE, 2010). Thus, the projections modeled in the IRP provide a likely composition of South Africa's energy mix to cover the expected demand of 454 TWh in 2030. As input parameters such as technology, demand, financial conditions, electricity prices or emission costs might be subject to change in the future, the IRP will need to be revised every two years. Though due, an update has not yet been released since the end of 2012.

Figure 2: Policy-adjusted scenario for capacity new-builds as adopted in IRP 2010



Source: Own illustration, adapted from (DoE, 2010).

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[2] As specified in the IRP, relevant constraints and risks include: a) reduction of carbon emissions, b) new technology uncertainties such as costs, operability and lead time to build, c) water usage, d) localization and job creation, e) Southern African regional development and integration, and, f) security of supply.

Figure 2 illustrates committed and uncommitted additional new capacity builds until 2030. If the scenario modeled in the policy-adjusted IRP will materialize, 42% of uncommitted new capacity will be from RES. Accordingly, RE would then account for 9 % in total electricity production by 2030. If already committed new-builds are included in the picture, the capacity share of renewable energy new-builds in South Africa would shrink to 38.8%, a drop that was also criticized by Paul (2011).

REBID

The REBID program replaced the REFIT scheme in July 2011. With the move to a competitive bidding process, the DoE hoped to finally secure required investments into RES. The REBID process is organized that the DoE decides on a number of new capacity to be installed and then fixes a price ceiling for the most expensive projects. This price ceiling was close to the numbers in the 2009 REFIT tariff. In a call for proposals, IPPs are then encouraged to underbid themselves to secure a project. In that way, the government tries to obtain efficient allocations for RES projects. In order to be eligible to bid, IPPs must first apply for a license issued from the NERSA.

Economists have expressed ambivalent opinions about South Africa’s new REBID policy: Becker and Fischer (2012) declared that the bidding concept has been proven successful in other emerging countries such as China and India. Nevertheless, they also identified a pitfall in the fact that a bidding process includes a higher risk for project developers, which has to be compensated for and thus increases their bidding price. Furthermore they argue that auctioning generally favors large and financially solvent companies and might represent an entry barrier for new start-up companies in the sector. On the other hand, Pegels (2012) demonstrated that the introduction of the REBID scheme has provided more security and stability to the RE market and is thus positive for South Africa.

Initially, the DoE has committed to a capacity purchase of 3725 MW from RES in three bidding rounds. The bidding process is now formally called the Renewable Energy Independent Power Producer Programme (REIPPP). During a first bidding phase, 1452 MW of capacity enlargement were auctioned at the least cost, leading to 28 different projects in Wind, PV and CSP to come online before the end of June 2014.[3] In a second bidding round, 1044 MW of capacity builds were secured in 19 projects. According to the OECD (2013), the price for solar PV projects was driven down by 40% in the second

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[3] CSP projects have to reach commercial operation by 2016.

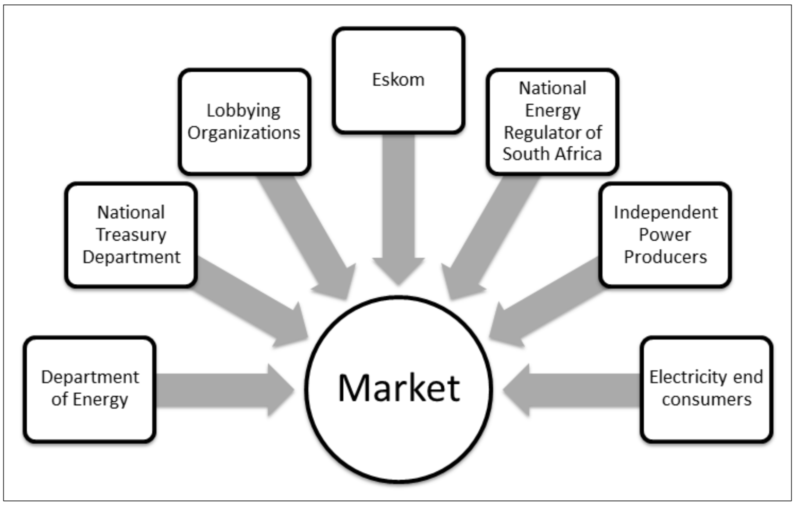
bidding phase compared to the beginning. The entirety of the REIPPP was valued at ZAR100-billion and further plans for an additional procurement of 3200 MW until 2020 are in the pipeline as energy minister Peters confirmed (Creamer, 2012a).

The recent developments show that policies for RE have been very unforeseeable from an investors perspective. Consequently, these have to cope with a high level of uncertainty regarding support mechanisms for RE deployment in South Africa. Nevertheless, interest in developing RE is prevalent, a fact that can be seen by the number of bids submitted in the REIPPP tenders. Sebitosi (2008b) sees a main reasons for the difficulty in establishing effective energy policies in the lack of availability of good and reliable energy data.

2.1.3 Stakeholders

In this section the most important stakeholders with an influence on the South African electricity market will be introduced. Figure 3 gives an overview of these:

Figure 3: Overview of stakeholders in the electricity market



Source: Own illustration.

Department of Energy (DoE)

The main task of the DoE is to ensure "…exploration, development, processing, use and management of South Africa's energy resources" (GCIS, 2011). The department was established in 2009 and is currently led by the Minister of Energy, Ms Dipuo Peters. It emerged from the former DME which was split into two separate state departments for minerals and for energy. The DoE initiates new energy legislation and suggests them to the Parliament. It has also the responsibility to oversee the State-Owned Entities (SOE) that play a role in the energy sector. These are two regulatory bodies, the National Energy Regulator of South Africa (NERSA) and the National Nuclear Regulator (NNR), as well as the Nuclear Energy Corporation of South Africa (NECSA), the Petroleum, Oil and Gas Corporation of South Africa (PetroSA), the South African National Energy Development Institute (SANEDI) and the Central Energy Fund Group (CEF).

National Electricity Regulator

The National Electricity Regulator (NER) was established in 1995 as the national regulatory authority for the electricity industry. It was replaced by the NERSA in 2004.

National Treasury Department

The National Treasury is responsible for coordinating South Africa’s macroeconomic fiscal policy. It took a role in terminating the REFIT scheme when it questioned its competitiveness, cost-effectiveness and constitutional legality. It was also involved in developing the REIPPP auctioning process and authors such as Pegels (2012) were surprised by the strong role it plays in shaping South Africa’s renewable energy policy.

Lobbying Organizations

There exists a wide spectrum of industry associations and lobbying organizations to support literally any interest in the Southern African energy landscape. An overview of the most important ones can be found in Appendix 1.

Electricity Distribution Holdings (EDIH)

The Electricity Distribution Holdings was incorporated in 1999 as a vehicle to transform the electricity distribution sector. EDIH’s mandate was to establish six independent REDs. The intention of this measure was to remove risks from a large number of small distributors and to create a regional distribution structure that would be secure, reliable, affordable and easier to regulate (Patel, 2004). In reality, negotiations with many municipalities continued for a long time, and many of them were reluctant to give away their distribution assets which were often an important source of income for them. These difficulties finally lead the DoE to the decision to abandon the idea of REDs and the EDIH was terminated in March 2011. As a consequence, a serious backlog in investments in the distribution grid has occurred over the last years, which is also seen as a major problem for South Africa’s distribution grid by ex-EDIH chief operating officer De Beer (2011, cited in (Hutchinson, 2011) and Eberhard (2012).

Eskom Holdings SOC Limited

Eskom was corporatized into Eskom Holdings SOC Limited with the Eskom Conversion Act of 2001. The transformation into a public company was part of a broader process of restructuring of South African SOEs and the company is since then subject to tax liability and dividends payments. The state holds 100% of Eskom’s shares. With almost 45,000 employees, Eskom is the dominant market player in South Africa’s electricity market. Business operations comprise generation, transmission and distribution of 95% of the electricity consumed in the country. In 2012, Eskom generated 90.4% of its electricity from coal, 5.6% from nuclear, 0.8% from hydro, 1.2% from pumped storage, 0.3% from gas, while 1.7% were purchased from IPPs (Eskom, 2013b).

National Energy Regulator of South Africa (NERSA)

The NERSA replaced the NER in 2004. With this transformation, the government pursued the goal to pool the regulatory needs for the gas, the petroleum pipelines and the electricity sector under one responsible regulatory body.

NERSA has obtained its mandate for the electricity sector from Section 16(1) (a) and (b) in the Electricity Regulation Act No. 4, 2006, which consists in approving the rates and conditions of service that Eskom is allowed to charge for the electricity delivered (2006). This way, the NERSA has a direct influence on the revenue stream that Eskom will have. Approval is only justified, if Eskom can demonstrate that a change in its tariff is merited, due to increasing or decreasing costs. Eskom’s pricing policy is thus driven by a cost of service methodology, where prudent and efficient costs are recovered through the allowed tariffs and where incentive mechanisms are provided to improve technical and economic efficiency (Eskom, 2012e). This are means to regulate the state-owned monopoly supplier at least to some extent.

In practice, price regulation has materialized in the formulation of Multi-Year Price Determinations (MYPDs) with the first one established in April 2006. Since then, Eskom is entitled to apply for an average increase of its tariffs over the next 3-year periods.[4] This average increase is calculated based on separate price increases for municipal and non-municipal tariffs. Within the MYPD phases, Eskom can apply for cost adjustments if costs are believed to differ with regard to the 3-year forecasts. Factors that allow for price adjustments might be fuel price volatility, fuel mix uncertainty, energy demand uncertainty

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[4] In the 3rd MYPD round from 2013 – 2018, NERSA approved a 5-year price determination period.

and calorific value uncertainty with regards to coal supplies. To allow for a more transparent and participative process of price determination, NERSA has hosted several public hearings and consultations rounds with regard to changes in the methodology of the MYPD schemes. From the draft consultation paper (NERSA, 2008) can be inferred that Eskom has had considerable influence on the design and update of the MYPD regulations.

Stakeholders such as Greenpeace (2012) have criticized the role of NERSA and claim that the regulator became only fully operational in 2008. They have also argued that NERSA’s power in controlling South Africa’s monopolized generation and transmission sectors is rather weak, and that its main role consisted in adjudicating Eskom’s price applications.

Independent Power Producers (IPPs)

IPPs are defined as independent if neither Eskom nor the public has a stake in their company assets (SAIPPA, 2011). According to Pegels (2010), they play a major role in the desired liberalization and diversification of the South African electricity market in the way that they bring more innovation and competition to a market where Eskom is acting with core competencies in fossil fuel technologies. However, she advocates that a functioning level playing field cannot yet be observed as Eskom still remains the monopsonic buyer of IPP-produced electricity with its single buyer office (SBO). Fortunately, the government has understood that there exists a conflict of interest for Eskom when it is obliged to buy energy from its potential competitors and it thus initiated an improvement of the situation with planned introduction of an Independent System and Market Operator (ISMO).

The possibility for IPPs to sell renewable energy under the REIPPP program has drawn the attention of many potential market entrants. As Buthelezi (2012) alluded, Eskom has received as many as 599 expressions of interest by September 2012 from IPPs who wanted to engage in power production projects. Unfortunately, it had to refuse most of them as only IPPs with whom the Eskom SBO has signed PPAs under the REIPPP are legally allowed to have grid access. It appears that this is a major disadvantage of a policy instrument which dictates the amount of RES to be deployed and consequently limits market growth.

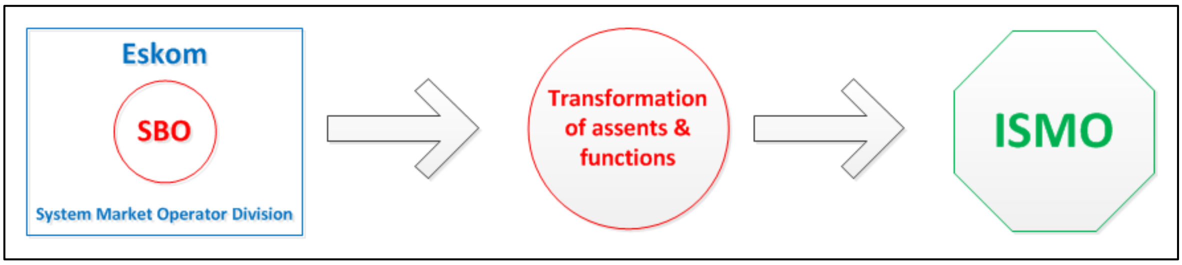
Independent System and Market Operator (ISMO)

If the number of IPPs and with them the amount of installed RE capacity becomes larger, the potential for a conflict of interest between the Eskom SBO and other Eskom departments is likely to increase. In such a more complex market with an aimed IPP share of 30%, Eskom could quickly experience trade-offs between prioritizing own projects and fulfilling system integration obligations for IPPs. Therefore, the concept of an independent entity that takes care of planning and operating the transmission system and the market was considered by President Jacob Zuma (2010) in his state of the nation address in 2010. This initiative has been supported by Pegels (2010) who argued that the creation of an independent entity for operating both the transmission system and the market is indispensable to a more enabling environment for renewable energy producers. This would indeed be a major step to reduce the market power of Eskom and improve investment conditions for IPPs.

Consequently, a draft ISMO bill has been tabled in the Parliament in March 2012 but has not yet been adopted since then and is still subject to public consultation (Independent System and Market Operator Draft Bill, 2012). It was suggested that ISMO would be responsible for electricity generation planning, system operation and expansion, buying electricity from generators, and selling it to customers. Critics of the bill, such as Haffejee, (2010, in Creamer, 2010) and Eskom itself, advocated that a transformation from an Eskom SBO to ISMO would require two to three years. This would be too longsome in the current situation, where a quick accommodation of IPP- power as defined in the IRP is necessary.

If the bill is adopted though, the SBO will be transformed from a ring-fenced entity within Eskom’s System Market Operator Division into the ISMO. The envisaged stepwise transformation process is highlighted in figure 4:

Figure 4: Phased deployment model for ISMO



Source: Own illustration based on Independent System and Market Operator Draft Bill (2012).

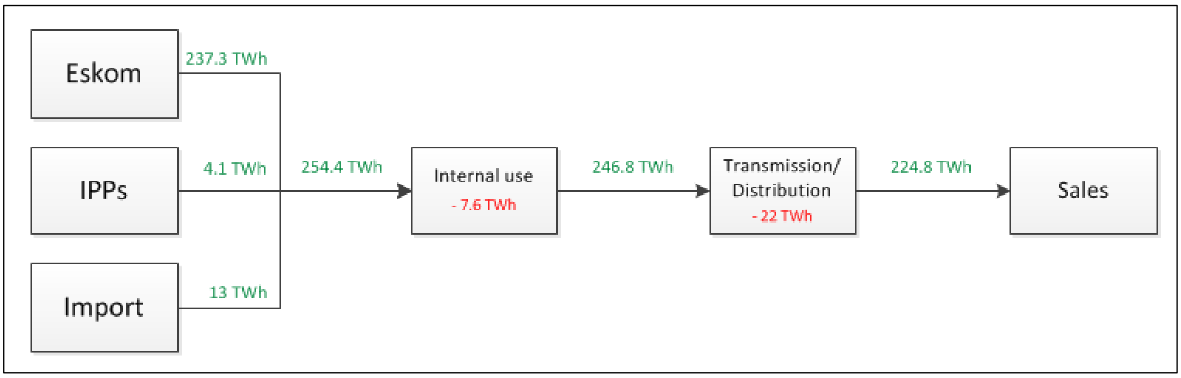
After the development of the electricity sector was outlined in the previous chapters and relevant stakeholders and policies that influence the market have been introduced, the following chapter will portray the socio-economic characteristics of the electricity market.

2.2 Socio-economic aspects

2.2.1 Market size

In 2010, South Africa was Africa’s biggest market in terms of electricity supply. In total, the country accounted for 39.8% of the continent’s electricity production, which placed it largely in front of Egypt and Algeria (IEA, 2012c). During Eskom’s financial year 2012, total electricity supply amounted to 254.4 TWh, with the major share coming from Eskom’s own power production and minor shares originating from electricity imports and IPP production. Internal use for wheeling, pumping[5] and internal sales accounted for 7.6 TWh. A further 22 TWh were lost during transmission and distribution processes and in the end 224.8 TWh were available for sales in order to cover the electricity demand. Figure 5 illustrates the supply-side power flows in the year 2012:

Figure 5: Power flow in South Africa’s ESI in 2012



Source: Own illustration based on (Eskom, 2013b).

Despite a stagnating demand over the last six years, Eskom was not physically able to cover South Africa’s entire electricity demand with the 224.8 TWh it delivered in 2012. Van Heerden (2011 in (Lazenby, 2011) has estimated the supply/demand gap for 2012 at approximately 6-9 TWh, but as measures to reduce the demand were in place, it is actually very difficult to come up with a meaningful figure about the supply shortfall in 2012. The situation was mainly problematic during evening peak demand hours and it was recorded that Eskom was not in a position to cover the weekly peak demand[6] from its own generation portfolio on 43 out of 52 weeks in 2012 (Eskom, 2012f). To fill the gap, electricity had to be imported through the SAPP. In addition, measures to conserve energy were put in place under the Integrated Demand Management Programme (IDM), in which Eskom had adopted elements from Brazil that faced a similar situation in 2001. Measures

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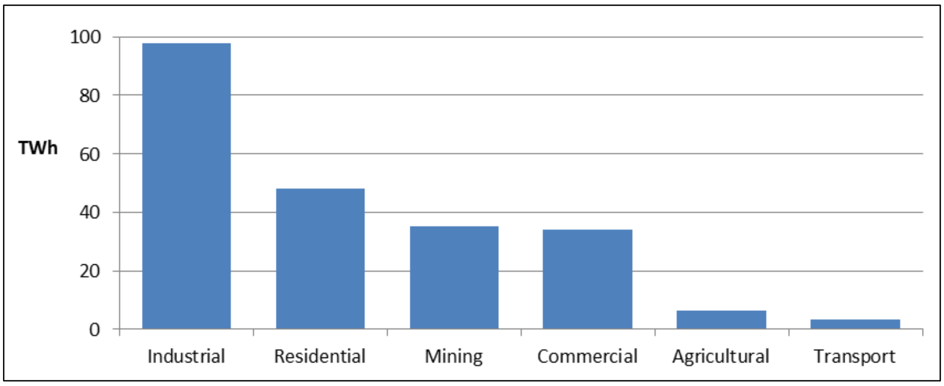
[5] Electricity for pumping is required in Eskom’s Drakensberg and Palmiet pumped-storage hydro schemes.

[6] The average daily peak demand was 35,526 MW in 2012.

included for example the “49-million campaign” targeted at the private sector to save electricity, as well as contracts with companies from the Energy Intensive User Group (EIUG) that allow for load shifting (Eskom, 2011a, Timm, 2012). Figure 6 depicts that these two sectors accounted for the biggest part of electricity demand in 2012, followed by the commercial sector which was as important as the mining sector:

Figure 6: Eskom power sales in according to sectors in 2012



Source: Own illustration based on (City of Cape Town, 2011, Eskom, 2013b).

Future electricity demand as modeled in the IRP scenario is projected to grow on average by 2.8 %[7] per year until 2030. However, there is discordance among economists about the methods used in the forecast and several authors have come up with alternative projections. For instance, Amusa (2009) suggested that different sectors would respond differently to price variations in the future as a result of their differing price elasticity of demand. In their decomposition analysis, Inglesi-Lotz and Blignaut (2011) compiled that additional factors with considerable influence on future electricity demand in South Africa were changes in production outputs, energy efficiency measures and structural change. Ziramba (2008) argued that electricity demand from South Africa’s residential sector will not be affected much by electricity price changes and consumption will not increase significantly with higher incomes due to his low estimates on price and income elasticity of 0.011 and 0.33.

By now it should have become obvious to the reader that current generation capacity does not suffice to cover South Africa’s electricity demand. Investments into capacity expansion become necessary and some projects are currently under construction. In order to understand the trade-offs that this situation implies, an overview about the technology mix existent in the supply industry is helpful. This is provided in the following chapter.

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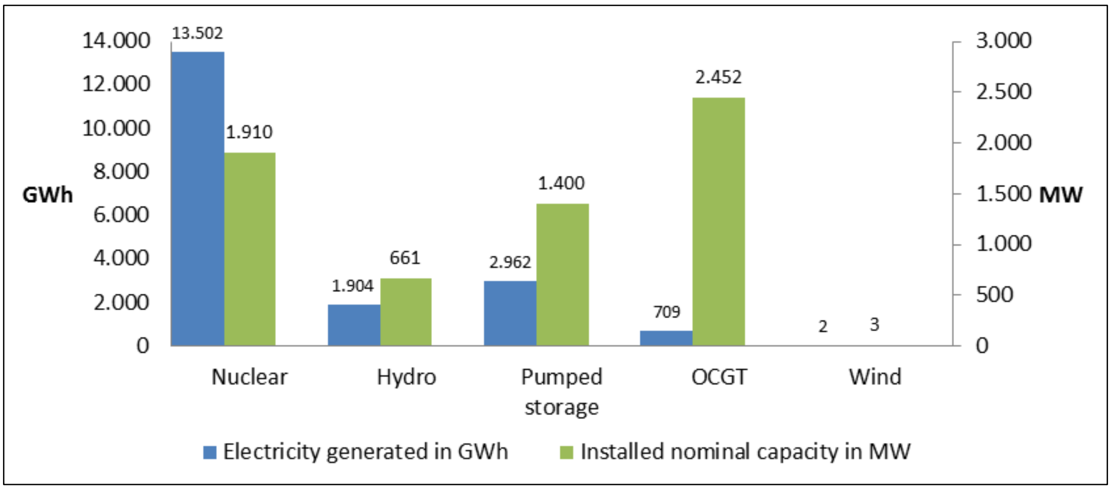
[7] This number is based on the following formula for logarithmic growth: $g = e^{\left(\frac{\ln x_t - \ln x_0}{t}\right)} - 1$; where g is growth, x_t is the demand in 2030, x_0 is the demand in 2010 and t equals time in years.

2.2.2 Generation technology mix

Overall, the generation technology mix is not very diversified in South Africa's industry. In 2012, power generation continued to be extremely reliant on coal, even though IPPs contributed to power generation with more than 4.1 TWh.[8] Due to pressures from the demand side, the mothballed coal power plants Komati, Camden and Grootvlei had to be re-commissioned. As a result, a massive 92% of Eskom's 2012 electricity output of 237.3 TWh was generated in coal power plants with a total nominal capacity of 37,745 MW. For the remaining 8% of electricity generated, nuclear power accounted for 5.7%, while pumped-storage hydro power contributed with 2% to electricity supply. Other technologies that contributed to the remainder were OCGT (fired with diesel oil) and wind, while PV and biomass were only deployed on a non-commercial scale (IEA, 2012c). Figure 7 portrays the importance of alternative energy technologies other than coal in South Africa, and contrasts them with regard to electricity generated and generation capacity installed.

Figure 7: Contribution to electricity supply from technologies other than coal



Source: Own illustration based on (Eskom, 2013b, Eskom, 2013g, IEA, 2012c).

Committed new build program

To overcome the existing supply/demand gap, the South African government has committed to increase the capacity of the existing generation portfolio. New capacity is to be delivered both from Eskom and from IPPs. Although policies aim at a reduction of Eskom's market penetration to 70% and at a 34 % reduction of carbon emissions by 2020 compared to the 'Business as Usual' emission growth trajectory (Patel, 2011), the major part of committed new capacity is to come from Eskom's new coal power plants. Eskom's

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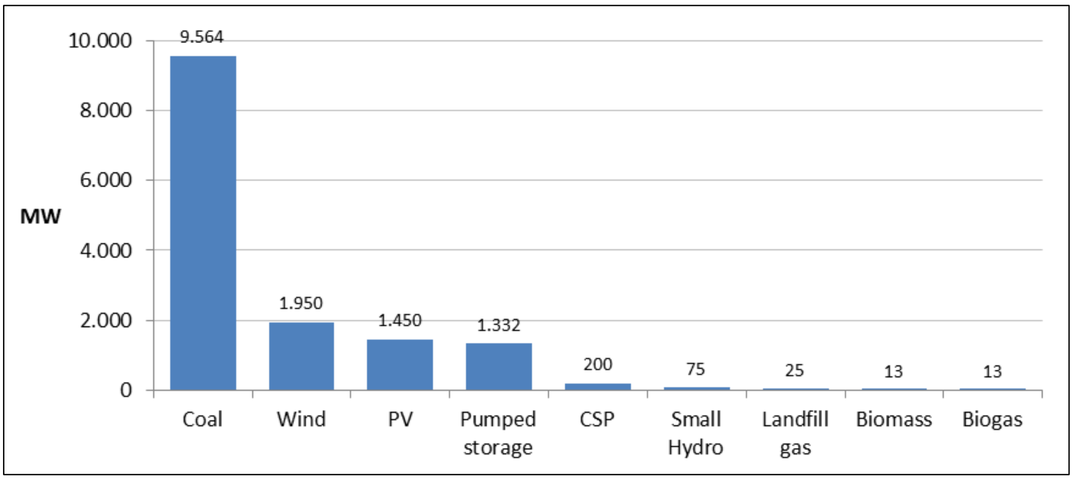
[8] Information about the origin of IPP power generation could not be obtained, but it is estimated that the 4.1 TWh were produced from non-renewable sources in municipal power stations. IPP power production is not included in the 92% coal share of Eskom.

new builds currently under construction include the 4th and 5th largest coal power plants in the world, Kusile (4800 MW) and Medupi (4764 MW), the Ingula Pumped Storage scheme (1,332 MW) and the Sere Windfarm with a nominal capacity of 100 MW. Combined, new nominal capacity amounts to 10,996 MW and is to be commissioned in its entirety by 2018/19 (Eskom, 2012b). In addition, the government has committed to purchase 3,725 MW of RES from IPPs which are targeted to be online latest in 2016 (DoE, 2012b). In total, nominal installed capacity in South Africa will increase by 33% in 2018/19 compared to 2012 levels, if all projects are realized in due time. Figure 8 highlights the importance of generation technologies for committed capacity increases:

Figure 8: Nominal capacity of committed short-term new builds by technology



Source: Own illustration based on (Eskom, 2012b, DoE, 2012b, Maphosa, 2012).

Other options for new builds

South Africa also possesses a favorable resource base for a variety of other technological options that have not been mentioned or deployed on a larger scale so far. These include CSP, PV, wind, shale gas, wave power, small-scale hydro and biomass. The resource potential of each of these alternatives will be introduced briefly.

South Africa is endowed with one of the most favorable levels of direct normal solar irradiation (DNI) in the world. Yearly DNI levels go beyond 3000 KWh/m² in the north-western part of the country, which makes the resource potential for direct and indirect solar power a vast one. A demonstration-scale CSP project is currently developed by Eskom in Upington under conditions that were modeled by Suri (2011) at a DNI of 2816 KWh/m² per year. This project is targeted at gaining further knowledge in the CSP central receiver technology as a large-scale application, a technology that Eskom (2013c) sees as a key concept for future power stations. In addition to CSP technology, the resource potential is also given for other direct and indirect solar power applications such as PV and direct solar heating.

Wind power is another important option for future bulk electricity generation in South Africa, and its technical potential to satisfy part of South Africa's energy demand was confirmed in a study by Micklem (2010). Her conclusions were based on a classification of the South African territory by Hagemann (2009), but the South African National Energy Research Institute (SANERI, 2012) has published a more sophisticated study in 2012, the South African Wind Energy Atlas. Here, the resource potential proved to be even higher than in previous studies, as more accurate data was collected. What all assessments and modeling showed is that South Africa generally possesses many very suitable sites for wind turbines, especially along the coast and at exposed locations in the inner part with annual average wind speeds of 9-10m/s and higher. A wind-use culture is already developed with widespread small-scale off-grid applications on farms. First bulk-electricity generation projects are constructed by Eskom and IPPs.

Recently, shale gas has been discovered in rock formations under South Africa's Karoo desert. The Department of Mineral Resources (DMR) claimed that a quantification of recoverable resources shapes up as difficult, if not impossible, due to a lack of data (DMR, 2012). Other scientists have come up with estimates and according to Lloyd (2011, in Botha and Yelland, 2011), resources are in the order of 1000 trillion cubic feet and could be a game changer for South Africa's energy mix, if extracted for power generation. A more conservative estimate with a total of 485 trillion cubic feet of recoverable reserves was published by Kuuskraa et al. (2011). If the lower estimates are true, South Africa would sit on the 5th largest known unconventional gas reserves. A use of this resource could potentially transform the ESI and contribute to a reduction of the share of coal. However, the resource is unconventional and thus a controversially discussed issue in South Africa. Questions about the sustainability of inevitable fracturing processes and the necessary use of scarce water resources are raised by opponents to the technology such as the Karoo Action Group (2012) and these have created a strong negative opinion among parts of the population towards the extraction of the gas resources. Nevertheless, the South African government has lifted an initial moratorium on fracturing in September 2012 and has since then issued technical cooperation permits (TCPs) that allow for initial research into the Karoo's shale gas potential, as reported by Dittrick (2013).[9]

Another potential technology that could deliver electricity in South Africa is wave power. The Agulhas current is a consistent ocean current and delivers a constant amount of energy of 40-60 KW/m (Holman, 2009). If harnessed through existing wave power technologies[10], Gunn and Stock-Williams (2012) estimate that more than 18.7 TWh of power can be extracted at the South African coast line per annum. According to Van Niekerck (2012, in Dardagan, 2012), director of the Centre for Renewable and Sustainable Energy Studies at the University of Stellenbosch, technology is available and only a lack of funding and political recognition from the DoE persist as remaining barriers to deploy this technology. Advantages he mentioned about wave power were short lead construction times of about two years for power plants, as well as their stable and predictable output patterns in electricity generation. Eskom has also recognized the potential of this technology and has awarded a contract to Hydro Alternative Energy (HEA) to build a 5 MW tidal pilot power plant in eThekwini on the KwaZulu-Natal coast in order to assess the economic and technological feasibility of larger-scale projects (Botes, 2012). Furthermore, Eskom has installed several monitoring systems and data is being collected to gain knowledge about other potential sites.

Last but not least, biomass is a source of energy that can be used to generate bulk electricity. Dasappa (2011) has estimated the power potential from biomass for South Africa at 643 MW or roughly 4.8 TWh[11], based on his assumption that 30% from current cereal production and agricultural residues are available as fuel material. His estimate is based on current levels of production and does not even include a raw material supply structure that is especially targeted for the use of biomass. He attests another advantage to biomass with the fact that load factors above 70% are possible in biomass power plants, which would make their performance comparable to other centralized power plants. As Creamer (2012b) reports, Eskom considers biomass a promising option and is about to start a co-generation project in its Arnot power plant in early 2013. As fuel material torrefied black pellets will be used. Koko (2012, in Creamer, 2012b) believes this process to be

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[9] TCPs are hold by Shell, a Sasol, Chesapeake Energy Corporation and Statoil joint venture and a Falcon Oil & Gas Ltd. and Chevron joint venture.

[10] Resource estimate based on Pelamis power matrix, with a conversion efficiency of 3.1% under South Africa conditions.

[11] Estimate based on a 85% capacity factor in a biomass power plant.

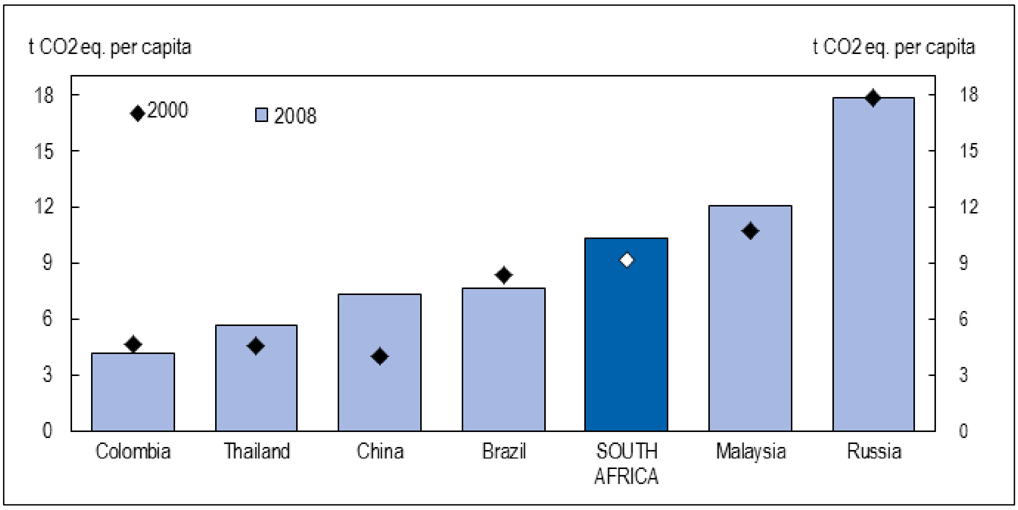
profitable from a cost, emission reduction, rural development, industrialization and regional integration perspective. But Eskom (2013a) also considers that large scale production of biomass could lead to competitive situations with other agricultural activities, complex requirements on logistics and substantial need for land areas.

2.2.3 Market failures

South Africa's strong reliance on fossil fuels has its downside also: It is the primary cause for a considerable amount of costs borne by society at large. The strategy of non-diversification of the ESI has in part resulted from below market-price access to coal supplies and a non-consideration of external costs in investment choices. The OECD (2013) concludes that electricity must be underpriced in South Africa. This is also confirmed by Vorster et al. (2011) who describe that "the country is not yet at the point, where the true costs of climate change are fully reflected in the relative prices of goods and services, or where future public and private investment strategies in the energy and industrial sectors assume an escalating price on carbon".

In fact, South Africa emitted an absolute amount of 457.6 MtCO$_2$–eq.[12]in 2010. Thereof, Eskom emitted more than 49% through its power plant fleet. On average, 0.97 kg/KWh of CO$_2$-eq. were released to the atmosphere (Eskom, 2010). According to calculations from the OECD (2013), this was about 60% above world average. If this performance is compared with other middle-income countries, South Africa is amongst the most emission-intensive middle-income economies. This is highlighted in figure 9:

Figure 9: GHG emissions per capita in middle-income countries in 2008



Source: (OECD, 2013)

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[12] CO$_2$-equivalents are calculated based on the definition from the 4th UNFCCC Assessment Report.

Apart from GHG emissions, the OECD and Eskom also publish statistics on other externalities occurring from the activities of the South African ESI. These include releases of SO_2, NO_x, particulates and radiation, radioactive waste disposal, water consumption, employee fatalities and transmission losses. No statistics on indirect health effects of these technologies and on benefits from electrification were published though.

Three studies have been published so far that focused on a monetary quantification of externalities related to electricity generation in South Africa (Thopil and Anastassios, 2010). A first study was conducted by Dutkiewicz and de Villiers in 1990 following a top-down damage cost approach. Resulting external costs were rather lower than in comparable international studies. A second study was conducted in 1996 by Van Horen (1997). After the ANC came into power, he was asked to reevaluate costs for electricity generation. Backed with international financial support, site-specific data and the help of the EXMOD modeling tool, Van Horen was able to apply a bottom-up damage cost approach. His major findings were that the nuclear industry benefited from high subsidies and that GHG emissions represented the major part of externalities from coal power, followed by health impacts.

Building on Van Horen’s study, Spalding-Fecher and Matibe (2003) focused on a more comprehensive definition of externalities. Using a damage-cost approach as underlying methodology, Spalding-Fecher and Matibe accounted for both positive and negative externalities from electricity generation. Positive externalities included, for example, health benefits resulting from fuel switching[13] or from the reduction of public wood scarcity. Negative externalities included air pollution, health effects and climate change damages. In their study, they calculated the net sum of external costs in Eskom coal-fired production to be between 1.4 and 9.3 c/KWh, with a central estimate of 4.4 c/KWh.[14] Inflated to 2011 real Rand values, these costs would increase to 3.37 c/KWh for the low, to 10.58 c/KWh for the central and to 22.36 c/KWh for the high case scenario respectively. The category with the highest effect on total external costs was reported to be climate change damages. At a standard average electricity price[15] of 52.3 c/KWh in 2011 (Eskom, 2011b), the

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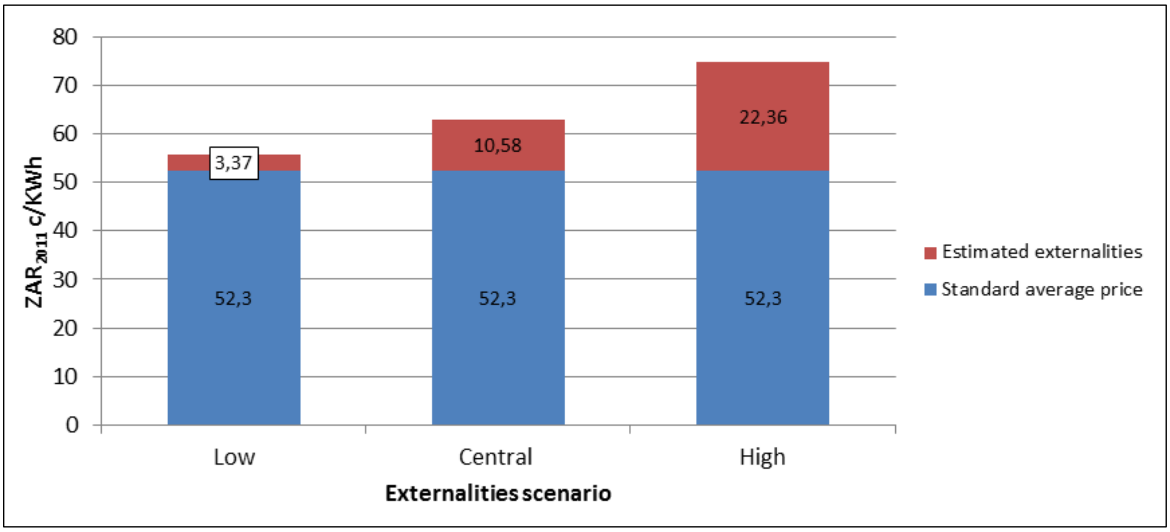
[13] An example for fuel switching would be a switch from paraffin, wood or charcoal towards the use of electricity for individual household energy consumption.

[14] Measured in real 1999 ZAR.

[15] The average standard price is the average price over different tariffs Eskom offers to different market segments and includes generation, transmission and distribution.

inclusion of these external costs would increase the electricity price considerably under the central and high estimates as depicted by figure 10.

Figure 10: Quantification of coal-related externalities in domestic studies



Source: Own illustration based (Eskom, 2011b, Spalding-Fecher and Matibe, 2003).

From that perspective, an aggregated consideration of externalities from a country's aging power fleet is not meaningful to channel investments into preferable technologies from that perspective. Consequently, externalities have to be evaluated individually for new power stations and for each technology. As external costs come on top of the costs paid by a power producer and thus affect the final price paid by the consumer, one should look at electricity prices first in South Africa.

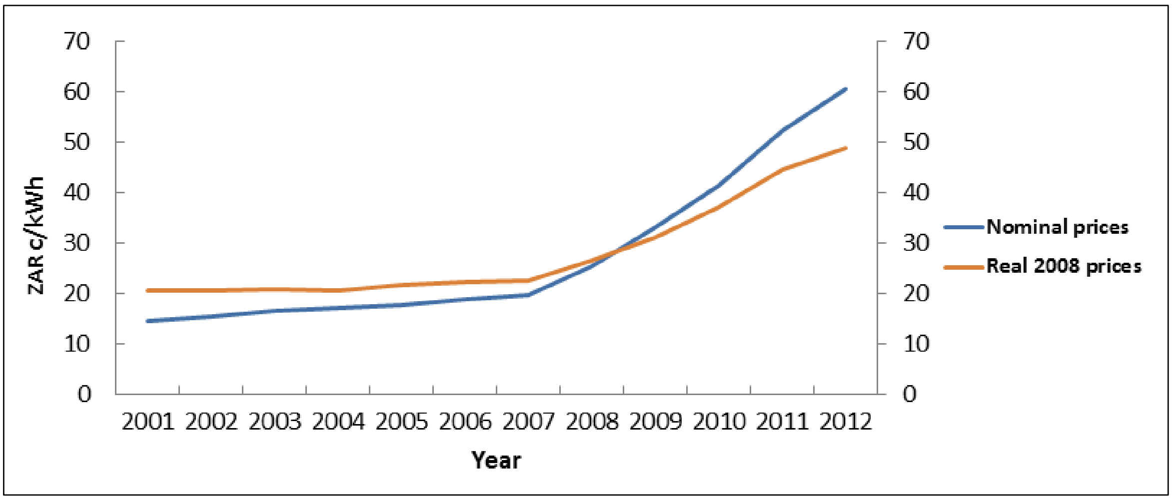
2.2.4 Electricity prices

Due to the monopolistic market structure in South Africa, electricity prices are not determined via the market mechanism. To limit possible monopoly rents from situations where Eskom reduces its output and charges a higher price than in equilibrium, electricity prices in South Africa are subject to approval by the NERSA. For that matter, NERSA's goal is to ensure cost-reflective pricing. Therefore, Eskom forecasts output and costs and submits an 'allowed revenues application' to NERSA. A process of pubic consultation helps to adjust the average standard price and the way it should increase. This mechanism is called Multi-Year Price Determination (MYPD). If forecasts prove to be inaccurate, Eskom can apply for further adjustments of the agreed tariff at the beginning of each new fiscal year. The application has to be based on updated sales and cost projections. During MYPD3 for example, a yearly price increase of 8% was approved. Eskom is allowed to cover its full cost, plus a "reasonable margin or return". This is defined in the Electricity

Regulation Act No. 4 (2006). While the allowed margin was not specified in the Act, NERSA approved returns ranging between 14.1 to 16.2% of total allowed revenues under MYPD3 (NERSA, 2013b).

Over the last decade Eskom charged among the lowest prices for electricity in the world (Spalding-Fecher and Matibe, 2003). Although nominal prices increased every year, real prices have been kept relatively stable up until 2007. Since then, real prices increased by factor of 2 to account for rising costs of electricity generation, which is highlighted in figure 11.

Figure 11: Development of average standard electricity price in nominal and real prices



Source: Illustration[16] adapted from (OECD, 2013, Eskom, 2012g, NERSA, 2013b).

This real price increase ultimately reflects the politically wanted transition towards a cost-reflective electricity price in South Africa (Creamer, 2013a). Even though Eskom’s average purchase price for coal is still 80% below the South African export price (OECD, 2013), McKay (2012) confirms that increasing coal prices drive the cost for electricity production upwards. This happens because many long-term supply contracts from Eskom are expiring in the next years, while the price negotiation position of mining companies improves with rising coal export prices. Other important price drivers were identified by Eskom’s CEO Dames (2012) with a maintenance and investment backlog, which puts the system under pressure and makes unplanned power outages more likely and maintenance more costly. Also, anticipation of an introduction of a carbon tax in South Africa leads to early price adjustments (Treasury Department, 2010).[17]

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[16] Note: Figures after 2004 based on Eskom financial year from 1 April to 31 March.

[17] An example for such a price adjustment is the inclusion of an environmental levy of 3.5 c/KWh for electricity generated from non-renewable sources.

Technically, electricity prices charged in South Africa consist of several components. Nel (2012) decomposed them in variable costs (KWhs consumed), fixed costs (network access and metering), levies (electrification and rural subsidy, environmental levy) and taxes (VAT). During the financial year 2013/14, the average standard electricity price was approved at 65.51 c/KWh. As illustrated in table 3, this price will increase to 89.13 c/KWh in 2017/18.

Table 3: Allowed revenues, standard average prices and percentage price increases

Financial Year	Allowed revenues from tariff-based sales (mZAR)	Forecast sales to tariff customers (GWh)	Standard average price (c/KWh)	Percentage price increase (%)
2013/14	142746	217890	65.51	8.0
2014/15	155477	219744	70.75	8.0
2015/16	171838	224877	76.41	8.0
2016/17	189396	229495	82.53	8.0
2017/18	209025	234519	89.13	8.0

Source: (NERSA, 2013b).

If compared internationally (Eskom, 2012d), the standard average price in South Africa was still at a very low level in 2010, and the OECD (2013) claims that it is still below Eskom's marginal costs of generation. Eskom (2013f), on the other hand, reported total generation costs[18] of 51 c/KWh in 2013, while admitting that the standard average price was not cost-reflective. So far, the government's target of a cost-reflective electricity price has not been reached and current standard average prices still do not cover all direct costs of electricity generation.

2.2.5 Access to power

Access to power depends on the availability of two factors: physical electricity generation and a means of transport of that electricity to the point of use. The aspects of transport are relevant for the producers and for the consumers' point of view.

Access to power is a very important and topical subject in South Africa. Given the size of the country and the concentration of power generation in the Mpumalanga region, power is transported through a national transmission grid and regional distribution grids. Although Bazilian et al. (2012) confirm that the electrification rate is by far the highest for a Sub-Saharan Africa country, there is still a considerable way to go before universal access is realized with 82.7% of South African households having a grid connection in 2011 (StatsSA, 2012a). This electrification gap stems essentially from the country's socio-

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[18] Excluding transmission and distribution.

political history, where access to electricity was mainly a privilege for the white population. As Bekker et al. (2008) point out, electricity distribution was the responsibility of local authorities during the 1970s and 1980s. Consequently, there was not much drive behind building new grid connections, due to limited financial capabilities especially of poorer municipalities. However, this has changed over the past 20 years with the introduction of the Integrated National Electrification Programme (INEP). Since 1991, about 4.2 million additional households have been connected (Eskom, 2013f). By 2014, the government aims at a electrification rate of 92% (GCIS, 2011).

In addition to the installation of new grid connections for households, two other initiatives were brought forward to improve universal access to energy in South Africa: a solar water heating program and an off-grid PV program with solar home systems (SHS). The solar water heating program was rolled out by Eskom to provide warm water to disadvantaged households, being identified as a very efficient means of energy provision. According to Zuma (2013), 315,000 solar water geysers have been distributed by early 2013. The SHS program was introduced in 1999 with the aim to reach households that were located uneconomically far away from a regional distribution grid. The performance of this program was evaluated both by Lemaire (2011) and Wlokas (2011) and each of them confirmed considerable improvements for the rural population despite the many barriers the program faced. These included a skills shortage in rural areas and lacking financial resources of the rural population to pay a contribution to the SHS. Another important mental barrier that the already disadvantaged citizen faced was identified by Niez (2010) in their misconception that renewable energy meant rural energy and was of a lower value.

In a broader context, South Africa’s access to power is also secured through the participation in the SAPP market. Potential large-scale projects such as the Grand Inga Dam in the Democratic Republic of Congo could also increase the long-term access to power and security of supply (Rosnes and Vennemo, 2012).

2.3 Future policy plans

With regard to South Africa’s energy planning, there are several topics that are currently discussed and that could considerably influence the costs of different technologies. These include, inter alia, South Africa’s role in global GHG abatement, new economic tools of pricing externalities such as a recently discussed carbon tax, plans for rural development and a general transition of the industry to a less carbon-intensive structure.

South Africa’s role in global GHG abatement

Compared with other emerging economies (c.f. Figure 8), South Africa has relatively high emissions of GHG, both in emissions per capita an in total terms. About 80% of all emissions in South Africa originate from the energy supply sector with half of it being released from the ESI (Government of South Africa, 2011). To limit the impact of emissions and to take on a credible role in global climate change abatement, South Africa committed to restrain their growth at the COP15 UN Climate Change Conference in Copenhagen in 2009. As with other emerging economies, the difficulty for policy makers in South Africa is to balance a reduction of emissions from the energy supply industry with an increasing hunger for energy driven by prospects of economic growth and poverty alleviation (Ojha, 2005). For that matter, South Africa agreed on limiting its total emissions by 42% relative to a ‘Business As Usual’ (BAU) scenario until 2025. This is a scenario, where emissions are growing under the assumption of no negative impact on climate and ecosystem. The BAU scenario itself is defined by an upper and lower bound. Therefore, a 42% reduction relative to the upper bound of the BAU scenario would still translate to an allowed absolute increase of emissions from 457 Mt to more than 620 Mt of CO_2-equivalent by 2025, compared with 2010 levels (IEA, 2012a). In addition, the commitment is conditional on transfer of technology and financial resources from Annex I countries as defined in the Kyoto protocol (OECD, 2013). However, the OECD (2013) is skeptical towards the political willingness to implement measures that actually facilitate achievement of the committed emission path. Rafey and Sovacool (2011) confirmed that the technology mix as envisaged in the current IRP is seen as far too carbon-intensive with an over-allocation on coal-fired power plants and that a main contribution for emission reductions must come from sectors other than energy generation if targets are to be reached.

Introduction of a carbon tax

One policy instrument to include externalities from carbon emissions into the market price for electricity is the introduction of a carbon tax. With such a tax, a certain amount of money has to be paid for each unit of CO_2 emitted. In that way, the Treasury Department (2010) claims, “lower emissions, greater energy efficiency and the use of cleaner, low carbon technologies” will be triggered in the ESI. The political challenge is to design a carbon tax in a way such that it is equal to marginal external damage costs from GHG emissions in the long-run, while confronting affected sectors immediately with the full price could make them uncompetitive on international markets (Government of South Africa, 2011). The best way to avoid this is believed to be an increasing tax rate, starting from a relatively low level. Vorster et al. (2011) have modeled different carbon prices to find such an optimal tax rate. They found that a gradually increasing tax rate, starting from 100 ZAR/tCO_2-eq. and gradually increasing to 750 ZAR over the next four decades would be most efficient. Their calculations reveal annual potential savings of 600Mt of CO_2-equivalents by 2050 based on the carbon tax. As outlined in the National Treasury's Budget Review (2012), a carbon tax is likely to be introduced in 2013. A starting price of 120 ZAR per ton of CO_2–equivalent is expected with annual increases of 10% until 2020. It is also expected that 60% of all sectors will have their pollution excluded from tax liability to smoothen the immediate burden to vulnerable sectors. Thus, Winkler (2012) estimates the effective tax rate to be reduced to 48 ZAR/tCO_2-eq.. Newbery and Eberhard (2008) have pointed out that Eskom is already factoring-in a shadow-price for its CO_2 emissions, which equals 50% of the price set in the European Emissions Trading Scheme (ETS), in order to smoothen the transition to a tax regime.

Development of rural areas

In South Africa, there is still a big difference in terms of development between rural and urban areas. When it comes to access to electricity, about 3.4 million households are not yet connected to the electricity grid. Table 4 gives an overview of the electrification situation in 2009:

Table 4: Electrification rate in South Africa in 2009

Province	Total Number of Households	Backlog	Households not electrified
Western Cape	1,333,886	191,366	14%
Northern Cape	272,958	50,405	18%
North West	914,070	196,605	22%
Gauteng	3,127,991	740,569	24%
Free State	823,972	201,919	25%
Mpumalanga	879,082	231,485	26%
Limpopo	1,250,716	329,440	26%
Kwa Zulu-Natal	2,405,165	818,708	34%
Eastern Cape	1,667,435	669,421	40%
Total	**12,675,275**	**3,429,918**	**25%**

Source: Adapted from Niez (2010).

One problem identified by Niez (2010) is that about half of the disadvantaged households are situated in informal dwellings that cannot be economically electrified. She clarifies that before these households can be electrified, the residents must either move to formal dwellings or their dwelling must be formalized, so that the provided public infrastructure is preserved from storms. Thus, the main efforts from the government will be in a better development of informal dwellings and rural areas. In his ‘State of the Nation Address 2013’, president Zuma (2013) announced increased activity in rural development. Inter alia, he promised fast-tracked work during the next two years in the North West, a region that lags behind in the provision of basic services. Other initiatives will contain 28 renewable energy projects in the Eastern Cape, Western Cape, Northern Cape and the Free State and the set-up of new transmission lines. One example for increasing investments in rural areas is a CSP project to be built in Upington in the Northern Cape.

Transition of the ESI

The last important aspect that will be guided by future policies concerns the transition of the industry. Energy planning in the IRP is an iterative process, were both latest market data and contributions from the scientific community are included in the revisions of the IRP policy document. One factor that is subject to change over time is future energy demand. Nel (2012) argues that energy demand is driven by changing energy intensity ratios and economic growth of an economy. Thus, changes in the structure of the economy, for instance a further shift towards the tertiary sector, play an important role for policy development and provide benefits that attenuate pressures from economic growth. Nel (2012) identified such benefits in a reduction of the carbon intensity from South Africa’s shift to the tertiary sector, from time gains for investment decisions, from reduced exposure to fuel price volatility and from better access to international carbon-sensitive markets. Other parameters that will change in coming IRP iterations are the LCOE for different generation technologies. These depend on global learning rates, technological breakthroughs, price developments for capital and commodities and on external shocks, such as the Fukushima accident has shown for nuclear technology, when risks must be reevaluated. Thus, it is easy to understand that policies and political targets concerning a transition of the ESI are not always straightforward in South Africa.

If the market structure of the ESI is implemented as envisaged in the ISMO draft bill, the transition towards a more open market for IPPs could lead to a re-allocation of assets. In this case, (Maleka et al., 2010) expect that some of Eskom’s power stations will be sold to IPPs. In addition, new questions about managing the intermittency and dispatchability of technologies will arise at the time when the planned 17.8 GW of new RES are to be integrated in the national grid. Then, it would indeed be better to have a neutral ISMO, which is also acknowledged by Nel (2012). At the level of individual power plants, the completion of the two base-load coal power plants Medupi and Kusile will add new capacity of 9564 MW and equally increase the carbon budget of the country. From this, it is likely that other zero-emission technologies will become more popular in energy planning to offset increasing carbon emissions, which might include nuclear and natural gas. Nuclear new-builds account for 9.6 GW in the current IRP (2010) and they are currently scheduled to be brought online by 2029. However, a site assessment report from February 2013 is being held from the public and doubts about the capacity of the country to build out such capacity were expressed by (Goldman, in Blackman, 2012). Thus, policy changes in this sense are possible and the release of the next revised IRP will show more about this option. In addition, the outcome of explorations and the political willingness to harness shale gas might have the potential to transform the ESI towards a less carbon-intensive path (Creamer, 2013b). Though, besides existing environmental concerns, the net energetic balance has to be taken into account when evaluating the attractiveness of the fracturing technology.

These four areas policies discussion are important and dynamic factors that may influence the conditions under which technologies are to be evaluated. Consequently, they must be accounted for when developing a framework for an evaluation of different generation technologies. This framework will be developed in the next chapter.

3. Research Methods

This chapter on research methods refers to the second sub-objective defined for this thesis, which was to introduce and evaluate critically the levelized cost of electricity (LCOE) framework, to elaborate its shortfalls and to develop a comprehensive framework that allows comparing potential electricity generation technologies for South Africa on a common basis. The usefulness of this approach is justified by Fakir (2012) who has called for a new normative framework for energy planning in South Africa, that is governed by the following parameters: “social outcomes, reducing carbon intensity, getting more from limited finances, accounting for externalities, ensuring long-term flexible energy security and diversifying the industrial base”.

Consequently, the goal of this chapter is to develop a multi-dimensional framework for an economic evaluation of electricity supply options in South Africa. The parameters Fakir (2012) called for will guide the elements contained in the framework too. However, to keep the scope focused throughout this work, main emphasis will be put on the key aspects.

First, the LCOE methodology, a method to measure direct costs of electricity generation, will be introduced and formalized and subsequently its shortfalls will be pointed out. Then, non-market priced cost elements, namely externalities from electricity generation will be discussed and an approach will be developed to incorporate them into the standard LCOE analysis. This will be complemented with a quantification of risks with nuclear energy generation, being the only technology that is exposed to a higher risk class, proven by the fact that these risks cannot be fully insured on the market. Moreover, non-quantifiable aspects of energy resource planning will be discussed for each technology. This includes the aspects of job creation potential, availability of electricity, and energy security. Finally, a combined approach will be formalized, putting all monetary and non-monetary dimensions together. The chapter ends with a brief discussion of the limitations with regard to the methodology developed.

3.1 Direct costs of electricity generation

3.1.1 Levelized Cost of Electricity

The LCOE methodology is a practical tool for economic evaluation of power generation investments and it represents the most transparent framework currently in use for energy planning and policy development (IEA/NEA/OECD, 2010). The clear advantage of this approach is that it allows for comparison of investments that differ in physical principles, fuel types or their economic plant life. When calculating the LCOE of a power plant project, all discounted direct project costs over the life-time of the project are divided by the discounted sum of the electricity that it generates over its life-time. From a financial perspective, LCOE can also be described as the constant level of revenues necessary per year to recover all expenses over the life of a power plant (Roth and Ambs, 2004, NREL, 2010). In the standard approach, these expenses include plant costs, operation & maintenance costs (O&M), and fuel costs. In the end, the calculation will allow for a comparison between different options on a constant unit cost basis, in this thesis in ZAR per MWh.

In practice, two approaches to calculate LCOE have evolved: the simplified LCOE approach (sLCOE) and the Financial Model Approach (FMA). These differ in that the sLCOE approach gives “the minimum price at which energy must be sold for an energy project to break even (or have present value of zero)” while the FMA “solves for the required revenues to achieve a certain internal rate of return” of a specific investor (Black and Veatch, 2011). This internal rate of return is based on company-specific project discount rates, tax liability, financing costs and revenue requirements. The FMA is thus preferable for integrated companies that might have to take internal investment decisions between several technologies. The sLCOE approach, at the other hand, is preferable to policy makers, as it makes projects comparable without accounting for specific requirements that might vary from company to company and thus a single discount rate for all projects is applied. For these reasons and also because company specific data are difficult to obtain for outsiders, the latter approach will be used throughout this thesis. Subsequently, when referred to LCOE, it is the sLCOE approach that is meant.

To calculate the LCOE of a project, capital costs, O&M costs and fuel costs have to be levelized over the life-time of the power plant. Subsequently, these three cost components will be reviewed separately and then combined into a complete LCOE formula.

Plant costs (c_p) are defined as the costs that occur to set up the power plant. Often, for such analysis, the concept of overnight costs is applied, which simulates the case where the costs to install the plant occur ‘overnight’ following the investment, and the plant is ready to operate straight after the investment. Regularly, such data is available in the form of currency per unit of capacity. As all costs have to be levelized on a unit of electricity output, e.g. in ZAR/MWh, plant costs are divided by the time the power plant actually produces electricity in a year. This is given by the 8760 hours of a year (*H*), which are multiplied by a capacity factor (*f*), indicating the percentage of the time the power plant actually produces electricity. So far, this calculation gives capital costs per unit of electricity over one year. In reality, a power plant operates over years or even decades. This is why a capital recovery factor (*CRF*) has to be included in the calculation. This CRF is known as the annuity factor in finance and here defined as the portion of plant cost that the revenues must cover during a year of operation to break the whole project even at the end of the plant life. The CRF thus converts a flow of annual payments over a project life into a present value. It depends on the discount rate (r) applied to the project and plant operation time (*T*). Capital costs can be calculated with the following formula:

$$Capital\ costs = \left[\frac{CRF \cdot c_p}{H \cdot f}\right]$$

$$where\ CRF = \frac{r \cdot (1+r)^T}{(1+r)^T - 1}$$

The second component in LCOE is O&M costs. O&M costs occur during the operation of a power plant and can either be expressed in fix (c_{fom}) or variable (c_{vom}) terms. This depends on the data available. Like capital costs, fixed O&M costs are divided by the multiplier of *H* and *f* to see how much of them occur during one year of production. What is different though is that O&M costs can be subject to increase with growing plant age, caused by technical degradation. Consequently, the sum of fixed and variable O&M costs is multiplied with a levelization factor (*l*). This *l* levelizes all O&M costs over plant life and accounts for possible cost increases by incorporating a price escalation rate (e). By considering a discount rate (r) and project life time (*T*), everything is expressed in net present values.

$$O\&M\ costs = \left[l \cdot \left(\frac{c_{fom}}{H * f} + c_{vom}\right)\right]$$

$$where\ l = \frac{r \cdot (1+r)^T}{(1+r)^T - 1} \cdot \frac{(1+e)}{(r-e)} \cdot \left[1 - \left(\frac{1+e}{1+r}\right)^T\right]$$

The third component in LCOE is fuel costs (c_f). These costs do only exist with technologies, where fuel is physically needed to produce electricity. It is thus an important price factor for fossil-based power plants while negligible for most RES. As with O&M costs, fuel prices are mostly subject to variation over time and consequently, current price levels have to be multiplied with a separate levelization factor for fuel. The formula for fuel costs looks as follows:

$$Fuel\ costs = \left[l \cdot \left(\frac{c_f}{H * f}\right)\right]$$

Including all cost components, the full LCOE formula is then:

$$LCOE = \left[\frac{CRF \cdot\ c_p}{H \cdot f}\right] + \left[l_{om} \cdot \left(\frac{c_{fom}}{H * f} +\ c_{vom}\right)\right] + \left[l_f \cdot \left(\frac{c_f}{H * f}\right)\right]$$

3.1.2 Underlying assumptions

The analysis of LCOE always depends on assumptions about price escalation rates and discount rates. Most often, such estimates are based on historical data and thus projections of their future developments always include a level of uncertainty. As the IPCC (2011) clarifies, *e* and *r* cannot be observed directly, thus assumptions about future real rates must rely on expectations about inflation and price developments. This is why LCOE are often indicated as a range, based on upper-bound and lower-bound levels for *r* and/or for *e*. To account for this, a sensitivity analysis with regard to different levels of r will be provided in chapter 4.2.

It is also important to make clear whether *r* and *e* are expressed in constant real terms, excluding effects of inflation, or in constant nominal terms, as a stream of values in nominal currency, including inflation (Black and Veatch, 2011). For the scope of this thesis, constant real rates, adjusted for inflation, will be applied and results will thus be expressed as ‘real LCOE in 2012 ZAR currency’.

In addition and according to Steyn (2006), discount rates are insofar subject to debate as it is not clear whether they should reflect private risk faced by a monopolist or whether social discount rates should be applied. They would be much lower and in the order of 4-5%, as Griffin (2009) suggests. Especially if high costs arise in the future, the choice of a higher discount rate may considerably affect the LCOE in favor of technologies where high costs arise in the future (IPCC, 2011). In the scope of this thesis, all cost calculations in chapter 4 will be discounted with 5%. The separate sensitivity analysis will make variations of the results from other discount rates visible.

Finally, it must also be noted that LCOE depend on the location of the power plant project to be evaluated. The capacity factor is a technical performance parameter that strongly depends on location, especially in the case of RES. Other technology-dependent parameters such as life-time, investment cost and O&M cost might also depend on local market conditions, wages and maturity of technology (IPCC, 2011). In the analysis, best available locations will be selected for energy projects and consequently, optimistic parameters will be applied. Economically, it makes sense to choose these locations first.

3.1.3 Flaws

LCOE is a good and practical approach to compare costs of different energy technologies on a common basis, but it comes with several serious flaws that limit the significance of the results for reality. In the standard approach, Roth and Ambs (2004) criticize that only costs directly associated to the plant-level are taken into account for economic evaluation, while indirect costs are deprived from entering the equation.

As confirmed by the IPCC (2011), indirect costs miss out in the calculation of LCOE and must thus be thought about separately in a consideration of the competitiveness of a power plant. In the electricity sector, the list of such indirect costs is long and includes, inter alia, externalities (e.g. carbon price mark-up, pollution, or health costs), cost for back-up power that stems from the intermittency of some RES, grid integration and transmission costs, system cost increase from a change of the energy mix, outages of base-load power plants due to maintenance, and path dependence which refers to sunk costs from given investments.

Another flaw in the LCOE methodology is the fact that some direct cost occur far in the future, such as decommissioning costs of a power plant or waste disposal, and are often not included with the argument that given high discount rates, they do not have a significant effect on LCOE anyway (OECD/Nuclear Energy Agency, 2010).

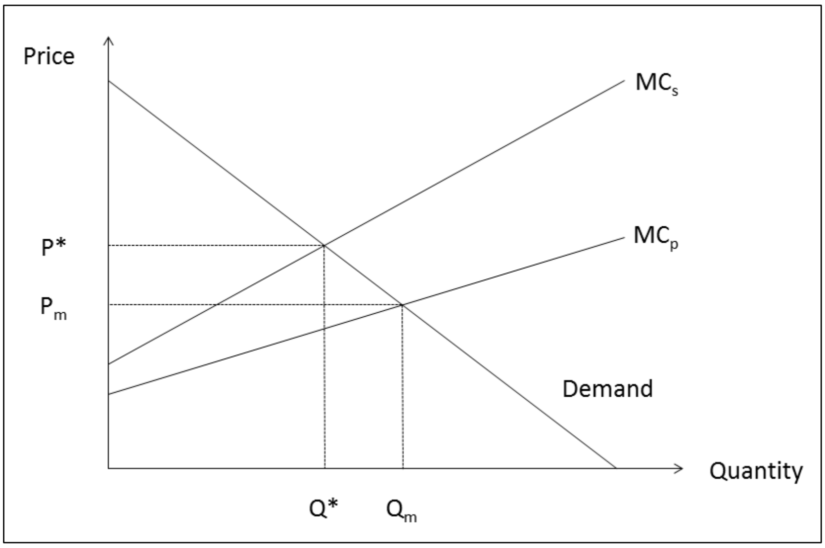
In his concept of a smart energy policy, Griffin (2009) called upon emerging economies to question their willingness to pay for clean and secure energy. Consequently, evaluations of investments in the electricity sector must include the externalities, risks and other problem areas described above to reflect the true willingness to pay and to avoid miss-allocations, as Vorster et al. (2011) acknowledge. A framework including indirect costs and non-monetary aspects of energy planning will be developed below and included to the LCOE methodology in order to provide more realistic prices as decision criteria for energy planning in South Africa.

3.2 Indirect costs of electricity generation

3.2.1 Economic reasoning behind an inclusion of externalities into full costs

The quantification of externalities and their inclusion into market prices for electricity is not a new concept and various studies exist, that have tried to quantify externalities occurring with electricity production. Surprisingly, only few of the studies have been directly combined with the concept of LCOE and to the knowledge of the author, no such combined analysis has been published recently for the case of South Africa. Blignaut (2002) advocated that the downside of a non-inclusion of external costs into market prices is a long-term miss-allocation of resources and this has occurred for the benefits of coal in South Africa, as the Treasury Department (2010) confirms. The economic reasoning behind this situation is simplified in Figure 11.

Figure 12: Electricity market allocation with private and social marginal costs



Source: Own illustration, adopted from Blignaut and King (2002).

Here, the case is depicted where an electricity supplier sells an additional unit of electricity produced from coal at his marginal private cost (MC_p). In equilibrium, this leads to the quantity of Q_m demanded at price P_m. However, the true costs that society faces include externalities from burning the coal and are higher than MC_p. They are depicted by the marginal social cost (MC_s). Thus, the equilibrium including externalities is at a higher price P^* and a lower quantity Q^*. What can be concluded from this situation is that either the electricity price without externalities is too low ($P_m < P^*$) or the quantity of electricity demanded is too high ($Q_m > Q^*$). Blignaut and King (2002) acquiesce that it is also an indication for too much externalities produced and for too few incentives that exist to reduce them. To correct for the root of this market failure, it makes sense to force the electricity supplier to include the externalities into his pricing function.

3.2.2 Externalities studies for South Africa

A meta-study on externalities from the South African electricity sector was compiled by Edkins et al. (2010c) with the aim that this study be included in the next revision of the IRP. It summarizes the research published in previous reports from Dutkiewicz and De Villiers, Van Horen (1997) and Spalding-Fecher and Matibe (2003) and is thus the best local source of data available. The study comprises all technologies used in South Africa, including coal, nuclear, CCGT-gas, OCGT-diesel, biomass, small hydro, wind, CSP and PV. In their study, the authors identified both negative and positive externalities. Negative externalities cover impacts from the entire life-cycle of a power plant, reaching from construction, manufacturing activities, utilization of the plant, fuel production, transport and utilization, to waste management, while positive externalities include avoided health costs from increased access to electricity. Unfortunately, these benefits from electrification were reported Edkins et al. as a uniform value for all technologies per customer electrified. As a result, relative prices between technologies are not affected by this number and for this reason it will be excluded from the analysis. Furthermore, it would only make sense to include these positive impacts from electrification as long as there are still households left to electrify. As soon as a 100% electrification rate is reached, it would not make any economic sense to account for these benefits over the rest of a plant’s life-time.

Impacts from climate change and outdoor air pollution were identified to be the most important drivers that influence negative external costs from coal-based electricity generation. This finding was confirmed in a separate international study from Nicholson et al. (2011). However, Edkins et al. (2010c) admitted that damage costs from GHG emissions seem to be outdated in their local meta-study, if compared with international studies. They also added that international studies out-costed local studies on health impacts from acid mine drainage by a factor of 10. Finally, they acknowledged that their meta-study had been compiled under severe time pressure. Consequently, values for damage costs from emissions and for negative impacts from coal mining will be sourced from international studies.

A detailed externality study for the new Kusile coal-based power plant has been published by Blignaut et al. (2011). This study achieved to overcome the flaws of previous studies in terms of evaluating global damage costs for GHG emissions and health impacts. It incorporates the latest scientific consensus on these issues. Their externality estimates for coal power plants will therefore be applied in this analysis. For all other technologies, results from the local meta-study will be used. Where this one is flawed, as described above, the data-transfer method will be applied and estimates will be adopted from recent international studies.

3.2.3 Data-transfer method from international studies

In order to estimate external costs from GHG emissions (EX_{GHG}) as accurately as possible in this research, estimates for damage costs from GHG emissions (DC_{GHG}) are adopted from recent international peer-reviewed publications. These are multiplied with emission intensity factors of a technology (EI_{rt}), if no concrete estimates on GHG output for a specific reference plant are available.

$$EX_{GHG} = [EI_{rt} \cdot DC_{GHG}]$$

To make data transfer meaningful, Nahman (2011) suggests that values for local pollution impacts based on estimates from other countries have to be adjusted simultaneously for relative income differences between countries and preferences for local environmental quality by using the following formula:

$$\bar{E}_{SA} = \left(E_{BC} \cdot \frac{I_{SA}}{I_{BC}}\right)^{Q},$$

where ($\bar{E}_{SA}$) is the estimated value for South Africa, (E_{BC}) is the estimated value for the benchmark country, (I_{SA}) and (I_{BC}) are the per capita incomes based on purchasing power parity (PPP) rates and (Q) is the income elasticity for environmental quality.

Finally, external costs are added up and included into LCOE. Technically, this is straightforward if all data is provided on a per-unit basis (ZAR/KWh) as in the given studies. In the same way like variable O&M costs, net externalities (EX_{net}) will then be multiplied by a levelization factor l and added on top of the LCOE:

$$Levelized\ externalities = [l \cdot EX_{net}]$$

The difficulty which arises is to determine a reasonable value for l that reflects the cost development of externalities of the plant life. The smallest value that could be assumed for l is the inflation rate, but as all calculations in this analysis are based on real values, inflation will be factored out. An assumption for l would then be a value of one for reasons of simplicity.

To account for uncertainties with the quantification of externalities, lower-, median- and upper-bound values will be reported, consistent with the LCOE methodology. Where prices are available in foreign currency or real values based on a specific base year, they will be converted to ZAR in the base pricing year of the source and then inflated with the South African producer price index (PPI) to standardized 2012 real values.

3.2.4 Risk

As planned by the DoE (2010) in the last IRP iteration, South African policy makers currently face a decision situation concerning an upgrade of the country's nuclear fleet by 9.6 GW of new capacity, which is targeted to be brought online until 2029. However, the deployment of this technology induces profound risks. Yet, the possibility of major accidents, as well as long-term management issues of waste treatment remain controversially discussed issues (OECD/NEA, 2003). Even though probabilities of major accidents seem to be very small, a second major accident happened in 2011 in Japan. This accident has shown that consequences from situations out of control can be immense and costly and are in great part borne by the society at large. In a responsible energy planning, it is thus an imperative to include the risks associated with this technology into its economic evaluation. In this sense, a risk premium for the costs of a major nuclear accident must added to the LCOE for nuclear power, in addition to other external costs from its fuel cycle. This is indeed almost an impossible task, given potentially high external costs and low probabilities for a major accident. Only two scientific studies from Rabl and Rabl (2013) and Meyer (2012) are available, who have both tried to quantify the costs resulting from nuclear accidents based on experiences from the Chernobyl and Fukushima cases. As with other externalities studies, lower-, upper- and central-bound scenarios are reported and these will be included in the full-cost evaluation of nuclear power in South Africa. However, the assumptions made in these studies can be subject debate and their relevance for the case of South Africa will be discussed in the analysis part on nuclear energy, in chapter 4.1.2.

Apart from quantifiable direct and indirect costs of electricity generation, there are also non-monetary aspects that must be evaluated during integrated resource planning. Qualitative and quantitative methods to do so will be described in the following chapters.

3.3 Non-monetary aspects of integrated resource planning

3.3.1 Job creation potential

Job creation from a diversification of the industrial base is a macro-economic factor with special importance for emerging economies such as South Africa, where many people have to struggle to participate in economic development. Even if job creation potential is hard to quantify in numbers, it is still a valid qualitative and social aspect for policy makers in their decisions concerning the IRP for the electricity sector (DoE, 2010). In theory, new jobs can arise from investments into any new energy technology. Maia et al. (2011) allude that existing jobs can be lost if the capacity of one technology is substituted with that of another. At this point, it should be recalled to the reader’s mind that South Africa has committed itself to reduce its future GHG emissions compared to a baseline emissions scenario and conditional on transfer of technology from developed countries. Such a transfer of technology, as Pegels (2012) argues, will induce a shift of the ESI towards new ‘green’ industries and ultimately the creation of new jobs. From a policy maker’s perspective, the relevance with this is that job creation is only valuable, if local companies and human capital are involved in a changing value chain of South Africa’s ESI.

The effects of different energy technologies (t) on job creation have been subject to research. Recently, South Africa-specific estimates about the job creation potential of different energy technologies have been published in reports from Edkins et al. (2010b), Van Wyk et al. (2011) and Maia et al. (2011). Even though differences in the underlying methodology for their projections exist, all of these studies have in common that they consistently specify the job creation potential from various sub-categories such as construction ($J_{c,t}$), manufacturing ($J_{mf,t}$), installation ($J_{in,t}$), operation ($J_{o,t}$), maintenance

($J_{mn,t}$) and fuel processing ($J_{fp,t}$). The sum of these ($\sum J_{i,t}$) gives the total job creation potential of a technology and is reported in jobs created per MW of installed capacity.

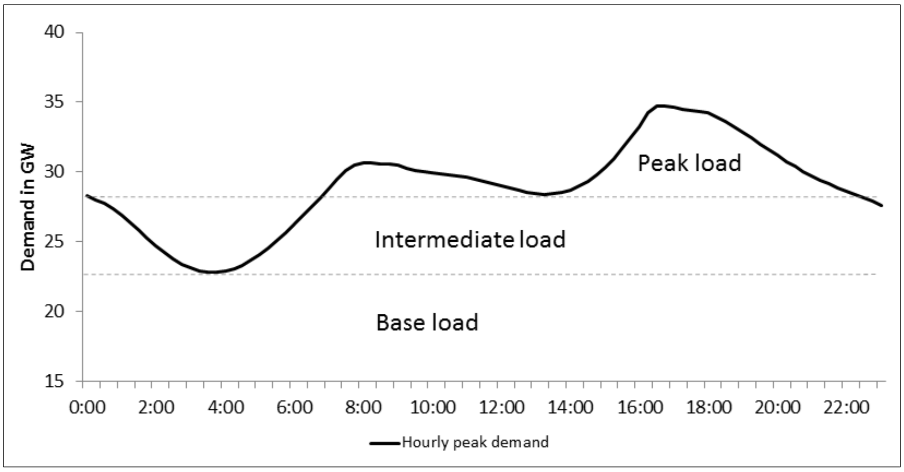
In the analysis part, best estimates for the job creation potential (JCP_t) of each technology will be drawn based on the arithmetic mean of the results from these studies. This will allow for a comparison of the relative job creation potential between technologies:

$$JCP_t(J_{i,t}) = \frac{1}{n}\sum_{i=c}^{fp} J_{i,t}$$

3.3.2 Availability of electricity

Electricity is a good that has to be consumed instantly if it is not stored in another medium. For this reason the concept of availability of electricity becomes another important aspect in a non-monetary evaluation of different generation technologies. Usually, electricity demand is not constant during a day, but depends on how many electric appliances are turned on at a moment. A typical daily demand profile for electricity in South Africa from 2012 is depicted by Figure 13. It must be noted that this demand profile is not identical over time, but seasonal and week-day varieties in demand patterns exist. However, for the scope of this analysis, this typical demand curve will be used for reasoning.

Figure 13: Sketch of typical hourly electricity demand patterns in 2012



Source: Illustration adapted from (Eskom, 2009a, Eskom, 2013h, Sigauke and Chikobvu, 2012).

The electricity load that is put on the system to match demand comes from various energy sources and must be predicted in advance, and the required output of power stations must be planned and dispatched accordingly (Sigauke and Chikobvu, 2011). While base load and intermediate load are relatively easy to predict and provide, peak load must be produced from very flexible power stations that are able to adjust their output instantly. In South Africa this is currently done with OCGT or pumped-storage hydro technology, but the situation will change if more renewable energy capacity will be connected to the grid. Then, it is important to assess the degrees of dispatchability and back-up power capabilities, which are expressed by capacity factors, and the flexibility to adapt power output. These aspects will be discussed qualitatively in the analysis chapter. More complex discussions such as the market value of variable RES based on merit-order-effects or correlation effects, as for example suggested by Hirth (2012) will not be covered here. Such analysis would only be meaningful in a competitive market were market forces influence relative prices, which is not given in the case of South Africa as Sigauke and Chikobvu (2011) advocate.

3.3.3 Energy security

Energy security is one of three pillars of a smart energy policy as defined by Griffin (2009) and it has played a leading role for previous energy investment decisions in South Africa. Politicians have regularly called upon energy security as the main justification to upgrade coal power capacity or to justify investments into the domestic coal-to-liquid (CTL) industry. Rafey and Sovacool (2011) stipulate that such reasoning was legitimate, if one interprets the concepts of energy security and climate change with local reference to the South African history, market and stakeholders. However, the country is progressing and the issue of global climate change imposes new responsibilities on emerging countries to reconsider their concepts of energy security.

In this sense, Sovacool and Mukherjee (2011) have defined energy security as a multi-dimensional phenomenon consisting of availability, affordability, efficiency, technology development, sustainability and regulatory aspects of energy. An evaluation of a technology and its potential to contribute to energy security must thus include a consideration of these aspects. To quantify such aspects, the authors established an exhaustive list of indicators over six dimensions, but admit that selecting a few of them might be sufficient for a reasonable evaluation. Even though their framework was developed to compare energy security between different countries, indicators that allow for a comparison between technologies can be found. In the underlying case, this could be the following indicators in table 5:

Table 5: Selected indicators and metrics for measurement of energy security dimensions

Dimension	Indicator	Metric
Availability	Proven recoverable energy reserves, Total renewable energy resource endowment	Reserves-to-production ratio in years, resource endowment in GW
Affordability	Social marginal cost of electricity generation	ZAR/KWh
Efficiency	Energy end-use efficiency	η, percentage of energy input to output
Technology Development	Lead time for construction of power plant	Years
Sustainability	Energy payback ratio	Number

Sources: Adapted for technology comparison from (Sovacool and Mukherjee, 2011).

3.4 A combined approach / framework

The final and comprehensive approach to evaluate all technology options will consist of a combined monetary evaluation and qualitative discussion as outlined in the previous chapters. LCOE, externalities and risks will be added and levelized on a per-unit basis of electricity output. Job creation potential and energy security will be measured with the metrics introduced, while the availability will be discussed qualitatively. For all calculations, lower, central and upper bound estimates will be made where appropriate. In a summary statistics chapter, all technologies will then be compared directly with each other and the sensitivity to variations in important input factors will be analyzed.

3.5 Limitations

The methodology developed claims by no means to be exhaustive, given the many aspects that play a role in energy resource planning. Besides, parameters that underlie calculations and qualitative evaluations might be subject to controversy. One important example is the choice of an appropriate discount rate which reflects the diminishing value attributed to future cash flows. This choice is especially important when costs occur very far in the future. However, such ethical discussions will not be included here, but it must be noted that different schools of thought were expressed by economists such as Stern (2006), Weitzman (2010), or Nordhaus (2008). To account for possible differences in outcomes from the selection of discount rates, a sensitivity analysis with regard to this parameter is provided in chapter 4.2.2.

Other issues that might limit the validity of the results are availability and quality of data for South Africa. Much of the data is provided through Eskom, a company that is ultimately controlled by the government and possible biases towards certain technologies that seem most profitable might at least be imaginable. Over and above, some of the calculations that rely on previous studies might be subject to mistakes or impreciseness given that the data-transfer method is applied and mistakes that occurred in previous studies are consequently incorporated into this analysis. The same issue applies to analysis of externalities of RES which are partially based on international data, transformed to local circumstances. Thopil and Anastassios (2010) advocate, that accurate analysis can only be performed ex-post, once RES are installed and in operation.

Calculations of projections might be of limited reliability, when these are based on historical events. Consequently, there is no guaranteed certainty that inferences about the future will hold true. In this analysis, such uncertainties concern future energy demand, learning rates as well as job creation potential.

4. Economic, environmental and social analysis of technologies

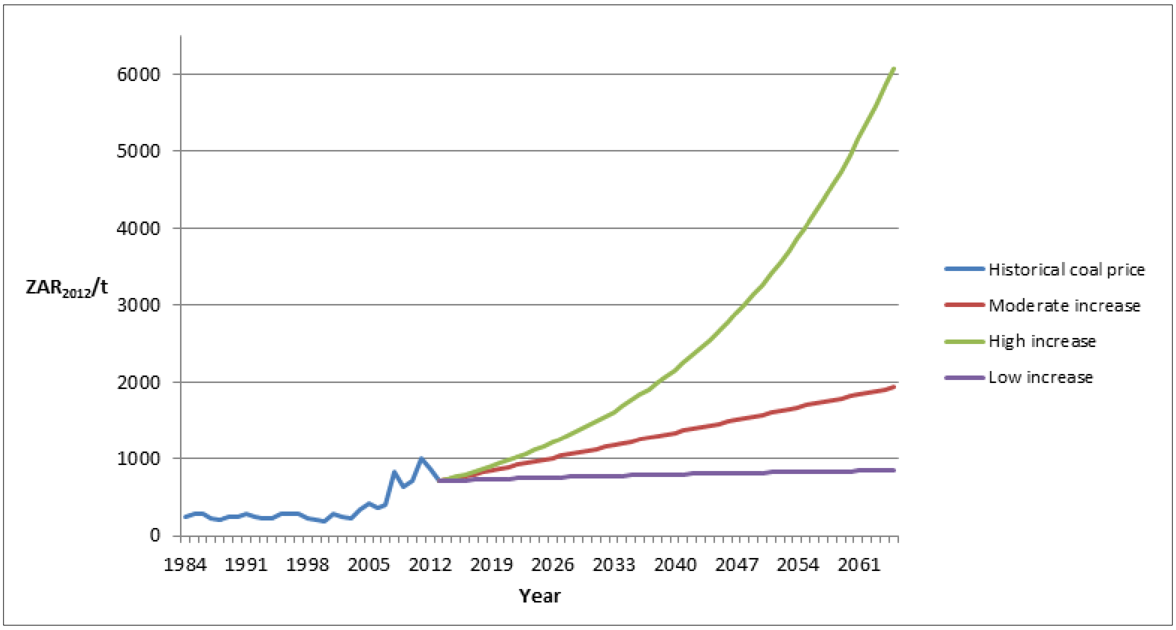
4.1 Research Findings

This chapter reviews relevant electricity generation technologies for South Africa according to the methods described in chapter 3. These will be individually evaluated and findings are presented from chapter 4.1.1 through chapter 4.1.7. In chapter 4.2, results will be synthesized and discussed with regard to sensitivities from parameter variations.

4.1.1 Coal

Coal is the predominant energy source for electricity generation in South Africa and is thus the technology that serves as a benchmark in an economic evaluation of other technologies. Unlike with other technologies, it is not very capital intensive during the commissioning of the plant, but it is very sensible to fuel costs and their future development. Even though Eskom has signed supply contracts with the mining industry which are well below international export prices for South African coal, McKay (2012) and Creamer (2013c) expect the future purchasing price for a metric ton (t) of coal to increase substantially for South Africa's state utility. Thus, it is expected here that the coal price will converge with the international export price in the long-run. Projections for future prices are based on historical coal export prices and on extrapolations of their logarithmic, linear and exponential regressions, as depicted in figure 14.

Figure 14: Price projections for South African sub-bituminous coal export prices



Source: Own projection based on historical coal price (IndexMundi, 2013).

Taking these as a basis, Eskom's coal purchase price is then expected to increase from 349 ZAR/t in 2015 (McKay, 2012) to either 848, 1930 or 6080 ZAR/t in 2065, depending on the scenario. The corresponding price escalation rates from 2015 to 2065 are calculated based on the geometric growth formula[19]. All other relevant parameters underlying the LCOE calculation are presented in Appendix 3 and the Medupi power station, a new dry-cooled super-critical power station with flue gas desulphurization (FGD) was chosen as reference case. When the formulas described in the previous chapter are applied, LCOE for this coal power plant range between 614.49 and 973.13 ZAR/MWh, with 712.97 ZAR/MWh being the median scenario. This is partly in line with what Dames, Eskom's CEO said in (2012, in Yelland, 2012) when he claimed that LCOE from the new Medupi and Kusile power stations would come significantly below 0.71 ZAR/KWh. However, Yelland (2012) reported that critics believed the LCOE to be significantly higher than indicated by Dames, given increasing costs.

If externalities are added to an economic evaluation of coal power, the cost of electricity from that source is subject to an enormous increase. A study from Blignaut et al. (2011) reports external costs between 0.97 and 1.88 ZAR/KWh.[20] Inflated to ZAR_{2012} values and converted to the unit of analysis (ZAR/MWh), costs translate to 1111.38, 1635.53 and 2159.67 ZAR/MWh respectively. These indirect costs are higher than direct costs associated with this technology and include externalities from health impacts, GHG emissions, water use and coal mining. All numbers are based on conservative assumptions, taking for example a global carbon cost of 12.78 and 20.67 USD_{2010}/tCO2-eq. as basis. The greatest portion comes from opportunity costs of water consumption which account for almost 70% of total external costs. All underlying parameters are presented in Appendix 3.

In terms of job creation potential, a new super-critical coal power plant requires on average 3.1 jobs per MW of installed capacity (Edkins et al., 2010b, Van Wyk et al., 2011). About 80% of the jobs are involved in the construction and the manufacturing of the power plant, while only one fifth is attributed to O&M of a coal power plant.

A super-critical coal power plant provides base load power, has a typical capacity factor of 85% and a hot ramp-up time of about one hour. This means that this technology provides a relatively stable amount of electricity output which can be used to satisfy a constant level

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[19] $X_t = X_0*(1+g)^t$, where g is the growth rate, X_t the end value, X_0 the initial value and t is time in years.

[20] The computed average value is 1.43 ZAR/KWh. The average value was not reported in the study, but is will be used here as a proxy for the median-case scenario.

of market demand. At the same time, coal power plants are impractical to cover demand peaks given their low degree of flexibility. An energy system that is based on a high share of coal, as it is the case in South Africa, must thus use an international market to balance system load in times of under- or oversupply. In the long-run, when more flexible or intermittent energy sources might be connected to South Africa's grid, new measures to increase load flexibility and load change velocity of the existing power fleet will become necessary. Hesler (2011) argues that these will be challenging and that existing power plants are not really designed to meet these criteria.

In terms of energy security, coal power plants perform as follows. In 2011, proven reserves amounted to 48 Gt, while production in that year was 250.317 Mt. Thus, the reserves-to-production ratio is about 192 years. Social marginal costs range, according to this analysis, between 1726 and 3133 ZAR/MWh at a discount rate of 5%. The total efficiency of a coal power plant from coal input to electricity output is around 40% and the plant needs to produce energy for about 7 years to offset the energy used during its construction. The Medupi power station will likely need a construction lead time of 10 years, which is very long. The results are depicted in Table 6:

Table 6: Overview energy security indicators for super-critical coal power plant

Dimension	Indicator	Metric	Values	Source
Availability	Proven recoverable energy reserves	Reserves-to-production ratio	192	(Maleka et al., 2010)
Affordability	Social marginal cost of electricity generation	ZAR/MWh	1725.87 – 3132.80	calculated
Efficiency	Energy end-use efficiency	η, ratio energy input to output	0.4	(EURELECTRIC, 2003)
Technology Development	Lead time for construction of power plant	Number of years	10	(Eskom, 2013e)
Sustainability	Energy payback ratio	Life-time energy output to input	7	(Gagnon, 2005)

*Sources:*Various sources, see table.

4.1.2 Nuclear

The latest version of the IRP anticipates a nuclear new-build capacity of 9.6 GW, even though its necessity was challenged in a recent study from the ERC (2013). This upgrade would come in addition to one existing nuclear power station in Koeberg near Cape Town, which has a capacity of 1800 MW, and the Safari-1 research reactor in Pelindaba. A nuclear purchasing program is likely to be commenced in mid-2013, and Campbell (2013) reported that Eskom expects offers from Areva, Korea Electric Power Corporation, Rusatom and Westinghouse for Generation III or III+ reactors. Thus, LCOE are calculated for such a power plant design. Parameters are drawn from the IRP (DoE, 2010) and from the ERC (2013) study which provides updated assumptions on capital costs. This data is complemented with estimates from Stott (2012, in Kotzé, 2012) about uranium fuel costs. Further assumptions had to be made with regard to the escalation rates for O&M costs and fuel costs. Bruynooghe et al. (2010) estimate that O&M costs will increase and a value of 0.5% above the inflation rate is assumed here.

It is also estimated that fuel prices will be subject to increase in the future, given that the IAEA (2001) forecasted a long-term scarceness and increasing exploration costs for natural uranium. Eskom currently covers about 25% of its nuclear fuel needs from natural uranium purchases in South Africa, Namibia and other African countries, while 75% of the fuel is purchased as enriched uranium from suppliers in Europe and Russia (Kotzé, 2012). Consequently, it can be concluded that some level of dependency to international market prices exists and that prices will increase by 1% per year. Yet data on fuel cost calculations are nontransparent in the IRP, especially with regard to the enrichment process, and calculated fuel costs would result in unrealistically low values. That is why the number assumed for fuel cost will be drawn from Stott (2012 in Kotzé, 2012), who has estimated fuel cost for nuclear power plants at 40% of those from coal power plants. All data underlying the LCOE calculation are shown in Appendix 4. LCOE of 658.45 ZAR/MWh result from these calculations.

Rabl and Rabl (2013) estimated the externalities of nuclear power in a post-Fukushima study. Taking into account both external costs from normal operation, which include current operation and waste management, and external costs from accidents, they obtain total external costs between 0.25 and 3.22 Eurocents/KWh, with a central estimate of 0.79 Eurocents/KWh. Adjusted to the context in South Africa with the formula suggested by Nahman (2011), external costs translate to 8.02, 25.33 and 103.26 ZAR/MWh.

In addition, external costs which include the risk of an accident have been assessed in a study by Meyer (2012). She reported a range of risk-adjusted external costs between 10.7 and 34 Eurocents/KWh as realistic, averaging at 22.35 Eurocents/KWh. Adjusted to the South African context with Nahman’s formula, these numbers translate into 300.96, 628.65 and 956.33 ZAR/MWh. It must be noted that Meyer’s estimates vary by an order of magnitude of 9-36 from Rabl and Rabl’s, but these two studies are the only recent studies identified that quantify risks and costs of nuclear accidents. When taking the precautionary principle as the underlying normative framework to evaluate a technology, it is compelling to contemplate all possible events and to consequently use the entire bandwidth of estimates as scenarios. Although nuclear power is also a very water-intensive technology which requires high amounts of water for thermal cooling, no water use externalities are included in the South African context. This is because Eskom (2013d) uses once-through cooling systems which are based on sea-water cooling where the water is released back to the sea after usage without consuming any fresh-water. Thus, no opportunity costs of fresh water are included in the analysis for nuclear.

In terms of job creation, a new nuclear program could be beneficial for the South African economy. If the 9.6 GW capacity extension program is rolled out as planned, Kirillov (2013, in Campbell, 2013) estimates the permanent employment potential at approximately 4000 engineers and 27000 construction workers.[21] This would translate into 3.2 jobs/MW. Edkins et al. (2010b) have come up with a similar value and project a job creation potential of 2.5 jobs/MW for the nuclear industry in South Africa. However, Sokolov (2013, in Campbell, 2013) alludes that the establishment of an effective nuclear industry sector depends on how well legal, regulatory, technical, human, industrial, safety and security aspects are developed.

Similar to a coal power plant, nuclear power serves the base load fraction in an electricity system (Rabl and Rabl, 2013). In fact, nuclear power plants produce the most stable load output, but are also the most inflexible option of electricity generation. The main argument that is brought forward in favor of expanding the South African nuclear program is that nuclear is a cost-effective and CO_2-neutral option of diversifying the country’s electricity supply, even more important in times when coal prices are subject to increase in a carbon-constrained world (DME, 2008). It is thus seen by many as the preferable option to increase security of supply. The associated performance parameters are depicted in table 7:

Table 7: Overview energy security indicators for nuclear power plants in South Africa

Dimension	Indicator	Metric	Values	Source
Availability	Proven recoverable energy reserves	Reserves-to-production ratio	>100	(NEA/IAEA, 2012)
Affordability	Social marginal cost of electricity generation	ZAR/MWh	666.47 – 1614.78	calculated
Efficiency	Energy end-use efficiency	η, ratio energy input to output	37 %	(WNA, 2013)
Technology Development	Lead time for construction of power plant	Number of years	16	(DoE, 2010)
Sustainability	Energy payback ratio	Life-time energy output to input	14 - 16	(Gagnon, 2005)

*Sources:*Various sources, see table.

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[21] Here, construction jobs are counted towards permanent jobs given a lead time of 16 years for this project.

4.1.3 Natural gas

In 2013, natural gas is virtually non-present as a fuel in South Africa's ESI, but may become an important option if unconventional gas will be recovered from the Karoo Basin (Botha and Yelland, 2011). Instead, diesel fuel sourced from the domestic CTL industry fires five Eskom power stations with open-cycle gas turbine technology (OCGT), which have a combined capacity of 2452 MW. These flexible power stations are built to supply electricity during peak demand hours and for system stabilization. Two new OCGT peaking stations are currently being constructed by IPPs, Avon and Dedisa, adding another 1005 MW of capacity (International Power GDF SUEZ, 2011) to the grid. If new supplies of domestic natural gas were available on a larger scale, these seven OCGT power plants could easily be upgraded into more efficient combined-cycle gas turbine power plants (CCGT) running on natural gas. Moreover, it is also possible to retrofit aging coal-fired power stations into gas power stations at economic benefits, which has been disclosed by Silverstein (2013) who claimed that a switch to gas was beneficial for climate and job creation. This has been shown in the US and other countries, where shale gas supplies become increasingly important. Consequently, it is worthwhile to have a closer look at CCGT power plants as a flexible option to cover peak demand, intermediate demand as well as base load in South Africa. Subsequently, three alternative capacity factors of f = 5%, 50% and 85% will be taken as basis for an analysis of the CCGT option.

The outcome of LCOE analysis based on the parameters described in Appendix 5 adds up to lowest LCOE of 640.54 ZAR/MWh, for a gas power plant producing base load at f = 85%, to 698.25 ZAR/MWh for a CCGT plant delivering intermediate load at f = 50% and finally to LCOE of 1959.61 ZAR/MWh for peak electricity output, when the plant is only used at a capacity factor of 5%. This considerable variance in LCOE shows that the cost for electricity from a gas power plant is pretty much fuel intensive and thus fluctuates with the plant utilization (f).

External costs from CCGT power plants are estimated to range of 1326.75, 1589.42 and 1840.43 ZAR/MWh. However, it must be admitted that the given external cost analysis for shale gas combustion is by no means complete, given the novelty of the technology and the resulting lack of empirical data and contributions to the scientific research body. This concerns, inter alia, estimations on external costs resulting from a diminishing value of land property close to gas wells, as Muehlenbachs et al. (2012) allude. In addition, it is a difficult task to quantify the harm to society from large amounts of fresh water necessary and from groundwater contamination which occurs during fracturing processes. While statistics on life-cycle fresh water consumption for shale gas-powered CCGT power plants have been published by Laurenzi and Jersey (2013), these have to be read with caution as they are financed by ExxonMobil Research and might be biased in favor of gas businesses. A too optimistic description of the benefits from this unconventional resource may be a result. Barth (2013), as well as Kinnaman (2011), elaborate on this deficiency more in detail. It also appears that Eskom's average water costs of 3.47 ZAR/m^3, paid in 2012, do not appear to reflect the true value of water in a water scarce country. Consequently, opportunity costs of water consumption had to be estimated. To do so, the same methodology and alternative technologies as used by Blignaut et al. (2011) were applied and opportunity costs of 1.14 ZAR/KWh to solar, 1.31 ZAR/KWh to wind and 1.49 ZAR/KWh to coal were detected.[22] This seems more reasonable, given the fact that shale gas extraction is more water intense than coal mining. Resulting median full cost estimates from shale gas-powered CCGT are then 2229.96, 2278.67 and 3549.03 ZAR/MWh, depending on underlying capacity factors.

According to The Economist (2012), businesses and proponents of the gas industry generally describe job creation potential from their activities as substantial. However, it is at least questionable by how much the local rural population of the Karoo could directly benefit from a developing gas industry. This is also dependent on policies to be developed. Should CCGT power stations be built, Edkins et al. (2010b) and Van Wyk et al. (2011) estimate an average of 2.39 jobs per MW of installed capacity.

As described earlier, the advantage with a CCGT power plant is that it can dispatch its output of electricity in a flexible way, being the most flexible of all fossil generation options. As a result, it offers a maximum availability factor. Within 5-7 minutes, capacity can be ramped-up and the power output can be adjusted to demand (Eskom, 2009b). If gas supplies should once be secured from domestic extraction of unconventional shale gas and power stations be deployed on a larger scale, both availability and energy security will benefit from it, as shown in table 8:

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[22] See appendix 5.

Table 8: Overview energy security indicators for gas power plants in South Africa

Dimension	Indicator	Metric	Values	Source
Availability	Proven recoverable energy reserves	Total resource endowment	Explorations ongoing	(DMR, 2012)
Affordability	Social marginal cost of electricity generation	ZAR/MWh	1967.29 – 3800.04	calculated
Efficiency	Energy end-use efficiency	η, ratio energy input to output	50%	(Godoy et al., 2010)
Technology Development	Lead time for construction of power plant	Number of years	3	(Lazard, 2012)
Sustainability	Energy payback ratio	Life-time energy output to input	2.5 – 5	(Gagnon, 2005)

Sources: Various sources, see table.

4.1.4 Concentrating Solar Power

CSP is an important option to generate electricity and heat in countries with good solar irradiance. Thus, this form of electricity generation is very interesting for South Africa, and Fluri (2009) has estimated the technical resource potential at 548 GW, or based on current plant capacity factors, at 1919 TWh per year, which exceeds South Africa's electricity demand manifold. Different technologies have evolved to capture sun energy, but all have in common that the solar irradiation is concentrated on a central location to heat a medium. When the heat is extracted, a conventional steam turbine can be powered from this (Coley, 2008). In the IRP, the DoE (2010) committed to install a total CSP capacity of 1.2 GW by 2025 in South Africa. Ahearne (2012) reported that 150 MW of parabolic through technology and 50 MW of solar tower technology have been allocated to IPPs in the first two REIPP bidding rounds. He added that a further 800 MW will be allocated in upcoming bidding rounds and that the remaining 200 MW will be constructed by Eskom. A bidding cap has been installed at 2.85 ZAR/KWh. Many plant designs exist, which makes it difficult to compare them in terms of LCOE. In this study, a power plant using solar tower technology with 3 hour storage capacity has been selected as the reference technology. Ernst&Young and Enolcon (2013) estimate local employment potential to be the highest for this kind of technology. When considering input parameters as summarized in Appendix 6, CSP in South Africa induces LCOE of 1308.66 ZAR/MWh. Like other RES, it is a capital intensive technology, but has the advantage of zero fuel costs and moderate O&M costs. In the literature, some variation concerning capital costs has been identified, therefore a conservative value of 59860 ZAR/MW has been chosen.

Externalities of the solar tower technology are very moderate and include health impacts and GHG emissions. For different scenarios of global damage costs from GHG emissions, total external costs amount to 11.26, 15.80 and 18.78 ZAR/MWh. So, full costs for CSP come down to a range between 1319.92, 1324.46 and 1327.44 ZAR/MWh. The heat carrier medium of CSP power tower technology can be based on molten salt and consequently, such power plants are not dependent on fresh water consumption.

CSP offers substantial potential for job creation in South Africa, as Ndebele (2012, in Ahearne, 2012) affirms. His assessment was confirmed in a survey conducted by Ernst & Young and Enolcon (2013), who revealed medium to high potential for several fragments in the value chain of a CSP project. In Spain, local value creation increased from an initial 50% to 80% in the present, increasing the number of jobs in the country. Based on studies from Edkins et al. (2010b), Maia et al. (2011) and from the International Labour Office (Van Wyk et al., 2011), an average JCP of 17.6 jobs/MW is projected from construction and operation of a CSP plant in South Africa.

With regards to availability of electricity, CSP offers a possibility to disassemble the collection of sun-energy (heat) and the production of electricity by means of thermal storage. Consequently, the degree of intermittency of that technology is reduced. Today, it is possible to build plants that are able to store heated liquids for up to 15 hours for electricity production. Therefore, the range of CSP plants can be extended from late morning hours through most of the night, which makes it suitable to serve intermediate and peak load during these hours. Through the means of storage, output becomes highly dispatchable. Nicholson et al. (2011) categorized CSP even as a base load technology. Improving the availability of an intermittent source is also a result of a stochastic analysis of the variability of weather patterns. Suri (2011) has reported a minimum of 2796 KWh/m² of sun energy at the 90% confidence level near Upington, the location of the first plants to be constructed. Energy security patterns of CSP are illustrated in table 9:

Table 9: Overview energy security indicators for CSP plants in South Africa

Dimension	Indicator	Metric	Values	Source
Availability	Proven recoverable energy reserves	Total renewable energy resource endowment	548 GW, or 1919 TWh	(Fluri, 2009)
Affordability	Social marginal cost of electricity generation	ZAR/MWh	1319.92 – 1327.44	calculated
Efficiency	Energy end-use efficiency	η, ratio energy input to output	40 %	(Lazard, 2012)
Technology Development	Lead time for construction of power plant	Number of years	2	(Lazard, 2012)
Sustainability	Energy payback ratio	Life-time energy output to input	80	(Jacobson, 2009)

Sources: Various sources, see table.

4.1.5 Solar Photovoltaic

Solar PV is the second technology option to harness sun energy in South Africa. Yet, an analysis of this technology can quickly become complex: various types of solar panels have evolved until today and there is still no “gold standard” for a dominant technology between silicon-based and thin-film applications. Another argument is that solar PV can be employed on different scales, ranging from residential to utility-scale applications which can either be grid connected or isolated. Moreover, the electricity output from solar panels depends on local solar irradiation levels as well as on tilt angles in which the panels are positioned. All in all, there are many different possible combinations of parameters and consequently, Darling et al. (2011) argue that parameter distributions must be used to estimate the LCOE of this technology in a realistic way. However, this is not feasible within the scope of this research, and thus one exemplary technology in combination with typical parameters must be chosen. As most interesting options to look at, a rural utility-scale PV power plant (RUS) with 10 MW capacity and a residential roof-top application (RRT) with 1 KW capacity, both located near Upington and composed of polycrystalline silicon PV panels were selected as the reference projects for analysis. This makes sense as bulk energy generation options are compared throughout this analysis. Besides, both CSP and PV can be compared on a common basis if their output is measured under identical geographical conditions. Finally, it makes economically sense to install solar power plants in the most favorable places first.

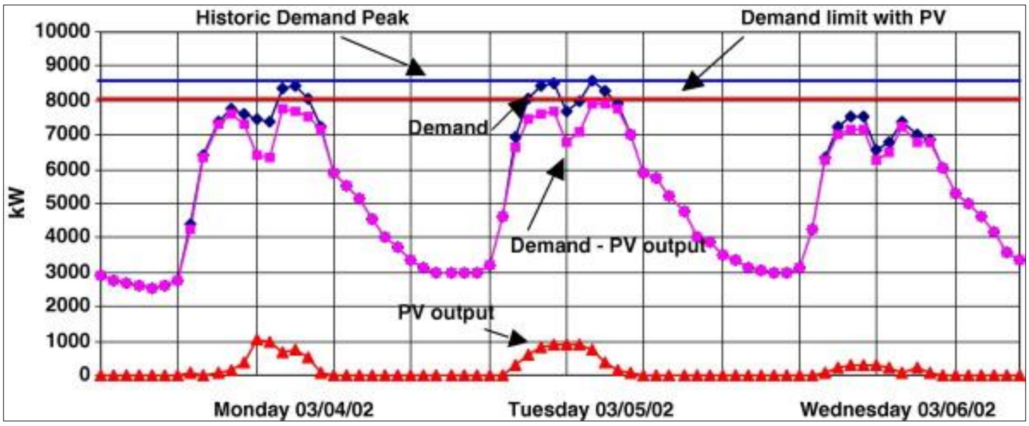
All other technical parameters related to the analysis have been taken from most recent literature available and are specified in Appendix 7. For such exemplary applications, LCOE range between 939.90 ZAR/MWh for RUS and 1456.28 ZAR/MWh for RRT.

During the lifecycle of a PV power plant, quantifiable externalities stem from GHG emissions and health issues during the production process of plant components. Given low GHG emission factors which range between 23 – 44 kg CO_2-eq./MWh (Peng et al., 2013) and moderate health effects of 2.32 ZAR/MWh (Edkins et al., 2010c) external costs remain low compared to other generation options. Consequently, external costs of a PV power plant in South Africa range between 2.47, 6.55 and 11.33 ZAR/MWh dependent on assumptions on GHG abatement costs.

A development of the PV sector could become a job motor in South Africa, especially additional manufacturing facilities for solar panels will be opened up. All three studies on job market potential in South Africa's ESI attribute a high job creation potential to new PV power plants. On average, Edkins et al. (2010b), Van Wyk et al. (2011) and Maia et al. (2011) report a number of 30.1 jobs/MW of installed PV capacity. Maia et al. thus conclude that PV is among the top generators of new direct employment from RES.

Contrarily to CSP there are not yet any reliable large-scale storage concepts for PV-generated electricity and this energy source is thus still dependent on weather conditions. Although commercial advances in storage technology are likely to be introduced soon, it is more realistic to estimate that a utility-scale PV power plant will feed its production directly into the grid in South Africa. Still, this has advantages: daily output patterns of PV can be very favorable for the load management of an electricity system. As PV electricity is generated during day-time with output peaking around noon, PV power plants can reduce the burden on the electricity system, which has then a reduced residual peak demand. This functionality has proven successful in Brazil and was described by Rüther et al. (2008). It is outlined in figure 15.

Figure 15: Effect of PV feed-in on peak electricity demand



Source:(Rüther et al., 2008).

Even though solar PV is an intermittent source of energy, its economic value might be significant as marginal costs during peak demand hours could be lower than that of other peak generation options. Furthermore, deployment of PV on a larger scale in South Africa might be a substitute to demand reduction programs which are generally more difficult to handle for utilities and customers. This way, PV is a source of energy that scores well in many dimensions of energy security, which are listed in Table 10:

Table 10: Overview energy security indicators for PV in South Africa

Dimension	Indicator	Metric	Values	Source
Availability	Proven recoverable energy reserves	Total renewable energy resource endowment	1000 TWh	(Edkins et al., 2010a)
Affordability	Social marginal cost of electricity generation	ZAR/MWh	942.37 – 1467.61	calculated
Efficiency	Energy end-use efficiency	η, ratio energy input to output	12%	calculated
Technology Development	Lead time for construction of power plant	Number of years	2	(Lazard, 2012)
Sustainability	Energy payback ratio	Life-time energy output to input	5.7 – 26.7	(Peng et al., 2013)

Sources: Various sources, see table.

4.1.6 Wind Power

Wind power is the third important option for renewable electricity generation in South Africa. In search of low-carbon electricity generation alternatives, the DoE (2010) has included new wind power capacity of 8400 MW in its policy-adjusted scenario in the IRP. Consequently, new wind farms will be developed throughout the next years, with about 400 MW coming online each year during the next decade. Several wind farm projects are already under construction.

The economic value of a wind power station depends on a multitude of factors. Most important for the performance of a wind turbine are location and the prevailing average wind speed patterns that determine how much energy the power plant can capture. Other important factors are the choice of optimal parameters of the power plant, which include rated turbine capacity, hub height, rotor diameter, cut-in and cut-out wind speeds[23] and other factors that influence operation and maintenance requirements for the plant. According to Ayodele et al. (2012), who have recently modeled the technical potential of wind power plants at 10 different measurement sites in South Africa's Western Cape region, the combination of all these factors sets the optimal choice of turbine specifications and the maximally achievable capacity factor at that site.

Based on the results from Ayodele et al., a state of the art onshore turbine with 3 MW rated capacity, a hub height of 80m and a rotor diameter of 112m, was chosen as the relevant technology for LCOE analysis. The achievable capacity factor for the wind power plant was estimated at 35%, based on the range of capacity factors reported in the modeling results from Ayodele et al. (2012). With these parameters (listed in Appendix 8), LCOE for a wind power turbine amount to 529.73 ZAR/MWh.

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[23] These are the wind speeds at which the turbine starts production (cut-in) and at which it is stopped if wind speeds are too strong (cut-out).

One main advantage of wind power is the low level of external effects associated with this technology. In recent total life-cycle assessments of wind turbines, emission intensity factors between 4.97 and 9.00gCO_2-eq./KWh were reported by Wang and Sun (2012) and Guezuraga et al. (2012). Apart from minor health effects during the production of the power plant, no significant and measureable external effects have been identified in the literature body (Kaygusuz, 2010). Thus, external costs only add up to 1.13, 1.98 and 2.94 ZAR/MWh for different scenarios.

A growing number of wind power projects will have positive employment effects for the value chain of wind power in South Africa. Averaged over existing employment impact studies carried out by Edkins et al. (2010b), Maia et al. (2011) and Van Wyk et al. (2011), wind power projects generate as much as 9.1 jobs/MW of new installed capacity. Van Wyk et al. (2011) argue that this figure is conditional on a threshold level of 150-200 MW of new capacity per year that must be brought online over at least three years in a row in order to trigger the development of a domestic wind power manufacturing industry in South Africa.

Despite all advantages, wind energy has the draw-back of being an intermittent and non-dispatchable source of energy. Consequently, an energy system cannot only rely on wind energy, as the wind might just not blow at a given point of time. However, measurements of historical wind patterns are currently collected and condensed in the Wind Atlas of South Africa (WASA). The WASA helps to predict the power outcome of certain sites with a degree of certainty. A thorough analysis by Ayodele et al. (2012) has shown that on average, wind blows regularly during evening peak demand hours in South Africa and at these times higher capacity factors can be reached with wind power plants. Complementary to higher solar outputs during the morning peak, wind power is therefore a near ideal fit to reduce the demand peak pressure in South Africa. Furthermore, intermittency and dispatchability factors can be improved much in favor of wind power through a combination with storage capacity, for instance with pumped-storage hydro technology (Avery, 2007).

Hence, wind power contributes to South African energy security, scoring particularly well in the availability, affordability, technology and sustainability dimensions. All results are displayed in Table 11:

Table 11: Overview energy security indicators for wind power in South Africa

Dimension	Indicator	Metric	Values	Source
Availability	Proven recoverable energy reserves	Total renewable energy resource endowment	80 TWh	(Hagemann, 2009)
Affordability	Social marginal cost of electricity generation	ZAR/MWh	530.86 – 531.97	calculated
Efficiency	Energy end-use efficiency	η, ratio energy input to output	40-45%	(Chen et al., 2009)
Technology Development	Lead time for construction of power plant	Number of years	1	(Lazard, 2012)
Sustainability	Energy payback ratio	Life-time energy output to input	34	(Gagnon, 2005)

Sources: Various sources, see table.

4.1.7 Other renewable energy sources

In addition to the energy sources analyzed thoroughly in the previous chapters, there are other RES which have the potential to play a role in South Africa's future ESI. However, their potential contribution seems to be limited either by physical or technological constraints. These energy sources include wave power, different forms of biomass and small-scale hydro power. For reasons of completeness, the main issues with these sources will be discussed briefly here.

Among other renewable energy sources, wave power is the most promising option for future electricity generation, with a technical potential of about 18.7 TWh per annum. This substantial estimate led to more focused research on that technology, and measurements are currently carried out by research institutes, Eskom and other private companies. It is likely that this technology may contribute to the supply industry in a not so distant future. However, as of today it is very difficult to evaluate these options economically, given the immatureness of the technologies and the few real-world applications that exist.

Biomass is already an important source of energy in South Africa and it could become more important for the electricity sector. Dasappa (2011) estimated the potential contribution of biomass to the supply mix at a further 643 MW which translate to about 4.8 TWh. This estimate is based on a sustainable use of biomass from agricultural residues, and takes neither extra plantations of cereals nor wood cutting into account. He argues that unlike other RES, biomass power plants or co-firing in compatible coal-fired power plants would have the advantage of high load factors and lower carbon intensity. Biomass is thus one of the few RES suitable for base load generation. An additional benefit with biomass is that its collection is very employment intensive and thus beneficial for job creation.

Last but not least, hydro power is limited by low levels of precipitation in South Africa, which receives only half of the world average in rainfall. While large hydro power plants have mostly been developed where economically feasible, opportunities for small-scale hydro applications remain. Although not very effective for bulk-energy generation, Van Vuuren et al. (2011) estimated a technical potential of 0.9 TWh per year from small-scale hydro power plants in South Africa. This is mainly originating from a large number of existing dams which could be retrofitted with small-scale generation turbines at comparably low investment costs. In addition, supplementary artificially built pumped-storage schemes could still play an important role as a means of storage for solar and wind energy, in case the share of such intermittent RES in the system is increased.

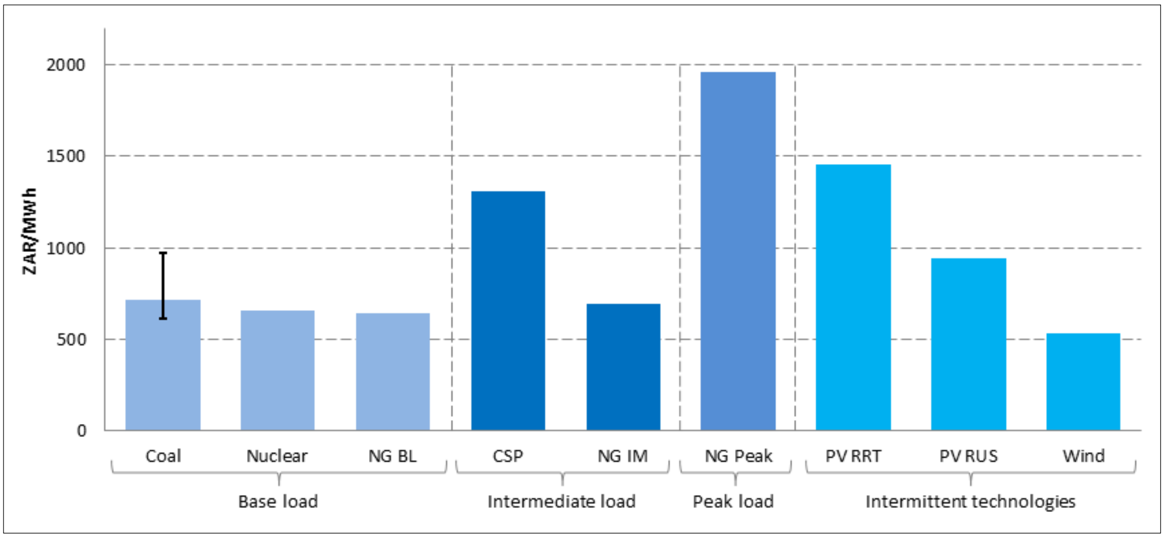
4.2 Discussion

4.2.1 Summary statistics

Throughout chapter 4.1, comprehensive impact analyses of all technologies have been carried out and were presented individually. The results obtained are now contrasted and discussed in this chapter.

The first direct comparison of technologies is made at the LCOE level: while the LCOE for coal power are indicated as a range of possible costs with a lower and upper bound, median LCOE were reported for all other technologies. This was owed to the uncertainty with the future development of the coal price in South Africa. Other fuel intensive technologies compared are nuclear and natural gas. The mechanisms of fuel pricing in the nuclear industry were found to be very intransparent. The price of natural gas from domestic shale gas resources was estimated to remain constant over the 30-year life-time horizon of a CCGT plant. In contrast, costs are more firm to foresee for the capital cost-intensive technologies and so median LCOE are a reasonable estimate to make with CSP, PV and wind. This is why all LCOE figures other than coal are expressed as median cost estimates. Figure 16 contrasts the results from the analysis, grouped into base load, intermediate load and peak load generation options. Intermittent energy sources are separately displayed in the last column.

Figure 16: Summary median LCOE all technology options

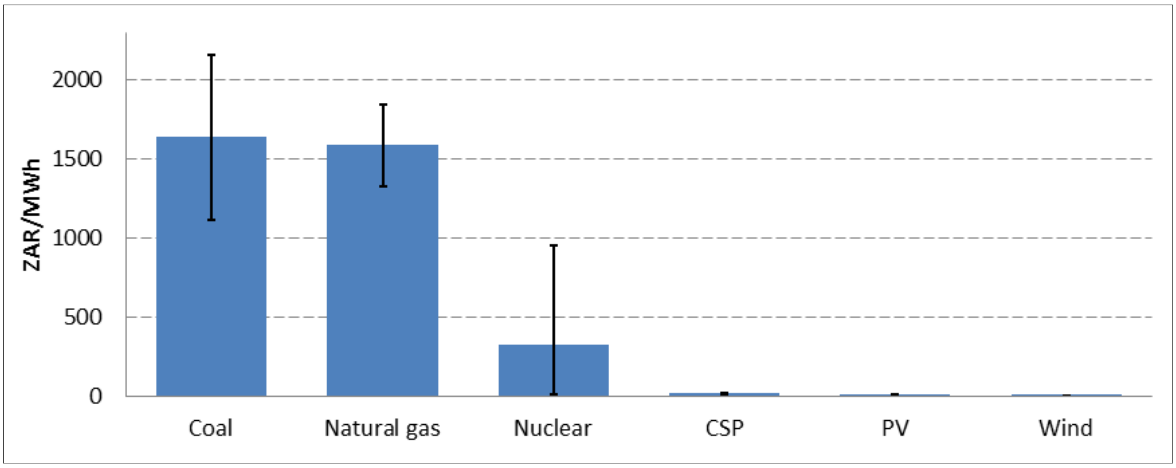


Source: Author.

From figure 16, it can be inferred that median LCOE for base load technologies are comparably low and almost balanced. Coal is an outlier in the sense that there is the possibility of being slightly cheaper or considerably more expensive than nuclear and base load natural gas. Among intermediate load technologies, natural gas has LCOE which are about 48% lower than for CSP. For the peak load sector, natural gas is the only option examined and its LCOE more than double with respect to base and intermediate load. The highest LCOE of all technologies is caused by the low capacity factor of the option with a resulting high share of fix costs attributed to each unit of electricity generated. Unfortunately, this option is the only dispatchable back-up power at present, apart from diesel fired-OCGT and a pumped-storage scheme with limited capacity. When it comes to intermittent energy sources, substantial differences exist between wind and solar power. While wind power was found to have the lowest LCOE of all technologies, PV RUS is cost-competitive with intermediate load CSP. On the other hand, PV RRT is due to many small scale implementations the second most expensive option, but it is still considerably cheaper than peak load natural gas.

In a second step, indirect costs of all technologies were evaluated. The results from lower, upper and median case scenarios are visualized in figure 17:

Figure 17: Summary external costs all technology options



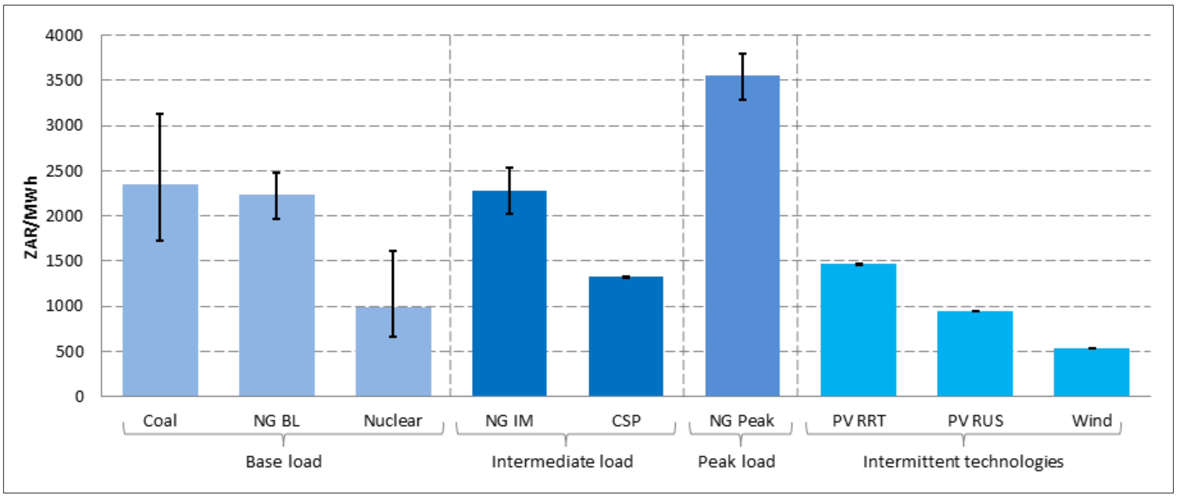
Source: Author.

The figure shows that burning coal causes the highest externalities if median externalities estimates are compared. Yet, coal could still be topped by natural gas in the lower bound scenario, when low GHG damage costs and opportunity costs for water a taking are assumed in the externalities evaluation. In either case, both technologies impose far higher levels of external costs to the society at large than all other technologies. While the possible variation of externalities is much higher for coal, external effects from shale gas are not subject to this much deviation, given their comparatively relatively low emission intensity compared with coal.

Next, nuclear power is a special case in terms of risk assessment and indirect costs. The large error bar in relation to other technologies is a clear sign for the difficulty to reasonably evaluate the risk of this technology. For example, Rabl and Rabl (2013) report probabilities of major accidents, which are only based on two past events in Chernobyl and Fukushima. Whether this approach allows for inferences about the frequency of future accidents can at least be doubted. In addition, their study fails to consider several other factors that might also influence the probability of accidents. These include increasing frequency of natural disasters from climate change, increasing average age of the power plant fleet and an increasing total number of plants. Also, it seems early to objectively evaluate health damages from the Fukushima accident, and Gluzman et al. (2012) point out that there even remains controversy about the number of thyroid cancers resulting from Chernobyl. All these factors bias the results and make an objective evaluation of nuclear power difficult. The last observation from figure 17 is that CSP, PV and wind power entail considerably lower external costs to society than all other technologies.

The logical next step is now to consolidate direct and indirect costs of the technologies to have a say about their overall economic impact and competitiveness. The outcome of this process is expressed by figure 18:

Figure 18: Summary full costs all technology options



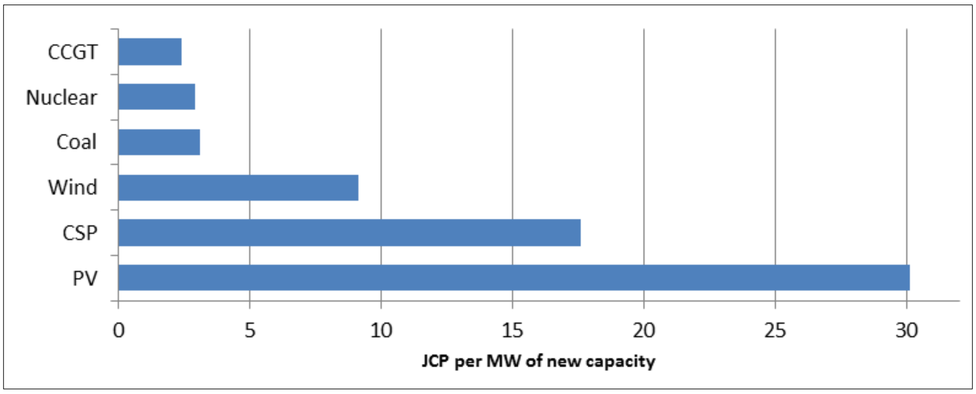
Source: Author.

It can be noted quickly, that an accommodation of indirect costs has effects on the ranking order in the base load and intermediate load segments. In the new picture, NG BL becomes the second most expensive technology option in terms of median full costs, only surpassed by coal. Due to its large error bar, coal can either be the most expensive base load option or be almost competitive with high-cost nuclear. Still, median full cost of nuclear are lower than that of coal and NG BL, if one accepts the risk-evaluation from the studies cited.

In the intermediate load segment, CSP has now become substantially cheaper than natural gas. Both options are not very reactive to variations in indirect costs, a fact that improves the level of certainty of the outcome. In the peak load segment, short-time supply gaps have to be covered by CCGT at full costs ranging between 3286.36 and 3800.04 ZAR/MWh. Last but not least, intermittent technologies have become competitive with most technologies in other load segments. From a full-cost perspective in the context of South Africa, these RES gain an economic advantage over fossil-based generation technologies.

The next dimension of analysis is employment impacts for the economy from investments into new power plants. Figure 19 contrasts estimates for permanent job creation potential of different technology options in the value chain of the South African Energy industry.

Figure 19: Summary job creation potential all technology options

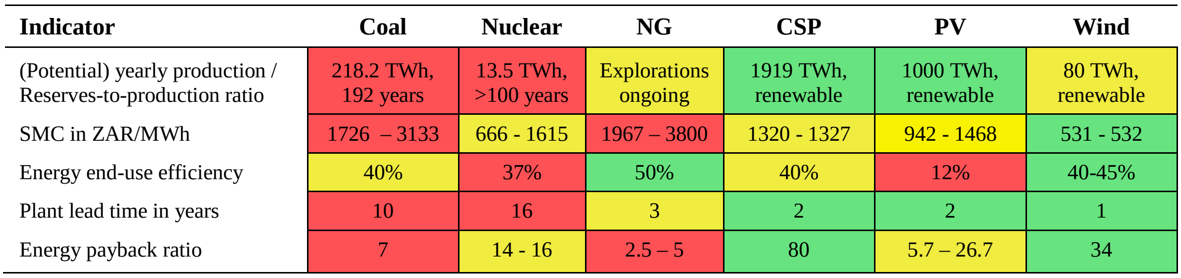


Source: Author.

The graph highlights that fossil-based energy sources are more employment-efficient in terms of jobs/MW and contribute to fewer new jobs in the economy if chosen for energy investments. However, this does not express anything about the options to be preferred from a project developers' or policy makers' cost-benefit point of view, and employment creation itself is a political topic with the question of interchangeability of capital and labor at its heart. Assuming however, that employment creation for domestic jobs is a result from transfer of technology and from a localization of segments of the energy industry value chain, then new "green industries" are often praised as a preferable political goal for the government of an emerging economy (Maia et al., 2011). In the case of South Africa, PV, CSP and wind are then technologies with higher value in terms of new job creation.

The last assessment is made between energy security indicators. This is a challenging comparison because a “numerical ranking” between options with differing degrees of flexibility[24] might not be compelling at a first glance. Nevertheless, technical options to overcome this issue[25] exist and are being developed to improve the balance of an electricity system. Thus, it makes sense to compare the relative performance of technologies by grouping them into the categories “worst performance” (red), “average performance” (yellow) and “best performance” (green). Table 12 contrasts the resulting scorings of all technologies:

Table 12: Summary energy security indicators all technologies



Indicator	Coal	Nuclear	NG	CSP	PV	Wind
(Potential) yearly production / Reserves-to-production ratio	218.2 TWh, 192 years	13.5 TWh, >100 years	Explorations ongoing	1919 TWh, renewable	1000 TWh, renewable	80 TWh, renewable
SMC in ZAR/MWh	1726 – 3133	666 - 1615	1967 – 3800	1320 - 1327	942 - 1468	531 - 532
Energy end-use efficiency	40%	37%	50%	40%	12%	40-45%
Plant lead time in years	10	16	3	2	2	1
Energy payback ratio	7	14 - 16	2.5 – 5	80	5.7 – 26.7	34

Sources: Author.

From this table, a general trend can be identified which seems contradictory to what many stakeholders involved in South African energy planning claimed: that coal and nuclear are the only technologies that bring energy security to South Africa. Contrarily, it can rather be detected that these two technologies score particularly poor compared to the other technologies. It can also be noticed that Wind and CSP score particularly well in the categories reported and thus contribute to enhanced energy security. It must be added that the selection of indicators is a selection carried out by the author of this research and might thus not be completely representative, but the results are nevertheless remarkable.

4.2.2 Sensitivities of results

As mentioned previously, results of cost analyses are always sensitive to the various input parameters chosen. More specifically, full costs depend on assumptions made for LCOE and for externalities valuation. LCOE can be sensitive to variations in capital costs, O&M

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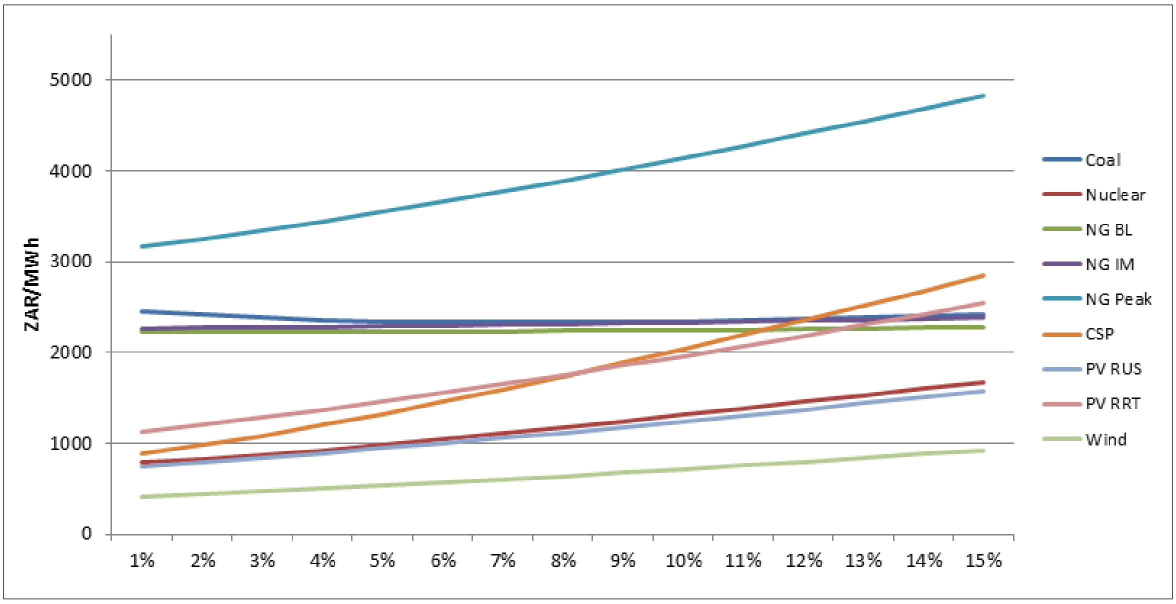
[24] Flexibility in this sense was characterized by base load, intermediate load, peak load and intermittency of energy sources.

[25] For example, smart-grids, improvement in storage technologies or geographical dispersion of intermittent energy sources can improve overall flexibility of a system.

costs or fuel prices. When all these parameters are kept constant, results can still be sensitive to the discount rate chosen for analysis. At the other hand, external cost estimates are mainly sensitive to assumptions on a global carbon price and to opportunity costs for water consumption. While a price on carbon emissions was mentioned by Nicholson et al. (2011) as the main factor influencing externalities and consequently has been included into the analysis ex-ante with CO_2 damage costs varying between 6.71 and 204.76 ZAR/tCO_2-eq., one important finding of this thesis was that opportunity costs for fresh water also considerably influence the competitiveness of coal and natural gas in South Africa. A variation in the value of opportunity costs of fresh water consumption might thus be of interest, especially given differences in water scarcity levels between many regions. Hence, two sensitivity analyses will be carried out and their impact on median full costs will be evaluated: first, alternating discount rates between 1-15% will be incorporated into analysis, and second, opportunity costs of water will be adjusted between decreased and increased by 50% each.

Resulting shifts of median full costs of different technologies as a result of differing discount rates are illustrated in figure 20:

Figure 20: Sensitivity of median full costs to discount rate

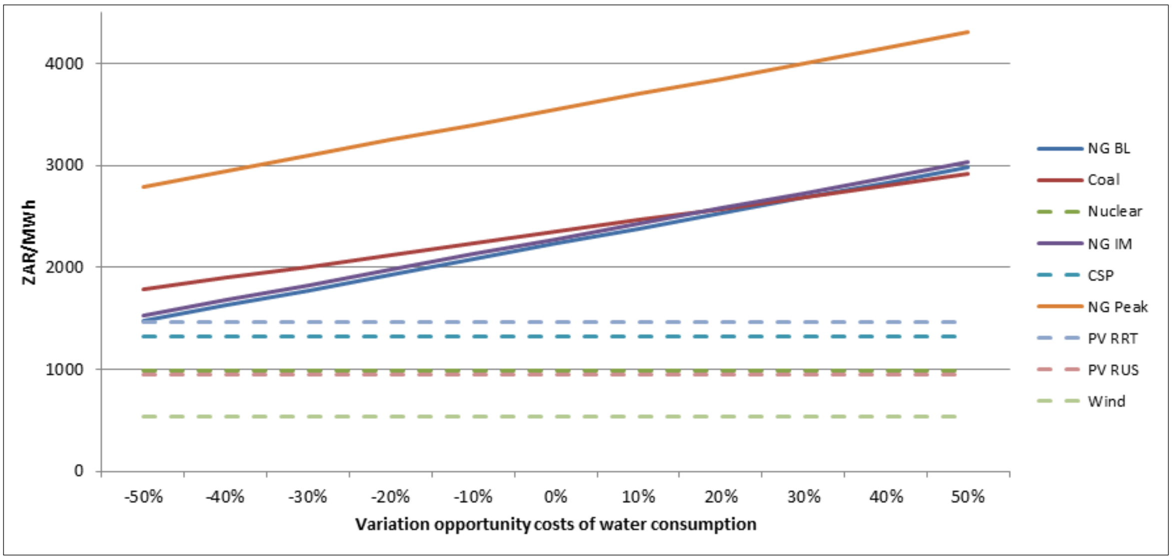


Source: Author.

From this illustration can be concluded that the choice of a higher discount rate benefits fuel-cost intensive technologies, whereas technologies requiring high initial investments become relatively more expensive. Consequently, the ranking order changes for CSP with regard to PV RRT at discount rates above 8.5% and both technologies become more expensive than NG BL, NG IM and coal discount rates above 11%. Also, it can be observed that wind remains the lowest-cost alternative independent of the discount rate chosen, while peak load gas remains always most expensive. Interestingly, nuclear and PV RUS seem to remain at around the same price level over the full range of discount rates.

The second sensitivity analysis was conducted with regard to opportunity costs of water consumption for coal and natural gas. The results are presented in figure 21:

Figure 21: Sensitivity of median full costs to opportunity costs of water consumption



Source: Author.

This graph shows that natural gas is the most sensible technology with regard to assumed water costs. This fact can be derived from the steepness of the functions' slopes from different NG technologies. Moreover, it can also be concluded that NG BL and NG IM become more expensive than coal at an opportunity cost of water of around 1.80 ZAR/KWh. Thus, dry-cooled coal power stations become competitive with natural gas power plants, if opportunity costs for water are valued above the mentioned threshold. Overall, full economic costs of water-intensive technologies remain above those of non-water intensive technologies, and come only close to the most expensive non-water intensive technology (PV RRT) in case of a 50% over-estimation of water costs (reduction of water price by -50%). Yet if water costs were under-estimated, the costs of fossil base- and intermediate load would indeed double with respect to alternative energy sources.

5. Conclusion

5.1 Introduction

This research was guided by the main research aim of facilitating informed decision making with regard to new investments options for the electricity sector in South Africa. To ensure the best possible improvement for the country from the status-quo, such choices are to comply with the goals of a smart energy policy as defined by Griffin (2009), implying cost effectiveness (cheap) and long-term societal benefits (clean & secure). Based on that, three sub-objectives were derived and conceptualized, and corresponding data and information were analyzed, interpreted and synthesized throughout this work. In this chapter, the most important results from the research sub-objectives are summarized and relevant conclusions are drawn. From this process, recommendations for South African stakeholders will be derived and advises on their implementation will be given. Finally, the work will be rounded off with a critical reflection on its limitations and with suggestions for further research that turned up during the research process.

5.2 Conclusion on Research Objectives

The first sub-objective of this work was share background knowledge on South Africa's electricity market.

Revealed through an in-depth literature review, South Africa's electricity market presented itself as a rather static market, transforming at a slow pace to a more competitive, diversified, and open market setting. This nexus is mainly owed to its history, to the structures created and to locked-in investments into the coal-minerals complex that occurred over the past decades. Nevertheless, if put into the regional context of Sub-Saharan Africa or of other emerging economies, history has shown that South Africa performed well with regard to two important goals of a functioning electricity market: it guaranteed cheap prices and accessibility to electricity.

However, it can be concluded that this comparably good performance has not resulted from deliberate energy planning, but from massive and phase-wise investments into capacity enlargements based on the domestic resource of coal. The advantages of these over-investments and resulting under-valuation of the good "electricity" are now reversed into obstacles for further development of South Africa. By the end of the first decade of the 21st century, things seemed to have turned upside down in many international supply markets and rising electricity prices can be observed in many markets. In the meanwhile, growing demand in electricity has resulted in new supply/demand gaps in South Africa and decision makers consequently scheduled the new builds of Medupi and Kusile coal power plants.

At the same time, worldwide tendencies for more sustainable energy pathways given scientific consensus about climate change gained foothold in the developed world and many governments started to focus on alternative energy systems instead. Given unprecedented worldwide transparency resulting from international trade, emerging economies and developing countries become more and more urged to join industrialized countries on a more sustainable path with their energy systems and are forced to include carbon costs into their export products and services. As a result, countries such as South Africa find themselves in a situation where they must face seemingly conflicting goals with regard to a smart energy policy. Often renewable energy sources seem expensive at a first glance and are thus perceived as “luxury” options if measured with established metrics such as the LCOE. Niez (2010) argued that this has been the case in South Africa. From this perspective, it can be understood that only marginal amounts of renewable energy capacity entered policy plans such as the IRP, still prioritizing other options such as coal, nuclear, and gas. Supporting mechanisms and structures for RES were developed, but often not successfully implemented, something which has led to great market uncertainties for investors. Examples for such initiatives are the REFIT program, which failed or the still-not-implemented unbundling of services through an ISMO. This would level the market playing field for new IPPs. However, Pegels (2012) pointed out that such problems were not uncommon, and that many countries, including developed countries, seemed to undergo phases of experimentation and market adaption with renewable energy policies.

All in all, it can be adhered that the South African market structure is in a process of slow transformation and that stakeholders have learned from mistakes done in the past. However, if South Africa wants to reach its policy goals of market opening, electrification, diversification of supply sources, lowering of emission trajectories and increasing security of energy supply in due time, then the transformation would have to be considerably accelerated.

The second research-objective was to develop a comprehensive framework which allows for a full-cost analysis of energy technologies, including economic, environmental and social aspects of energy planning.

The LCOE approach was introduced as the standard tool in the literature to compare costs of electricity produced from different technologies. It was argued that relying on this approach alone would lead to an over-allocation of investments into technologies that might not be favorable given environmental and social outcomes. Thus, indirect costs of electricity generation and risk in the case of nuclear have been inserted to the LCOE approach. Furthermore, non-monetary aspects where formalized to account for other important dimensions in energy planning. These included the potential for job creation, availability of electricity and energy security.

Consequently, the framework covers far more aspects than merely the direct costs of a technology (LCOE), which are too often used as the sole proxy in simplified argumentations in favor or against one specific technology. While external costs were found easier to be included from a methodological point of view, other dimensions such as, job creation potential, energy security or nuclear risk were challenging to be captured in a sound approach. Thus, job creation potential was chosen to be measured in permanent jobs created over the entire value chain of a project, while some of Sovacool and Mukherjee's (2011) energy security indicators were selected by the author based on dimensions and metrics that were "measureable by numbers". Nuclear risk was incorporated through results taken out of two studies, but these were found to be incomplete in their measurements and full-cost results for nuclear are thus flawed. By grouping technologies into different load segments, the notion of "availability of energy sources" was also included also into the analysis. It can thus be concluded that framework developed in this study is more comprehensive and includes parts that allow for quantitative evaluation and parts that must be evaluated with a mixture of quantitative and qualitative aspects.

The third sub-objective of this research was to apply the framework to relevant technology options given South Africa's resource potential. In this sense, coal, nuclear, natural gas, CSP, PV and wind were identified as most important options and these technologies were assessed one by one. Comparing the full cost of these technologies revealed that an inclusion of external costs and risk altered the ranking between some of the technologies. The analysis confirmed what Roth and Ambs (2004) already predicted earlier: "*In the no-externality case, fossil fuel technologies are highly attractive but as XCs* [externalities] *increase, their fuel intensity and emissions raise their LCOEs well above those of wind….*" While these authors also saw CCGT plants very competitive due to their "clean" emissions and high efficiencies, this research found out that South Africa would face high opportunity costs of fresh water consumption which considerably increase the price of coal and natural gas from shale resources. A sensitivity analysis with regard to this factor revealed that water costs remain a prohibitive factor in economic terms, even if over-evaluated by up to 50%. A second sensitivity analysis was conducted with regard to the discount rates chosen in the evaluation of the LCOE of technologies. It showed that fuel-intensive technologies benefited from higher discount rates, because the present value of fuel costs occurring in the future is lower at high discount rates. Consequently, the ranking of technologies changed in the intermediate load segment for $r > 11\%$, with natural gas being cheaper than CSP in that case, while the rankings in other segments were not affected by a variation of the discount rates between 1-15%. Hence, the results from the full-cost analysis are rather solid with regard to this parameter.

From the examination of job creation potential and energy security indicators, it can be concluded that wind, CSP and PV are attractive options for South Africa. As a result, a smart energy policy for South Africa should consider CSP for intermediate load and natural gas for peak load new-builds, but include as much wind and rural utility-scale PV as possible to support peak generation. An objective conclusion for the base-load sector cannot be derived based on this analysis, due to the controversial risk evaluation with nuclear and the overlaps between the lower and upper scenarios with coal and natural gas.

This result is valid if policy makers want to realize long-term benefits for South Africa. However, a diversification of the industry might prove difficult to be realized, as long as externalities are not yet included in today’s market prices. While an inclusion of carbon costs will likely be realized in most developed and emerging economies and thus has only limited effects on international competitiveness, high opportunity costs of fresh water use are predominantly a local problem for South Africa. They present a serious impediment for the competitiveness of the electricity sector. Logically, there are only two solutions to deal with the problem of high water costs: either society at large continues to pay for this factor through foregone opportunities, or the South African economy loses in international competitiveness, if true costs are included into domestic electricity prices, but this is something that Griffin (2009) sees as unrealistic to expect from an emerging economy.

Based on these findings, recommendations for South African policy makers can be derived. These will be discussed in the next chapter.

5.3 Recommendations

As revealed in the conclusion, wind, solar PV and CSP are the technologies that perform best in their respective load segments with regard to the three goals of a smart energy policy. They are the options to be preferred for a diversification of South Africa's electricity sector. Consequently, it is recommended that these options should gain more weight in future energy planning. Especially CSP is currently undervalued with only 1.2 GW of planned and committed capacity in the IRP (c.f. figures 2 and 7), which is by no means the capacity it economically deserves. To deal with their intermittent character, the relative full-cost advantage of these technologies could be used for investments into a reduction of their degree of intermittency. Improved storage technologies such as thermal, chemical or pumped-storage could help to do so.

If higher shares of the aforementioned technologies are incorporated into the next IRP, the logical challenge concerns the choice of policy measures that guarantee actual deployment of preferable technologies. This is especially problematic as (some) preferences regarding technologies change when indirect costs and non-monetary aspects of energy planning are included in the evaluation. Hence, sensitive policies that balance the interests of all local stakeholders must be developed to ensure a successful deployment of preferred technologies, which still seem expensive from a purely market-based point of view.

Therefore, frameworks should be shaped and regulations should be enacted that entail market mechanisms to optimally allocate investment decisions with a focus on long-term benefits. To diversify the electricity supply, it is recommendable to open the supply market towards IPP investments. Whether an optimal share of IPPs should be limited at 30% is another question and will not be discussed here. However, the large interest observed in South African solar, wind and gas markets is an indication that independent market participants will certainly bring the technological knowledge, innovativeness, required capital and competitive spirit to build out renewable energy projects and to stimulate the creation of new industries and employment opportunities. Thus, it is not only recommended that the South African government should regulate the market frameworks and trigger an unbundling of services through adoption of the ISMO, but also that investment certainty is increased for all stakeholders. Current discussions on new policies send out positive signals, but still fail to create momentum for a kick-start of sizeable renewable energy projects and the creation of domestic solar and wind clusters.

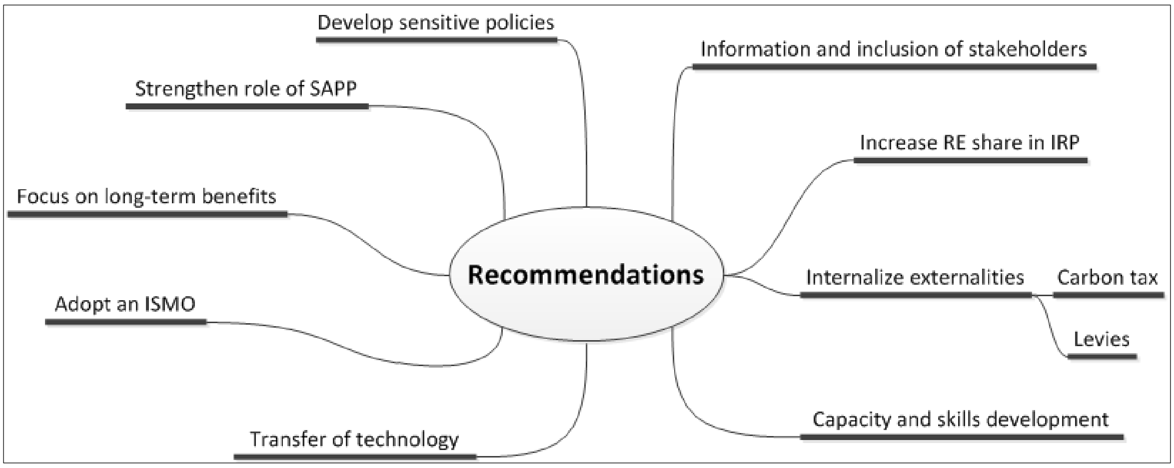
Realistically, it is clear that the market alone cannot be the sole vehicle to achieve the desired balance between cheap, clean and secure energy. Externalities are not market-priced goods and aspects such as nuclear risk or opportunity costs of fresh water consumption are difficult to quantify. Thus, the government is advised to interfere and guide investments into the desired direction. This becomes especially evident in a decision on a new nuclear program, where this work cannot recommend a build-out based on Gen. III-III+ technology, given the uncertainty and irreversibility of such an investment. Contrarily, the REBID bidding process and the adoption of a carbon tax that will eventually reflect marginal damage costs of GHG emissions seem promising tools to ensure cost-reflective pricing. Another tool to internalize externalities would be the adoption of increased levies on non-preferred technologies that compensate for the damages caused. However, this is only effective if the government invests the money obtained at the benefit of the stakeholders concerned.

Furthermore, a successful transition of the electricity supply industry also depends on the people engaged in that transition. Thus, it is recommended that South Africa focuses on domestic capacity and skills development and fosters on transfer of technology to ensure sustainable management of its energy resources (Winkler et al., 2009). This is, for example, not only essential in managing the challenges with regard to domestic shale gas resources and the representation of local and domestic long-term interests against international petroleum companies. It is also a necessary condition for the development of a green industry and the attraction of parts of solar and wind value chains in the country.

In addition, electricity consumers must be actively engaged, informed and convinced about energy planning and transformation processes in the supply industry. Generally, this works well if the government can demonstrate that consumers can save money with a new measure. Here, starting points would be the residential sector with PV RTT priced at 14.63 c/KWh which is below many of Eskom’s rates charged during peak hours (Eskom, 2013i). Another sign for the increasing competitiveness of alternative energy sources with rising electricity prices was put forward by Nel (2012), who observed that large electricity users began to develop their own generation options as they start to be competitive with Eskom’s marginal costs of new generation.

Last but not least, it can be recommended that South Africa should engage in intensified international cooperation for a diversification of its electricity sector. The existing SAPP market structure is a decent starting point, but to realize substantial positive effects in the region, physical exchange of electricity must increase. Then, in the medium run, South Africa could also supply other markets with wind and solar energy and benefit from better opportunities to balance domestic supply and demand. All in all, the derived recommendations can be summarized as in figure 21:

Figure 22: Summary of recommendations



Source: Author.

It is hence a combination of different market-based and non-market-based measures that are recommended for South Africa to achieve a good balance between cheap, clean and secure supply of electricity. If, however, the implementation of these recommendations fails and South Africa continues to invest in seemingly cheaper coal-based or nuclear generation options, the following quote of Nicolas Sarkozy (2010, in Stiglitz et al., 2010), former French president, might highlight the consequences of such behavior:

"It is possible to go for a long time without paying the true price of scarcity and risk, while being convinced of the contrary, but sooner or later the true price has to be paid. The bill is then much heavier, as behaviors based on these erroneous economic calculations have heightened the scarcity and the risk."

As explained earlier, a research process is a dynamic process during which new challenges and questions may occur. Given the limited scope of this research, not every issue that popped up could be considered. Thus, some of the major limitations in the scope of this work are described in the last chapter and suggestions for further research are made based on them.

5.4 Limitations of the work and suggestions for further research

Apart from the conceptual limitations in the methodology underlying the analysis conducted, which were discussed in chapter 3.5, the following scope-related limitations might also bias the results and recommendations of this work.

The scope of this research was limited to technologies which were considered as most important in the IRP2010. However, this pre-selection could have been incomplete and other technologies such as biomass, wave and tidal power, geo-thermal power or other yet unknown sources might turn out as favorable technologies for the context of South Africa. Thus, it might be fruitful analyze the potential of these technologies in more depth.

This work suggests that higher shares of intermittent energy sources should be deployed in South Africa. With pointing to the example of Germany, Hirth (2013) argued that countries can often be include smaller shares of RES without major problems, while larger fractions will lead to impacts on the entire system. Then, questions such as load-management, necessary capacities for back-up power generation and transmission network must be addressed in further research.

Other limitations appeared at the technological side and include the case of shale gas and water costs. As the IPCC (2011) pointed out, hydraulic fracturing of shale gas reserves may pose risks from spills of chemicals that have not yet been quantified in scientific research. Thus, quantification of such risks would be highly appreciated and these should then be included in economic analysis of South African natural gas.

The literature review showed that a sound evaluation of nuclear power is difficult because the validity of results from existing externality studies seems limited. Given the long-term and large-scale impacts from this technology, new ethical standards based on international consensus must be developed to evaluate its risks and indirect costs.

Last but not least, the issue of water requirements can be discussed controversially, as the water scarcity in South Africa implies conflicting use of fresh water. Consequently, water resources in South Africa must be allocated carefully and the needs of the energy sector must be evaluated against the needs of rivaling sectors such as the agriculture sector or the residential sector. As fresh water is a prerequisite for any on human life on earth, additional research on the true opportunity costs of fresh water consumption is suggested here.

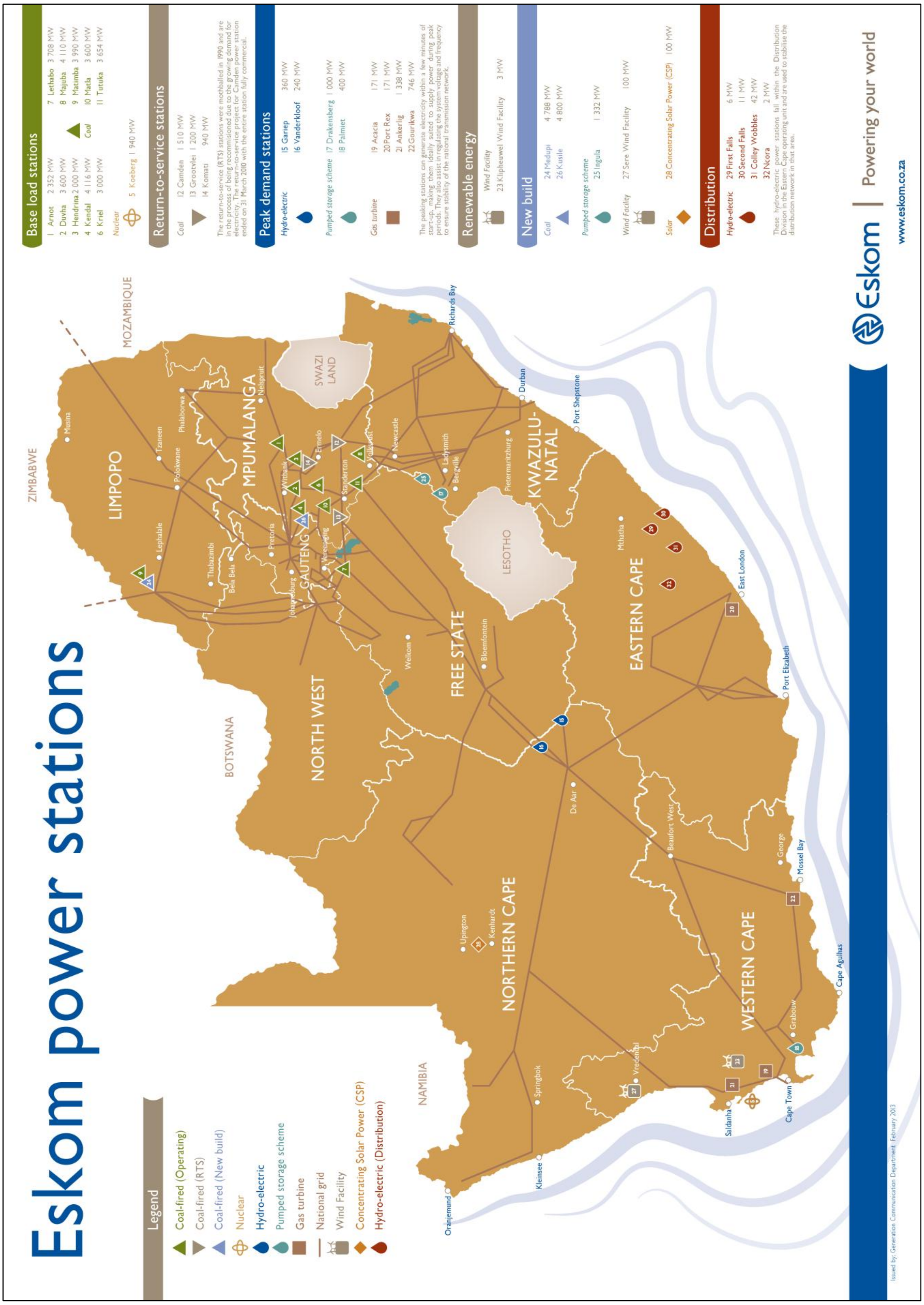
Appendices

Appendix 1: Overview of associations with an interest in South Africa’s electricity market

Field	Name of organization	Acronym	Core interests
All fields	South African National Energy Association	SANEA	Provide platform for all stakeholders to mingle
All fields	South African Independent Power Producers Association	SAIPPA	Competitive electricity supply market
Coal	South African Coal Ash Association	SACAA	Promote coal combustion products
Coal	Coaltech Research Association		Competitiveness of South African Coal industry
Coal	South African Colliery Managers’ Association	SACMA	Promote and bundle coal mining activities
Coal	Southern African Coal Processing Society	SACPS	Promote coal processing
Coal, Nuclear	Energy Intensive User Group	EIUG	Promote affordable energy and security of supply
Energy efficiency	Southern African Association for Energy Efficiency	SAEE	Increase awareness for energy efficiency
Energy services	South African Association of Energy Services Companies	SAAEs	Industry voice for energy services companies
Nuclear	Coalition Against Nuclear Energy	CANE	Oppose expansion of nuclear program
Nuclear	Koeberg Alert Alliance	KAA	Oppose expansion of nuclear program, promote RES
Nuclear	South African Nuclear Energy Corporation Ltd.	NECSA	Promotion of nuclear energy
RES	Southern African Alternative Energy Association	SAAEA	Promote RES deployment, promote sustainable products
RES	Wildlife and Environment Society of South Africa	WESSA	Promote RES and lower energy demand
RES	GreenCape Initiative		Promote a green economy in the Western Cape
Solar	Sustainable Energy Society of Southern Africa	SESSA	Promote use of solar-based energy
Solar	Southern Africa Solar Thermal and Electricity Association	SASTELA	Promote CSP projects
Solar	South African Photovoltaic Industry Association	SAPVIA	Promote PV market in South Africa
Solar cooking	Association for Renewable Energy Cooking Appliances	AFRECA	Promote product development
Wind	African Wind Energy Association	AfriWEA	Promote wind energy development
Wind	South African Wind Energy Association	SAWEA	Promote wind energy development

Source: Own illustration.

Appendix 2: Overview of Eskom power stations in South Africa



Eskom power stations

Base load stations

Coal		
1	Arnot	2 352 MW
2	Duvha	3 600 MW
3	Hendrina	2 000 MW
4	Kendal	4 116 MW
6	Kriel	3 000 MW
7	Lethabo	3 708 MW
8	Majuba	4 110 MW
9	Matimba	3 990 MW
10	Matla	3 600 MW
11	Tutuka	3 654 MW

Nuclear

5 Koeberg 1 940 MW

Return-to-service stations

Coal		
12	Camden	1 510 MW
13	Grootvlei	1 200 MW
14	Komati	940 MW

The return-to-service (RTS) stations were mothballed in 1990 and are in the process of being recommisioned due to the growing demand for electricity. The return-to-service project for Camden power station ended on 31 March 2010 with the entire station fully commercial.

Peak demand stations

Hydro-electric	15 Gariep	360 MW
	16 Vanderkloof	240 MW
Pumped storage scheme	17 Drakensberg	1 000 MW
	18 Palmiet	400 MW
Gas turbine	19 Acacia	171 MW
	20 Port Rex	171 MW
	21 Ankerlig	1 338 MW
	22 Gourikwa	746 MW

The peaking stations can generate electricity within a few minutes of start-up, making them ideally suited to supply power during peak periods. They also assist in regulating the system voltage and frequency to ensure stability of the national transmission network.

Renewable energy

Wind Facility

23 Klipheuwel Wind Facility 3 MW

New build

Coal	24 Medupi	4 788 MW
	26 Kusile	4 800 MW
Pumped storage scheme	25 Ingula	1 332 MW
Wind Facility	27 Sere Wind Facility	100 MW
Solar	28 Concentrating Solar Power (CSP)	100 MW

Distribution

Hydro-electric	29 First Falls	6 MW
	30 Second Falls	11 MW
	31 Colley Wobbles	42 MW
	32 Ncora	2 MW

These hydro-electric power stations fall within the Distribution Division in the Eastern Cape operating unit and are used to stabilise the distribution network in that area.

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Source: (Eskom, 2013g).

Appendix 3: Input parameters for dry-cooled coal power plant, super-critical technology with FGD

Capital costs	**Value(s)**	**Conversion to ZAR$_{2012}$**	**Source**
cp	2300 USD$_{2012}$/kW	18860	(Eskom, 2012b)
H	8760		given
f	85%		(EPRI, 2010)
CRF	5.47%		calculated
r	5%		given
T	50		(Eskom, 2013e)
O&M costs	**Value(s)**		**Source**
Fixed O&M	455 ZAR$_{2010}$/kW-yr	523.80	(EPRI, 2010)
Variable O&M	44.4 ZAR$_{2010}$/MWh	51.11	(EPRI, 2010)
e	3.5%		(StatsSA, 2012b)
Fuel costs	**Value(s)**		**Source**
LHV	17.9 GJ/t		(IEA/NEA/OECD, 2010)
Thermal efficiency	40%		(AfDB, 2009)
Coal price in 2015	349 ZAR$_{2012}$/t		(McKay, 2012)
Coal prices in 2065	848.06 ZAR$_{2012}$/t (low) 1930.48 ZAR$_{2012}$/t (medium) 6080.26 ZAR$_{2012}$/t (high)		Projections from author
e (low increase)	1.79%		Calculation from author
e (moderate increase)	3.48%		Calculation from author
e (high increase)	5.88%		Calculation from author
Economic parameters			
2008 exchange rate ZAR/USD	8.30		(World Bank, 2013)
2012 exchange rate ZAR/USD	8.20		(World Bank, 2013)
2008 PPI	14.2%		(StatsSA, 2012b)
2009 PPI	-0.1%		(StatsSA, 2012b)
2010 PPI	6.0%		(StatsSA, 2012b)
2011 PPI	8.4%		(StatsSA, 2012b)
2012 PPI	6.2%		(StatsSA, 2012b)

Externalities Scenarios	**low**	**median**	**high**	
Health externalities in ZAR$_{2010}$/KWh	0.006	-	0.007	(Blignaut et al., 2011)
Conversion to ZAR$_{2012}$/MWh	6.91		8.06	calculated
Climate change externalities in ZAR$_{2010}$/KWh	0.097	-	0.165	(Blignaut et al., 2011)
Conversion to ZAR$_{2012}$/MWh	111.67		189.95	calculated
Opportunity cost of water use in ZAR$_{2010}$/KWh	0.66	-	1.311	(Blignaut et al., 2011)
Conversion to ZAR$_{2012}$/MWh	759.80		1509.23	calculated
Coal mining externalities in ZAR$_{2010}$/MWh	202,40	-	393,00	(Nkambule and Blignaut, 2011)
Conversion to ZAR$_{2012}$	233,00		452,43	calculated
Total externalities ZAR$_{2012}$/MWh	1111.38	1635.53*	2159.67	calculated

**) Computed average value, given lack of median values.*

Appendix 4: Input parameters for nuclear power plant, generation III type

Capital costs	**Value(s)**	**Conversion to ZAR_{2012}**	**Source**
cp	7000 USD_{2012}/kW	57400	(ERC, 2013)
H	8760		given
f	90%		(Lazard, 2012)
CRF	5.28%		calculated
r	5%		given
T	60		(Tidball et al., 2010)
Plant capacity	1600 MW		Assumption
O&M costs	**Value(s)**		**Source**
Fixed O&M	0 ZAR_{2010}/kW-y	0	(DoE, 2010)
Variable O&M	95.2 ZAR_{2010}/MWh	110.67	(DoE, 2010)
e	0.5%		Assumption
Fuel costs	**Value(s)**		**Source**
Energy content uranium	3900 GJ/kg		(Lazard, 2012)
Thermal efficiency	37%		(WNA, 2013)
Price natural uranium	81.00 USD_{2012}/kg	664.20	(TradeTech, 2013)
Calculated variable fuel cost	1.66 ZAR_{2012}/MWh		Calculation from author
Total fuel cost	135.50 ZAR_{2012}/MWh		(Kotzé, 2012)
e	1 %		Assumption
Economic parameters			
2007 exchange rate ZAR/USD	7.10		(World Bank, 2013)
2012 exchange rate ZAR/USD	8.20		(World Bank, 2013)
2008 PPI	14.2%		(StatsSA, 2012b)
2009 PPI	-0.1%		(StatsSA, 2012b)
2010 PPI	6.0%		(StatsSA, 2012b)
2011 PPI	8.4%		(StatsSA, 2012b)
2012 PPI	6.2%		(StatsSA, 2012b)
Externalities			
I_{SA} (GNI South Africa (2011) PPP in intl. $)	10710		(World Bank, 2012)
I_{BC} (GNI Euro area (2011) PPP in intl. $)	35250		(World Bank, 2012)
I_{BC} (GNI Germany (2011) PPP in intl. $)	40190		(World Bank, 2012)
2012 exchange rate ZAR/EUR	10.55		(ECB, 2013)

Externalities Scenarios	**low**	**median**	**high**	
External cost of accident, in $Eurocent_{2012}$/KWh	0.08	0.38	2.29	(Rabl and Rabl, 2013)
Conversion to ZAR_{2012}/MWh	8.44	40.09	241.60	calculated
External cost of current operation, in $Eurocent_{2012}$/KWh	0.07	0.21	0.63	(Rabl and Rabl, 2013)
Conversion to ZAR_{2012}/MWh	7.39	22.16	66.47	calculated
External cost of waste management, in $Eurocent_{2012}$/KWh	0.10	0.20	0.30	(Rabl and Rabl, 2013)
Conversion to ZAR_{2012}/MWh	10.55	21.10	31.65	calculated
Total external cost, in $Eurocent_{2012}$/KWh	10.70	22.35*	34.00	(Meyer, 2012)
Conversion to ZAR_{2012}/MWh	1128.85	2357.93	3587.00	calculated
Total externalities ZAR_{2012}/MWh (Rabl & Rabl)	26.38	83.35	339.72	calculated
Adjusted to South African PPP	8.02	25.33	103.26	(Nahman, 2011)
Total externalities ZAR_{2012}/MWh (Meyer)	1128.85	2357.93	3587.00	calculated
Adjusted to South African PPP	300.96	628.65	956.33	(Nahman, 2011)

**) Computed average value, given lack of median values.*

Appendix 5: Input parameters for CCGT gas power plant

Capital costs	**Value(s)**		**Conversion to ZAR$_{2012}$**	**Source**
cp	5780 USD$_{2010}$/kW		6653.98	(EPRI, 2010)
H	8760			given
f	5%, 50%, 88%			(Lazard, 2012)
CRF	6.51%			calculated
r	5%			given
T	30			(EPRI, 2010)
Plant capacity	800 MW			Assumption
O&M costs	**Value(s)**			**Source**
Fixed O&M	148 ZAR$_{2010}$/kW-y		170.38	(EPRI, 2010)
Variable O&M	0 ZAR$_{2010}$/MWh			(EPRI, 2010)
e	0.5%			(Roques et al., 2006)
Fuel costs	**Value(s)**			**Source**
Price natural gas	73.56 ZAR$_{2012}$/GJ			(NERSA, 2013a)
Thermal efficiency CCGT plant	50%			(Godoy et al., 2010)
Conversion factor GJ/MWh	3.6			given
Total fuel cost	481.48 ZAR$_{2012}$/MWh			calculated
e	1 %			(Roques et al., 2006, ERC, 2013)
Economic parameters				
2010 PPI	6.0%			(StatsSA, 2012b)
2011 PPI	8.4%			(StatsSA, 2012b)
2012 PPI	6.2%			(StatsSA, 2012b)
Externalities				
Average emission intensity CCGT power plant	470 gCO$_2$-eq./KWh			(Nicholson et al., 2011)
Upstream emission intensity shale gas	103 gCO$_2$-eq./KWh			(Laurenzi and Jersey, 2013)
Health impacts from power generation	0.34 ZAR$_{2009}$ cents /KWh		0.42	(Edkins et al., 2010c)
Health impacts from fuel production	0.14 ZAR$_{2009}$ cents /KWh		0.17	(Edkins et al., 2010c)
Biodiversity loss	0.39 ZAR$_{2009}$ cents /KWh		0.48	(Edkins et al., 2010c)
Loss in property values	not quantifiable, lack in research			(Muehlenbachs et al., 2012)
CCGT life cycle fresh water consumption	224 gallon/MWh			(Laurenzi and Jersey, 2013)
Externalities Scenarios	**low**	**median**	**high**	
Global damage cost in ZAR$_{2010}$/t CO$_2$-eq.	5.83	109.80	177.79	(Blignaut et al., 2011)
Conversion to ZAR$_{2012}$/MWh	6.71	126.40	204.67	calculated
External cost from GHG emissions, in ZAR$_{2012}$/MWh	3.75	70.72	114.51	calculated
Opportunity cost of water use in ZAR$_{2010}$/KWh	1.14	1.31	1.49	calculated, based on (Blignaut et al., 2011)*
Conversion to ZAR$_{2012}$/MWh	1312.38	1508.08	1715.30	calculated
Total externalities ZAR$_{2012}$/MWh	1326.75	1589.42	1840.43	calculated

*) Calculation opportunity cost of water use based on (Blignaut et al., 2011)

	Technology	**NMR of water**	**Difference**	**Water volume**	**Net generation output**	**Society-wide loss**	**Opportunity cost**
	ZAR/m³	ZAR/m³	ZAR/m³	m³	MWh	mZAR	ZAR/KWh
Baseline	Gas CCGT	7872		27455636	32300748		
Alternative 1	Solar	14667	-6795	5405495	18237164	-36730	-1.14
Alternative 2	Wind	930736	-922864	45989	12102466	42442	-1.31
Alternative 3	Coal	9717	-1845	26166365	32300748	-48276	-1.49

Appendix 6: Input parameters for CSP power plant, solar tower technology with 3 hour storage

Capital costs	**Value(s)**	**Conversion to ZAR$_{2012}$**	**Source**
cp	7300 USD$_{2012}$/kW	59860	(Lazard, 2012)
H	8760		given
f	40%		(Lazard, 2012)
CRF	5.83%		calculated
r	5%		given
T	40		(Lazard, 2012)
Plant capacity	100 MW		Assumption

O&M costs	**Value(s)**		**Source**
Fixed O&M	80 USD$_{2012}$/kW-y	656	(Lazard, 2012)
Variable O&M	3.00 USD$_{2012}$/MWh	24.60	(Lazard, 2012)
e	2.5%		(Timilsina et al., 2012)

Economic parameters			
2007 exchange rate ZAR/USD	7.10		(World Bank, 2013)
2012 exchange rate ZAR/USD	8.20		(World Bank, 2013)
2008 PPI	14.2%		(StatsSA, 2012b)
2009 PPI	-0.1%		(StatsSA, 2012b)
2010 PPI	6.0%		(StatsSA, 2012b)
2011 PPI	8.4%		(StatsSA, 2012b)
2012 PPI	6.2%		(StatsSA, 2012b)

Externalities			
Emission intensity in g CO$_2$-eq./KWh	38.00		(Burkhardt et al., 2012)
Health externalities in ZARcent$_{2009}$/KWh	0.09	1.10	(Edkins et al., 2010c)

Externalities Scenarios	**low**	**median**	**high**	
Global damage cost in ZAR$_{2010}$/t CO$_2$-eq.	5.83	109.80	177.79	(Blignaut et al., 2011)
Conversion to ZAR$_{2012}$/MWh	6.71	126.40	204.67	calculated
External cost from GHG emissions in ZAR$_{2012}$/MWh	0.26	4.80	7.78	calculated
Total externalities ZAR$_{2012}$/MWh	11.26	15.80	18.78	calculated

Appendix 7: Input parameters for PV plants, rural utility scale (RUS) and residential roof-top (RRT)

Capital costs	**Value(s)**			**Conversion to ZAR$_{2012}$**	**Source**
cp_{RUS}	2375 USD$_{2012}$/kW;			19475	(Lazard, 2012)
cp_{RRT}	3250 USD$_{2012}$/kW			26650	(Lazard, 2012)
H	8760				given
f_{RUS}	27%				calculated
f_{RRT}	22%				(Lazard, 2012)
CRF	8.02%				calculated
r	5%				given
T	20				(Lazard, 2012)
Plant capacity	10 MW				Assumption
Average annual solar irradiation in Upington	2796 KWh/m²				(Suri, 2011)
Dimensions Solaire SDT1000 - 100W	1190 x 670 x 35 mm				(Sustainable.co.za, 2013)
Area needed for 1 KWp	7.79m²				calculated
Performance ratio solar panel	0.75				(Hult et al., 2005)
Module efficiency	16%				(Darling et al., 2011)
Degradation rate module per year	0.6%				(Darling et al., 2011)
Average electricity production per KWp	2570 KWh				calculated
Plant capacity	10 MW				Assumption
O&M costs	**Value(s)**				**Source**
Fixed O&M	500 ZAR$_{2011}$ /kWp-y			531	(SAPVIA, 2011)
e	2.5%				(Timilsina et al., 2012)
Economic parameters					
2012 exchange rate ZAR/USD	8.20				(World Bank, 2013)
2010 PPI	6.0%				(StatsSA, 2012b)
2011 PPI	8.4%				(StatsSA, 2012b)
2012 PPI	6.2%				(StatsSA, 2012b)
Externalities					
Health externalities in ZARcent$_{2009}$/KWh	0.19				(Edkins et al., 2010c)
Conversion to ZAR$_{2012}$/MWh	2.32				calculated
Externalities Scenarios	**low**	**median**	**high**		
Emission intensity in g CO_2-eq./KWh	23.00	33.50	44.00		(Peng et al., 2013)
Global damage cost in ZAR$_{2010}$/t CO_2-eq.	5.83	109.80	177.79		(Blignaut et al., 2011)
Conversion to ZAR$_{2012}$/MWh	6.71	126.40	204.67		calculated
External cost from GHG emissions in ZAR$_{2012}$/MWh	0.15	4.23	9.01		calculated
Total externalities ZAR$_{2012}$/MWh	1.13				calculated

Appendix 8: Input parameters for onshore wind power plant

Capital costs	**Value(s)**			**Conversion to ZAR$_{2012}$**	**Source**
cp	1857 USD$_{2012}$/kW			15227	(Lantz et al., 2012)
H	8760				given
f	35%				(Ayodele et al., 2012)
CRF	8.02%				calculated
r	5%				given
T	20				(Lazard, 2012)
Plant capacity	3 MW				(Lantz et al., 2012)
Hub height	80m				(Lantz et al., 2012)
Rotor diameter	112m				(Lantz et al., 2012)
O&M costs	**Value(s)**				**Source**
Variable O&M	16 USD$_{2012}$/MWh			131.20	(Lantz et al., 2012)
e	0%				(Lantz et al., 2012)
Economic parameters					
2012 exchange rate ZAR/USD	8.20				(World Bank, 2013)
2010 PPI	6.0%				(StatsSA, 2012b)
2011 PPI	8.4%				(StatsSA, 2012b)
2012 PPI	6.2%				(StatsSA, 2012b)
Externalities					
Health externalities in ZARcent$_{2009}$/KWh	0.09				(Edkins et al., 2010c)
Conversion to ZAR$_{2012}$/MWh	1.10				calculated
Externalities Scenarios	**low**	**median**	**high**		
Emission intensity in g CO$_2$-eq./KWh	4.97	6.99	9.00		(Wang and Sun, 2012, Guezuraga et al., 2012)
Global damage cost in ZAR$_{2010}$/t CO$_2$-eq.	5.83	109.80	177.79		(Blignaut et al., 2011)
Conversion to ZAR$_{2012}$/MWh	6.71	126.40	204.67		calculated
Total externalities ZAR$_{2012}$/MWh	1.13	1.98	2.94		calculated

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