Role of nuclear technology in South Africa

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ABSTRACT

Role of Nuclear Technology in South Africa

South Africa is in the critical process of determining the profile of its power composition for the next 30 years and beyond. From the IRP2010 it seems that too much emphasis is placed on renewable energy, coal and other technologies and too little on nuclear power. In the revision of the IRP2010, the renewable portion of the energy composition has been increased substantially from 11.4 to 17.8GW, where nuclear remains on 9.6GW (DME, 2011). The purpose of this research is to investigate and compare power-generating technologies. The investigation of the different technologies is corroborated through modelling the IRP2010 planned energy mix efficiency, as well as a proposed energy mix. These models will be built using Microsoft Excel. Topics not investigated are socio-economic impacts and politics around nuclear energy in South Africa.

The main finding of the research is that nuclear power is the best option for base load energy in order to meet South Africa’s growing demand for electricity. It has the highest load factor, longest economic life, best safety record, adheres to the Kyoto protocol, uses the least fresh water and is economically competitive. It addresses all the concerns stipulated in the IRP2010 and the technology also offers benefits outside the electricity industry, such as the mining, medical, agriculture and research sectors. This versatile, reliable and powerful technology holds great benefits and has the potential to uplift the quality of life for the whole South African nation.

KEYWORDS

- Nuclear energy
- Nuclear safety
- Nuclear technology
- Renewable energy
- Energy economics
- Base load energy
- Peak load energy

OPSOMMING

Rol van Kerntegnologie in Suid-Afrika

Suid-Afrika is in die kritiese proses om die profiel van sy energiesamestelling vir die volgende 30 jaar en meer op te trek. Vanuit die IRP2010-dokument blyk dit dat te veel klem op herwinbare energie, steenkool and ander tegnologie geplaas is en te min aan kernenergie. In die hersiende weergawe van die IRP2010 is die herwinbare porsie van die energiesamestelling aansienlik verhoog van 11.4 na 17.8GW, teenoor kernenergie wat op 9.6GW bly (DME, 2011). Die doel van die navorsing is om ondersoek in te stel en ‘n vergelyking te tref tussen die verskillende elektrisiteit opwekkingstegnologieë. Die ondersoek word verder aangevul deur ‘n model van die energiesamestelling soos in die IRP2010-dokument aangedui, asook ‘n voorgestelde energiesamestelling. Hierdie modelle sal in Microsoft Excel gebou word. Die ondersoek sluit nie die sosio-ekonomiese en politiese impak van kernenergie op Suid-Afrika in nie.

Die hoofbevindinge van die navorsing is dat kern energie die beste opsie is vir verskaffing van basislading om Suid-Afrika se groeiende elektrisiteitsaanvraag te bevredig. Kernenergie het die hoogste ladingsfaktor, langste ekonomiese leeftyd, beste veiligheidsrekord, voldoen aan die Kyoto protokol, gebruik die minste vars water en is ekonomies kompeterend. Kernenergie adresseer ook verdure vereistes soos in die IRP2010-dokument uiteengelê. Industrieë soos die mynbou-, mediese, landbou- and navorsingsinstansies kan almal baatvind by die ontwikkeling van kerntegnologie in Suid-Afrika. Die kragtige, betroubare en meervoudige tegnologie het die potensiaal om die lewenskwaliteit van die hele Suid-Afrikaanse nasie op te hef.

SLEUTELTERME

- Kernkrag
- Kernkrag veiligheid
- Kerntegnologie
- Herwinbare energie
- Energie ekonomie
- Basis lading
- Piek lading

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Soli Deo Gloria.

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ABBREVIATIONS

AC	– Alternating Current
AEMO	– Australian Energy Market operator
AP1000	– Advanced Pressurised Water Reactor (American/Westinghouse Design)
CANDU	– Canadian Deuterium Uranium Reactor
CCGT	– Closed Cycle Gas Turbine
CSP	– Concentrated Solar Plant
DC	– Direct Current
DNI	– Direct Normal Irradiation
EPR	– Advanced/Enhanced Pressurised Water Reactor (French/Areva Design)
EPRI	– Electric Power Research Institute
EU	– European Union
FGD	– Flue Gas Desulphurisation
GDP	– Gross Domestic Product
GW(e)	– Gigawatt (electrical)
HTR	– High Temperature Reactor
IRP	– Integrated Resource Plan
LCOE	– Levelised cost of Electricity
Mtoe	– Million tons of oil equivalent
MW(e)	– Megawatt (electrical)
NEA	– Nuclear Energy Association
NECSA	– Nuclear Engineering Council of South Africa
O&M	– Operating and Maintenance
OCGT	– Open Cycle Gas Turbines
OECD	– Organisation for Economic Co-operation and Development

OHS – Occupational Health and Safety

PET – Positron Emission Tomography

PV – Photovoltaic

PBMR – Pebble Bed Modular Reactor

PWR – Pressurised Water Reactor

RSA – Republic of South Africa

SAFARI – South African Fundamental Atomic Research Installation

TMI – Three Mile Island

USD – United States Dollar

WNA – World Nuclear Association

1. INTRODUCTION

1.1 Chapter overview

The purpose of this chapter is to provide a problem statement, introductory paragraph, scope of work, objectives, deliverables and structure of the document.

1.2 Problem statement

The energy mix as proposed in the revised IRP2010 for 2030 would not be able to successfully meet the electricity requirements of South Africa. The renewable portion of 17.8GW, or 21% of the total generation capacity, is too large as the output of these sources is unpredictable and uncontrollable. This would put the hydro pump storage, gas turbines, coal stations and nuclear units under pressure to compensate for the volatility of these sources. If South Africa had a renewable portion of 21% in the national grid today (July 2014), it would not be able to meet the base load or peak requirements of the consumers. More output controllable sources should be considered for the energy mix.

1.3 Introduction

Unfortunately, nuclear technology could not have been introduced to the world in a worse manner than through the bombs that were deployed on the Japanese towns of Hiroshima and Nagasaki shortly before the end of the Second World War in 1945 (Philips, 2013). A few years later, the accidents of Chernobyl and TMI seemed to have sealed the fate of nuclear power, which is again under debate following the recent 2011 Fukushima incident.

Even though nuclear technology has revolutionised and evolved, proving to be a much cheaper and safer technology than before, some countries and organisations are still indecisive on this technology, even strongly opposed to it. South Africa seems to be indecisive on this technology as well, having previously postponed a large nuclear expansion programme in 2008 as a result of the world economic crisis (WNA, 2013). There is no room for procrastination in defining and implementing the composition for power generation over the next couple of decades. Even though a new strategy has been set up and captured in the IRP2010 document, there are still many unknown factors to be resolved before funding is secured and ground is levelled. Time is running out as these factors are deliberated, and action needs to be taken as soon as possible.

A stigma has developed, and reasonably so, that nuclear technology is expensive and unsafe. Arising from this belief, the current and projected role nuclear technology plays in base load power generation appears to be minimised. However, if the general public as well as the influential stakeholders could be advised and convinced beyond a reasonable doubt that nuclear technology is safe, reliable and economically competitive, the role of nuclear technology could be increased. The nuclear industry can help to address topics relating to the South African context, such as Gross Domestic Product (GDP) growth, job creation and water conservation.

In the revision of the IRP2010, the renewable portion of the energy composition has been increased substantially from 11.4 to 17.8GW, where nuclear remains on 9.6GW (DME, 2011). This research will lead to an objective comparison on nuclear technology versus renewables and hydrocarbon sources considering cost, safety and reliability. Before any conclusions are made, consider the possibility that one may be both pro-nuclear *and* environmentally friendly.

1.4 Scope of work

The scope of work for this research entails the following approach in addressing the problem statement:

- Compare the different power production technologies under consideration by the South African government in the IRP2010. Compare power production technologies on safety, economics, security of supply, environmental impact and water usage. The goal is to show the advantages of nuclear power plants compared to other power sources.
- Model in Microsoft Excel the planned energy mix proposed in the IRP2010 document to establish suitability in meeting demand. A second model of a proposed energy mix with a larger nuclear base load capacity is also to be compiled.
- Briefly investigate and discuss the involvement of nuclear technology in other industries and the advantages it can potentially offer in addressing the socio-economic needs of South Africa.

Excluded from the scope are the following:

- A political and detailed socio-economic study regarding the role of nuclear technology in South Africa.
- Energy options outside the IRP2010 document, such as fracking and imported hydro-electric power from the Congo River.

1.5 Objectives

The objective of the research is to highlight the role nuclear technology should play in South Africa by:

- Highlighting the advantages nuclear power has to offer through a comparison with other technologies.
- Determining the role of nuclear power in the future power generation profile; specifically, identifying the proportion of nuclear power required to ensure stable and reliable electricity supply.
- Identifying a proposed energy mix in contrast to the energy mix planned in the IRP2010. Model both energy mixes to determine its suitability in meeting the demand of South Africa.

1.6 Structure

Chapter 2 provides background information on the topics to be investigated. This is followed by an investigative chapter where the strengths and weaknesses of each proposed power production technology are analysed. The investigation also considers the suitability of these sources in a model. Some interpretations and results from the investigation are drawn together in chapter 4, and these are rounded off in a concluding chapter. It is suggested that the hurried reader should read only the investigative section found in chapter 4 and the conclusions in chapter 5.

1.7 Outputs and deliverables

The research is published in this document which encapsulates the results and conclusions of the investigation. A list of recommendations is drawn up from the research to address the problem statement. The nature of the research is theoretical only and no physical deliverables accompany the research.

1.8 Summary

Having established the introduction to this research, the researcher has paved the way to start the investigation. A background chapter which follows now provides insight into relevant topics and concepts.

2. BACKGROUND

2.1 Chapter overview

The purpose of this chapter is to provide the reader with relevant background information. The first section provides an overview of nuclear, renewable and hydrocarbon energy sources. There is also an overview of the proposed IRP2010to provide clarity on the South African context regarding energy considerations as compared to world energy statistics. The chapter is concluded by introducing the concepts of base load, peak load and load following.

2.2 History of nuclear technology

The utilisation of nuclear technology follows several scientific discoveries. The most noticeable of these are the following (NAE, 2013):

1905: Albert Einstein's theory of relativity states that the speed of light is not dependent on the motion of its source. The most famous and celebrated result derived from this theory is the relationship between mass and energy, defined by $E = m.c^2$, with *c* representing the speed of light.

1932: James Chadwick discovers the neutron by bombarding beryllium with alpha particles.

1939: Physicist Otto Hahn and Fritz Strassmann of Germany, along with Lise Meitner of Austria and her nephew Otto Frisch, split uranium in a process known as fission. The release of energy from fission proves Einstein's original theory.

These discoveries quickly paved the way for a series of events which the world had never anticipated. The following engineering, political and military events are worth highlighting:

1939–1945: The Manhattan Project is established in the United States to develop the first transportable atomic bomb.

1942: Enrico Fermi from the University of Chicago built the first low-powered reactor which had a self-sustaining nuclear chain reaction and the ability to shut down.

1945: The United States bombs the cities of Hiroshima and Nagasaki ending World War II.

1951–1953: The Experimental Breeder Reactor I built in Idaho produces the world's first electric energy from nuclear energy. In 1953 the first in a series of boiling water experiment reactors is also built.

1955: The boiling water reactor, BORAX-III, provides an entire town (Arco, Idaho) with electricity. The first nuclear-powered submarine, the *USS Nautilus*, performs trial runs.

1979: The nuclear power station at Three Mile Island, Pennsylvania, experiences a partial core melt accident in its Unit 2 reactor. This accident was a result of an extremely unlikely series of human error and mechanical failures.

1986: The infamous Chernobyl nuclear disaster occurs in the former Soviet Union. Unlike in the case of the accident at Three Mile Island, the mechanics and plant equipment performed as per design function. The accident was purely a result of human error and illegal conduct, as several safety systems were overridden in order to perform a plant test.

1991: South Africa completely dismantled its nuclear weapons programme, being the only country in the world to do so voluntarily. On 10 July South Africa joined the Treaty on the Non-Proliferation of Nuclear Weapons as a non-nuclear weapon state (NTI, 2011).

2.3 Nuclear technology in South Africa

In South Africa the coal reserves are concentrated in the far north-east, yet large loads are on the coastal areas. Since transportation of both coal and electricity over long distances is expensive and inefficient, it was decided by Eskom in the early 1970s to construct Koeberg near the city of Cape Town.

It was only in 2006 that Eskom initially approved a plan to double total generating capacity to 80 GWe by 2025, of which 20 GWe would be from nuclear sources (WNA, 2013). The French EPR and American AP1000 were shortlisted, and both companies offered to construct the entire 20 GWe required at that stage. The new programme would have started commissioning of the first units of a 4 GWe fleet in 2016. However, in December 2008 Eskom announced that it would not proceed with either of the bids as a result of a lack of finance, and the government confirmed a delay of several years (WNA, 2013).

These nuclear stations would have reduced carbon emissions and diversified the energy mix. South Africa is still in the same load and supply predicament as described, and all of the proposed nuclear sites for the IRP2010 are located in coastal areas.

In spite of these set-backs, South Africa has been very much involved with nuclear technology over the last decades and has proved to be a worthy participant in this field. The highlights of the achievements are summarised in sections 2.3.1 to 2.3.5.

2.3.1 Koeberg Power Station

South Africa constructed its first and only nuclear power station in the early 1970s and has safely supplied electricity to the national grid from that station since April 1984. The 1840 MWe PWR plant was constructed by Framatome (now Areva) and was based on the design used in the reactors supplying most of France's electricity.

It is strategically located on the coast of the Western Cape for the supply of electricity, as all the coal reserves and coal stations are in the far north-east parts of the country. Although the station is a generation II PWR, several safety modifications have been made following the 2011 Fukushima accident.

Currently, the plant supplies 5% of the total supply of electricity for South Africa. A life extension project has been approved for Koeberg that will allow it to operate for 60 years, until 2044. This would require replacement of the steam generators in 2018. Koeberg ranks amongst the safest of the world's top ranking PWRs of its vintage and is the most reliable Eskom power station (Eskom, 2013).

2.3.2 NECSA

The NECSA facility was built to produce weapons-grade uranium for use in South Africa's nuclear bomb arsenal. Since the nuclear weapons were voluntarily dismantled (RSA being the only country to do so), NECSA now pursue nuclear technology excellence for the sustainable social and economic development. The mandate and mission of NECSA now includes:

- Undertake and promote research and development in the field of nuclear energy and radiation sciences and technology.
- Process and enrich source material and nuclear materials.
- Fulfilling the State's nuclear obligations.
- Contributing to the development of skills in science and technology.
- Total commitment to health, safety and care for the environment.
- Developing and empowering our human resources base.
- Satisfying stakeholder experience. (NECSA, 2013)

The state-owned company continues to operate the SAFARI-1 research reactor and manages the Vaalputs waste disposal facility. It produces a range of radiation based products for the life sciences, healthcare and industry for both local and foreign markets.

2.3.3 Pebble Bed Modular Reactor (PBMR) project

The Pebble Bed Modular Reactor (PBMR) design is a Generation IV type HTR (High Temperature Reactor), based on German technology and developed through a collaborative initiative by NECSA, Eskom, Government and academic institutions. Just before a pilot plant was to be erected, the government unfortunately terminated the PBMR project on the brink of the global economic recession of 2008. Reasons given by the minister at the time are:

- No customer secured for the PBMR.
- In addition to the R9bn already invested, a further R30bn was required for completion of the project.
- The project has missed deadlines consistently.
- The opportunity to participate in the USA's next generation nuclear plant had been lost.
- New build programmes would make use of Generation II or III technology, not Generation IV.
- Government spending had to be prioritised in light of the recession.(WNA, 2013)

2.3.4 iThemba Laboratory

iThemba Laboratory is a leading African organisation for research, training and expertise in accelerator-based sciences and technologies. They provide state-of-the-art-facilities and programmes for world class research and nuclear sciences for the benefit of South Africa and the continent in general. There are four sub-atomic particle accelerators in SA, making it the biggest facility of its kind in the southern hemisphere. Core activities include research, radionuclide/radiopharmaceuticals production, medical radiation, education and training (iThemba Lab, 2013).

iThemba Laboratory is a registered manufacturing pharmacy and produces radionuclides such as Na-22, As-73, Ge-68 and Sr-82 to over 60 clients worldwide. They are also the only Na-22 positron source producers in the world. In order to appreciate more clearly the importance of these radionuclides, consider these applications (iThemba Lab, 2013):

- Ga-67 citrate is used for scintigraphy (diagnostic testing in the field of nuclear medicine) in the diagnosis of malignant lymphomas, lung carcinomas, melanoma, hepatoma, tumours, sarcomas, and miscellaneous indications in inflammations and infections (sarcoidosis, TB, AIDS and other infectious diseases) (Wikipedia, 2010).
- I-123 capsules or solution for injections is used for non-invasive diagnostic investigations of thyroid abnormalities or dysfunction.

- F-18 is used for glucose metabolic studies after Positron Emission Tomography (PET).
- Ge-68 is used for diagnosis of neuroendocrine tumours.
- Na-22 and Na-22 positron sources are used in material sciences for positron annihilation studies.
- Sr-82 is used to obtain Rb-82 for PET scans.

2.3.5 Uranium mining

South Africa is very involved in the uranium mining industry, and it is estimated that roughly 5.5 to 7% of the world's uranium deposits are found within SA (WNA, 2011). Uranium mining has mostly been a by-product of gold and copper mining in South Africa. In 2011, 730t of uranium was produced, and this quantity is expected to grow to 2 000t by 2020 (Kotze, 2012). Figure 1, below, shows the top five countries with regard to uranium and oil production. South Africa is blessed not only with abundant coal reserves, but also with large uranium reserves:

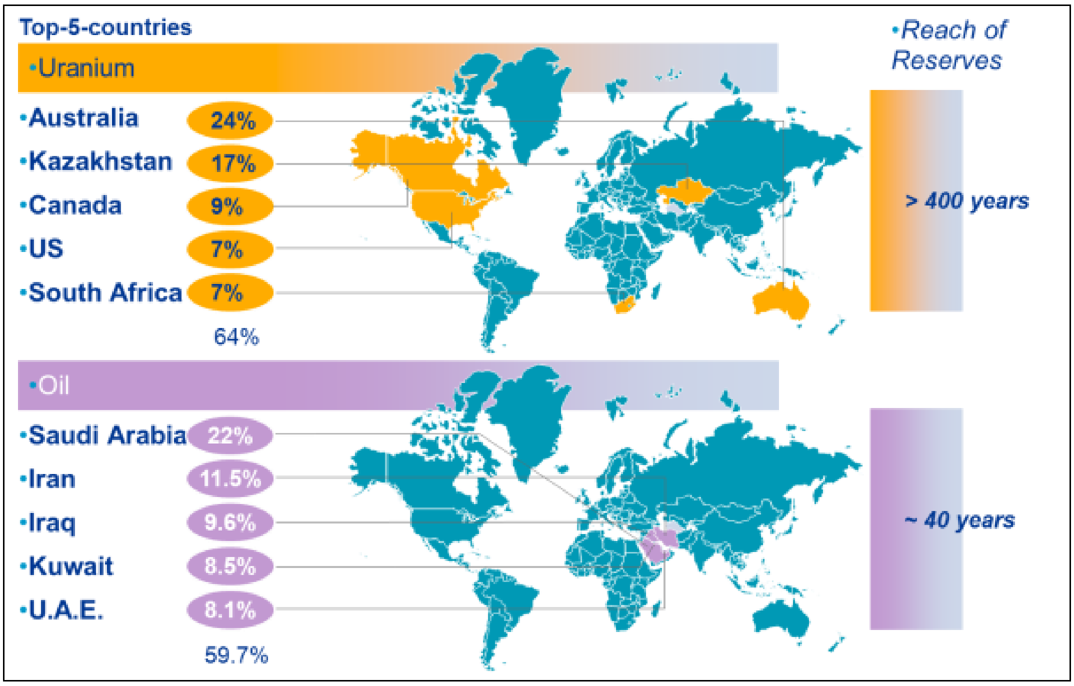

Figure 1: Top 5 Uranium- and oil-producing nations (WNA, 2006)

This could potentially be a very important resource in the future. South Africa could position itself in the uranium mining, processing, enrichment and nuclear fuel production industries. Even if the local nuclear fleet is not expanded, South Africa can still benefit economically by selling enriched uranium or even fuel assemblies to the world nuclear market.

2.4 Renewable technology in South Africa

Eskom has constructed a small assortment of wind turbines, and is in the process of approving two larger renewable energy plants. These are the Sere wind farm on the west coast and the CSP for construction near Upington. South Africa is a member country of the Kyoto Protocol, committed to reducing carbon dioxide and other greenhouse gas emissions. There are rebates and financial support offered by international organisations for green projects (Lomborg, 2001). Eskom and, indeed, the world are expanding their renewable energy portion. This increase can be seen in the graphs under section 2.7, as well as the planned renewable expansion in the IRP2010, found under section 2.6.

2.5 Hydrocarbon technology in South Africa

Hydrocarbons consist of all fossil-type fuels known as coal, oil and gas. Hydrocarbon fuels derive their name from their chemical composition, since they contain hydrogen and carbon. South Africa is fortunate to have abundant and readily available coal reserves and have taken full advantage of this. Most of its electricity is generated from burning coal, roughly 85%, and higher grade coal is exported to stimulate the economy. Open cycle gas turbines (OCGTs) are also fired at great cost during peak periods to meet electricity demands. The fact that OCGTs are fired for such long periods testifies to the desperate state of affairs of the electricity shortage in South Africa.

Although there are many deliberations from where to source our energy for future generations, it is clear that most of the first-world intends to segregate itself from hydrocarbon fuels. There are many opinions as to the motivation of this movement, such as environmental reasons, political reasons, or perceived fuel depletion. The most important of them all are most likely financial implications.

The choice whether or not South Africa wants to build coal stations or not is slipping out of its hands as global financial institutions become indignant in providing loans for such projects. It also appears that more and more governments are subsidising ‘green’ projects (Lomborg, 2001). In fact, carbon tax may be implemented for utilities as well, according to the Kyoto Protocol, of which South Africa is a member country. This puts the country in the compromising position of either paying up or implementing technologies such as carbon capture and flue gas desulphurisation on our coal stations.

2.6 Integrated Resource Plan (IRP2010)

The Integrated Resource Plan of 2010 (IRP2010) is a document that is set up by the South African government through collaboration with various stakeholders. The primary purpose of this document is to determine long-term electricity demand and detail how this demand should be met in terms of generation, capacity, type, timing and cost. The energy capacity in 2010 and the planned total energy capacity for 2030 shown in figure 2 below summarise the vision of the document:

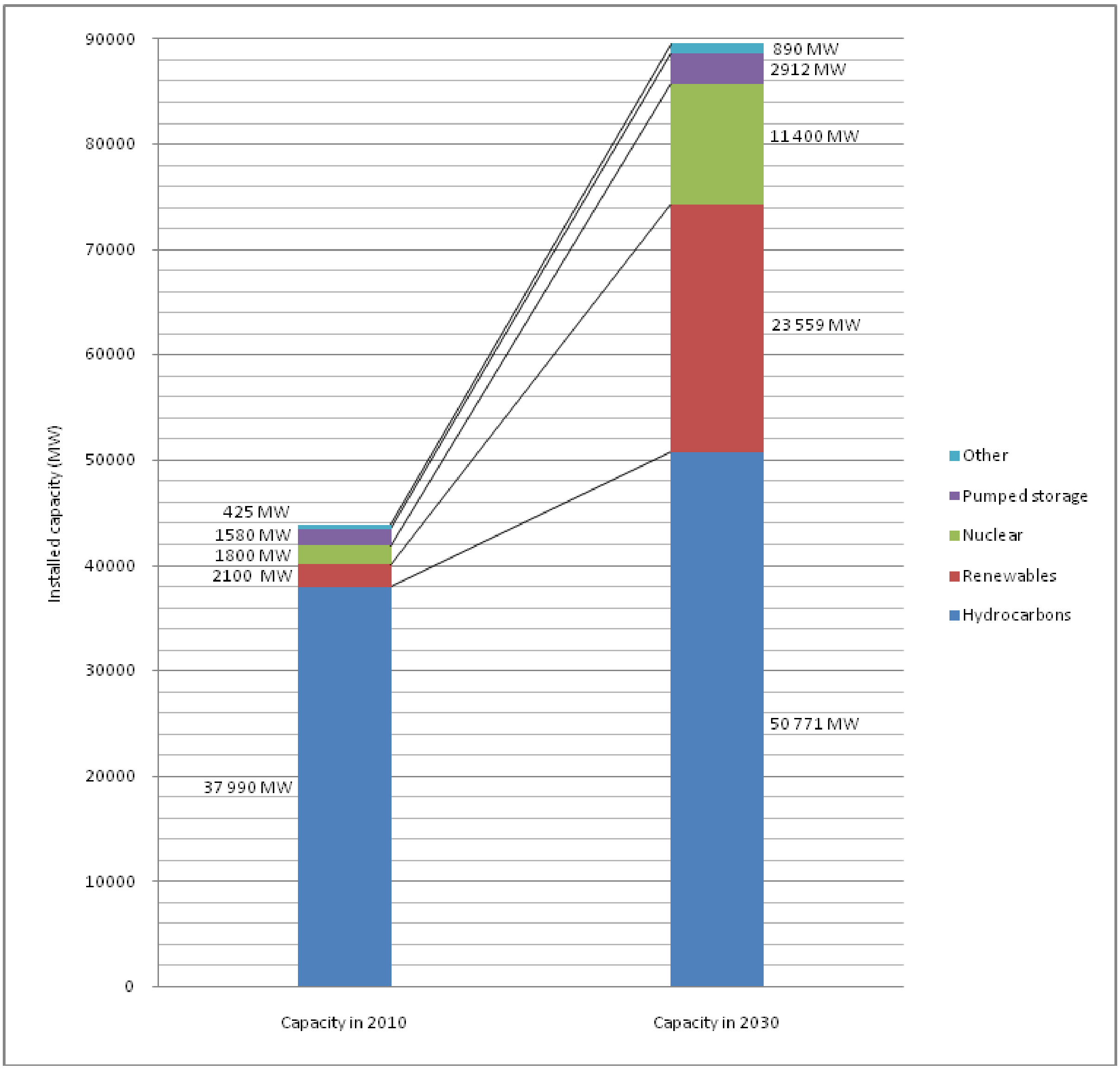

Figure 2: 2010 capacity vs. total capacity planned for 2030 according to the IRP2010

The IRP interdepartmental task team focused on the following factors during the capacity expansion evaluation (DME, 2011):

- Affordability/Funding availability
- Reducing carbon emissions/Climate change mitigation

- New technology uncertainties such as costs, operability, lead time to build, and so on
- Water usage
- Localisation, regional development and job creation
- Security of supply
- Diversity of energy sources.

Taking these factors into consideration, the policy aims to diversify the energy mix and reduce dependency on coal. The three major sources planned to provide the bulk of electricity in 2030 are: hydrocarbon, renewable and nuclear. The main components of the renewables are wind (8400 MW), solar PV (8400 MWe) and CSP (1000 MW) (DME, 2011).

The document further investigates various scenarios regarding different technologies and build options in especially the hydrocarbon and renewable sectors. The various scenarios cater for different levels of water consumption, carbon dioxide emissions, capacity and costs. For more information on the various scenarios reference Appendix AA of the Executive Summary of the Draft Integrated Resource Plan for South Africa. A summary of the proposed scenarios is attached as an appendix below.

2.7 Composition of global power sources

The global need for energy is met by various sources. According to the chart, the predominant source up until 2010 is fossil type fuels (coal, oil and natural gas). However, there has been a significant increase in the nuclear share (IEA, 2012). Consider figure 3 and 4 below:

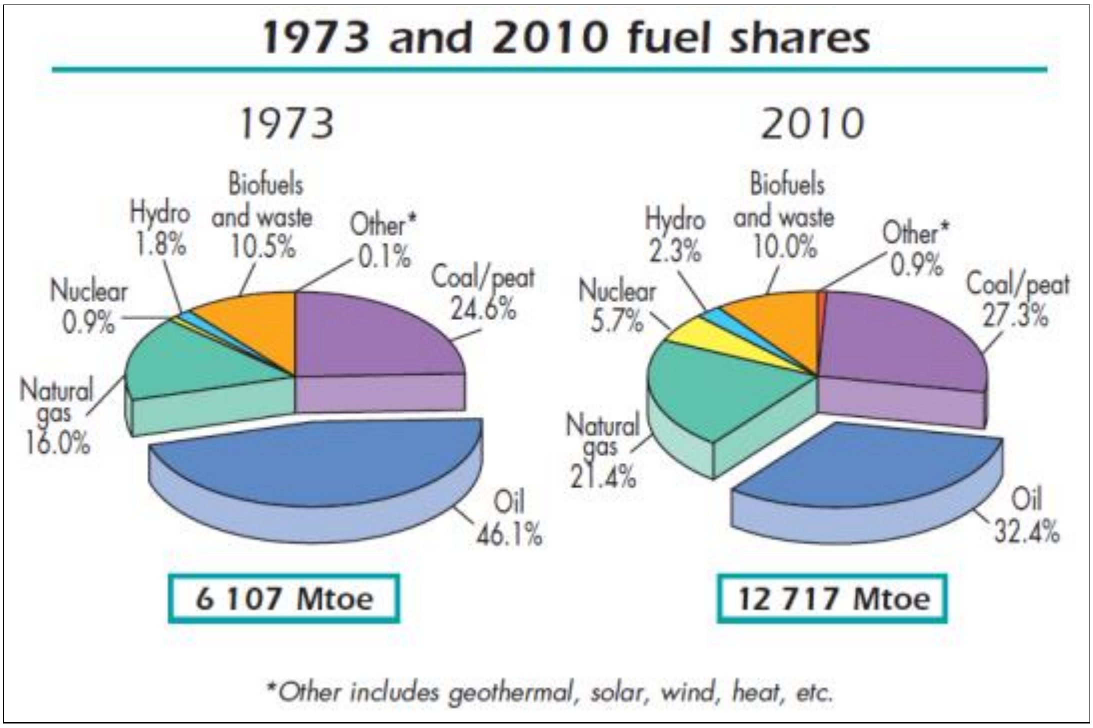

Figure 3: Comparison of fuel shares for total primary energy supply (IEA, 2012)

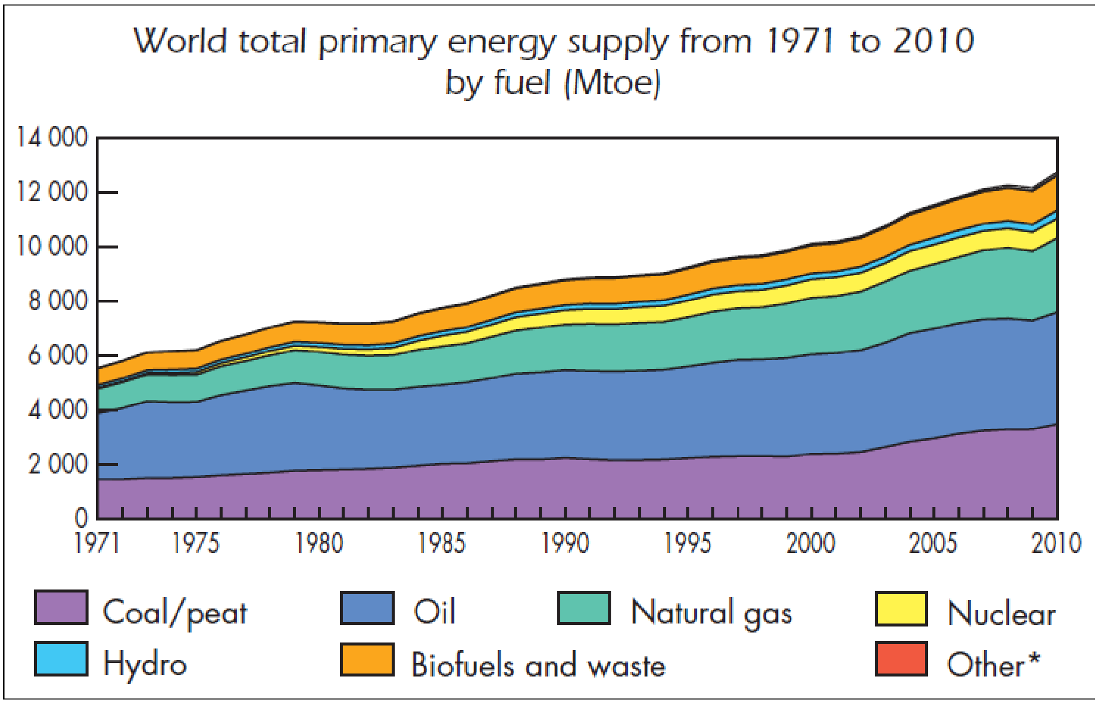

Figure 4: World total primary energy supply from 1971 to 2010 by fuel (IEA, 2012)

2.8 Base load supply, peak demand and load following

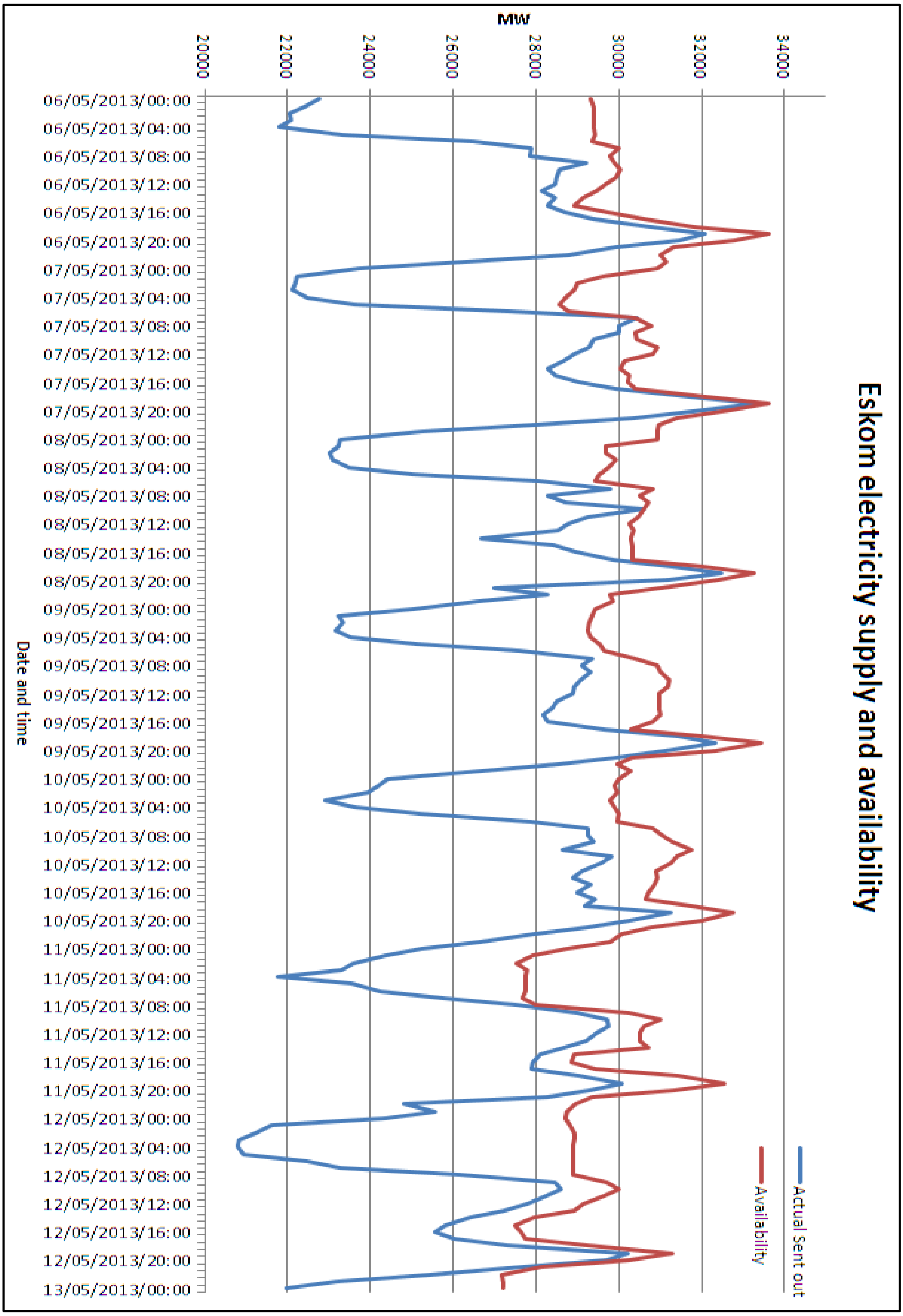

Figure 5: Eskom supply and availability over one week (Eskom National Control Centre, 2013)

Figure 5 indicates national electricity supply and availability over the period of one week. The fluctuations indicate just how much power consumption varies between day and night time, and a slight overall decline towards the weekend. This variance is typically in the order of 10GW.

The concepts of base load electricity and peak demand are to be introduced here. Electricity cannot be stored and has to be used as generated; therefore, in order to sustain the country's economy, we need a steady and reliable 24/7 supply of electricity. All major industries such as mines, smelters and even power stations require a constant supply of electricity at all times. As can be seen on the graph, actual usage varies from ~22GW (during night time) to ~33GW (evening peak), reflecting the constant supply of electricity required. The energy required by South Africa for one week would be the area below the blue curve, and this is met by the base load capacity. Ideally the base load capacity should cater for at least a 15% spare capacity at all times. The base load supply is therefore the constant and reliable supply of electricity required to sustain and grow the economy.

Figure 6 shows a qualitative depiction of base load supply and peak load demand.

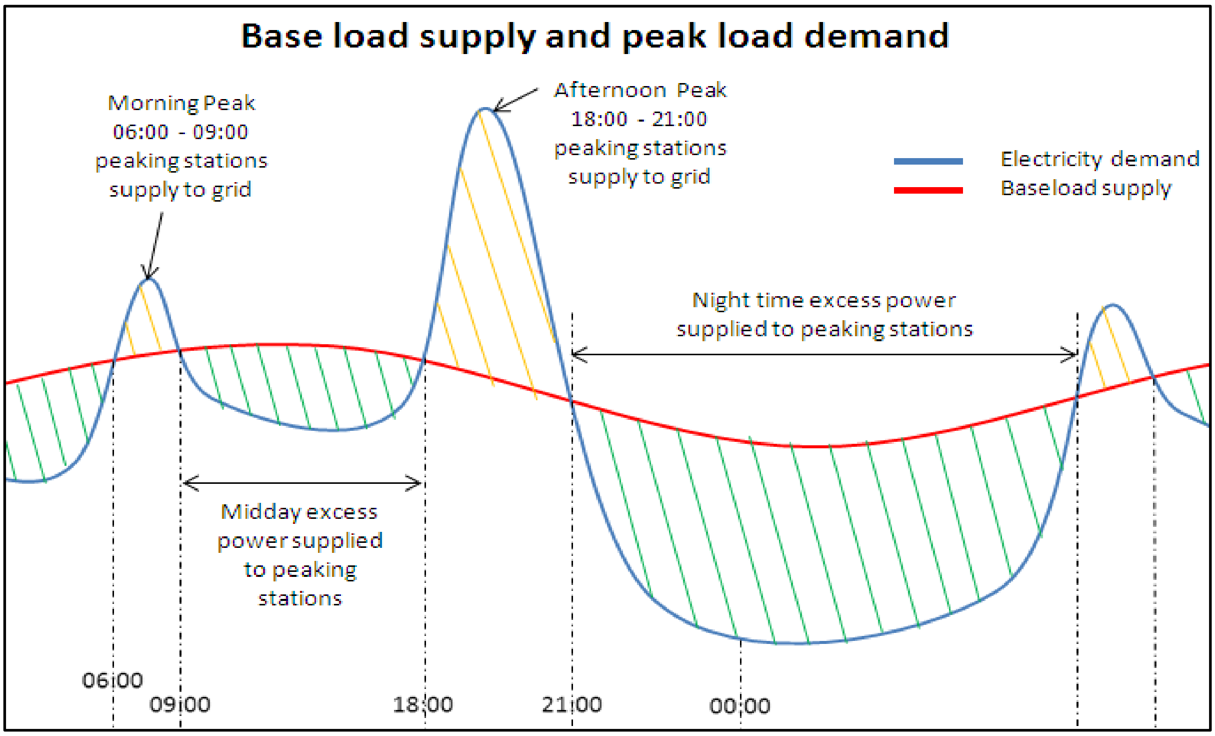

Figure 6: Qualitative graph showing base load energy against actual demand

Ideally power stations would operate at constant power as long as possible. Large boilers and reactors cannot constantly change power levels to cater for the change in consumer load as this causes inefficiency and thermal stresses. Peaking stations are therefore connected to the grid to cater for the variability factor. As the demand rises rapidly during the signature peaking hours, demand is partially met by peak stations with fast load-changing characteristics. In SA these are mainly gas turbines (low capital cost, high running cost) or pumped storage (high capital cost, low running cost). There are also the mid-merit stations (smaller coal station boilers) with the ability to change load faster than the large base load boilers in order to assist with peak load demand.

The last concept linking in to this section is that of load following. Load following is a measure of how rapidly a generating technology can change power levels to accommodate demand. Often this is measured in percentage of total power per hour (%/h) or in Megawatt per hour (MW/h). A plant can perform load following in either the positive direction or the negative, thereby increasing or decreasing power as the grid demands. A more detailed model regarding the base load and load following requirements of South Africa is presented in the next chapter.

2.9 Eskom-installed power plant profile

Figure 7 paints a rather concerning picture regarding the age of Eskom's power plants. Eskom is on the verge of large-scale decommissioning of some of its biggest units. Fortunately, the construction of both the Medupi and Kusile plants is well underway. However, they will replace decommissioned capacity only up to the year 2022. Furthermore, this appears to be an almost insignificant contribution compared to the sizeable shut-down of 28 000MW of generating capacity planned during 2023, followed by another 23 000MW during 2028. So even with the two large planned stations, Eskom is not nearly out of the woods yet. Note that the graph does not indicate the approved 20-year life extension programme for Koeberg.

It is therefore clear that the government has to urgently commit to and execute new-build projects in order to replace the planned decommissioned capacity and ensure growth of electricity supply for South Africa. The construction of large-scale base load power plants has to commence in the near future in order to prevent catastrophic economic devastation. The IRP2010 document is some evidence of government's intention to address this issue.

It can be pre-emptively stated here that the only two options for base load power sourcing economically available to South Africa in the near future are coal and nuclear stations. Fracking and hydroelectric power from the Congo River is outside the scope of this research as it is not yet a guaranteed source of energy for South Africa.

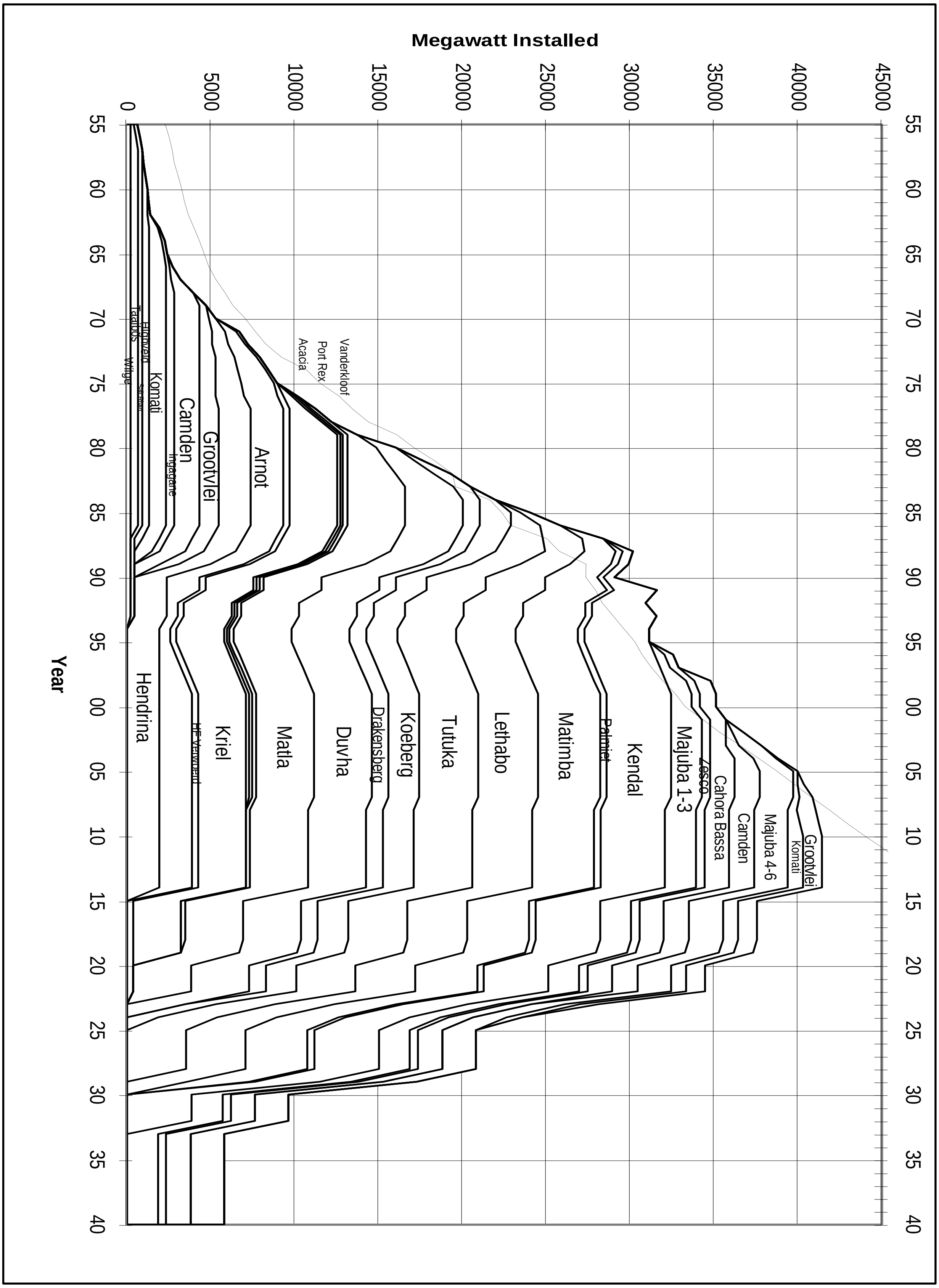

Figure 7: Eskom's installed capacity profile

2.10 Summary

Nuclear technology has come a long way indeed. Even before man's discovery of nuclear forces, the universe was powered by nuclear fusion occurring in the stars. This fusion process produces solar radiation for the earth, sustaining all living creatures and powering solar panels. Heat from this process also causes differential pressure zones in the earth, resulting in wind (and waves) on the surface of the earth.

The world is utilising nuclear energy to supply roughly 6% of its energy needs. This percentage is bound to increase substantially as there are many reactors planned and under construction worldwide, according to the World Nuclear Association. South Africa still has an opportunity to be a leader in the nuclear renaissance and to participate in various global nuclear expansion projects. Nuclear technology has the potential to uplift the economic welfare of the whole of South Africa.

3. INVESTIGATION

3.1 Chapter overview

The purpose of this chapter is to investigate the various viable energy sources for South Africa.

From the IRP2010, the identified sources for this investigation are renewables, constituting wind and solar energy, hydrocarbons and nuclear. Unfortunately, South Africa has no large-scale geothermal energy and hydroelectric power is mostly pump storage; therefore these are not to be considered in the investigation. Hydroelectric power is represented to some degree by the peaking stations operating in South Africa. The availability of crops for biomass in South Africa is very limited and also not considered in this investigation. Other options for future electricity generation are imported hydroelectricity from the Congo River and shale gas in the Karoo, but these sources will not form part of the scope for this analysis as they are not yet a guaranteed option for South Africa. Therefore only existing infrastructure along with wind, solar, hydrocarbon and nuclear energy forms are to be considered for this analysis.

3.2 Wind energy

Wind turbines are mostly marketed as a renewable source of energy with no greenhouse gas emissions during operation. The South African government is committed to reducing greenhouse gas emissions as stipulated in the Kyoto Protocol by expanding its renewable energy profile (UN, 2013). In the IRP2010, the proposed 8 400 MW from wind by 2030 testifies to this commitment. South Africa can also benefit from the following advantages of wind energy (EPRI, 2010):

- The ‘fuel’ is absolutely free.
- Wind generators can be erected in isolated areas and need not be integrated into the national grid.
- Capital costs are relatively low (see figure 17) and maintenance infrequent.
- Wind turbine technology is increasing allowing better efficiency and availability factors, up to 40.6% and 97% respectively.
- Wind energy projects are supported and subsidised by many financial institutions and governments.

Wind energy certainly has many positive attributes. Eskom has also constructed wind turbines to investigate the possibility of wind energy:

- Klipheuwel demonstration facility (3.17MW):
  - Vesta660kW
  - Vestas750kW
  - Jeumont750kW

The Klipheuwel facility was installed in 2002 as a pilot wind investigation project. Unfortunately, as a result of lack of proper wind resource data, the facility was not built in an effective area and it has a load factor of less than 20% (Kenny, 2012). The Jeumont turbine is also not currently operational.

- Darling wind farm (5.2 MW):
  - 4 x Fuhrlaender1.3MW

The Darling facility was installed early in 2008 and was expected to have a load factor of >30%. In actual fact, the load factor turned out to be 18.9% (Kenny, 2012). Other studies have suggested that the figure is as low as 13.9%.

- Coega Industrial Zone (1.8MW)
  - Vestas1.8MW

This turbine was built right before the 2010 Soccer World Cup; unfortunately no official production data are available.

Wind turbines have also been used for many decades for household electricity in conjunction with battery storage. The occasional traffic information display screen and other road signs are also wind powered. The most popular application of wind energy, however, is the use of about 300 000 windmills used to pump groundwater for farms and isolated communities.

In light of the IRP2010, the proposed 8 400MW supply of wind energy may be technologically achievable, but would not be the best choice for South Africa in terms of security of supply, load following, and technological uncertainty. Wind turbines do not provide base load supply. If you were to extrapolate and imagine that wind turbines were the only source of energy supplying the South African grid, you would have to agree that they would not work without a mechanism to store energy. This makes large scale grid power application of wind energy unrealistic.

Figure 8indicates the load factors of several wind farms in Australia:

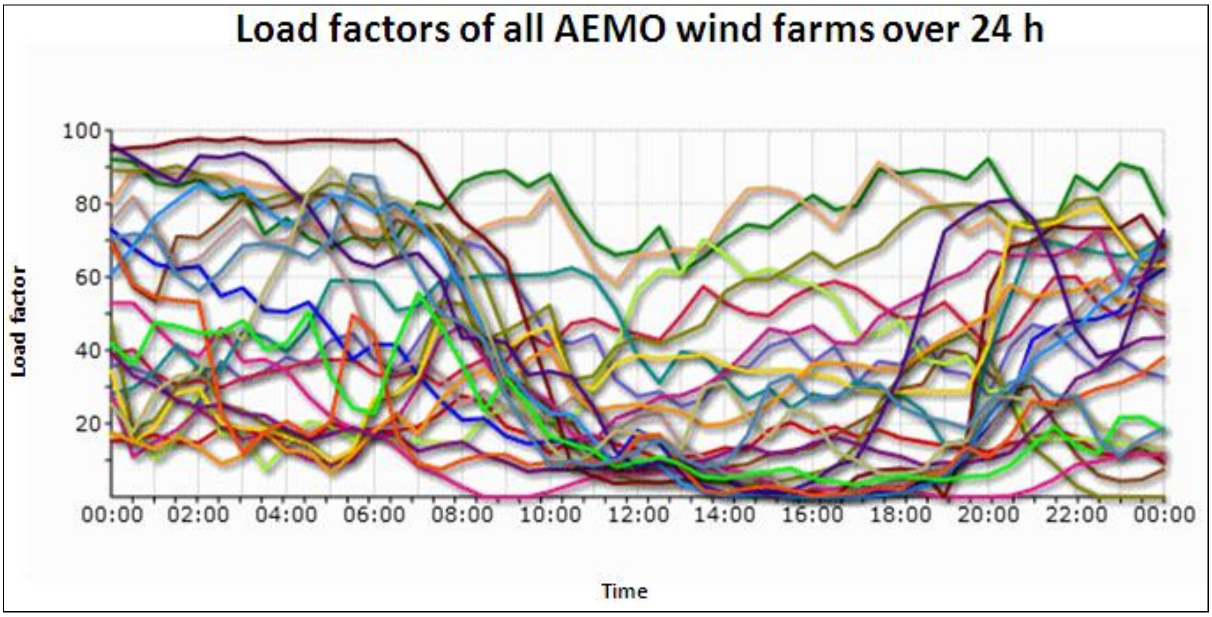

Figure 8: Load factors from Australian Energy Market Operator wind farms (Ramblings DC, nd).

Since all the wind farms are spread out in different regions in the above graph, the average supply of electricity is relatively even, but still unpredictable. Tracing any individual line would indicate the variable nature of wind energy. This should not be a problem, however, since South Africa has many coal-fired units that can operate in load follow to compensate for the intermittent supply from wind farms. However, in order to achieve this generating synergy, sufficient excess capacity is required. Currently, the grid is very constrained and most of the time all Eskom units operate at maximum possible capability; even the gas-fired units are operated at very high cost in order to supply base load demand. In the current scenario, therefore, if any supply is to be added to the grid, it has to offer stable power supply. Eskom would not be able to take units offline for maintenance if wind energy is the last line of supply to the grid.

Since wind turbines provide electricity rather than heat, the only realistic option would be to implement an efficient pump storage scheme. This would prove to be very expensive and require large-scale access to hydroelectric power, which is not available in South Africa. South Africa currently has a pumped storage capacity of 1 580MW, with potential expansion of 7 000MW (DME, 2002). The point here is that if 8 400MW, or 15% of our electricity, were to come from wind, it would have to provide assurance of constant supply, which wind cannot currently do as it would operate in base load domain. The most logical large-scale deployment of wind is in conjunction with a pumped storage scheme and only if South Africa has an adequate margin of supply, neither of which is currently available.

Other challenges and bottlenecks to implementation of wind energy in South Africa are:

- Unprepared electricity transmission and distribution facilities
- Aesthetic impact and noise pollution (Wiesegart, 2010).

The above problems regarding wind technology can be solved and they certainly have a role to play in the energy mix of South Africa. It is advisable, however, to utilise wind energy for its proved benefits, which is small-scale remote power generation. Since South Africa is such a large country, this technology would be ideal for our numerous remote areas, especially along the coast. This would also save costs of erecting long transmission lines to these areas.

Wind energy should be deployed on a large scale only if it should prove to provide a secure supply of electricity economically through more pilot projects, or in conjunction with bigger pumped storage facilities. Even if this is to be done, the inability for wind turbines to follow load limits its base load, hence large-scale grid electricity, application.

In summary, the primary focus for South Africa currently is the expansion of its base load capacity as supply margins erode to decimal values. Smelters and mines are forced to shut down during peak times with detrimental economic consequences. Unfortunately, wind energy does not supply base load energy, and offers no solution in this domain.

3.3 Solar energy: photovoltaic (PV) panels or cells

Photovoltaic solar panels (or solar cells) convert solar irradiation directly to electricity. The construction of such a panel consists mainly of positive and negative type silicon-based semi-conductors connected to a conductor. The semi-conductor material absorbs photons from the light and in turn releases electrons, producing a direct current (DC) through the conductor. Figure 9 depicts a basic solar cell:

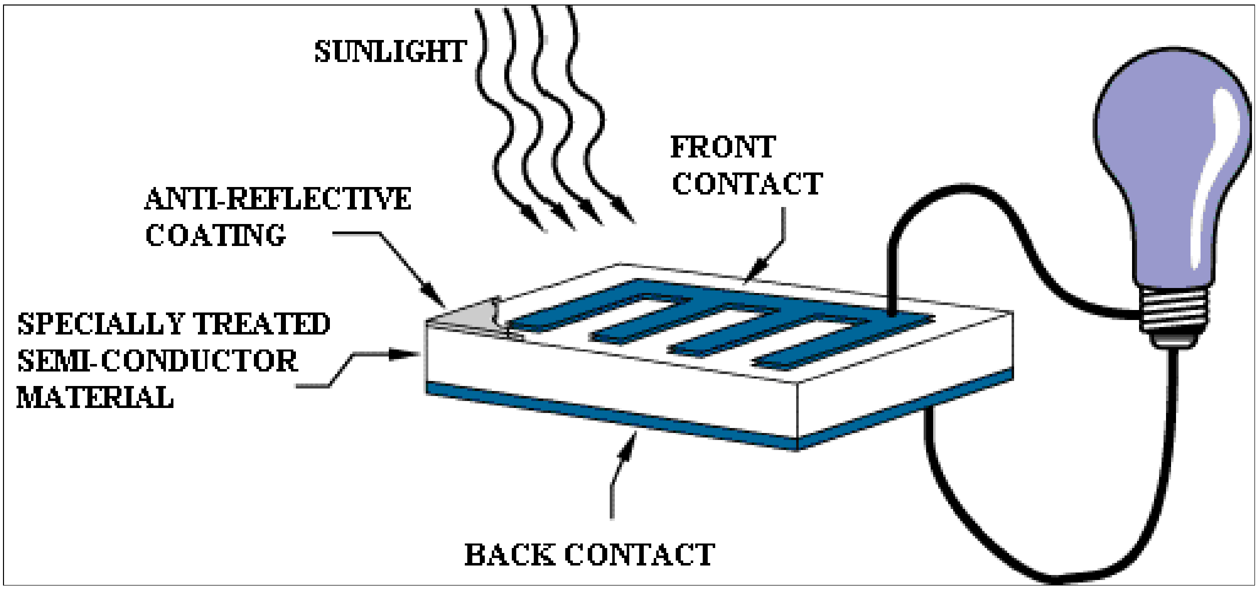

Figure 9: Basic diagram of a solar cell (Knier, 2011)

The IRP2010 proposes that a bulky 8 400 MW of photovoltaic solar electricity be added to the grid by 2030. Similarly to wind power, the advantages of solar energy are mainly free fuel, decentralised power generation, low maintenance, and low greenhouse gas production during operation (EPRI, 2010). Another noticeable advantage is the relatively short construction time of solar installations. Solar power also supports government's commitment to the Kyoto Protocol in reducing greenhouse gas emissions (UN, 2013).

South Africa most definitely has potential for solar energy, with solar radiation levels well above international levels. Figure 10 depicts a rough representation of the solar resource in South Africa:

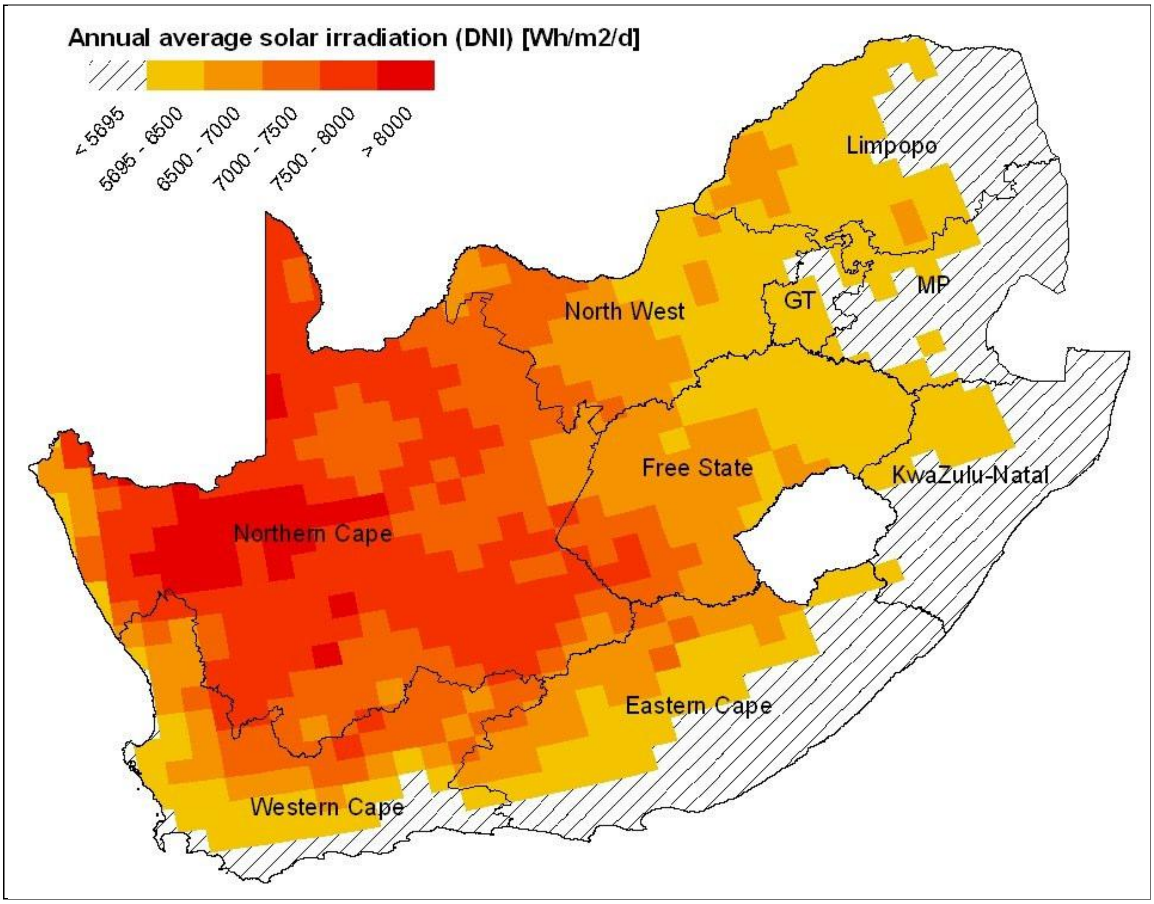

Figure 10: Annual solar radiation levels (Fluri, 2009)

Most of the solar energy potential is concentrated in the Northern Cape Province. There is little, yet widely distributed, load demand in this region, and this would be a good scenario for solar energy. As with wind energy, PV solar energy has a timing problem, as it generates electricity only in synchronisation with the sun's intensity. Apart from the fact that the sun, and therefore electricity production, peaks in midday, missing both the morning and evening peaks, there are many more causes for variability in light intensity/efficiency (Fluri, 2009):

- Day/Night
- Seasons
- Weather (clouds, fog, mist, and so on)
- Panel maintenance (for example, dust)

Figure 11: Aerial photo of 60 MW Olmedilla PV solar farm in Spain (Gravel Democrat, 2009)

Although space in South Africa might not be a limiting factor, consider figure 11, a photo of the then largest PV solar plant in the world upon its completion in 2008. The Olmedilla solar farm in Spain has a peak generating capacity of 60MW from its 270 000 solar panels (Gravel Democrat, 2009). This means that for one typical nuclear unit of 1 000MW, you would require just over 16 of the Olmedilla farms. Then, to offset the load factor differences, you would need roughly four times more, assuming a (solar load factor) / (nuclear load factor) of 0.25. Therefore, in order to retrieve the same amount of electrical energy from the sun as one nuclear unit, you would require approximately 64 Olmedilla farms. The equivalent of Koeberg would therefore be roughly 128 Olmedilla farms in extent.

Then, of course, there is the issue of base load supply: nuclear stations effectively run 24/7 compared to the skewed supply curve of solar, assuming that no energy storing mechanism is available. Solar energy peaks at midday, and is not in synchronisation with both the morning and afternoon peak demands (refer to the base load supply and peak demand discussed in chapter 2). Solar panels also produce DC, which has to be converted to AC in order to be connected to the grid, resulting in additional losses.

3.4 Solar energy: concentrated solar power (CSP)

The IRP2010 proposes to add 1 000 MW of concentrated solar electricity to the grid by 2030. Concentrated solar power (CSP) uses the sun's radiation directly to heat up a salt-type medium located in a central receiver, which is coupled to a steam generator. The steam generator supplies steam to a turbine in a typical Rankine cycle. The salt mixture usually consists of sodium and potassium nitrates and allows storage of heat energy for up to 8 hours.

Note, however, that the net supply of electricity from a CSP is very similar to that of an equivalent PV solar plant, even though the availability factor is much more. Roughly the same amount of solar energy is captured by both types of technology, but the CSP delivers it over a longer timeframe as opposed to the 'as-generated' delivery from the PV plant. The CSP therefore delivers less energy, but over a longer time. Figure 12, below, shows an overview of a typical CSP.

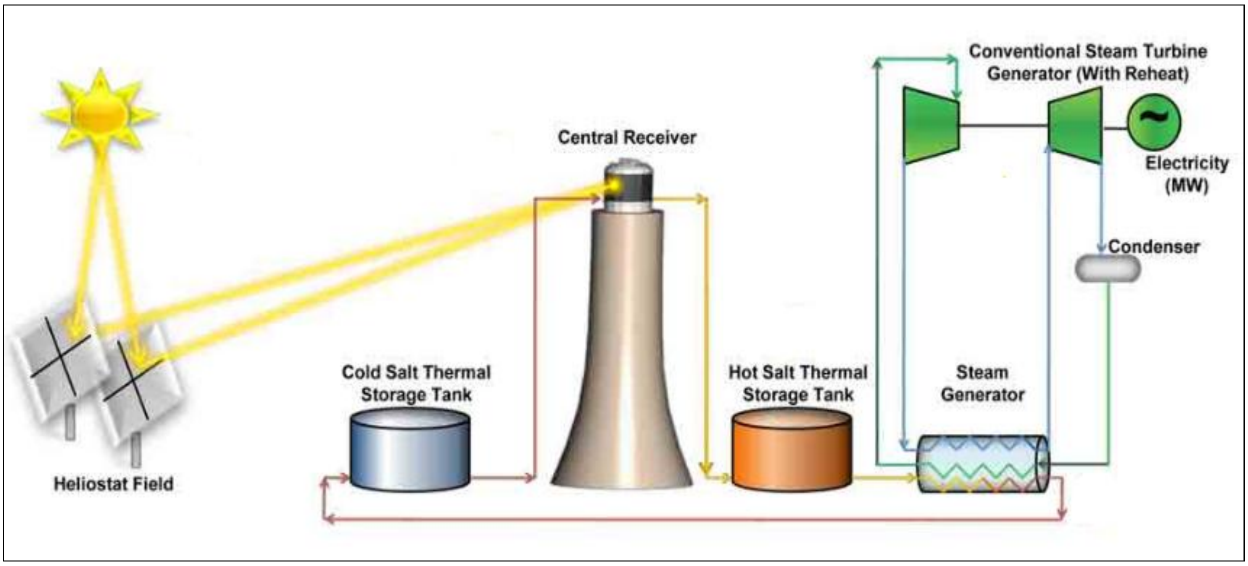

Figure 12: Overview of CSP (Solar Reserve, nd)

A pilot CSP has been approved for construction by Eskom near Upington. This is part of an initiative to explore renewable technologies, diversify Eskom's energy mix, and align itself with the vision of the Kyoto Protocol.

As indicated in the previous section, the Northern Cape province has the world's leading solar potential. To re-emphasise this point, consider Table 1 below:

Table 1: International annual radiation compared to South Africa (Eskom, 2010)

Location	Site latitude	Annual radiation (kWh/m^2)
South Africa		
Upington, Northern Cape	28˚S	**2.995**
United States		
Barstow, California	35˚N	2.725
Las Vegas, Nevada	36˚N	2.573
Albuquerque, New Mexico	35˚N	2.443
Other		
Northern Mexico	26–30˚N	2.835
Wadi Rum, Jordan	30˚N	2.500
Quarzazate, Morocco	31˚N	2.364
Crete	35˚N	2.293
Jodhpur, India	26˚N	2.200
Spain	34˚N	2.100

The CSP offers a higher availability factor, with some potential for load following. The capital costs for these plants are, however, extremely high, and lifetime is relatively short. As with wind energy, it is recommended that solar energy be utilised for its strength, which is isolated small-scale power production such as solar water heaters. Both wind and solar plants do not have load-following capability and they are not suitable for large-scale base load grid electricity. The Kyoto Protocol can still be adhered to with nuclear stations.

3.5 Hydrocarbons

Hydrocarbon fuels, mainly through coal stations, currently provide the bulk of energy to South Africa. Prior to recent environmental policy and standardisation of nuclear stations, this made good sense as coal was readily and cheaply available. Old-fashioned coal stations did not even have smoke stacks, but flue gas was vented out of the boiler through what can only be described as a chimney. In Eskom's coal station construction era, no ash removal and no greenhouse gas emissions were considered.

Advancements in the use of coal over the years, from flue gas precipitators to super-critical boilers with flue gas desulphurisation (FGD) and carbon capture has kept coal stations going. The low-end capital costs of erecting such large stations make it attractive for short-term remedial measures with regard to electricity supply. However, once again, nuclear outperforms coal as it has twice the lifetime with better load factors and much lower fuel costs (see figure 17). In coal stations, the total cost of coal can far exceed the capital costs of the station itself, not to mention the abhorrent costs of running an OCGT. According to the IRP2010, some characteristics for hydrocarbons are as follows. For comparison, the EPR nuclear plant data is attached as well:

Table 2: Hydrocarbon and nuclear characteristics according to the IRP2010 (DME, 2011)

	Pulverised coal with FGD	**Fluidised bed with FGD**	**OCGT**	**CCGT**	**Nuclear Areva EPR**
Life of programme	30	30	30	30	60
Typical load factor (%)	85%	85%	10%	50%	92%
Variable O&M (R/MWh)	44,4	99,1	0	0	95,2
Fixed O&M (R/kW/a)	455	365	70	148	–
Variable fuel costs (R/GJ)	15	7,5	200	80	6,25
Overnight capital costs (R/kW)	17785	14965	3955	5780	26575
Equivalent avail	91,7	90,4	88,8	88,8	92–95
Maintenance	4,8	5,7	6,9	6,9	N/A
Unplanned outages	3,7	4,1	4,6	4,6	<2%
Water usage, l/MWh	229,1	33,3	19,8	12,8	6000 (sea)
CO_2 emissions (kg/MWh)	936,2	976,9	622	376	–

	Pulverised coal with FGD	Fluidised bed with FGD	OCGT	CCGT	Nuclear Areva EPR
SO_x emissions (kg/MWh)	0,45	0,19	0	0	–
NO_x emissions (kg/MWh)	2,30	0,20	0,28	0,29	–
Hg (kg/MWh)	1,27E-06	0	0	0	–
Particulates (kg/MWh)	0,13	0,09	0	0	–
Fly ash (kg/MWh)	168,5	35,1	–	–	–
Bottom ash (kg/MWh)	3,32	140,53	–	–	–

3.6 Nuclear energy: pressurised water reactor (PWR)

The pressurised water reactor (PWR) derives its name from the fact that the primary loop operates with water which is pressurised. The fission of heavy atoms produces exceeding amounts of energy compared to oxidation, because the former process involves nuclear forces as compared to coulomb forces in the latter. The fission of one gram of uranium produces around 2 million times the energy as the oxidation of one gram of carbon. For every kilogram (small handful) of uranium, a bulky 2 700 tonnes of high quality coal is required, according to the European Nuclear Society.

There are several different nuclear power reactor designs, of which the most constructed is the pressurised water reactor type. The World Nuclear Association provides a tabulated overview of reactors in operation around the world in 2012 as follows:

Table 3: Nuclear power plants in commercial operation

Reactor type	Main countries	Amount	GWe
PWR	US, France, Japan, Russia, China	271	270.4
BWR	US, Japan, Sweden	84	81.2
CANDU	Canada	48	27.1
Gas-cooled	UK	17	9.6
Light Water Graphite Reactor	Russia	15	10.4
Fast Neutron Reactor	Russia	1	0.6
Total		**436**	**399.3**

3.7 Demand–supply profile

Although each technology presents certain strengths and weaknesses, the most important requirement remains electricity production. Since electricity cannot be stored, it is subject to a load profile dictated by the consumer. Each power production technology has a certain supply profile of its own, boundaries within which it can supply electricity and change load as and when needed. The proposed energy mix should be able to accommodate the worst case demand scenario in terms of peak load and load following requirements. Currently the grid (collective power producers) is able to supply the demand (collective power consumers), as Eskom has not enforced load shedding since 2008. In order to investigate the proposed energy mix, a model is to be drawn up using the data from the IRP2010 to ascertain whether it would be suitable under the current load profile. This is accomplished as follows:

- A load profile is to be drawn up for the month of winter month of July 2013. This provides the worst case scenario in terms of base load, peak load and load changes. Using current demand data eliminates the need to extrapolate future load profiles in order to provide the most accurate possible scenario.
- Using the proposed energy mix from the IRP2010 for the year 2030, a virtual grid is drawn up to model how it would supply the current demand. The proposed energy mix would be proportionally scaled down in order to model the future energy composition supplying the present demand. Each portion of the proposed mix would be ‘stacked’ to ‘meet’ the current demand, taking into account the load factors and load following capabilities.
- The load profile would also be modelled using a proposed energy mix for the year 2035 (see chapter 4). The year 2035 has been chosen for this model to take into account the pending large-scale decommissioning of coal stations.

Figure 13 indicates the load profile of Eskom for July 2013, indicating each day as well as the average for that specific month:

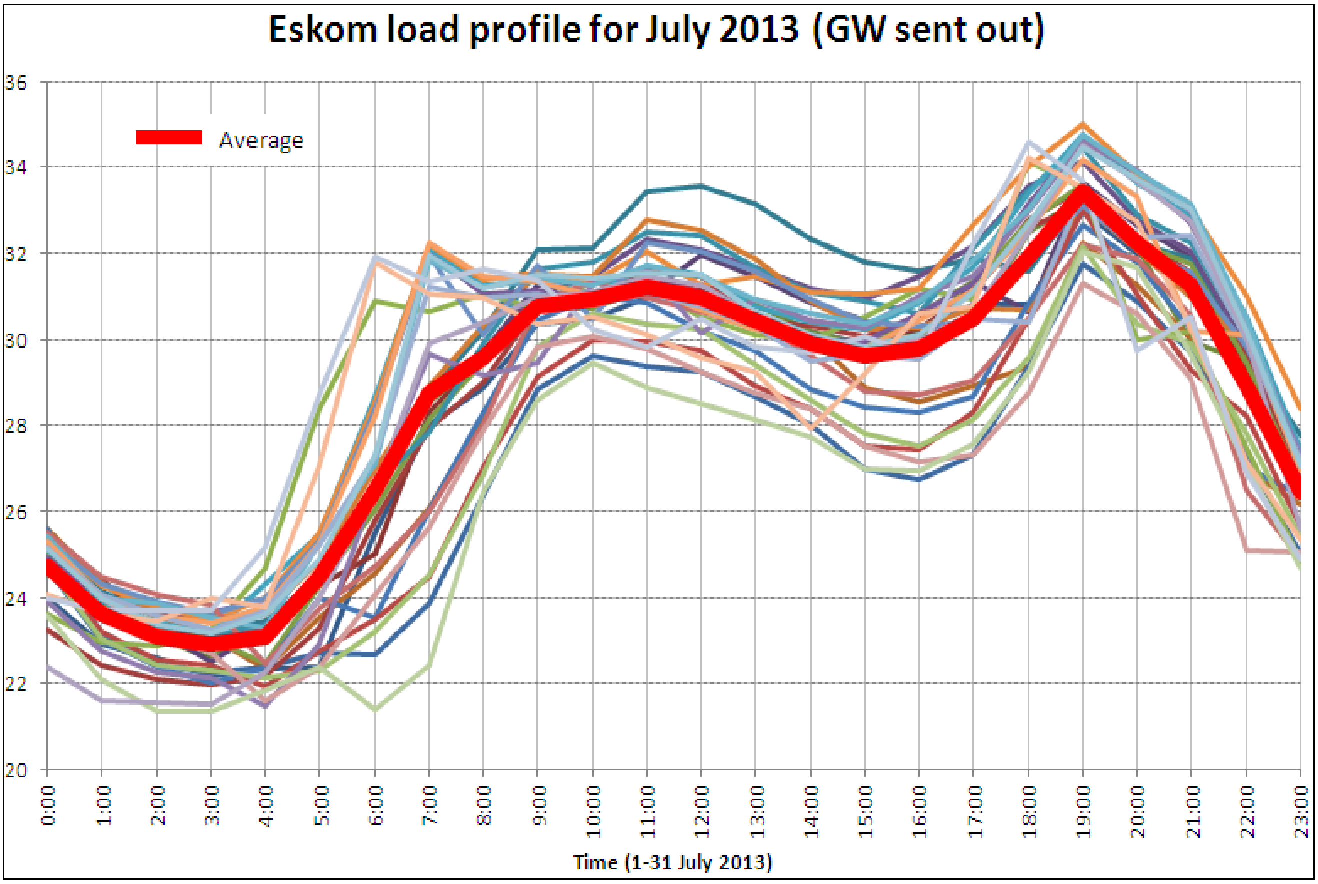

Figure 13: Eskom load profile for July 2013 (Eskom National Control Centre, 2013)

The following data can be extracted from the graph in order to quantify the average and worst case load following requirements for South Africa:

Table 4: Eskom load parameters for July 2013 (Eskom National Control Centre, 2013)

Peak load	**35010 MW**
Base load	**21355 MW**
Average positive load following	**3175 MW/h**
Average negative load following	**3001 MW/h**
Maximum positive load following	**4754 MW/h**
Maximum negative load following	**4497 MW/h**

The graph in figure 13 indicates the peak load to be around 19:00, and the base load reading is derived from the low night-time readings. On the average graph, it shows that power stations operate in positive load following mode (increase power) from 03:00 to 11:00; negative load following from 11:00 to 15:00; again positive from 15:00 to 19:00; and finally negative from 19:00 to 03:00. Consider the table below for an hourly profile of power production statistics. It is important to note that the proposed energy mix must have sufficient load following capability.

Table 5: Eskom hourly load profile for July 2013 (Eskom National Control Centre, 2013)

Time	Min power (MW)	Average power (MW)	Max power (MW)	Max load change (MW/h)
0:00	22396	24712	25603	–2466
1:00	21620	23600	24478	–1286
2:00	21360	23095	24053	–734
3:00	21355	22899	23997	1480
4:00	21480	23091	25161	3711
5:00	22282	24465	28707	4718
6:00	21406	26491	31901	4754
7:00	22411	28739	32264	4049
8:00	26349	29578	31618	2963
9:00	28578	30751	32080	1840
10:00	29452	30919	32101	1735
11:00	28876	31215	33456	–1494
12:00	28518	30964	33552	–1019
13:00	28138	30436	33148	–1319
14:00	27723	29910	32327	1298
15:00	27001	29604	31780	1407
16:00	26736	29775	31598	2567
17:00	27326	30475	32675	3454
18:00	28732	31896	34587	3054
19:00	31285	33446	35010	–3954
20:00	29740	32256	33930	–3152
21:00	29072	31265	33159	–4038
22:00	25094	28928	31001	–4497
23:00	24672	26445	28371	

Using the data from the policy-adjusted IRP2010, the proposed energy mix can be scaled down and applied to the 2013 demand profile. This is done in order to evaluate the effectiveness of the proposed energy mix. The planned total rated capacity for 2030 (84.4 GW) divided by the current total capacity (45.6 GW) produces a scaling factor of 0.54. This scaling factor is multiplied by the 2030 rated capacities to produce an equivalent proportional 2013 grid which can be used to match the load profile for 2013. The load factors are also presented and used to calculate the total energy equivalent for each source.

Table 6: Present equivalent grid scaled from planned 2030 energy data

Energy source	2030 rated capacity (GW)	2013 equivalent rated capacity (GW)	Load factor (%)	2013 equivalent multiplied by load factor (GW)	Total energy equivalent for 1 day (GWh)
Nuclear	11.4	6.16	0.92	5.67	136.00
Coal	41.8	22.58	0.85	19.20	460.71
Hydro (peak)	4.7	2.54	0.2	0.51	12.19
CCGT (gas)	2.4	1.30	0.5	0.65	15.56
OCGT (peak)	6.3	3.40	0.1	0.34	8.17
Solar PV	8.4	4.54	0.194	0.88	21.13
Solar CSP	1	0.54	0.437	0.24	5.67
Wind	8.4	4.54	0.29	1.32	31.59
Total	84.4 GW	45.6 GW		28.8 GW	691 GWh

For the purpose of meeting the load in this model, the following method is used in terms of utilising the different power sources: each source can add a total energy equivalent to the grid during the day, taking into account the load factor as represented by the last column in table 6. By multiplying the load factor with the rated capacity, the energy equivalent value therefore presents the energy source with its timing constraints (main factor for renewables and peaking) and maintenance requirements (main factor for base load). These values are then 'stacked' in order to meet the load, represented by the area below the load curve.

The total load under the load profile curve is 684.96 GWh, being met with 691.44 GWh of the proposed scaled down capacity. Energy sources are either base load, peaking or renewable of nature, indicative of its load following capability.

- Base load units: Nuclear, coal and CCGT.
- Peak load (intermittent supply): Hydroelectric and OCGT.

- Renewables: Wind, PV solar and CSP solar.

For the analysis, the energy equivalent values for each energy source are placed 'online' to supply the average load profile as below:

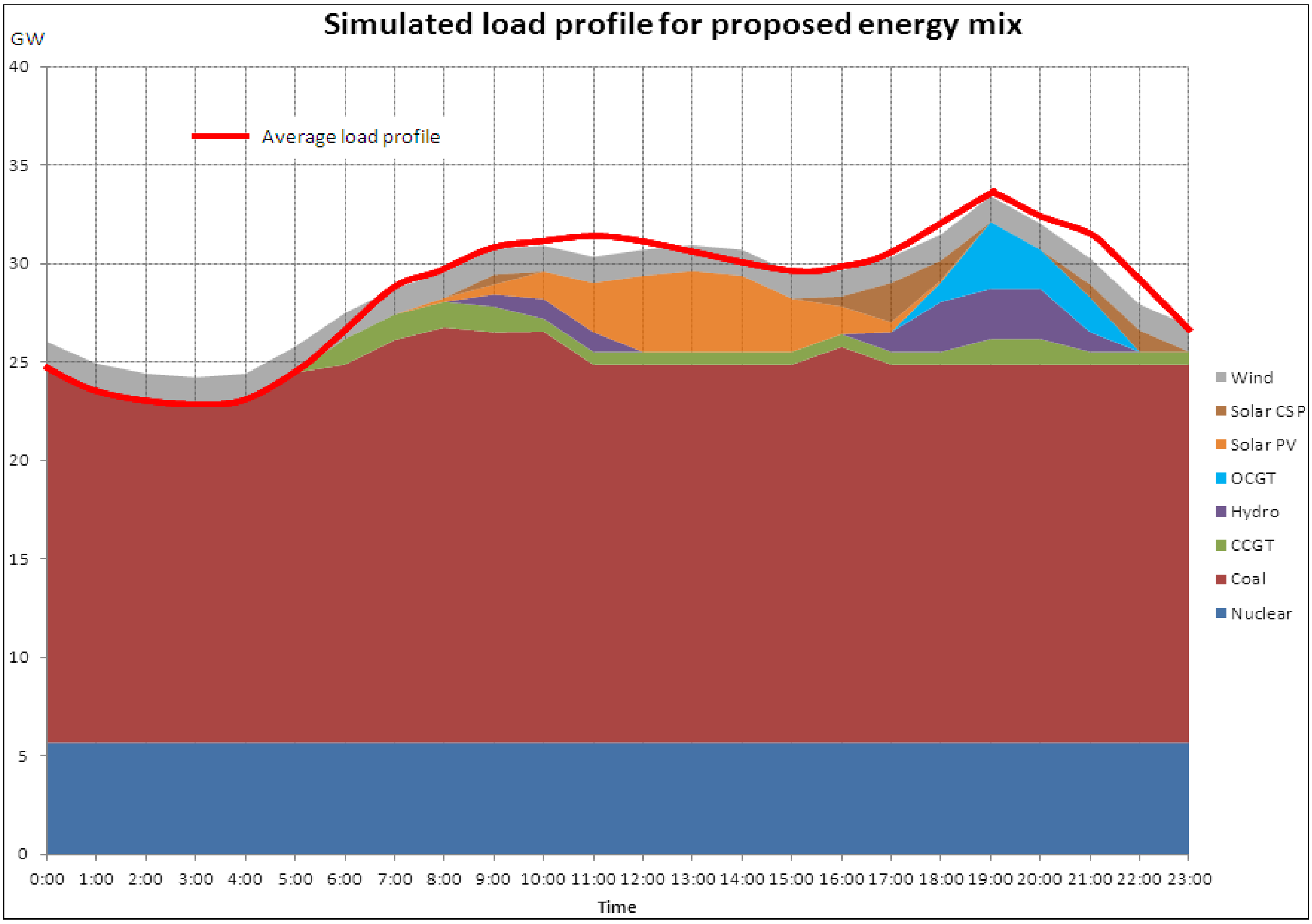

Figure 14: Modelled load profile for proposed energy mix

The most noticeable observation is that the load profile could not be matched by the proposed energy mix. There are some shortfalls between 10:00 and 12:00, as well as from 18:00 to 23:00, representing a total shortcoming of 4.123 GWd. However, there is ample excess supply of 9.6 GWd from 00:00 to 07:00, generated by wind. The problem is that renewables (most notably wind energy) supply energy to the grid intermittently, leaving sources with controllable power outputs to adjust for the balance of energy. This apparent symbiotic relationship is not very effective as constant changing of power levels results in loss of base load efficiency and plant life time. This is discussed further in the next chapter.

3.8 Summary

From the investigation it is clear that the only base load electricity options for South Africa are coal and nuclear stations. There is no potential for large-scale hydro-electricity, which can be imported only from the Congo River. Although each technology offers advantages in certain areas, the concern for South Africa is reliable and large-scale grid electricity production.

The load profile highlights the timing problem of renewable energies. A proposed model in the next chapter shows how nuclear energy eliminates these risks while adhering to environmental policies.

4. INTERPRETATION AND RESULTS

4.1 Chapter overview

The purpose of this chapter is to interpret the data from the investigation and provide results relevant to the South African context. The topics of comparison are chosen based on the IRP2010 document and represent the issues most relevant to South Africa. These are safety, economical, security of supply, environmental impact, water usage and job creation.

4.2 Safety

One has to address the question of how many people will lose their lives as a result of an electricity-generating technology. Consider the results of the following study done in collaboration with the World Health Organization, the Centre for Disease Control and the National Academy of Science, shown in figure 15:

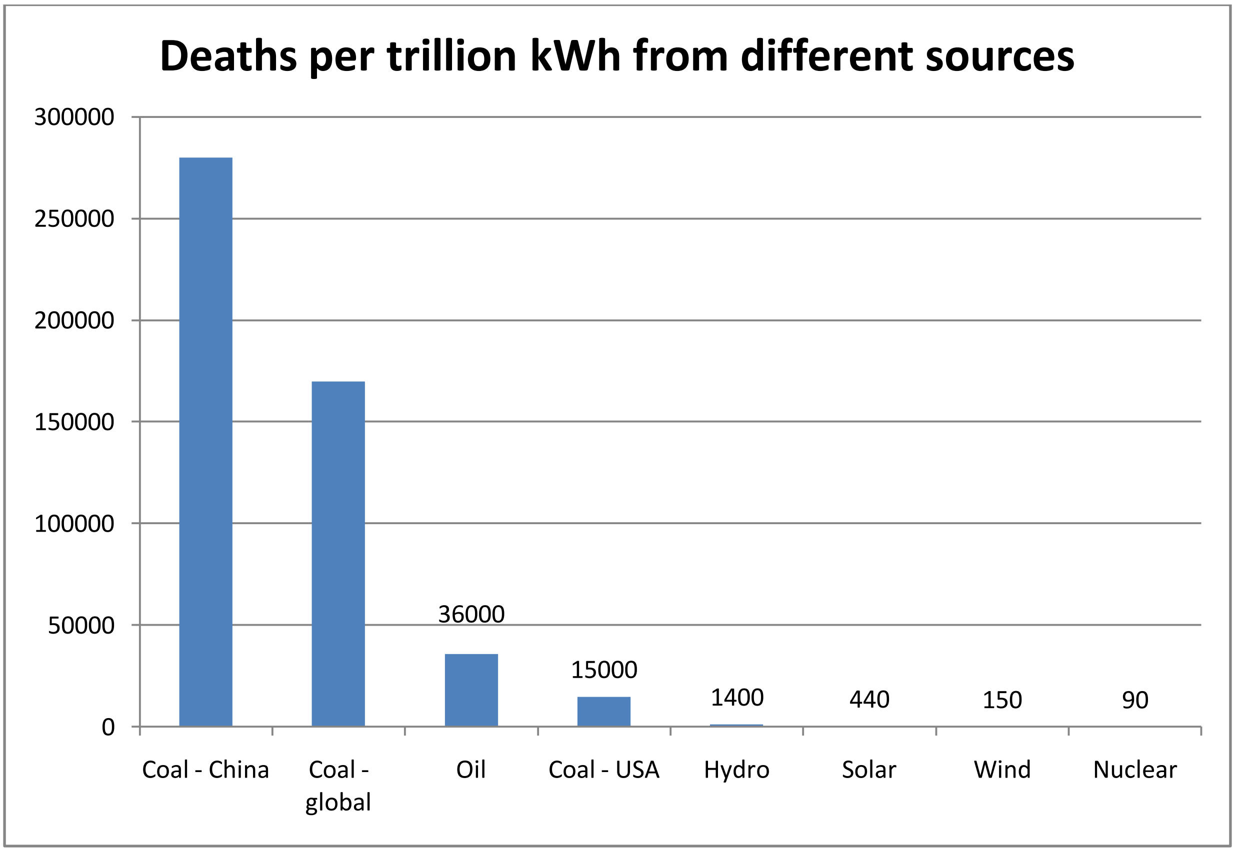

Figure 15: Deaths per trillion kWh from various sources (Garland, 2013)

These numbers include both direct and epidemiological fatalities. As can be seen, the main contribution to this statistic is coal. The best-faring technologies are wind and nuclear, and, coincidentally, it's also the two technologies with the lowest carbon footprint. This is discussed in the environmental impacts section. Hydroelectric technology typically has a very low frequency but high consequence accidents, much worse than conventionally thought of as being the case with nuclear plants. The dam failure at Banqioa, China, killing 171 000 people, is a typical example. In light of this, take note that the nuclear statistic above includes the TMI, Chernobyl and Fukushima accidents. Although nuclear accidents have great economic impacts, the studies clearly state that this is the safest technology from which to generate electricity (Burgherr & Hirschenberg, 2005).

Table 7 shows another study indicating the number of accidents as well as the fatalities from various base load sources. Note that latent fatalities are not added to the Chernobyl accident shown under the Non-OECD column. The data are converted to deaths/GWy in Table 8:

Table 7: Accidents and fatalities from various energy sources (Burgherr & Hirschberg, 2005)

	OECD		EU		Non-OECD	
Energy source	**Accidents**	**Fatalities**	**Accidents**	**Fatalities**	**Accidents**	**Fatalities**
Coal	75	2259	11	234	1146	22 848
Oil	165	3789	58	1141	232	16 494
Hydro	1	14	0	0	10	29 924
Nuclear	2	0	0	0	1	31

Table 8: Deaths per GWy from various energy sources (Burgherr & Hirschberg, 2005)

	Deaths per GWy	
Energy source	**OECD**	**Non-OECD**
Coal	0.157	1.605
Oil	0.135	0.897
Hydro	0.003	10.285
Nuclear	0	0.048

It's important to note here that all accidents from nuclear power stations are from Generation II plants. All newly built nuclear stations are Generation III stations, with new redundant and passive safety systems. Generation IV power stations are also in the design phase, and are to be constructed in the near future. Generation IV plants such as the PBMR guarantee that no core meltdown will take place, and no evacuation plan is necessary.

4.3 Economical evaluation

Next to safety, economic considerations are very important. In most cases, safety and costs are directly related: the more money is available, the more safely a product can be manufactured. The balance is, however, that one requires a technology that can meet the demand safely at an affordable price. The demand for South Africa is, of course, large-scale base load energy supply. With the recent and on-going electricity price hikes, there is due emphasis on cheap, reliable and long-term energy supplies.

The cost of generating electricity can be broken into three major categories:

- Capital/investment costs
  This is the money required to license, design, construct and commission the infrastructure that will develop the electricity. In the case of nuclear power, this includes costs of decommissioning and the long-term storage of waste materials. Provision is also made for plant refurbishments, upgrades and life extension projects.
- Operational and maintenance costs
  This involves operating and support staff such as operators, training, security and OHS representatives. Other costs are insurance, management and disposal of operational waste and routine maintenance.
- Fuel costs
  These costs depend on the type of technology, which relates directly to the type of fuel utilised. In renewables, these costs are mostly free. In the case of nuclear power, they include the purchase of fuel elements (uranium, conversion, enrichment, fabrication), as well as the disposal and/or reprocessing of the fuel.

Consider figure 16, a study from the NEA on the costs of generating electricity from various sources in various world regions:

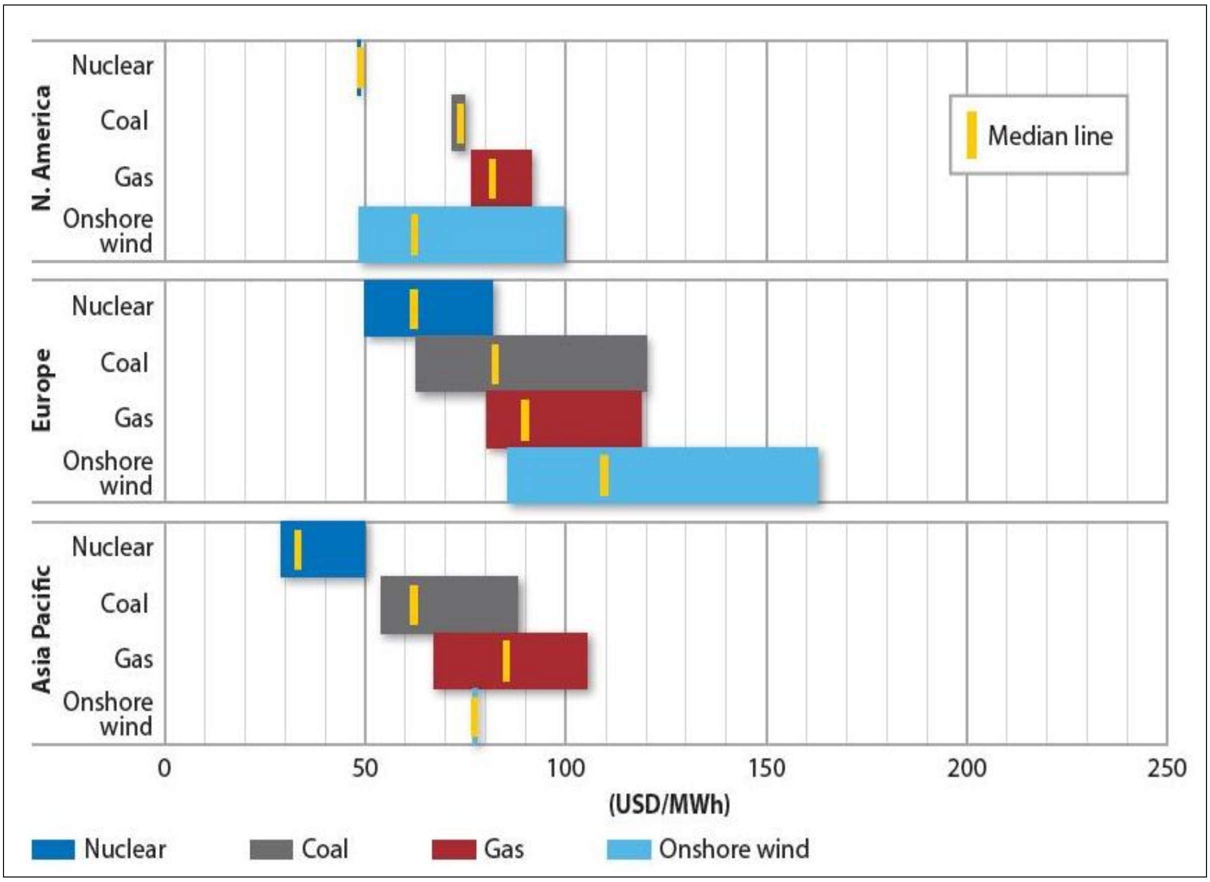

Figure 16: Regional LCOE for Nuclear, Coal, Gas and Wind (OECD, 2012)

The study above indicates that the cost of nuclear power in USD/MWh is on average the cheapest source in North America, Europe and Asia Pacific, using the levelised cost approach. This approach takes into account the total costs over the lifetime of the plant. In this study, the variability factor may cause coal to be cheaper in Europe than nuclear power. Bear in mind, however, that this study added carbon tax of 30 USD/t.

Note that this study takes into account the total cost of nuclear power production, from uranium mining through to long-term storage of radioactive waste. It is interesting to note how economically competitive nuclear technology is according to this report. This is mainly thanks to the long and consistent operating lifetime of the stations.

The EPRI report, "Technical Data for IRP of South Africa" produced the costs of various sources of energy shown in table 9:

Table 9: Costs of generating electricity from various sources (EPRI, 2010)

	Wind	EPR	AP1000	Coal	Coal + FGD	CSP + 9hrs storing	PV
Capital cost (R/kW)	16930	28290	33250	16880	19655	36225	37225
Fuel cost (R/GJ)	0	6.25	6.25	15	15	0	0
Fixed O&M (R/kW.y)	312	872	1090	379	502	603	502
Variable O&M (R/kW.y)	0	0	0	318	389	0	0
Economic life (years)	20	60	60	30	30	25	25
Converted to R/kW.y							
Capital cost (R/kW.y)	847	472	554	563	655	1449	1489
Fuel cost (R/kW.y)	0	197	197	473	473	0	0
Total O&M (R/kW.y)	312	872	1090	697	891	603	502

In order to compare the costs, all values are converted to R/kW.y. The capital cost per year is calculated by dividing the overnight capital cost with the economic life. The fuel cost is multiplied by a factor of 31.536 in order to convert the units from R/GJ to R/kW.y. The fixed and variable O&M costs are already given in R/kW.y and are added together to provide the Total O&M cost. The converted values are plotted in Figure 17 to provide the total cost of producing electricity per source.

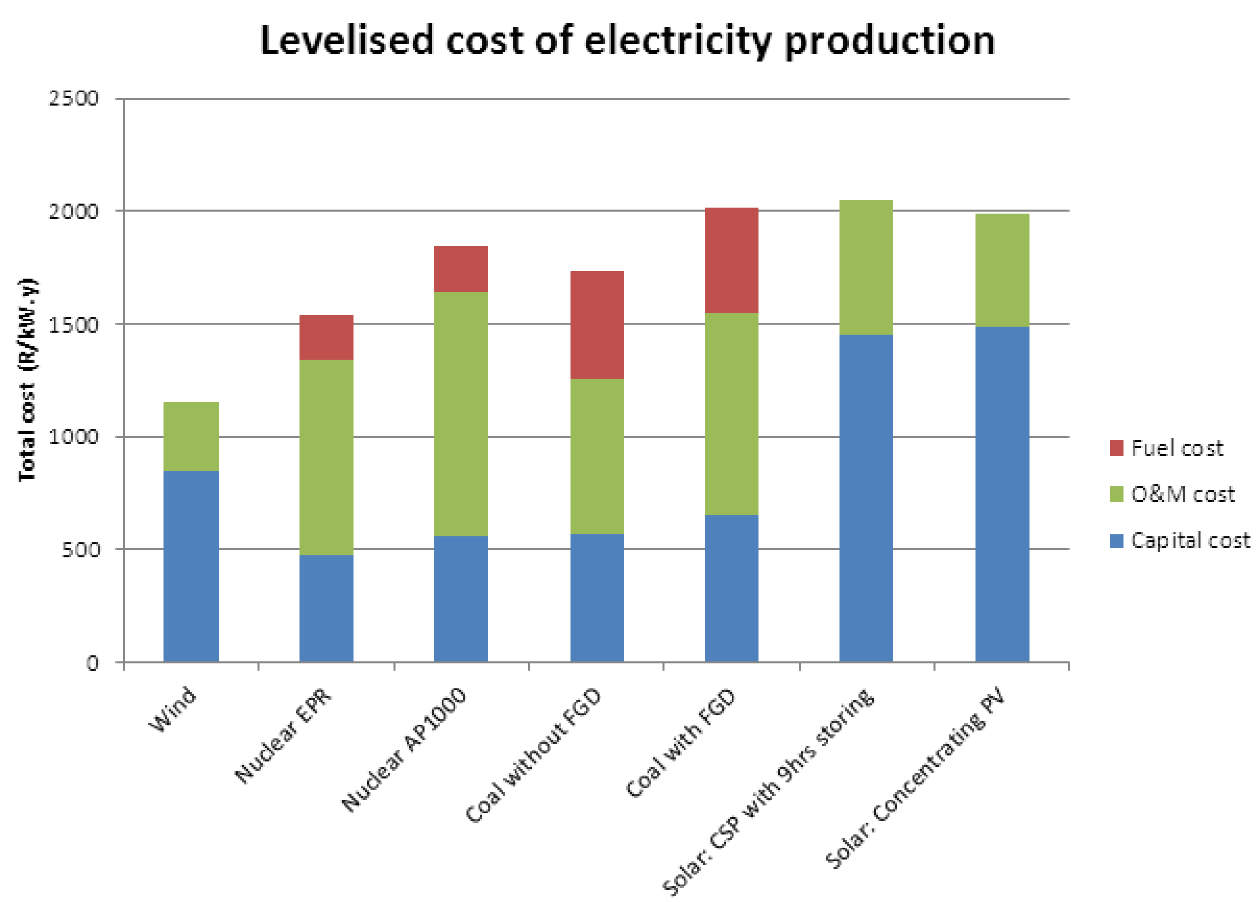

Figure 17: Relative cost of generating electricity from various sources (EPRI, 2010)

Apart from the very high capital overnight costs for solar energy, Figure 17 shows that nuclear technology is very cost competitive with coal. The price of a nuclear station is more sensitive to interest rate fluctuations as opposed to the rate of fuel and carbon taxes. Nuclear stations then have the further advantage of not producing any carbon or greenhouse gases, which would most likely be taxed in the near future, and this is not reflected in Figure 17. Note that the costs for nuclear power also include decommissioning and all long-term storage of waste. According to this study, nuclear technology is a cost-competitive technology. Westinghouse also states that energy produced by their AP1000 plant is "cheaper than coal" (Westinghouse, 2011). There are also currently about 68 reactors under construction worldwide in 15 countries (ENS, 2013). As for renewables, most projects are completed with public funding and tax rebates (Lomborg, 2001).

4.4 Security of supply

South Africa has very little reserve margin in its generation capacity, and security of supply therefore should be a critical consideration in the energy mix. According to national control, Eskom had a mere 64MW of excess supply on the evening peak of 13 June 2013 in spite of reducing the load to all smelters and mines as much as possible. It is quite a common occurrence in the last few years to have a supply margin of <1% of total supply. The international norm for a supply margin is 15%.

Security of supply is crucial to the industrial sector and for the economic growth of South Africa. Among other industries, mines, chemical processing plants and smelters all need a constant and reliable source of energy. All power stations also require a constant supply of electricity, known as the ‘house load’. It is this constant full-power demand that gives rise to the concepts of base load supply and security of supply.

Security of supply can almost entirely be represented by only one indicator, known as the load factor. This gives an indication of how much electricity a plant/unit/source can supply as a factor of its rated power when operated full-time. Additional to the load factor, ‘when’ it is available is also very important. For example, an energy source may have an acceptably high 60% load factor, but the availability is erratic and therefore provides no security of supply.

Both wind and solar then seem to have a timing problem, as the wind doesn’t necessarily blow and the sun shines when you need energy. Without proper mechanisms to store energy it appears that large-scale deployment of such projects is not advisable in light of supply security. Base load stations such as coal, hydro, gas turbines and nuclear power, are the only option that offers acceptable security of supply.

In order to gain a perspective, consider figure 18 indicating the load factors of the various electricity-generating technologies according to the IRP2010:

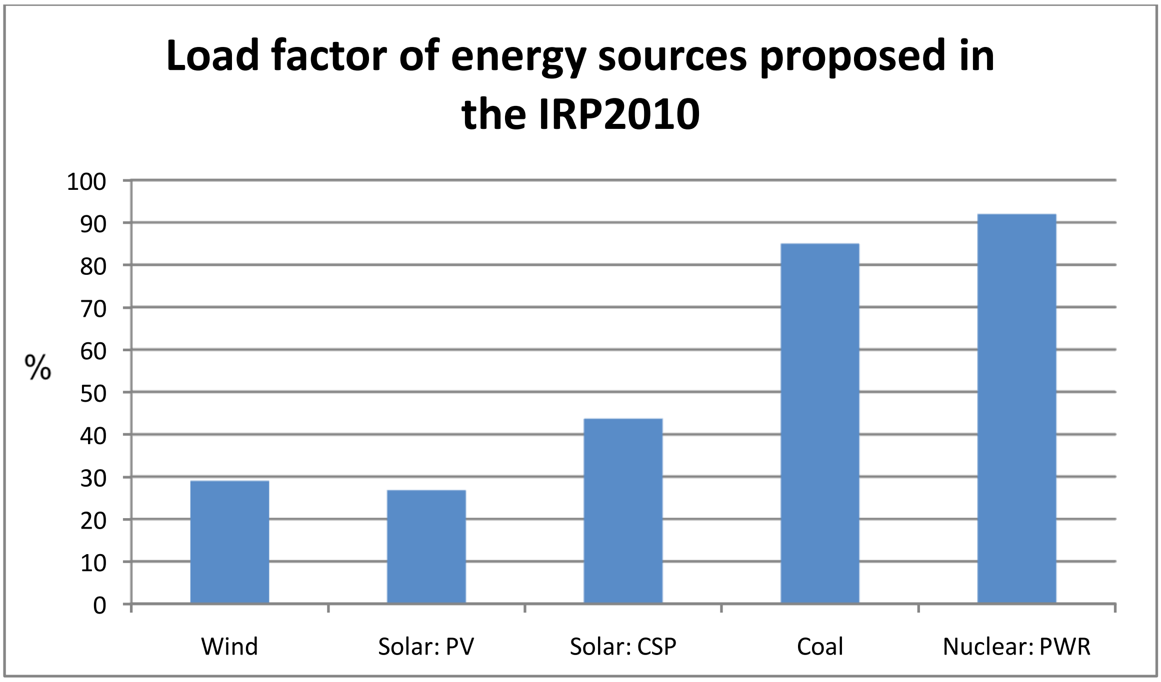

Figure 18: Load factors of power production technologies proposed by IRP2010 (EPRI, 2010)

It is clear that nuclear stations by a large margin most reliably provide the amount of electricity for which they are rated. This is reflected in Koeberg being the most reliable power station run by Eskom (Eskom, 2013). Just to put this into perspective, in order to have the same amount of electricity produced by nuclear power from wind or solar, roughly 3–4 times the amount of installed capacity has to be built to offset the low load factor, and then there is still the timing problem. From a load factor perspective, then, the only base load electricity options are coal and nuclear power. There are other technologies, such as biomass and gas turbines (open and combined cycles), offering load factors of 85% as well, but these are not economically suitable for base load energies in South Africa.

The other consideration in security of supply is the life of the programme or plant. Again, nuclear power stations stand out, with a remarkable operating life of 60 years. Wind and solar plants not only require three times the installed capacity to compete with nuclear because of their low load factor, but they have to be constructed three times over to equate in operating life as well. This adds the disadvantage of time lost during negotiations with vendors, conducting pre-construction studies, securing finance, actual construction, and so on. Therefore, from a plant age consideration, nuclear stations are the best choice. Figure 19 indicates the operable life of different power production technologies proposed by the IRP2010.

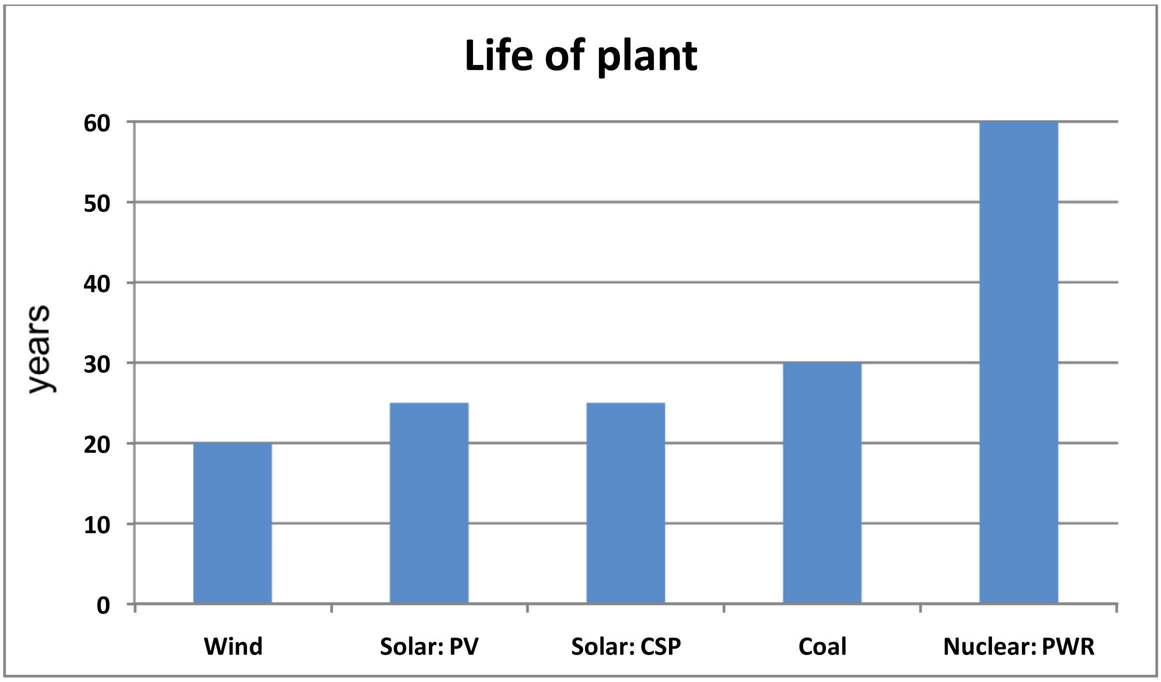

Figure 19: Life of power plants proposed by IRP2010 (WNA, 2011)

It is suggested outside the IRP2010 study that coal stations may have an operating life of 40 years. Even so, this is no comparison with the 60-year life cycle of nuclear power plants. This is a very important characteristic of nuclear power plants. The long lifetime of nuclear stations offers great stability in areas such as economics (since running costs are very low), long-term job creation and security of supply.

4.5 Environmental impact

All sources of electricity have an impact throughout construction, operations and decommissioning. The environment is impacted in several ways through solid, liquid and gaseous effluents. Probably the most discussed topic related to environmental impacts is the effect of greenhouse gases on global warming, also referred to as the carbon footprint. According to the IRP2010, gaseous emissions for the considered technologies are as shown in Table 9.

Table 10: Gaseous emissions from different generating technologies (DME, 2011)

Emission (kg/MWh)	Generating technology						
	Coal	Coal with FGD	OCGT	CCGT	Nuclear	Wind	Solar
CO_2	936.2	976.9	376	622	0	0	0
SO_x	0.45	0.19	0	0	0	0	0
NO_x	2.3	0.2	0.29	0.28	0	0	0
Hg	0.13	0.09	0	0	0	0	0

Only hydrocarbon-fuelled stations produce greenhouse gases during operation. The major reason for the drive in renewables is for a source of energy free from greenhouse gas emissions. Reasons such as free fuel should be interpreted as economic. Free fuel is not a perk if the capital costs are very high, as the case is with solar. The point here is that nuclear can indeed be considered a renewable source of energy in light of its zero emission footprint. And as for the fuel, there is enough fuel for thousands of years to come (Lomborg, 2001), so it can be considered renewable for all practical purposes, despite the fact that nuclear fuel can be recycled. So with regard to greenhouse gas emissions during operation, nuclear stations perform competitively with wind-turbines and solar panels.

Nuclear stations do, however, produce a carbon footprint during their lifecycle from construction to decommissioning. This is mainly due to concrete production and steel mining. A comprehensive study has been done by the World Nuclear Association (WNA) on this, sourcing data from 23 different studies (WNA. 2011a). Figure 20 shows the integrated results from these studies. For each energy source, a maximum value and minimum value indicates the highest and lowest value published throughout all the studies. A mean value is also shown, indicating the average carbon emission value for all the studies.

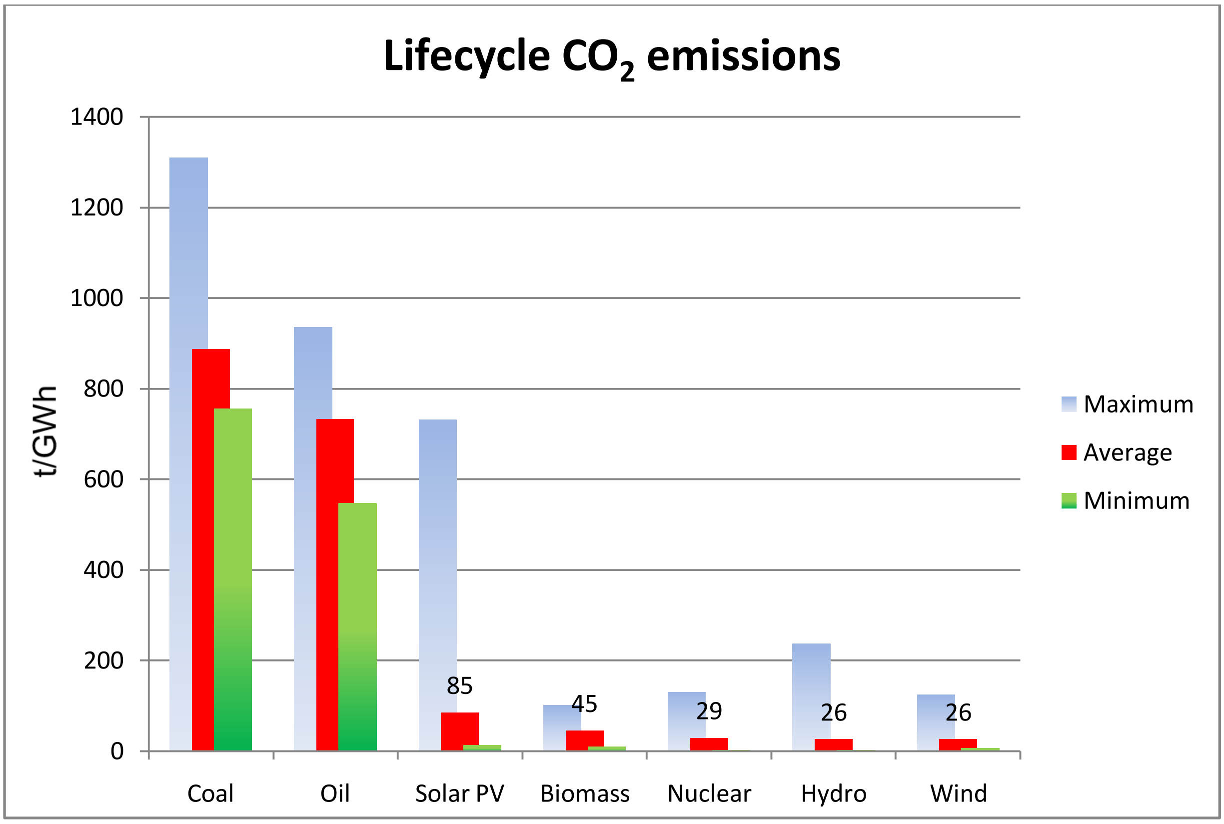

Figure 20: Lifecycle carbon emissions per energy source (WNA. 2011a)

Based on these studies, the following simple yet powerful observations can be made:

- Based on the lifecycle emission study, coal on average generates 30 times more greenhouse gases than nuclear and oil 25 times more.
- Greenhouse gas emissions from nuclear power stations are among the lowest of all electricity-generating technologies.
- Nuclear stations produce a third of the gaseous emissions in comparison with those from PV solar.

Nuclear stations therefore offer the same advantages as those of renewables. There is also no fly ash production, no sulphur or nitrogen oxides, mercury emissions, or any other greenhouse gas, such as methane, emissions. Note that a coal station and its periphery are more radioactive than a nuclear station due to the radioactive residue in the coal and ash (Hvistendal, 2007).

4.6 Water usage

South Africa is considered a very dry country. Average rainfalls are well below world averages, and therefore water usage requires special consideration (Lomborg, 2001). According to the IRP2010, the fresh water usage for different energy sources is as follows:

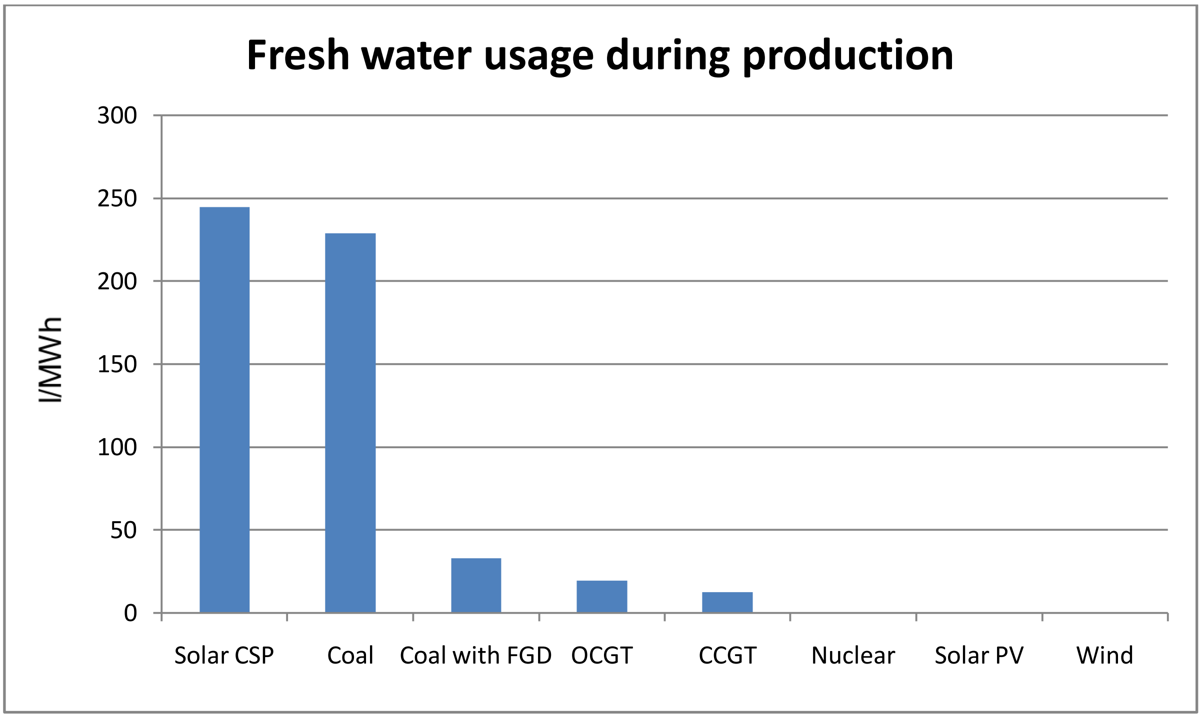

Figure 21: Fresh water usage during production (DME, 2011)

The major water consumers are CSP and coal stations. This is because fresh water is used for the heat sink to complete the thermodynamic cycle. Nuclear stations also have to reject a large heat load, however, as required by the Rankine cycle, but as with all Eskom's proposed nuclear sites, this can be done using seawater. This is a major advantage of nuclear stations, being independent of the proximity of South African coal mines.

Coal stations can also be cooled by oceans, but lack of coal in the coastal areas makes it uneconomical to build them there. Nuclear stations, then, are the only base load option that can be built at the coastal areas to supply the increase in demand there. It is inefficient and uneconomical to transfer either coal or electricity over long distances. Nuclear stations can also be built inland, given a sufficiently large cooling source such as a river or lake.

4.7 Job creation

The high unemployment figures in South Africa are a concern for government and unions alike as they threaten the economy, among other things, of the entire country. Although there seem to be several attempts from government to create employment, the nature of these jobs is usually of short duration. What the country needs is sustainable, long-term jobs which add value to the country, and the energy sector is an important mechanism to address this need. Although job creation is not a scientific consideration when establishing the superiority of an energy source, in the South African context, this element holds its weight, as repeatedly emphasised in the IRP2010. This is a difficult topic in the South African context, however, as government is desperate to create jobs, and international figures would not be applicable here. It would be reasonable to assume that all technologies would create a substantial number of jobs.

An advantage of nuclear stations is that they would create jobs for 100 or more years from planning to decommission. They would also create a broad spectrum of jobs, addressing the fallacy that only 'highly skilled' jobs are created. The nuclear engineering component is a very small portion of the manpower required. The majority of a nuclear plant is non-nuclear in nature; their construction and operational functions are very similar to those in other industries. In all disciplines only a small proportion of nuclear skills, if any, is required.

One also has to consider that the nuclear industry would only add, and not replace, jobs in South Africa. For example, there are fears that the nuclear industry would cause a decline in the coal mining industry. Consider the fact that uranium can be used only for power generation and nothing else. South Africa has plenty of uranium deposits which should be mined for this purpose as well as manufacture of fuel for exporting. Coal can, however, be used in a variety of industries and purposes and should always be mined regardless of the developments in the power industry. Coal can be exported and used in the production of oil, gas, plastics and other commodities.

4.8 Load profile model

The load profile model has been compiled in order to show whether the proposed energy mix would be suitable for the current load profile. The average load profile curve could not be met with the proposed energy mix, owing to the timing problem in respect of renewables. Although the proposed 8.45% renewable portion would provide enough equivalent energy to make up the balance of base and peak supplies, the timing has to be aligned with the peak loads, which is very unlikely. The model further shows that:

- Base load and peaking stations have to compensate for if and when renewable energy supplies electricity to the grid. The constant change in power levels is very uneconomical and may reduce plant lifetime.
- The intermittent supply from renewables also causes uncertainty in shutdown schedules of base load stations. The grid cannot rely on supply from renewables when base load stations are shut down for maintenance.
- According to this model, the grid relies on renewable sources to supply full-rated capacity for up to 17 hours per day to meet the load profile. This is a high-risk situation and could be mitigated by expanding base load capacity (coal, gas, hydroelectric and nuclear power).
- Output controllable sources (hydroelectricity, hydrocarbons and nuclear power) should be able to meet the full demand when renewables are not performing. In the modelled scenario, the maximum capacity of these sources is 35.98 GW, meaning that they are able to meet the highest peak load of 35.01 GW. However, this implies that every single coal station, every gas/hydro turbine, and all nuclear units are able to operate at 100% power. If more than 970 MW of supply is offline for maintenance, the grid once again has to rely on the availability of renewables. This is a very undesirable scenario, as typically 5 000–10 000 MW are offline for maintenance (Eskom National Control Centre, 2013).
- According to the load profile, the peak load occurs at 19:00, when solar PV is producing effectively zero energy. Only CSP can contribute towards peak load supply, and wind could intermittently add energy during this time.
- It would be more effective if intermittent renewable supply, especially from wind sources, were to be absorbed by pump storage stations. This would transform the renewables from an intermittent to a controlled supply. As mentioned in section 3.2, South Africa has 1.58 GW in pump storage schemes, with limited options for expansion. These stations are already fully committed to minimising load following by coal stations, and adding wind energy to the existing pump storage scheme would only shift the problem back to base load stations.
- The Generation III reactors such as the EPR and AP1000 are capable of operating in either load following or base load modes. This greatly enhances the role nuclear power can and should play in the long term future energy mix.

4.8.1 Proposed load profile model

In contrast to the energy mix in the IRP given for 2030, the proposed load profile model date is adjusted to 2035. The IRP energy mix for 2030 shown in figure 2 consists of a coal energy portion of 41.8 GW, or 49.5%. However, according to figure 7 most of the Eskom coal stations are nearing end of campaign, after which the IRP energy mix would be greatly impacted, even 5 years later. Therefore one has to consider the date beyond the 20 year outlook of the IRP aimed at 2030, and a proposed energy mix for 2035 is to be drawn up.

The aim of the proposed energy mix is to find the maximum possible portion of nuclear energy that can be integrated into the grid by 2035 and to evaluate whether peak loads will be met as well. Firstly, a total load of 76.8 GW is assumed for 2035. Secondly, the existing energy sources for the 2035 model to be included are as below. These estimated assumptions are based on figures in both the IRP and the EPRI reports on the resource planning.

- Nuclear (1.83 GW)
- Coal (17.8 GW)
- Hydro (9.3 GW)
- OCGT (6.3 GW)
- CSP (0.2 GW)
- Wind (0.9 GW)

Hence there are already 36.33 GW of dedicated energy sources for 2035. In order to meet the balance of the required 76.8 GW demand, 40.47 GW of new capacity is to be added by then. For this model, all of the new build capacity shall be from nuclear sources. Thus with Koeberg taken into account, a total of 42.3 GW of nuclear capacity is the maximum possible and recommended nuclear portion for 2035.

The properties of each energy source used in the model of the proposed energy mix are investigated.

4.8.1.1 Nuclear energy

The proposed model, maximizing nuclear energy, has a total of 42.3 GW of nuclear capacity. Nuclear energy is found to be the overall best performing source of energy according to the investigation in section 4.1 - 4.7. Nuclear energy has the best safety record, is economically competitive, environmentally friendly, low water usage, best security of supply and offers good job creation opportunities. It would be very beneficial for the South African economic growth and electricity security to increase the nuclear energy portion to 65% by 2035.

The properties of nuclear energy for the load modelling are (DME, 2011):

- Availability factor: 92-95%
    - This translates to 504 GWh per day added to the grid for this model
- Station life: 60 years
- Construction time: 16 years

The generation III nuclear power stations have excellent load following capabilities, with stations able to run from 100%-50%-100% within a 24 hour cycle. For this model however the nuclear stations are to be operated as base load only. Energy sources with high capital cost and low running cost, as shown in section 4.3, are most economical when operated at maximum output.

4.8.1.2 Coal energy

Eskom has a committed coal energy capacity of 17.8 GW by 2035 which is included into the model. For the 2013 equivalent model this is scaled to 9.6 GW. The relevant properties of coal energy for this model are as follow (DME, 2011):

- Availability factor: 85%
- Station life: 30 years
- Construction time: 9 years

In this model the burden of load following is largely carried by the coal stations. The load following capabilities of the supercritical coal stations above minimum load of 50% and the load requirements are as follow (Lindsay & Dragoon, 2010):

- Supply ramp rate of super critical boilers: 7%/min
- The average grid load ramp rate for the model is: 3175 MW/h
- The peak grid load ramp rate for the model is: 4754 MW/h

The maximum designed ramp rate of the coal stations of 672 MW/m (should all stations operate in load following) is able to easily meet the average load ramp rate. The maximum grid load ramp rate and average grid load ramp rate is plotted against the maximum rate of the coal stations in figure 22. Also included is the reduced ramp rate due to hydro stations being placed online, discussed in section 4.8.1.3.

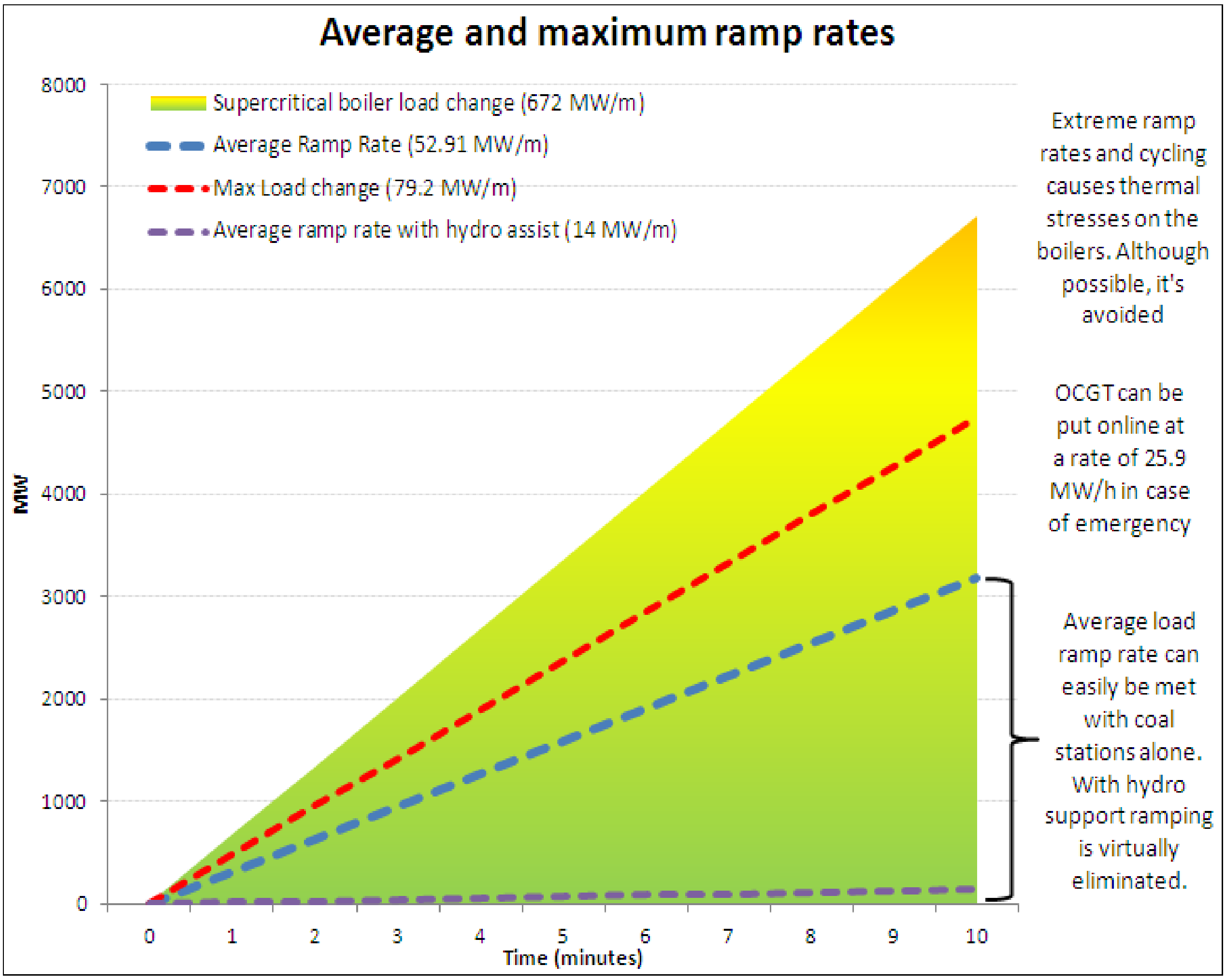

Figure 22: Average and maximum ramp rates

The coal stations are able to supply the highest recorded ramp rate well within design limits. In case of an emergency OCGT's can be placed online to assist with the ramp rate supply. In order to minimize the thermal stresses, pollution and economic consequences of cycling coal stations, hydro stations are placed online to allow more even operation of the large coal stations.

4.8.1.3 Hydro energy

Hydro energy, or rather peaking stations, play an important role in allowing even boiler operation at low loads and supplying energy during peak loads. During night time, boilers supply energy to the peaking stations which in return supply energy during peak times, as explained in section 2.8. For the model, the following are applicable (DME, 2011):

- Total capacity: 5 GW
- Load factor: 20%
- Total energy per day: 24 GWh

By running the peaking stations as a load during night time, supplied by the coal stations, the output of the coal stations is levelled out and the morning ramp rate is reduced as shown in figure 23. The average ramp rate of 3175 MW/h is reduced to 839 MW/h by having all the coal stations supply the peaking stations during night. This potentially stored energy (water pumped to higher elevation), is then resupplied during peak times again reducing the ramp rates of the coal stations.

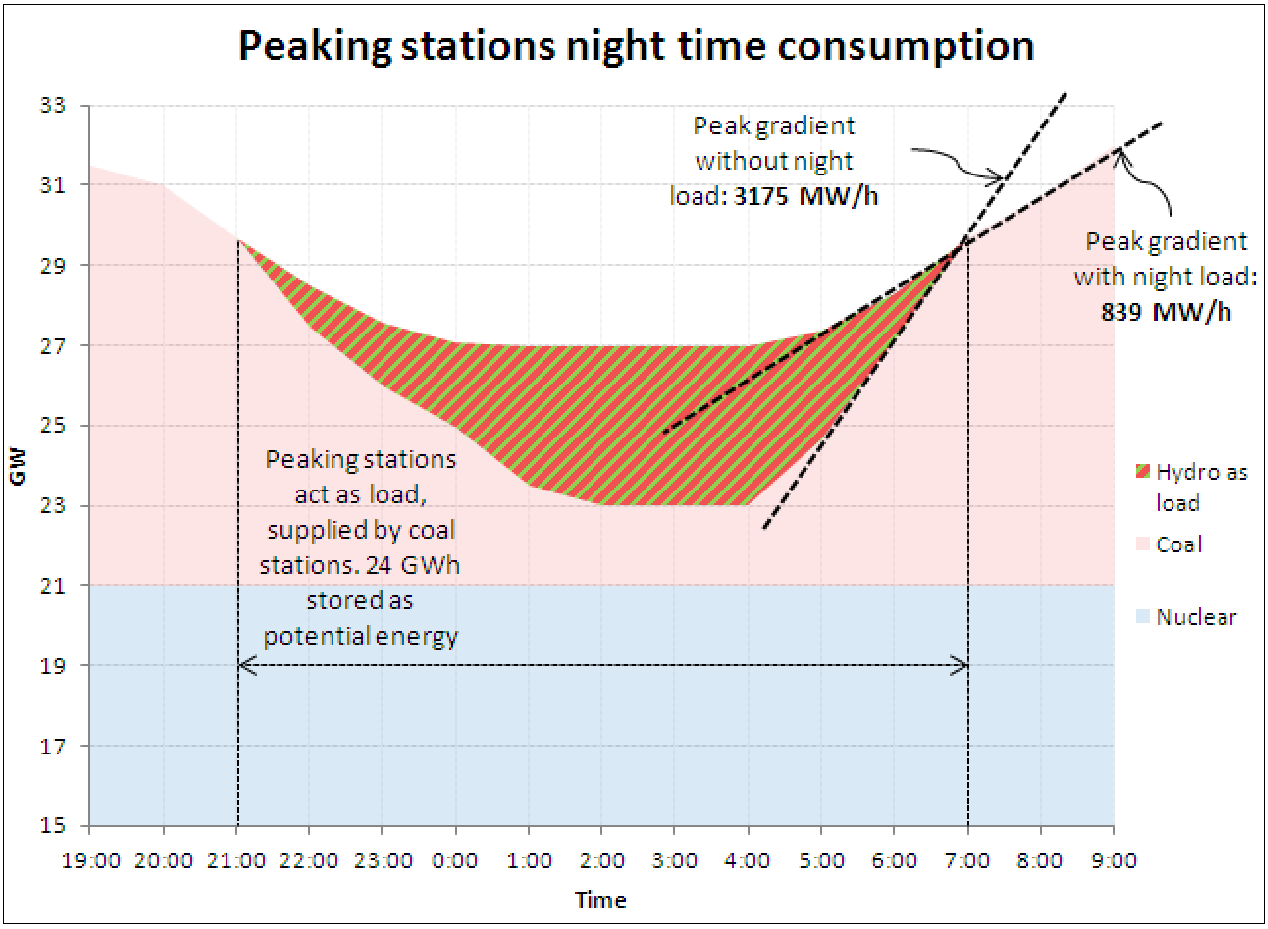

Figure 23: Peaking stations night time consumption and ramp rate reduction

Both the ramp rate during the morning hours (04:00 to 07:00) and the peak electricity consumption during evening hours (18:00 to 21:00) are assisted by the peaking hydro stations, operating in conjunction with the coal stations.

4.8.1.4 OCGT energy

The OCGT are designed to generate electricity for peak load demands. For this model the following are relevant (DME, 2011):

- Capacity: 3.4 GW
- Load factor: 10%
- Energy available per day: 8.16 GWh
- Running cost: R200/GJ

For the average load curve in the model, the OCGT are not operated. As opposed to nuclear energy, OCGT requires very low capital investment but has high running cost and are therefore only operated during emergency situations.

4.8.1.5 CSP and wind energy

In this proposed model the average load curve can be met with the output controllable sources only. Therefore the renewable sources are continuously running and supplies excess energy which is absorbed by the peaking hydro schemes. If in this model the renewables are supplying during 16:00 to 23:00 then that would replace some of the hydro capacity. This means that less of the potential energy is used and less coal needs to be burned during night to restore the hydro capacity used during peak times. In order to calculate the energy supplied to the grid on average per day, the following figures are used (DME, 2010):

<u>Wind Turbines</u>

Total capacity: 500 MW (based on model assumptions and conditions, discussed in 4.8.1)

Load factor: 29%

Energy available for one day (on average): 0.5GW x 24h x 0.29 = 2.48GW.h

Concentrated Solar Plant

Total capacity: 100 MW (based on model assumptions and conditions, discussed in 4.8.1)

Load factor: 43.7%

Energy available for one day (on average): 0.1 GW x 24 h x 0.437 = 1.05 GW.h

Therefore 3.53 GW.h is added to the grid from renewable resources on average per day. This is only possible due to the fact that hydro stations can absorb the intermittent supply from these sources. Also, it is a very expensive source of energy as discussed in section 4.3. A study by Kent Hawkins conducted in 2010 shows that integrating wind energy into a grid can lead to higher CO2 emissions as well due to the cycling of coal stations. The study suggests using gas turbines to meet extreme load ramp rates.

4.8.2 Proposed energy mix model

In order to model the proposed energy mix on the 2013 load profile, the proposed energy mix is scaled down to a 2013 equivalent by multiplying all portions with a factor of 0.54. The reason for scaling the proposed energy mix down to a 2013 equivalent is so that it can be used to model the 2013 load profile shown in figure 13. The daily energy available in GWh from each source is finally calculated by multiplying the load factor with the rating, and then multiplied with 24 hours. The daily energy availability is an average figure for that source showing how much energy it can add to the daily load profile, per day. The proposed energy mix, its 2013 equivalent and energy available for one day are tabulated in table 11.

Table 11: Proposed energy mix for 2035

Power source	Portion (%)	2035 (GW)	2013 equivalent (GW)	Load factor (%)	Energy available for 1 day (GWh)
Nuclear	64.91	42.3	22.83	92	504.0
Coal	25.22	17.8	9.6	85	195.84
Hydro (peak)	3.09	9.3	5	20	24.0
OCGT (peak)	6.19	6.3	3.4	10	8.16
Solar CSP	0.14	0.2	0.1	43.7	1.05
Wind	0.45	0.9	0.5	29	3.48
Total	**100**	**76.8**	**41.43**	**-**	**736.53**

Modelling the 2013 equivalent proposed energy mix on the 2013 average load profile would result in performance as shown in Figure 24. In order to meet the demand of the load profile, each energy source is ‘stacked’ to fill the area under the curve, representing the average daily load of 685 GWh. An hourly profile of the model is shown in table 12.

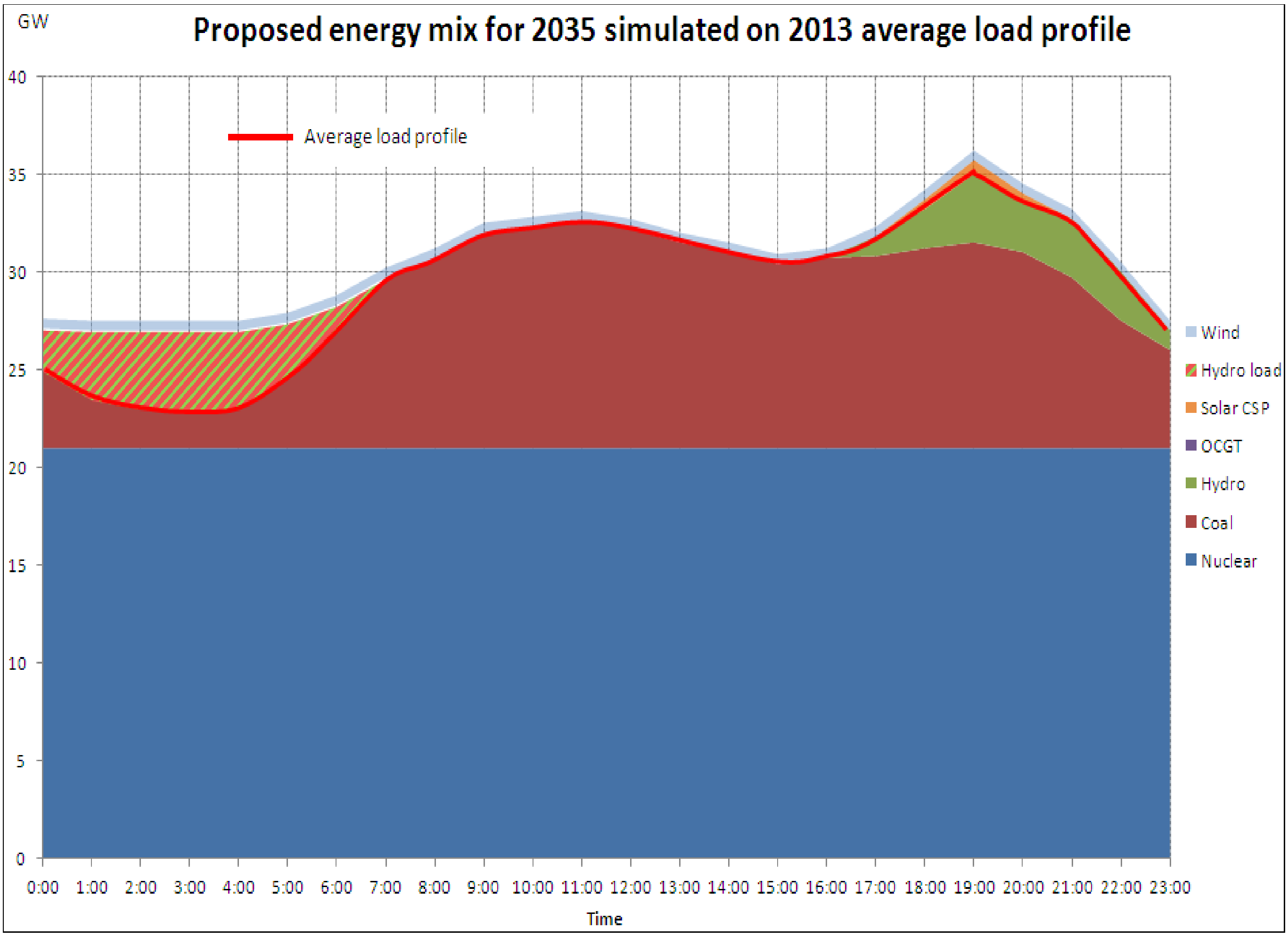

Figure 24: Proposed energy mix modelled on 2013 load profile

According to this model, the proposed energy profile can reliably meet the peak demands with output controllable sources alone (coal, nuclear and hydro). The renewable energy portions are stacked above the average load profile curve and therefore there is no dependency on intermittent supplies. The OCGT would also be above the curve and would on average not be required to meet the peak demand. The energy from the renewable sources can still be utilised by the grid by diverting it to the hydroelectric pump storage schemes in order to supply it during peak times as and when needed. This is in contrast with the model shown in figure 14, where, even though there is enough energy in terms of GW.h, the grid is dependent on the timing of the renewable sources in order to meet the peak demands. In other words, for the proposed energy mix in the IRP2010, should it have been applied today, would not have been able to meet the demand with output controllable sources alone. By shifting the nuclear portion from 19.69% (as proposed) to 64.91%, South Africa will successfully meet its energy demands.

Table 12: Hourly data of proposed energy mix used for figure 24

Time	Nuclear	Coal	Hydro	OCGT	Solar CSP	Hydro load	Wind	Total	Avg load
0:00	21	4	0	0	0	2.1	0.5	**25.5**	**24.7**
1:00	21	2.5	0	0	0	3.5	0.5	**24**	**23.6**
2:00	21	2	0	0	0	4	0.5	**23.5**	**23.1**
3:00	21	2	0	0	0	4	0.5	**23.5**	**22.9**
4:00	21	2	0	0	0	4	0.5	**23.5**	**23.1**
5:00	21	3.7	0	0	0	2.7	0.5	**25.2**	**24.5**
6:00	21	6.2	0	0	0	1.1	0.5	**27.7**	**26.5**
7:00	21	8.7	0	0	0	0	0.5	**30.2**	**28.7**
8:00	21	9.7	0	0	0	0	0.5	**31.2**	**29.6**
9:00	21	11	0	0	0	0	0.5	**32.5**	**30.8**
10:00	21	11.3	0	0	0	0	0.5	**32.8**	**30.9**
11:00	21	11.6	0	0	0	0	0.5	**33.1**	**31.2**
12:00	21	11.2	0	0	0	0	0.5	**32.7**	**31.0**
13:00	21	10.5	0	0	0	0	0.5	**32**	**30.4**
14:00	21	10	0	0	0	0	0.5	**31.5**	**29.9**
15:00	21	9.4	0	0	0	0	0.5	**30.9**	**29.6**
16:00	21	9.7	0	0	0	0	0.5	**31.2**	**29.8**
17:00	21	9.8	1	0	0	0	0.5	**32.3**	**30.5**
18:00	21	10.2	2	0	0.5	0	0.5	**34.2**	**31.9**
19:00	21	10.5	3.5	0	0.7	0	0.5	**37.9**	**33.4**
20:00	21	10	2.5	0	0.5	0	0.5	**34.5**	**32.3**
21:00	21	8.7	3	0	0	0	0.5	**33.2**	**31.3**
22:00	21	6.5	2.5	0	0	1	0.5	**30.5**	**28.9**
23:00	21	5	1	0	0	1.6	0.5	**27.5**	**26.4**
Total (GW.h)	**504**	**186.2**	**15.5**	**0**	**1.7**	**24**	**N/A**	**721.1**	**685.0**

4.9 Summary

This concludes the investigative chapter. All energy sources have strengths and weaknesses and different properties making it suitable for varying applications. This does not mean that all energy sources are equally safe or economical. In the investigative chapter it is shown that nuclear energy is indeed the best base load energy source.

5. CONCLUSIONS

5.1 Chapter overview

This chapter concludes the investigation chapter and offers recommendations in line with the results obtained.

5.2 Conclusions and recommendations

By presenting certain facts regarding a technology and strategically omitting others, one can easily paint a picture regarding a technology in any way one wants. However, the facts of nuclear energy speak for themselves and require no excessive emphasis in order to enhance their suitability as an energy source. Although there are emotionally aggravated areas, such as the long-term waste products of nuclear and potential radiation exposure, the truth is that it is a very reliable, relatively cheap and safe source of energy. Following are recommendations made according to the research addressing the objectives under general, power generation and IRP-related headings.

5.2.1 General recommendations

This research has shown that nuclear energy is superior in many ways. Apart from the large role it should play in the power generation industry, it also stimulates and demands a great deal of peripheral industrial development. Recommendations regarding the nuclear industry in general are made as follows:

- Investigate the viability of the PBMR to be constructed in South Africa, as previously committed to. This has the potential to place South Africa firmly as a leader in the nuclear industry and hold potential for great economic reward.
- Ensure that the nuclear skills pool and nuclear regulator manpower are increased in order to manage a nuclear fleet and localise functions as much as possible.
- Increase the mining of uranium, not only for the manufacture of fuel, but also for exporting purposes. This would contribute to job security and GDP growth. Please take note that the uranium mining should not replace coal mining, but should complement it. South Africa has abundant uranium reserves which can and should only be used for energy production. Coal, on the other hand, can be utilised in a vast array of industries world-wide.

- Explore the possibility of entering the nuclear market as an enriched uranium and nuclear fuel supplier. If a nuclear fleet is planned, fuel can be manufactured locally. Furthermore a fuel reprocessing plant will be very beneficial in reducing nuclear waste, saving costs and maximising utilisation of uranium resources.
- Invest in the profitable medical radiopharmaceutical market through construction of more particle accelerators and research reactor facilities.
- Gear more tertiary education institutions to provide training in the nuclear fields.
- Do a comprehensive cost analysis of integrating large scale wind energy into the national grid. The volatility of wind output would cause coal stations to respond with more severe cycling, reducing its operating lifetime and increasing its running costs. The purpose of the study would be to calculate the point at which the wind energy becomes uneconomical to integrate into the grid.

5.2.2 Power generation recommendations

Taking into account the current and projected energy mix as well as the properties of nuclear revealed in the research, the following recommendations are made regarding nuclear as an energy source:

- Start construction of nuclear power stations for base load and load follow power generation. The electric capacity of this fleet should replace the pending decommissioning capacity of the coal stations to accommodate economic growth and ensure base load margin of at least 15%. The first step of this nuclear fleet would also be in line with the recommendations made according to the IRP2010.
- Do not construct any new coal stations after Kusile, but replace this capacity instead with nuclear stations. This addresses all issues of security of supply, water usage, job creation and environmental commitments. Variable fuel prices and pending carbon tax on coal stations would drastically affect the future price of hydrocarbon energies. This can be avoided with nuclear stations. Although the capital cost of nuclear stations is greater than that of coal, the lifetime levelised approach indicates that they are overall cheaper than coal stations.
- Increase hydroelectric peaking capacity to allow adequate load following with nuclear stations as base load. This would also cater for small-scale pilot renewable projects with poor or no load-following characteristics to be connected to the grid.

- Ensure security of supply to support the economy before deploying renewable stations. Once these projects have proved the application context of renewables, only then implement them on a larger scale if feasible.
- Rather utilise renewables for widespread, targeted and small-scale power production such as solar geysers and windmills. This would reduce the overall demand for electricity by directly utilising the energy exactly where it is needed.
- Avoid connecting large-scale renewable energy sources to the grid as there is no sufficient pump storage scheme to compensate for the intermittent nature of supply. This would cause base load stations to change load continuously, resulting in loss of efficiency. First expand pump storage capacity in order to absorb intermittent renewable supply if it is to be connected as grid supply.
- By expanding the nuclear energy as both base load and load following, it can support expansion of grid load renewable energy projects.

5.2.3 IRP2010 proposal recommendations

From the load profile model for the year 2035, additional recommendations can be made. The model is shifted 5 years into the future as opposed to the IRP's chosen forecast date, since large scale coal station decommissioning will take place over the next 20 years as indicated in the background section. The decommissioning of virtually Eskom's entire fleet should not be ignored as it appears the IRP plan may be doing. From the model, taking into account the already committed generation projects, the following power production mix is proposed making up the energy deficit of 2035 with only nuclear sources:

Power source	Portion (%)	2035 (GW)	2013 Equivalent (GW)
Nuclear	64.91	42.3	22.83
Coal	25.22	17.8	9.6
Hydro (peak)	3.09	9.3	5
OCGT (peak)	6.18	6.3	3.4
Solar CSP	0.14	0.2	0.1
Wind	0.45	0.9	0.5

Eskom should aim to build 42.3GW of nuclear capacity in order to meet demand in 2035 after the large scale decommission of the existing fleet. The consequential benefits of committing to such a large scale nuclear fleet would open the doors for the uranium mining industry, uranium enrichment fuel manufacturing and nuclear fuel reprocessing plants.

A fleet of nuclear stations addresses most of the IRP's goals regarding clean energy (carbon emission goals), cheap electricity, water consumption, security of supply and job creation. In order to have such a large scale nuclear fleet as proposed would require large capital investment; however, refer to sections 4.3 and 4.4 on the economics and security of supply of nuclear. Not having sufficient energy would result in much higher costs in the long run, in terms of quality of life and GDP growth.

5.3 Nuclear in the long term

Nuclear technology is applicable in various disciplines and holds so much potential that it will probably never be fully exploited. Some of the exciting prospects in the nuclear field are:

- Gen IV reactors and beyond
- PBMR
    - Thorium fuel breeding
    - Proliferation, burning of plutonium
    - High temperature steam for desalination
- Fuel reprocessing
- Transmutation of long lived radionuclides
- Undiscovered medical applications
- Fusion
- Nuclear propulsion
    - Space applications (for example, a manned mission to Mars)
    - Personal transport

5.4 Summary

Nuclear energy is the best option in providing base load electricity to South Africa. Take into account the fact that all sources of energy come at a 'price'. If you are *against* nuclear, you are *for* hydrocarbon, as these are the only two base load options for South Africa. The author has seen the effects of both having resided in the town of Witbank for 2 years, which according to one study recorded in Times Live, has the dirtiest air in the world as a result of all the coal mining, domestic burning of coal and coal power stations. Now, residing 6 kilometres from Koeberg power station during the last two years has proved to be an entirely different experience. The air is clean, water can be consumed off-tap (not recommended in Witbank), and Koeberg operates quietly, nestled in a nature reserve. Roads are in good condition, too, as the station does not require trucking mountains of coal around or constructing ash dams, which in turn would result in the production of sludge residue.

It could be argued that if something goes wrong, it will be have drastic consequences; but the author would rather deal with this *extremely* unlikely ‘if’ than the guaranteed negative health impact of living in Witbank. Koeberg has been geared to withstand accidents surpassing that of Fukushima in a geographical location with a fraction of that risk. People are generally very sceptical with regard to the imagined widespread long-term effects of nuclear stations and much more accepting of the clearly proved widespread, long-term poisonous and carcinogenic effects of the coal industry.

Unfortunately there is no *do nothing* scenario, and as stated, all sources of energy have downsides. No reasonable person would advocate any damage to the environment; the objective then is to choose the best combination of energy sources to supply our electricity needs. Nuclear is this option, providing a secure powerbase for the sustainable growth and development of South Africa, enriching the lives of all South Africans.

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7. APPENDICES

7.1 Technology cost input according to the IRP2010

	Pulverised Coal with FGD	Fluidised bed with FGD	Nuclear ArevaEPR	OCGT	CCGT	Wind	Concentrated PV	PV (crystalline silicon)	Forestry residue biomass	Municipal solid waste biomass	Pumped storage	Integrated Gasification Combined Cycle (IGCC)	CSP, parabolic trough, 9 hrs storage
Capacity, rated net	6X750 MW	6X250 MW	6X1600 MW	114,7 MW	711,3 MW	100X 2 MW	10 MW	10MW	25 MW	25 MW	4X375 MW	1288 MW	125 MW
Life of programme	30	30	60	30	30	20	25	25	30	30	50	30	30
Lead time	9	9	16	2	3	3–6	2	2	3,5–4	3,5–4	8	5	4
Typical load factor (%)	85%	85%	92%	10%	50%	29% (7,8m/s wind @ 80m)	26,8%	19,4%	85%	85%	20%	85%	43,7%
Variable O&M (R/MWh)	44,4	99,1	95,2	0	0	0	0	0	31,1	38,2	4	14,4	0
Fixed O&M (R/kW/a)	455	365	-	70	148	266	502	208	972	2579	123	830	635
Variable Fuel costs (R/GJ)	15	7,5	6,25	200	80	-	-	-	19,5	0	-	15	-
Fuel Energy Content, HHV, kJ/kg	19220	12500	3,900,000,000	39,3 MJ/SCM	39,3 MJ/SCM	-	-	-	11760	11390	-	19220	-
Heat Rate, kJ/kWh, avg	9769	10081	10760	11926	7468	-	-	-	14185	18580	-	9758	-
Overnight capital costs (R/kW)	17785	14965	26575	3955	5780	14445	37225	20805	33270	66900	7913	24670	50910
Phasing in capital spent (% per year) (* indicates commissioning year of 1st unit)	2%, 6%, 13%, 17%*, 17%, 16%, 15%, 11%, 3%	2%, 6%, 13%, 17%*, 17%, 16%, 15%, 11%, 3%	3%, 3%, 7%, 7%, 8%, 8%, 8%, 8%, 8%, 8%, 8%, 8%*, 6%, 6%, 2%, 2%	90%, 10%	40%, 50%, 10%	2,5%, 2,5%, 5%, 15%, 75%	10%, 90%	10%, 90%	10%, 25%, 45%, 20%	10%, 25%, 45%, 20%	3%, 16%, 17%, 21%, 20%, 14%, 7%, 2%*	5%, 18%, 35%, 32%*, 10%	10%, 25%, 45%, 20%
Equivalent Avail	91,7	90,4	92–95	88,8	88,8	94–97	95	95	90	90	94	85,7	95
Maintenance	4,8	5,7	N/A	6,9	6,9	6	5	5	4	4	5	4,7	-
Unplanned outages	3,7	4,1	<2%	4,6	4,6	-	-	-	6	6	1	10,1	-
Water usage, l/MWh	229,1	33,3	6000 (sea)	19,8	12,8	-	-	-	210	200	-	256,8	245
Sorbent usage, kg/MWh	15,2	28,4	-	-	-	-	-	-	-	-	-	-	-
CO2 emissions (kg/MWh)	936,2	976,9	-	622	376	-	-	-	1287	1607	-	857,1	-
SOx emissions (kg/MWh)	0,45	0,19	-	0	0	-	-	-	0,78	0,56	-	0,21	-
NOx emissions (kg/MWh)	2,30	0,20	-	0,28	0,29	-	-	-	0,61	0,80	-	0,01	-
Hg (kg/MWh)	1,27E–06	0	-	0	0	-	-	-	-	-	-	-	-
Particulates (kg/MWh)	0,13	0,09	-	0	0	-	-	-	0,16	0,28	-	-	-
Fly ash (kg/MWh)	168,5	35,1	-	-	-	-	-	-	24,2	1226	-	9,7	-
Bottom ash (kg/MWh)	3,32	140,53	-	-	-	-	-	-	6,1	3000	-	79,8	-
Expected COD of 1st unit	2018	2016	2022	2013	2016	2013	2018	2012	2014	2014	2018	2018	2018
Annual build limits	-	-	1 unit every 18 months	-	2500 MW after 2017	1600 MW	100 MW	1000MW					500 MW

7.2 Summary of scenarios modelled for IRP2010

Scenario	Constraints	Kusile
Base Case 0.0	Limited regional development options No externalities (incl. carbon tax) or climate change targets	Committed
Base Case 0.1	As above	Excluded
Base Case 0.2	As above	Committed, but 24 month delay; and 12 month delay for Medupi
Emission Limit 1.0 (EM1)	Annual limit imposed on CO_2 emissions from electricity industry of 275 MT CO_2-eq	Committed
Emission Limit 1.1	As above	Excluded
Emission Limit 2.0 (EM2)	Annual limit imposed on CO_2 emissions from electricity industry of 275 MT CO_2-eq, imposed only from 2025	Committed
Emission Limit 2.1	As above	Excluded
Emission Limit 3.0 (EM3)	Annual limit imposed on CO_2 emissions from electricity industry 220 MT CO_2-eq, imposed from 2020	Committed
Emission Limit 3.1	As above	Excluded
Carbon Tax 0.0 (CT)	Imposing carbon tax as per LTMS values (escalated to 2010 ZAR)	Committed
Carbon Tax 0.1	As above	Excluded
Regional Development 0.0 (RD)	Inclusion of additional regional projects as options	Committed
Regional Development 0.1	As above	Excluded
Enhanced DSM 0.0 (EDSM)	Additional DSM committed to extent of 6 TWh energy equivalent in 2015	Committed
Enhanced DSM 0.1	As above	Excluded
Balanced Scenario	Emission constraints as with EM 2.0, Coal costs at R200/ton; LNG cost at R80/GJ, Import Coal with FGD, forced in Wind earlier with a ramp-up (200 MW in 2014; 400 MW in 2015; 800 MW in 2016 and thereafter, until 2025 when the annual limit of 1 600 MW applies)	Committed, but 24 month delay; and 12 month delay for Medupi
Revised Balanced Scenario	As with Revised Balanced Scenario, with the additional requirement of a solar programme of 100 MW in each year from 2016 to 2019 (and a delay in the REFIT solar capacity to 100 MW in each of 2014 and 2015). CCGT forced in from 2019 to 2021 to provide back-up options. Additional import hydro as per the Regional Development scenario	Committed, but 24 month delay; and 12 month delay for Medupi

7.3 Tabulated data of modelled energy profile for the energy mix proposed in the IRP2010 document

The table below shows the data used to draw the graph of the modelled proposed energy mix:

Table 13: Data in respect of IRP proposed energy mix used in grid model

Time	Nuclear	Coal	CCGT	Hydro	OCGT	PV	CSP	Wind	Total	Avg load
0:00	5.67	19.042	0	0	0	0	0	1.32	**26.032**	**24.712**
1:00	5.67	17.93	0	0	0	0	0	1.32	**24.92**	**23.6**
2:00	5.67	17.425	0	0	0	0	0	1.32	**24.415**	**23.095**
3:00	5.67	17.229	0	0	0	0	0	1.32	**24.219**	**22.899**
4:00	5.67	17.421	0	0	0	0	0	1.32	**24.411**	**23.091**
5:00	5.67	18.795	0	0	0	0	0	1.32	**25.785**	**24.465**
6:00	5.67	19.2	1.3	0	0	0	0	1.32	**27.49**	**26.491**
7:00	5.67	20.449	1.3	0	0	0	0	1.32	**28.739**	**28.739**
8:00	5.67	21.088	1.3	0	0	0.2	0	1.32	**29.578**	**29.578**
9:00	5.67	20.841	1.3	0.62	0	0.5	0.5	1.32	**30.751**	**30.751**
10:00	5.67	20.879	0.65	1	0	1.4	0	1.32	**30.919**	**30.919**
11:00	5.67	19.2	0.65	1	0	2.5	0	1.32	**30.34**	**31.215**
12:00	5.67	19.2	0.65	0	0	3.86	0	1.32	**30.7**	**30.964**
13:00	5.67	19.2	0.65	0	0	4.1	0	1.32	**30.94**	**30.436**
14:00	5.67	19.2	0.65	0	0	3.86	0	1.32	**30.7**	**29.91**
15:00	5.67	19.2	0.65	0	0	2.7	0	1.32	**29.54**	**29.604**
16:00	5.67	20.101	0.65	0	0	1.4	0.507	1.32	**29.648**	**29.775**
17:00	5.67	19.2	0.65	1	0	0.5	2	1.32	**30.34**	**30.475**
18:00	5.67	19.2	0.65	2.54	1	0.1	1	1.32	**31.48**	**31.896**
19:00	5.67	19.2	1.3	2.54	3.4	0	0	1.32	**33.43**	**33.446**
20:00	5.67	19.2	1.3	2.54	2	0	0	1.32	**32.03**	**32.256**
21:00	5.67	19.2	0.65	1	1.76	0	0.665	1.32	**30.265**	**31.265**
22:00	5.67	19.2	0.65	0	0	0	1.088	1.32	**27.928**	**28.928**
23:00	5.67	19.2	0.65	0	0	0	0	1.32	**26.84**	**26.445**
Total (GW.h)	**136.08**	**460.8**	**15.6**	**12.24**	**8.16**	**21.12**	**5.76**	**31.68**	**691.44**	**684.955**