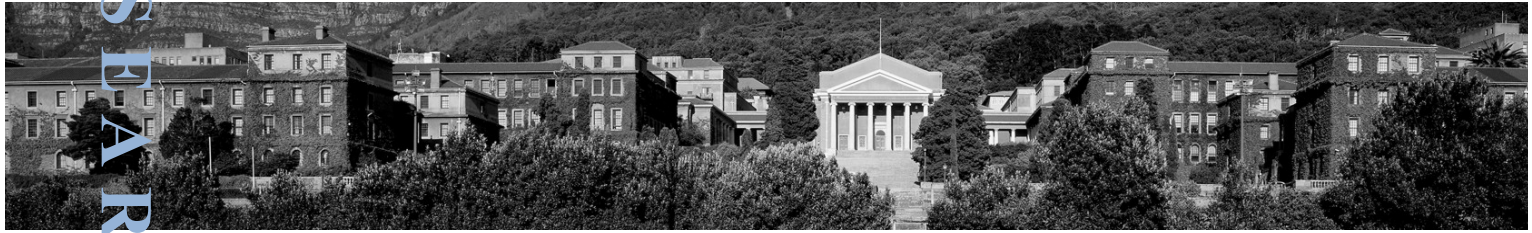


# **South Africa's proposed nuclear build plan: an analysis of the potential socioeconomic risks**

**Technical Report**



# South Africa's proposed nuclear build plan: an analysis of the potential socioeconomic risks

## Technical Report

ENERGY RESEARCH CENTRE  
2015

---

### Key points

- We analyse the South African Government's stated commitment to 9.6GW of nuclear power against other supply options. A flexible planning approach in the electricity sector is preferred to a commitment to the full nuclear fleet.
- In a future with high growth, assuming low costs for nuclear and limited and expensive alternatives, the commitment to nuclear power could have no significant impact on the electricity price and the economy.
- There is, however, a 94% chance that electricity prices will be higher in 2030 as a result of the commitment to nuclear power, which would have negative impacts on growth, employment and welfare in South Africa.
- In a future with lower growth, higher nuclear costs, and availability of other supply options, the commitment to nuclear power could have significant negative implications for growth, employment and welfare in South Africa.
- Consumers are likely to bear the burden of the investment through higher electricity prices and decreased employment.

*Suggested citation for this paper:*

Energy Research Centre, 2015. South Africa's proposed nuclear build plan: an analysis of the potential socioeconomic risks. Technical Report. Energy Research Centre. University of Cape Town. November 2015.

*Acknowledgements:*

The ERC would like to thank Earthlife Africa for funding this study as an independent, technology neutral and comprehensive technical study on the potential socioeconomic implications of South Africa's commitment to nuclear power. This is a first pass at a significant piece of work. It is hoped that this will start an important conversation, bring transparency to the procurement process and make consumers aware of the potential risks involved with such a large-scale investment. Of course, any errors in this report and in the analyses remain the authors' own.

Energy Research Centre  
University of Cape Town  
Private Bag X3  
Rondebosch 7701  
South Africa

Tel: +27 (0)21 650 2521  
Fax: +27 (0)21 650 2830  
Email: [erc@erc.uct.ac.za](mailto:erc@erc.uct.ac.za)  
Website: [www.erc.uct.ac.za](http://www.erc.uct.ac.za)

# Contents

<b>1. Introduction</b>	<b>1</b>
<b>2. Background</b>	<b>2</b>
2.1 Integrated Resource Plan	2
2.2 Potential nuclear vendors	3
2.3 Potential and preferred sites	4
<b>3. Methodology</b>	<b>5</b>
3.1 Linked SATIM-E and e-SAGE Models	5
3.2 Economic model (e-SAGE)	7
3.3 Energy model (SATIM)	8
3.3.1 Overall assumptions and exclusions	9
<b>4. Scenarios</b>	<b>10</b>
4.1 Key uncertainties and drivers	12
4.1.1 Economic growth and electricity demand	12
4.1.2 Nuclear cost parameters	14
4.1.2.1 <i>Overnight Investment Cost</i>	14
4.1.2.2 <i>Lead/Construction time</i>	15
4.1.2.3 <i>Nuclear capacity schedule</i>	15
4.1.2.4 <i>Nuclear Availability Factor</i>	16
4.1.3 Renewable energy parameters	16
4.1.3.1 <i>Centralised Photovoltaic</i>	16
4.1.3.2 <i>Concentrating Solar Power (CSP)</i>	17
4.1.3.3 <i>Wind</i>	18
4.1.4 Natural gas	18
4.1.5 Regional hydro imports	19
<b>5. Results</b>	<b>19</b>
5.1 Electricity sector and socioeconomic implications	19
5.1.1 Future 1 results: Best case for nuclear	19
5.1.1.1 <i>Electricity build plan</i>	19
5.1.1.2 <i>Investment levels and electricity prices</i>	21
5.1.1.3 <i>Growth and employment</i>	21
5.1.1.4 <i>Employment effects by labour category</i>	22
5.1.1.5 <i>Welfare</i>	23
5.1.2 Future 2 results: Worst case for nuclear	23
5.1.2.1 <i>Electricity build plan</i>	23
5.1.2.2 <i>Investment levels and electricity prices</i>	24
5.1.2.3 <i>Growth and employment</i>	25
5.1.2.4 <i>Employment effects by labour category</i>	26
5.1.2.5 <i>Welfare</i>	27
5.2 Quantifying the risks of a higher electricity price using Monte Carlo Analysis	28
<b>6. Discussion</b>	<b>30</b>
<b>7. Conclusion</b>	<b>32</b>
<b>8. References</b>	<b>33</b>

## **List of Figures:**

- Figure 1: Potential and preferred nuclear reactor sites
- Figure 2: The link between the economic model and the energy model
- Figure 3: Installed coal capacity in all scenarios
- Figure 4: Electricity Demand Trajectory
- Figure 5: Nuclear reactor lead times
- Figure 6: The availability factors of nuclear reactors currently online
- Figure 7: Overnight cost for Centralised PV
- Figure 8: Overnight cost for CSP with 6hr storage and ratio of costs for different storage options
- Figure 9: Overnight cost for Wind
- Figure 10: Electricity sector capacity in 2010, 2030 and 2040 for Future 1
- Figure 11: Comparison of investment and electricity price for committed nuclear versus flexible planning in Future 1
- Figure 12: Impact on GDP and employment of the nuclear commitment versus flexible planning approach in Future 1
- Figure 13: Impacts on household consumption of committed nuclear versus flexible scenario in Future 1
- Figure 14: Electricity sector installed capacity in 2010, 2030 and 2040 for Future 2
- Figure 15: Comparison of investment and electricity price for committed nuclear versus flexible planning in Future 2
- Figure 16: Impact on GDP and employment of the nuclear commitment versus flexible planning approach in Future 2
- Figure 17: Impacts on household consumption of committed nuclear versus flexible scenario in Future 2
- Figure 18: Difference in Electricity price between “forced” and “free” in absolute and percentage terms
- Figure 19: Cumulative probability distribution for the price impact of the nuclear program

## **List of Tables:**

- Table 1: Potential nuclear vendors
- Table 2: Summary of uncertain parameters for Future 1 and Future 2
- Table 3: Nuclear capacity schedule
- Table 4: Employment effects of committed nuclear versus flexible planning in Future 1
- Table 5: Comparison of electricity price divergence between committed nuclear and flexible planning in Future 2
- Table 6: Employment effects of committed nuclear versus flexible planning in 2040 for Future 2

# 1. Introduction

The Integrated Resource Plan 2010 effectively forced a full fleet of 9.6GW of nuclear power into the final build plan (DoE, 2011) and the South African Department of Energy has since made several statements firmly committing the country to the procurement of a fleet of nuclear power plants. However, the risks and uncertainties specific to a nuclear fleet, as well as those implicit in long term electricity sector planning more generally, have yet to be quantified. This study therefore aims to understand the potential effects on the South African economy of the government's stated commitment to invest in 9.6GW of nuclear power (DoE, 2011) through a technical analysis of the potential risks and uncertainties.

The study reviews this commitment in comparison to a more flexible approach to energy planning that is guided by the imperative of minimising costs. The analysis seeks to answer the following research questions:

1. Given the high level of uncertainty inherent in long-term electricity planning, how does the commitment to 9.6GW of nuclear power by 2030 compare to a more flexible planning approach in meeting government's stated objectives of economic growth, job creation, and welfare?
2. If we do commit to 9.6 GW of nuclear power, what are the risks of an electricity price increase and associated socioeconomic implications?

There are three main tiers of analysis in this study. In order to answer the first research question we first build two illustrative, contrasting futures, to understand the implications of different investment strategies (a commitment to nuclear power versus adopting a flexible planning approach for electricity sector investment). In the second tier, we quantify the socioeconomic implications of the commitment to build a nuclear power fleet versus adopting a flexible planning approach in each of these illustrative futures, examining the effects on economic growth, employment and welfare. Given that these illustrative futures are only two of an infinite number of futures that could unfold for South Africa, we employ a Monte Carlo analysis to analyse 1000 of these possible futures. This increases the robustness of this analysis. It is impossible to illustrate all of these futures and detail the socioeconomic implications of the commitment to nuclear power in each of them. We therefore focus on the impact that the commitment to nuclear power would have on the electricity price in each of these plausible futures. The risk of an electricity price increase with the commitment to nuclear power relates directly to the negative socioeconomic impacts of the commitment. This is quantified in the third tier of analysis and answers the second research question.

Our results highlight the impact of the nuclear decision on South Africa's electricity build plan, economywide and sectoral GDP growth rate, the investment required in the electricity sector, electricity prices, direct and indirect employment for different skilled groups, and household welfare.

## 2. Background

### 2.1 Integrated Resource Plan

There are three main government documents on which the nuclear programme is premised: the Nuclear Energy Act 46 of 1999, the Nuclear Energy Policy of 2008, and the Integrated Resource Plan 2010 (IRP), adopted in 2011.

The policy-adjusted scenario from the Integrated Resource Plan (IRP) is currently South Africa's official electricity build plan to 2030. A comprehensive IRP Update was released in November 2013, but to date has not been promulgated. The policy-adjusted IRP adds 9.6GW of nuclear power to the grid by 2030, which would result in nuclear power accounting for around 12.7% of South Africa's total capacity in 2030<sup>1</sup>. The 9.6GW of new capacity is split into 1.6GW increments of nuclear power coming online annually between 2023 and 2026, in 2028 and in 2029. Nuclear power did not feature in the cost optimal scenarios that were generated in the IRP process, but the proposed nuclear fleet was added as a policy consideration, "to account for the uncertainties associated with the costs of renewables and fuels" (DoE, 2011). Alternative scenarios in the IRP indicated that future electricity capacity requirements could be met without nuclear with the caveat that excluding it presented a risk to South Africa's security of supply.

Three policy options were given in the IRP (DoE, 2011):

- a) *Commit to the nuclear fleet as indicated in the RBS<sup>2</sup>,*
- b) *Delay the decision on the nuclear fleet indefinitely (and allow alternatives to be considered in the interim),*
- c) *Commit to the construction of one or two nuclear units in 2022-4, but delay a decision on the full nuclear fleet until higher certainty is reached on future cost evolution and risk exposure both for nuclear and renewables.*

The Department of Energy opted to commit to the full nuclear fleet as this would provide assurance for security of supply and also ensure sufficient dispatchable base-load capacity to meet system peak demand. The Department further stated that:

*"The Policy-Adjusted IRP continues to indicate a balance between different government objectives, specifically economic growth, job creation, security of supply and sustainable development...also security of supply concerns and affordability." (DoE, 2011)*

The IRP Update (DoE, 2013) was more circumspect regarding nuclear power investment and outlined some of the risks involved – namely the risk that the cost may be uncompetitive and that economic growth may not be high enough to warrant an investment in the full nuclear fleet. The National Development Plan (NDP) was also noncommittal and called for a thorough investigation into the risks and implications of the nuclear build plan (NPC, 2013). The NDP listed three objectives for the energy sector, similar to the key objectives for Integrated Energy Planning put forward in the National Energy Act (Act no. 34 of 2008):

---

<sup>1</sup> This is based on the official IRP, but is likely to be adjusted with the increases in capacity under the Renewable Energy Independent Power Producers Procurement Program (REIPPPP)

<sup>2</sup> RBS is the revised balanced scenario, the preferred case in the IRP 2010; after stakeholder engagement, the RBS was revised into the policy-adjusted scenario, which became the final electricity build plan for South Africa.

1. Economic growth and development through adequate investment in energy infrastructure. The sector should provide reliable and efficient energy service at competitive rates, while supporting economic growth through job creation.
2. Social equity through expanded access to energy at affordable tariffs and through targeted, sustainable subsidies for needy households.
3. Environmental sustainability through efforts to reduce pollution and mitigate the effects of climate change.

These elements and objectives speak not only to security of supply but more broadly to energy security in South Africa. This broader understanding of energy security as including affordability and access to energy (especially for low-income earners) and environmental sustainability is key to the energy policy objectives as outlined above, as well as in the 1998 White Paper on Energy Policy. It is critical that these objectives are considered in energy and electricity planning. For this reason, this study uses the broader definition of energy security to compare planning options recognising that energy security encompasses more complexity than merely security of supply and that the affordability and access to energy are imperatives in the South African context.

## 2.2 Potential nuclear vendors

South Africa has engaged with a number of prospective nuclear vendor countries over the last few years. Several 'nuclear vendor parade' workshops were held in late 2014 and in parallel the government has entered into negotiations and signed intergovernmental framework agreements with France, Russia and China - all as part of a pre-procurement process. Other agreements have also been signed with vendors in the USA and South Korea. According to President Zuma, "these agreements set out potential frameworks of cooperation that each country foresees where or how they can participate in South Africa's new nuclear build program" (WNA, 2014).

At the time of undertaking this analysis, South Africa's preferred choice of nuclear vendor was not yet clear. Table 1 lists the potential vendors and associated technology options that could be procured. The President has stated that the selection of potential nuclear vendors was based on those that had Pressurized Water Reactor nuclear technology, similar to South Africa's existing nuclear power plant, Koeberg, in the Western Cape (WNA, 2014). For the purpose of this study, the analysis is based on the specifications of Rosatom's VVER-1200 technology<sup>3</sup>.

---

<sup>3</sup> It should be noted that the costs, plant size and financing models are likely to differ according to the choice of vendor and choice of plant. The preferred vendor was not known at the time of writing.



	Provider	Technology	Generation	Size (MWe)	Notes
France	AREVA NP, Siemens	EPR	III+	1600	Two units under construction and both with delays. Bidder in the 2008 South African tender.
USA	Toshiba, Westinghouse	AP-1000	III	1110	Plants under construction in China, USA, Bulgaria, UK. Bidder in the 2008 South African tender.
China	CNCC in partnership with CGN	ACP-1000 or 'Hualong One'	III	1100	Various designs could be on offer from the three separate Chinese vendors. China has little experience in export markets.
	CGNPG	ACPR1000	III	1150	
	SNPTC	AP1000/CAP-1400	III		
Korea	KEPCO	APR-1400/APR+	III	1400 /1550	Plants under construction in Korea and UAE.
Russia	ROSATOM	VVER-1200 <sup>4</sup> /VVER-TOI <sup>5</sup>	III+	1198 / 1255	VVER-1200 units under construction in Russia and planned in Turkey, Ukraine and Finland. No VVER-TOIs have been commissioned to date.

Table 1: Potential nuclear vendors

### 2.3 Potential and preferred sites

Eskom undertook an initial Nuclear Site Investigation Program in 1982 and identified five potential sites for nuclear reactors in South Africa, shown below in figure 1. Thyspunt, an area outside of Cape St Francis Bay was declared the preferred site and is the only site where an Environmental Impact Assessment (EIA) has been concluded.

4

[http://www.rosatom.ru/en/resources/b6724a80447c36958cface920d36ab1/brochure\\_the\\_vver\\_today.pdf](http://www.rosatom.ru/en/resources/b6724a80447c36958cface920d36ab1/brochure_the_vver_today.pdf). Accessed 28-20-2015

5

[http://www.rosatom.ru/en/resources/cd8bd100447c26c38cb3ace920d36ab1/buklet\\_vver\\_toi\\_eng.pdf](http://www.rosatom.ru/en/resources/cd8bd100447c26c38cb3ace920d36ab1/buklet_vver_toi_eng.pdf). Accessed 28-10-2015.



**Figure 2: Potential and preferred nuclear reactor sites**

An investment in nuclear power will have micro (community and provincial level) impacts in these areas through an increase in construction and infrastructure development around the nuclear sites. These impacts are not, however, addressed in this study. It is unlikely, given the high-skills required for the construction and operation of a nuclear power plant that direct employment will increase in these communities. There could be some benefit in terms of indirect job creation and, depending on the localisation component of the procurement contracts, some associated industry development and associated job creation. This study is concerned with understanding the economy-wide impacts of different electricity sector technology choices and does not cover potential localisation and the development of a nuclear industry, however this does present an interesting avenue for further work.

### 3. Methodology

#### 3.1 Linked SATIM-E and e-SAGE Models

A linked model approach is used in this study firstly, in order to capture the complexities of the energy sector as well as the impacts of different build plans on the economy. Secondly this approach is employed to capture the feedback of price and investment effects on energy demand. This approach builds on extensive experience with energy models at the Energy Research Centre. The South African Times Model (SATIM), a technology rich energy model and e-SAGE (the energy extension to South Africa's general equilibrium model) are partially linked through the electricity sector and driven by similar assumptions<sup>6</sup>.

The linked model approach emulates the planning process of South Africa's IRP 2010, in which a generation build plan is proposed based on forecasts for future electricity demand and revised every few years according to new information and updated assumptions. It was noted in the IRP 2010 that there is a need for potential socioeconomic effects of the electricity build plans to be assessed, the linked model allows for this analysis to be done. By using the linked model approach, this report goes further by providing a comprehensive socioeconomic analysis of the scenarios from the IRP planning process. The benefit of using a linked model approach is that it captures the price effects of the electricity build plan on the entire economy (with sectoral and household responses to

<sup>6</sup> Work on linking other sectors of the energy model and the economic model is ongoing.

changing electricity prices); this means that the demand forecast, and subsequent final build plan, more accurately represents that of industry and consumer electricity demand through to 2040.

Our approach is illustrated below, along with the drivers that are passed between the energy and economic model through the linking process.

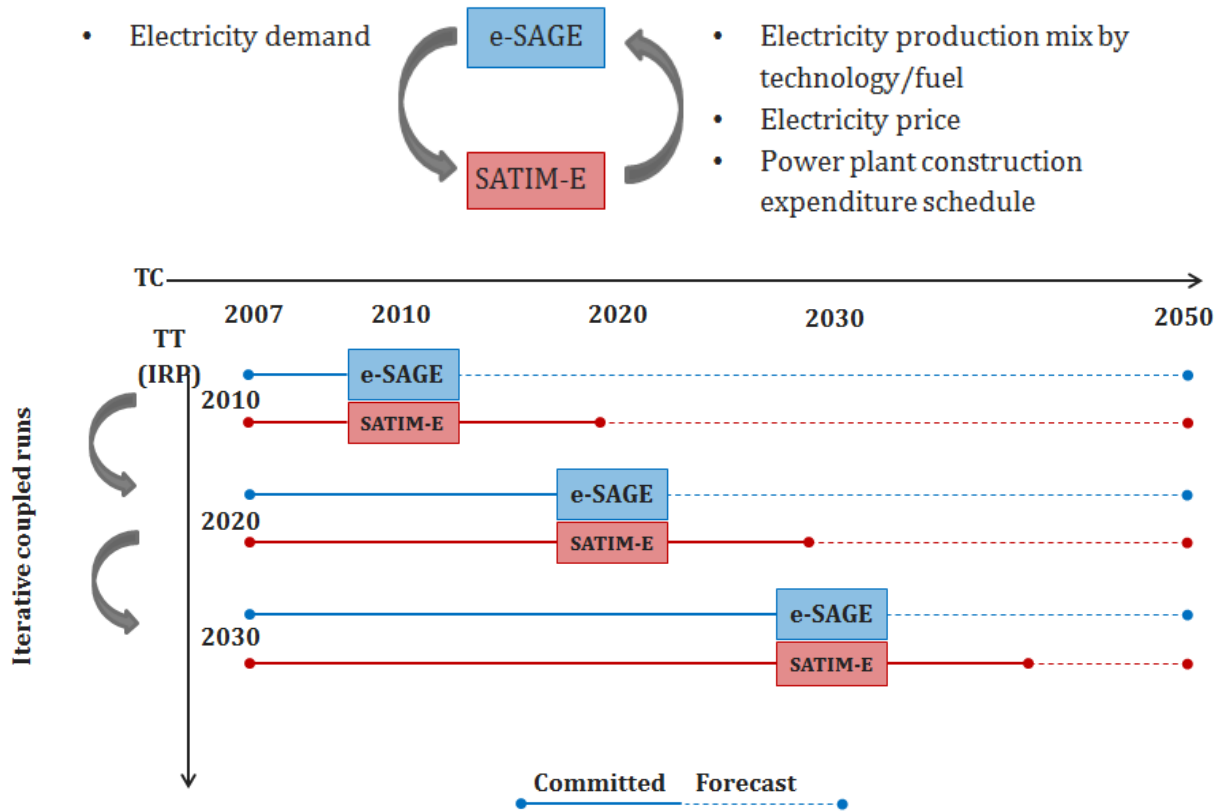


Figure 3: The link between the economic model and the energy model

Alternate runs of SATIM-E<sup>7</sup> and e-SAGE are performed from 2006 to 2050, each time exchanging information about fuel prices, electricity demand, investment and capital growth in the power sector, electricity production by technology group, and electricity price. Similar to the process of the IRP, SATIM-E computes an investment plan and an electricity price projection based on an initial electricity demand from e-SAGE. These are passed onto e-SAGE to determine the impact, if any, that the new price projection has on the demand, which then goes back to SATIM-E in the next iteration. After a few iterations convergence between the two models is reached, i.e. the models contain the same prices and demand paths. An iterative approach is beneficial as it allows stakeholders to follow the data exchange from model to model and understand the relationship between the electricity sector and the economy.

<sup>7</sup> SATIM can be run as a full energy sector model or as an electricity sector model (SATIM-E); we have used the latter in this analysis, since the study is an assessment of alternative electricity planning options.

### 3.2 Economic model (e-SAGE)

The e-SAGE model is a dynamic recursive computable general equilibrium (CGE) model developed by UNU-WIDER (Arndt et al., 2011). The main input is the 2007 South African Social Accounting Matrix (SAM). The SAM is a set of accounts that represents all of the productive sectors and commodities in South Africa, as well as factor markets, enterprises, households, and the 'rest of the world.' The 2007 SAM has 61 productive sectors (industries) and 49 commodities. The seven factors of production include land, four labour groups disaggregated according to level of education<sup>8</sup>, energy and non-energy capital (Arndt et al., 2011). The government, enterprises, 14 household groups based on their per capita expenditure, and the external account<sup>9</sup> are all represented (Thurlow, 2004). The behaviour of industries and households is governed by rational expectations (Thurlow, 2008). Industries and producers are thus assumed to aim to maximize profits while households aim to maximize their utility subject to their budget constraints. Product and factor market equilibrium are maintained.

The e-SAGE model is a dynamic recursive model, and as such has two periods, the "within-period" and the "between period". The static run of the CGE model makes up the within-period in which the economy adjusts to an annual shock. Some variables and parameters are updated based on the new equilibrium during the between period, for instance, capital accumulation and re-allocation are determined endogenously, whereas population growth, factor productivity and technical change in the energy sector are forecast exogenously (Alton et al., 2014).

An average population growth rate of 0.7% per annum to 2040 was assumed in this study. This is aligned with the United Nations' median estimates for population growth. The expected growth rate is quite low because, according to current trends, migration rates are likely to decrease and the rate of growth in the population of South Africa will decline between now and 2040<sup>10</sup>. The population in 2040 is forecast to be approximately 63 million people.

There are also several pertinent assumptions about labour supply growth to 2040. The study assumes a more optimistic view on the future of education and skills development than current skills/education levels would suggest. Labour supply for semi-skilled workers grows at 1.5% per annum, significantly faster than population growth, and the supply of skilled workers by 1% per annum. The result is an increase of semi-skilled and skilled labour to about 40% of the total labour force by 2040. There is a high demand for semi-skilled and skilled workers in South Africa, therefore full employment is assumed for these labour categories.

A key feature of the e-SAGE model is that non-energy industries can react to energy price changes during the between-period by shifting their investments to less energy intensive capital and technologies, how easy it is for these industries to switch is specified exogenously (Alton et al., 2014)<sup>11</sup>.

---

<sup>8</sup> Labour is disaggregated into four groups according to level of education and mapped to level of skill: individuals that have attained primary and middle-school education are considered unskilled, completed secondary school are semi-skilled, and tertiary education are skilled.

<sup>9</sup> External Account includes: global commodity prices, foreign financial flows, payments for imports and revenues from exports, and trade elasticities.

<sup>10</sup> Estimates for the population in 2050 range between 56 and 75 million people for various scenarios explored by the International Institute for Applied Systems Analysis (IIASA) and World Population Program (WPP) (2015 Revision) – the medium variant is slightly higher than 65.54 million. The IIASA estimates are too low for the initial years (between 54 and 55 million in 2020), therefore these were revised to a more reasonable estimate of 54.5 million in 2015.

<sup>11</sup> Energy is considered an intermediate input and the interaction between intermediates and factors is governed by a Leontief production function. To decrease the rigidity of using a Leontief

CGE models are governed by a set of closure rules that allow the model to reach equilibrium. The following closures are applied for all of the e-SAGE model runs:

- **Savings and investment:** Previous studies have found that the savings-driven investment closure is most appropriate for South Africa.<sup>12</sup>
- **Government:** Uniform sales tax rate point changes are allowed for selected commodities, while government savings remain fixed.
- **Foreign:** South Africa has a flexible exchange rate, therefore a fixed trade balance is assumed and the exchange rate is able to adjust and maintain equilibrium between the payments to and from other countries<sup>13</sup>.
- **Factor market:** A large portion of the low-skilled workforce in South Africa is unemployed, and some of this unemployment is structural. Therefore, it is assumed that low-skilled labour is not fully employed and that there are rigidities in the labour market.<sup>14</sup> Labour supply is flexible and allowed to adjust to meet the demand for labour in the economy. Skilled labour and semi-skilled labour on the other hand are assumed to be fully employed and mobile. Factor prices (i.e., rent or wages) are allowed to adjust to ensure equilibrium is reached and demand equals supply. Capital is assumed to be fully employed and activity- or sector-specific. Land is fully employed and mobile, that is, it can be used for different purposes.

### 3.3 Energy model (SATIM)

The South African TIMES Model (SATIM) is an inter-temporal bottom-up optimisation energy model of South Africa built around the Markal-TIMES platform. SATIM uses linear or mixed integer programming to solve the least-cost planning problem of meeting projected future energy demand, given assumptions such as the retirement schedule of existing infrastructure, future fuel costs, future technology costs, learning rates, and efficiency improvements, as well as any given constraints such as the availability of resources. The model is structured into five demand sectors and two supply sectors that can be analysed individually or together. The demand sectors are industry, agriculture, residential, commercial and transport, and the supply sectors are electricity and liquid fuels. The technical, economic and demand projection data for each sector is contained in

---

production function, there is ‘response elasticity’ that governs the amount sectors are able to change in their energy inputs per unit of output based on energy prices.

<sup>12</sup> The relationship between savings and investment continues to be a highly debated and controversial topic in macroeconomics (Nell, 2003). Neo-classical, and new endogenous growth theory maintains the view that it is former savings that decide an economy’s investment and output (Thurlow, 2004). Conversely, from a Keynesian perspective, it is investment that is exogenous and savings that adjust accordingly (Thurlow, 2004). Although, according to Nell (2003), analysis has established that in the case of South Africa, the long-run savings and investment relationship is associated with exogenous savings and no feedback from investment. In light of this, the SAGE model assumes a savings-driven closure (Arndt et al., 2011). This implies, amongst other things that the deficit (foreign debt) is kept constant.

<sup>13</sup> The IMF projections show South Africa maintaining a current account deficit similar to the current deficit to 2020 – this is in-line with the assumptions made in the model.

<sup>14</sup> To simulate unemployment, an upward sloping supply curve was assumed for low-skilled labour. Low real wage supply elasticities were also assumed to indicate that their unemployment is structural.

a set of databases.<sup>15</sup> This data is detailed in the ‘inputs and assumptions’ subsection. Demand is specified as useful energy demand (e.g., demand for energy services such as cooking, lighting, and process heat), and final energy demand is calculated endogenously based on the optimal mix of demand technologies. The model allows for trade-offs between supply and demand sectors, it explicitly captures structural changes (i.e., different sectors growing at different rates), process changes, fuel and mode switching, and technical improvements related to efficiency gains. The result of the optimization is both the supply and demand technology mix (e.g., capacity, new investment, production, and consumption) that would result in the lowest discounted system cost for meeting energy demand over the time horizon, subject to all other imposed constraints (Altieri et al, 2015).

The SATIM model can be run as an electricity sector only version (SATIM-E) or a full energy sector model. Currently, there is a partial link with only the SATIM-E model linked to the economic model.

### 3.3.1 Overall assumptions and exclusions

The results of a model are entirely dependent on the design of the model and its underlying assumptions. In order to provide transparency and some context for the results, the key assumptions used in the model and model exclusions are listed below:

#### General assumptions:

- The energy model runs to 2050 but the linked model runs to 2040.
- A discount rate of 8% is assumed.<sup>16</sup>
- The model solves every 5 years and the results are interpolated for the years in-between.
- A reserve margin of at least 15% must be maintained by the system. This constraint falls within the range of 14% to 19% recommended in the Electricity Master Plan (DME, 2007).
- Reliability of supply - The firm capacity assumptions of all thermal, pump storage and hydro units are assumed to be 1; a conservative estimate for wind of 0.15 is assumed and we assume zero for solar thermal without storage and solar PV (ERC, 2013).
- No new coal power plants are built after Medupi and Kusile. This assumption is based on past work on modeling national climate targets (Altieri et al, 2015), that shows that when national climate policy targets are imposed, sectors do not reduce their emissions pro-rata (based on the base-year inventory) as is assumed in the IRP, but given that the electricity sector offers lower cost opportunities for emissions reduction this is where most of the mitigation happens, and coal power is almost completely phased out by 2050 as shown in figure 3.<sup>17</sup>

<sup>15</sup> The databases that support the SATIM model are continuously updated according to any new information and therefore may be slightly different to those used in this report. The latest versions of these can be found on the ERC website, [www.erc.uct.ac.za](http://www.erc.uct.ac.za).

<sup>16</sup> A discount rate of 8% is used as it was equivalent to the yield on a 10Y Government bond at the time of writing - the benchmark was suggested by National Treasury.

<sup>17</sup> Altieri et al (2015) ran a full energy sector model that captures the trade-offs, costs and benefits of decarbonisation in the energy sector as a whole, whereas the IRP is an electricity-only model

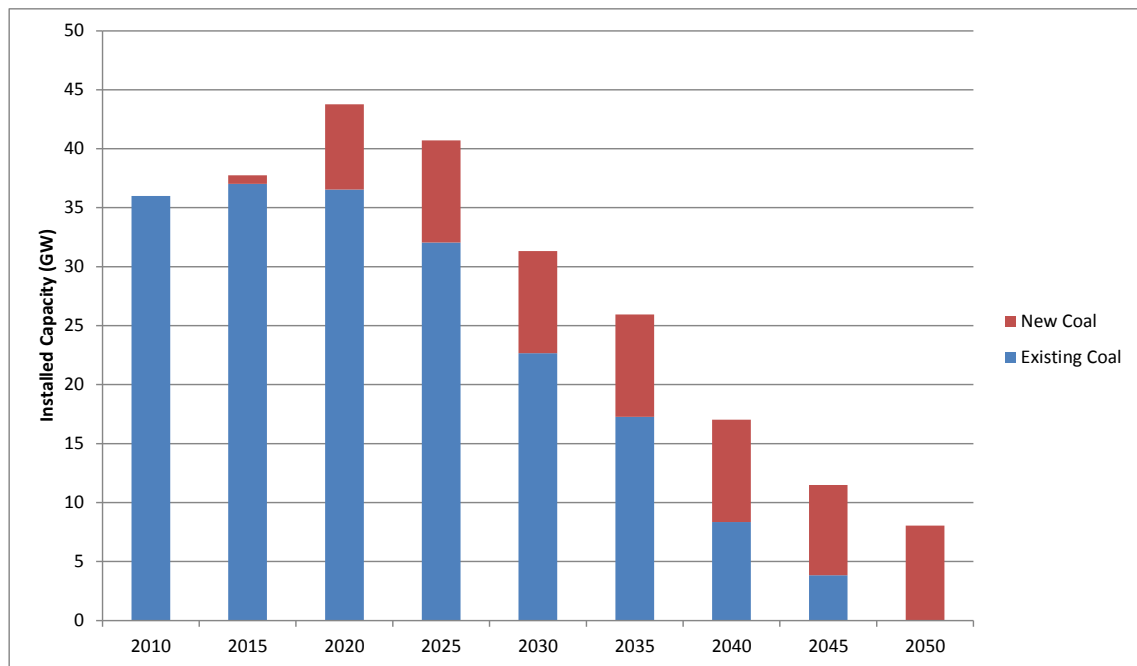


Figure 4: Installed coal capacity in all scenarios

Excluded from the modeling scope:

- The model does not include high resolution plant ramping limits or account for the efficiency/emission changes that would result from this
- Transmission costs are included in the technology cost estimates, but are not spatially disaggregated based on the geographic location of the plant or source of demand
- Life extensions of existing coal-fired plants are not considered, however Koeberg is assumed to run for its extended 60 year life
- Short term electricity system reliability analysis is not included in this analysis<sup>18</sup>
- Carbon Capture and Storage (CCS) is not included in this analysis
- A full analysis of the waste, decommissioning and implications on water-use.

## 4. Scenarios

We started with two potential and illustrative futures for South Africa (Future 1 and Future 2), each with specific conditions. The differences in each future related to parameters such as economic growth assumptions (because higher economic growth typically leads to increased electricity demand), technology costs (nuclear power versus renewable energy technologies) and the costs and availability of other sources of power such as domestic gas and regional hydropower.

In each of these futures, we then modelled the commitment to the nuclear fleet and compared this against a flexible planning scenario. In short, we model the policy

---

and assumes that other sectors will ‘do more’ in terms of decarbonisation, despite decarbonisation in the electricity sector being the cheapest option.

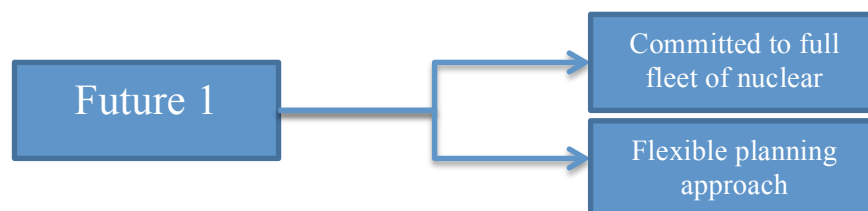
<sup>18</sup> An important next step would be to run the scenarios through a dispatch model to ensure reliability. This has been noted as an essential piece of future work.

decision to commit to nuclear against a counterfactual where South Africa adopts a flexible planning approach in two possible futures.

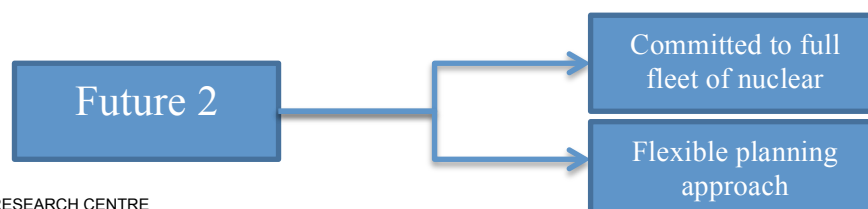
By flexible planning, we mean that we run scenarios that aim to build an electricity capacity expansion plan – as in the integrated resource plan – that minimises overall costs while meeting demand. The flexible scenarios are thus ‘least-cost’ and can be compared against scenarios with the nuclear commitment in each potential future. Given the uncertainties around economic growth, electricity demand, and costs, investment in large-scale, expensive electricity generation technology is always accompanied by some degree of risk and uncertainty. Steyn (2001: 31) outlines the literature on investing under conditions of uncertainty; he defines inflexible technologies as technologies characterised by: long construction lead times, large unit sizes, high capital intensity, dependence on dedicated infrastructure, non-incremental development strategies, and limited substitutability. These characteristics limit learning, responsiveness to changes in external conditions, and increase the costliness of errors. A flexible approach thus aims to ensure ‘least-cost’ planning and to reduce the risks inherent in inflexible decision-making.

In essence, there are an infinite number of futures that could materialise and it would be impossible to describe the socioeconomic implications of all of these. In order to narrow this down, we define two illustrative futures based on plausible and contrasting assumptions. This allowed us to compare the effects of the nuclear fleet under conditions of future uncertainty – because we do not know which future will materialise, it was important to understand the potential supply options and the impacts of those supply choices for different, uncertain futures. Whichever future materialises, we can compare the socioeconomic impacts of the committed nuclear build against a build plan that includes a diversity of supply options. In the third tier of analysis, the Monte Carlo simulations, we are able to analyse 1000 of these plausible futures. Given that it would be impossible to expand on all of these futures, Future 1 and Future 2 were chosen as they fall near the two extreme ends of the range of these 1000 futures.

Each future is described in more detail below.



Future 1 can be understood as the “best case” for nuclear power: it is a future world in which conditions are optimal for nuclear. In this future, South Africa experiences higher levels of growth between 2015 and 2040, averaging 3.6% per year. The assumed costs of nuclear power are lower, the decline in costs of renewable energy is assumed to be slower (i.e. renewable energy options are comparatively more expensive), and there are limited alternative options to nuclear power such as domestic gas resources and regional hydropower. Future 2, on the other hand, can be understood as a “worst case” for nuclear power. South Africa’s economic growth rate is lower (2.7% per year on average) and electricity demand is therefore lower; nuclear power costs are higher, renewable energy technologies are cheaper, and there are domestic gas and regional hydro options that are viable and competitive technology options.





The detailed parameters used as inputs into the modelling can be seen in Table 2:

Uncertainty parameter compared in each future	Future 1 (Best case for nuclear)	Future 2 (Worst case for nuclear)
Average Economic growth 2015-2040	~3,6%	~2,7%
<i>Nuclear parameters:</i>	<i>Optimistic</i>	<i>Pessimistic</i>
Overnight Cost (2014 \$/kW <sub>net</sub> )	Lower (~5100)	Higher (~7000)
Lead/construction time (years)	Shorter (6)	Longer (12)
Availability	Higher (90%)	Lower (75%)
<i>Renewable energy parameters:</i> (overnight cost reduction 2040:2015)	<i>Pessimistic</i>	<i>Optimistic</i>
PV (incl. rooftop and centralised)	-26%	-37%
CSP (all storage levels)	-25%	-34%
Wind	-1%	-10%
Cost and source of natural gas	Liquefied Natural Gas at \$12/MBtu	Domestic gas at \$9.5/MBtu
New Hydro Imports from the region incl. 2 phases of Inga	no	yes

**Table 2: Summary of uncertain parameters for Future 1 and Future 2**

A comprehensive explanation of these assumptions is given in section 4.1.

## 4.1 Key uncertainties and drivers

Each of the parameters used to define each future is described below in more detail.

### 4.1.1 Economic growth and electricity demand

Economic growth is a key driver of energy demand and given that many factors influence growth in the South African economy, it is particularly difficult to forecast. Higher economic growth forecasts are usually coupled with higher electricity demand forecasts. The magnitude of electricity demand growth being dependent on assumptions related to electricity intensity. Given the uncertainties around economic growth and ultimately electricity demand, investment in large-scale, expensive electricity generation technology is risky. A lower-than-expected realised electricity demand could result in lock-in and excess supply, as was the case in South Africa in the late 1980's and early 1990's (Steyn, 2001). On the other hand, a situation where electricity supply capacity is not sufficient to meet electricity demand could have a significant impact on the economy. As is currently the case in South Africa, where shortages in electricity supply continue to threaten the country's productivity, economic performance and competitiveness.

Given the uncertainty in economic growth projections, future 1 assumes a higher average annual GDP growth rate of 3.7% to 2050 and for future 2 an average annual GDP growth

rate of 2.7%<sup>19</sup>. These average annual growth rates are lower than those in the IRP update, between 5.4% and 2.9%, to 2050. There are two main reasons for this. Firstly, the electricity intensity in the linked model is slightly higher than those assumed in the IRP update, and so a lower growth rate means that the electricity demand projections are comparable to those in the IRP update (DoE, 2013). Secondly, there is no evidence that South Africa's growth rate will increase to the National Development Plan's aspirational economic growth rate of 5.4% per annum to 2030<sup>20</sup> (NPC, 2011) and, as stated in the IRP update, assuming this growth rate will be achieved raises the risk of overbuilding capacity to meet the target.

The electricity demand (energy in TWh) trajectories that result from the economic growth assumed in future 1 and future 2 described above are shown in Figure 5. This is the expected electricity consumed downstream of transmission. The figure also shows how those two trajectories compare to some of the demand projections used in the IRP update.

The electricity demand is a result of the assumptions in e-SAGE (the economic model) about the electricity needs of each sector (as a coefficient of intermediate input per unit of output, i.e. the amount of electricity required to produce goods in each sector) and household income in the economy. Electricity exports are kept constant at historical values. The current version of the linked model does not allow for substitution away/towards electricity from/to other fuels, but sectors are given some flexibility to reduce their electricity intensity in response to price increases as documented in Arndt et al. (2011), i.e. sectors have some flexibility in adjust their electricity use per unit of output as prices fluctuate.

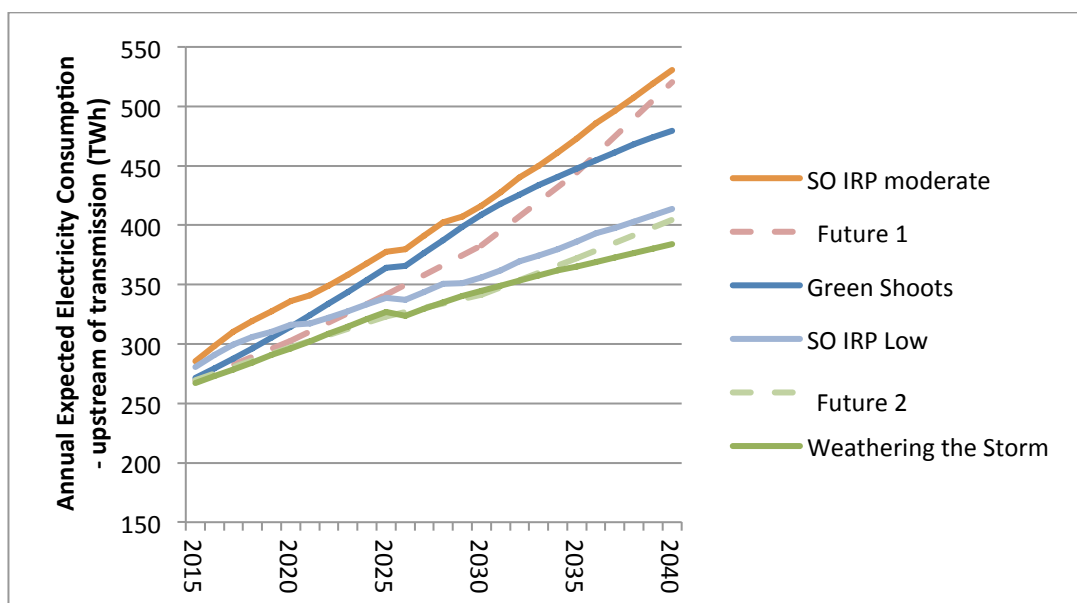


Figure 5: Electricity demand trajectory

<sup>19</sup> In the CGE model, the total factor productivity (TFP) rates were adjusted as well as the investment portion of absorption. In the lower demand scenario, TFP's grow at a declining rate of around 3% and assumed that there would be no change in South Africa's investment portion of absorption (~ 20.4%). The higher growth scenario assumed a slightly higher TFP growth rate (declining growth at 1% per annum) and a more optimistic view, aligned with the NDP, on the level of investment in South Africa (increasing to 25% by 2025).

<sup>20</sup> The World Bank estimates that in order for South Africa to reach its goal of at least 5.4% economic growth to 2030, economic growth would have to average at about 7.2% per annum to 2030.

As can be seen, the demand trajectories in our modelling are between the 'SO IRP moderate' and 'weathering the storm' demand forecasts in the IRP 2010 update<sup>21</sup>. This means that the electricity capacity requirements in two scenarios presented in this report are comparable to the capacity requirements modelled in the IRP update.

#### 4.1.2 Nuclear cost parameters

Several parameters impact the costs of nuclear power. These include the overnight capital cost (the cost of building a plant excluding interest payments; the construction or lead time to build the plant; the capacity schedule (when plants come online); and the nuclear availability factor (how much of the time the plant is running once online). Each of these factors is discussed in detail below.

##### 4.1.2.1 Overnight Investment Cost

The estimated overnight investment cost is one of the more important parameters when it comes to assessing the economic competitiveness of nuclear power. The fixed costs for construction make up the largest component of levelised or life-cycle costs of a nuclear power plant, around 70% of the total investment cost (Thomas, 2010). There is a large range in possible overnight costs for South Africa (Merven & Durbach, 2015), driven by the different costs of each technology, costs proposed by different vendors, varying material costs, labour costs and regulatory setup costs.

As previously mentioned, we assume that the preferred vendor is Rosatom and draw from the most recently quoted figures from Rosatom of \$ 40-50bn to build 8 units of their VVER-1200 (TASS, 2014) in South Africa.

The model requires overnight costs in R/kW. This is calculated by dividing the cost per unit by the net<sup>22</sup> capacity per unit. The cost per unit quoted by Rosatom most likely does not include the owner's costs. Owner's costs cover expenses that fall outside of the engineering, procurement and construction (EPC) costs such as site preparation, Environmental Impact Assessments, decommissioning costs, and the costs of setting up/augmenting regulatory frameworks. For nuclear this could make up between 10% and 20% of the total overnight costs (Black & Veach, 2012), a reasonable assumption given that Eskom estimates owner's cost to be about 15% of the total overnight cost<sup>23</sup>. By adding 10% to the lower end and 20% to the upper end this puts the range between \$44 billion and \$60 billion. The net capacity of the VVER-1200 is 1082 MW (IAEA, 2013). The range in cost per kW is therefore \$5,100 to \$7,000 per kW (shown in Table 2), which is consistent with the range used in the IRP update report (DoE, 2013).

To convert from \$/kW to R/kW we use the historical exchange rate for 2014-2015 of 11.45 R/\$ (Oanda, 2015), which gives a range of: ~2015 R 58,000/kW to 79,000/kW<sup>24</sup>.

<sup>21</sup> The growth rates on which the IRP 2010 are considered to be out of date and for this reason the comparison is made against the IRP 2010 update.

<sup>22</sup> Net generation capacity is equal to the gross generation of a power plant less the electricity used to operate the power plant (the power plants own use on pumps and fans, etc). The IRP uses gross generation capacity in the calculation of overnight costs, although it is generally accepted that the net capacity should be used in this calculation.

<sup>23</sup> Based on a personal communication with an Eskom employee.

<sup>24</sup> In 2012 Rands this gives us a range of R49 000/kW to R67 600/kW, which is consistent with the IRP update 2012 rand figures adjusted by the same 10% and 20% owner's costs.

#### 4.1.2.2 Lead/Construction time

Lead times for nuclear power plant builds vary significantly depending on a number of factors, which include technology type, skills and component availability, safety and licencing approval, funding availability and state, public and private sector interventions. Data from the Power Reactor Information Systems (PRIS) database (IAEA, 2015), shows that for reactors connected to the grid after 1990 lead times varied between 26 years and 9 months (ROSTOV-3, a VVER V-320 reactor in Russia) and 4 years and 2 months (SHIN-KORI-1, an OR-1000 reactor in Japan)<sup>25</sup>. The lead times used in this study were based on the assumptions in the IRP 2010 for future 1 (6 years) and based on the 75<sup>th</sup> percentile value from the IAEA data for future 2 (12 years). It could be argued that using the 75<sup>th</sup> percentile is optimistic, given some of the lead times shown in Figure 6. However, lead times of over 20 years are likely to be attributed to specific country experiences and delays that may not necessarily be relevant for the South African context. A lead time of over 12 years would amplify the negative impact of the forced nuclear scenario on the energy sector as well as on the economy.

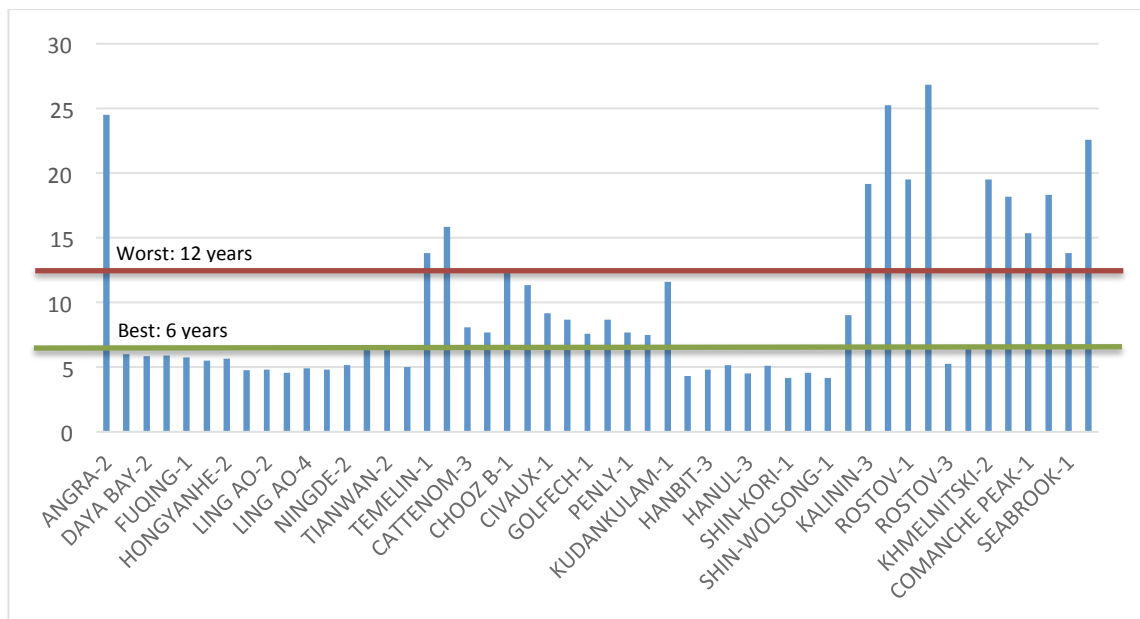


Figure 6: Nuclear reactor lead times (IAEA, 2015)

#### 4.1.2.3 Nuclear capacity schedule

The IRP Update states that the earliest date that the first unit of nuclear power could be commissioned is in 2025. This assumption was carried forward to our analysis and the date of commissioning the first unit, as shown below in table 3, is 2025. In order to have the full 9.6GW online before 2030, one unit is added to the grid every year until 2030. In future 2, with a lead time of 12 years and therefore a delay of 6 years for each unit, the schedule is pushed back and the first unit comes online in 2031<sup>26</sup>.

<sup>25</sup> These figures are taken from a reasonable sample of the data - only units connected after 1990 and larger than 900MW gross were used in the sample. Outliers were omitted as well as older technologies that are unlikely to be considered by South Africa as possible generation types.

<sup>26</sup> In a recent statement, Rosatom was quoted as saying that once the deal is finalised they would need at least three years of preparation before construction would commence (Business Day 2015). It would then take at least 60 months (5 years) to construct the first nuclear reactor, and subsequent units come online every 40 months (3 years and 4 months) (Business Day 2015). A more relaxed investment schedule such as this one would put less financial pressure on South Africa and dampen the negative short-term economic impacts of a large-scale

	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041
Nuclear IRP 2010 (Updated)	1.6	1.6	1.6	1.6	1.6	1.6											
Nuclear Delayed							1.6	1.6	1.6	1.6	1.6	1.6	1.6				
Nuclear (Rosatom)	1.6			1.6			1.6				1.6			1.6			1.6

Table 3: Nuclear capacity schedule

4.1.2.4 Nuclear Availability Factor

The availability factor is another important parameter in determining the levelised or life-cycle costs of power plant technologies. The PRIS data (IAEA, 2015) was used to determine the upper and lower bounds for the availability factors used in future 1 and future 2 respectively<sup>27</sup>. The assumed availability factors used in this study were a more optimistic 90% for future 1 and a less optimistic 75% for future 2, as shown below in figure 6.

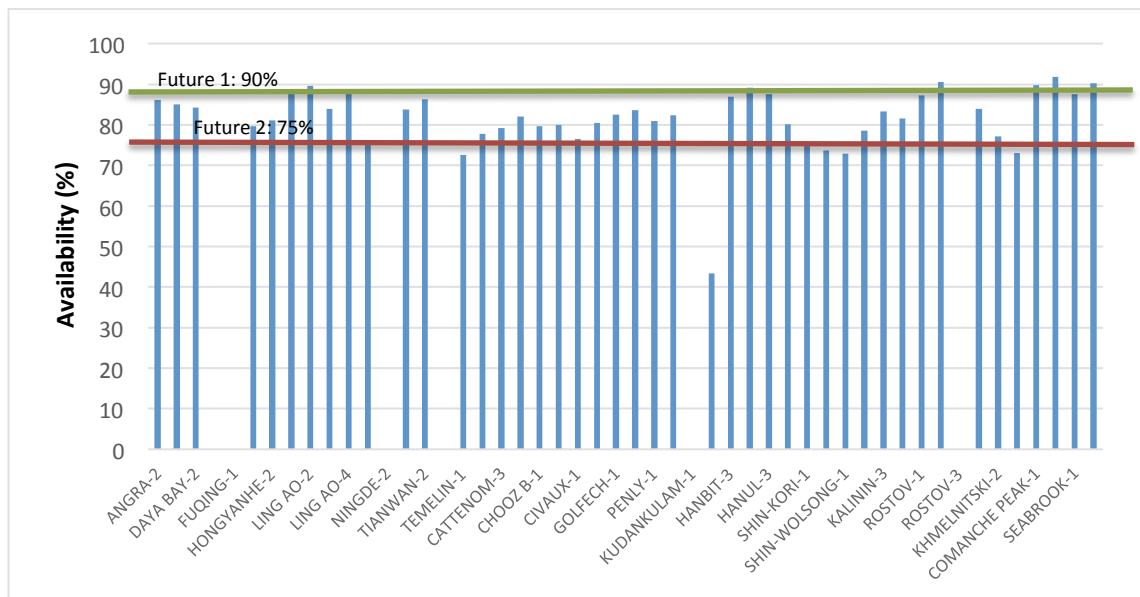


Figure 7: The availability factors of nuclear reactors currently online

4.1.3 Renewable energy parameters

4.1.3.1 Centralised Photovoltaic

The cost of Photovoltaic (PV) has reduced significantly in recent years, sustaining high learning rates of 20%-23% over the period 1976-2014 (IEA-ETP, 2014; 2015). Global installed capacity has steadily been increasing and is expected to continue to increase

electricity sector investment. This scenario was out of the scope of this study, but presents an interesting piece of future work.

<sup>27</sup> At roughly an 80% confidence interval.

over time. It is expected that as installed capacity increases further, there will be even more cost reductions, however, there is uncertainty around whether the high learning rate will be sustained and whether installed global capacity continue to expand at the current rate. The recent ERC-UNEP study looks at this in some detail (Merven & Durbach, 2015), by assuming probability distributions for the learning and future total global installed capacity. The 5th (UNEP-Optimistic used in Future 2) and 95th (UNEP-Pessimistic used in Future 1) percentile trajectories, as shown in Figure 8, are used in the analysis. It also shows how the projections compare to the assumptions in the IRP Update (DoE, 2013) and to the average overnight cost observed in the latest round (round 4) of the Renewable Energy Independent Power Producers Procurement Programme (REIPPPP).

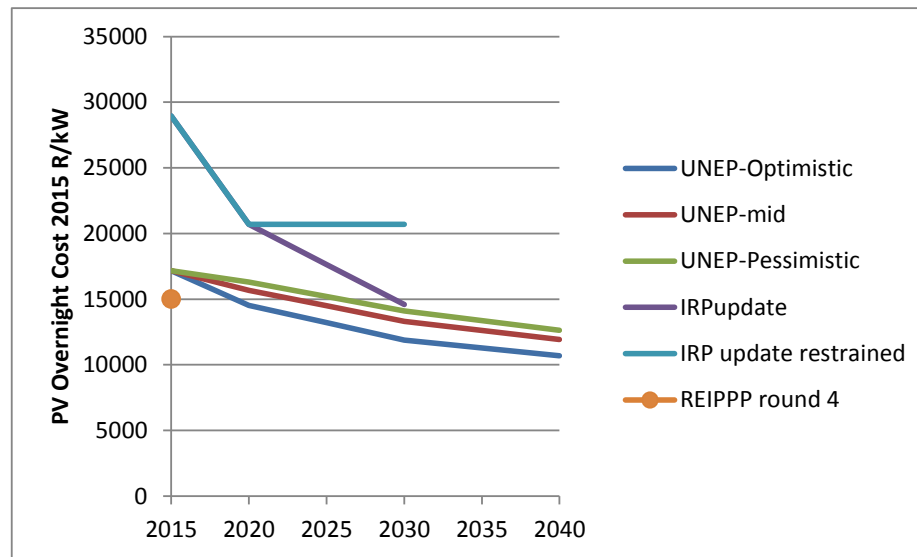


Figure 8: Overnight cost for Centralised PV

#### 4.1.3.2 Concentrating Solar Power (CSP)

A similar approach was used for Concentrating Solar Power (CSP). The ERC-UNEP study takes a range of learning rates and future global installed capacity to get a range of projections for the overnight cost of CSP. The 95% and 5% percentile trajectories for the plant with 6 hours of storage for Future 1 (optimistic) and Future 2 (pessimistic) respectively are shown in Figure 9. Plants with up to 14 hours of storage are considered. The costs of the different storage options are scaled from the 6-hour storage plant using constant scaling factors shown in Figure 9.

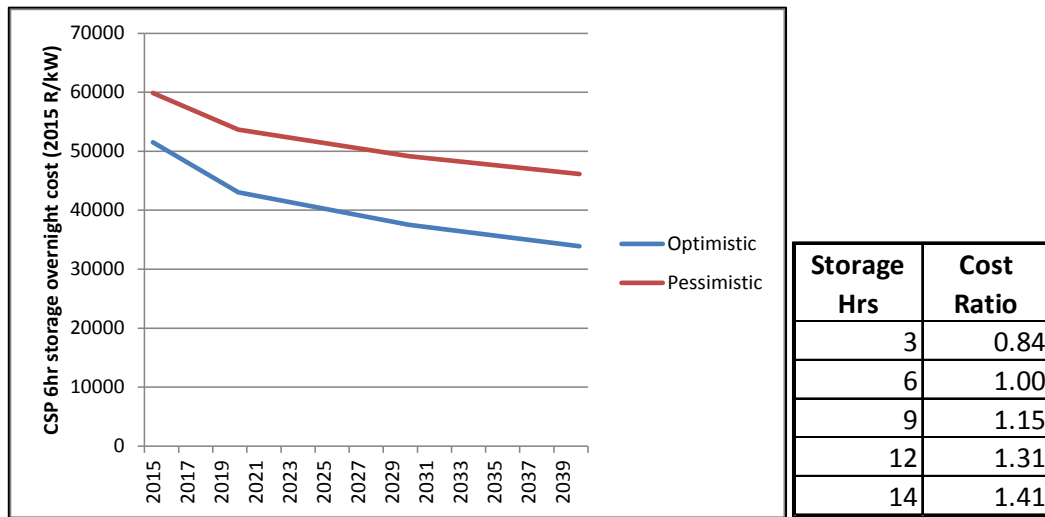


Figure 9 Overnight Cost for CSP with 6hr storage and ratio of costs for different storage options

4.1.3.3 Wind

The cost of wind has reduced significantly over the first four rounds of the REIPPPP. As with PV and CSP, there are uncertainties in the learning rate of wind in the future. To capture this uncertainty, two trajectories are considered for future 1 (optimistic trajectory) and future 2 (pessimistic trajectory), shown below in relation to the cost from round four of the REIPPPP in Figure 9<sup>28</sup>.

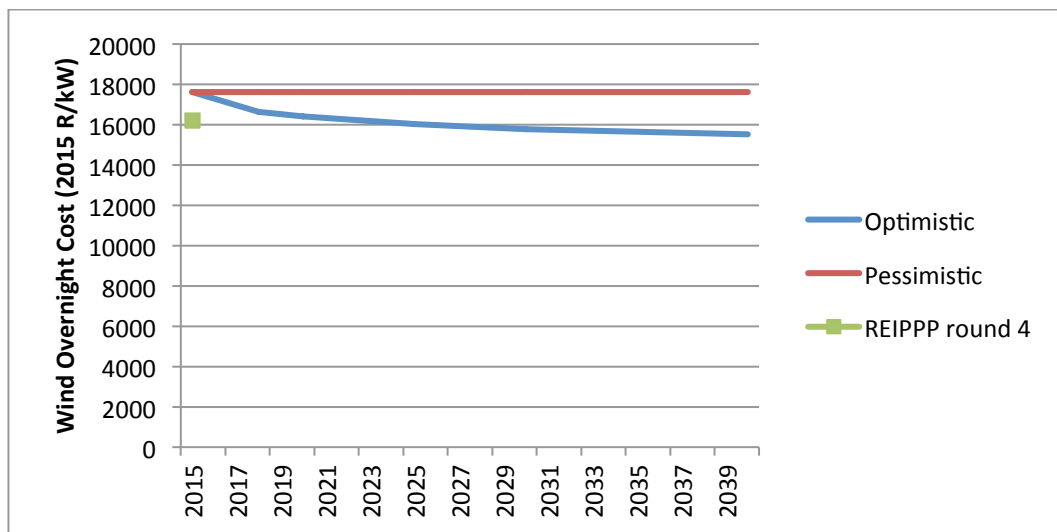


Figure 9: Overnight cost for Wind

4.1.4 Natural gas

South Africa could benefit from the availability of affordable natural gas via its shale resource. However, the size, quality, and extraction costs of the resource remain highly uncertain. In Future 2, it is assumed that up to 40 Tcf is available at \$9.5/MBtu to power plants located in the vicinity of the resource.

In Future 1, shale gas is not available to the power sector and natural gas is imported in the form of liquefied natural gas (LNG)<sup>29</sup>. The price of LNG (after regasification) is

<sup>28</sup> The cost assumed in this study is slightly higher than that of the REIPPPP, therefore it is likely that wind is more cost competitive than we assume and the take up of wind could be higher than the resultant electricity build plans, presented in the results section.

<sup>29</sup> It is assumed that the Sasol Southern Mozambique pipeline continues to operate to supply the existing Sasol gas power plants.

assumed to be \$12/MBtu, and is available to power plants in the vicinity of the LNG terminals.

#### **4.1.5 Regional hydro imports**

The Southern African Power Pool distributes electricity throughout the region via major infrastructure corridors. In Future 1, import options are limited and there are no new imported hydro options available. In Future 2, all the import options that are listed in the IRP (DoE, 2011) and IRP Update (DoE, 2013) are allowed, as well as two phases of Grand Inga.

During Phase 1 of Inga, up to 2.6 GW can be imported via the western corridor. The Phase 1 tariff is set at \$64.7/MWh on the basis of a levelised generation cost of \$35/MWh and a levelised transmission cost (including losses) of \$29.7/MWh (SNEL et al., 2011). The date of operation for Phase 1 is consistent with the updated version of the IRP (DOE, 2013) and is an import option from 2022.

Phases 2 of Inga plans for additional imports of up to 3.6 GW via other corridors (e.g. the Eastern Corridor and other routes). Imports are permitted from 2027 at a phase 2 tariff set at \$72.8/MWh on the basis of a levelised generation cost of \$35/MWh and a levelised transmission cost of \$37.8/MWh.

## **5. Results**

The results of the electricity sector and socioeconomic implications for each future as well as the results of the Monte Carlo analysis are detailed in this section.

### **5.1 Electricity sector and socioeconomic implications**

This section presents some of the key results from the linked energy and economy-wide modelling, bearing in mind the elements that, according to the NDP, should be promoted by the energy sector.

The results are reported for each future as a comparison of the case where South Africa commits to 9.6 GW of nuclear power versus the counterfactual where a flexible planning approach is adopted for the electricity sector. Given different underlying assumptions of the two futures a direct comparison between them is not analytically useful. The point of this analysis is to understand the possible macro- and socioeconomic implications of following through with the nuclear build plan versus adopting a flexible planning approach in two illustrative and extreme futures, knowing that the future that could unfold will fall somewhere between the two.

Key results include the mix of generation capacity in response to the assumptions for economic growth and imposed nuclear share, the resultant electricity price, electricity investment paths and the socioeconomic implications of these outcomes.

#### **5.1.1 Future 1 results: Best case for nuclear**

Here we compare the results of committed nuclear investment versus flexible planning in Future 1.

##### ***5.1.1.1 Electricity build plan***

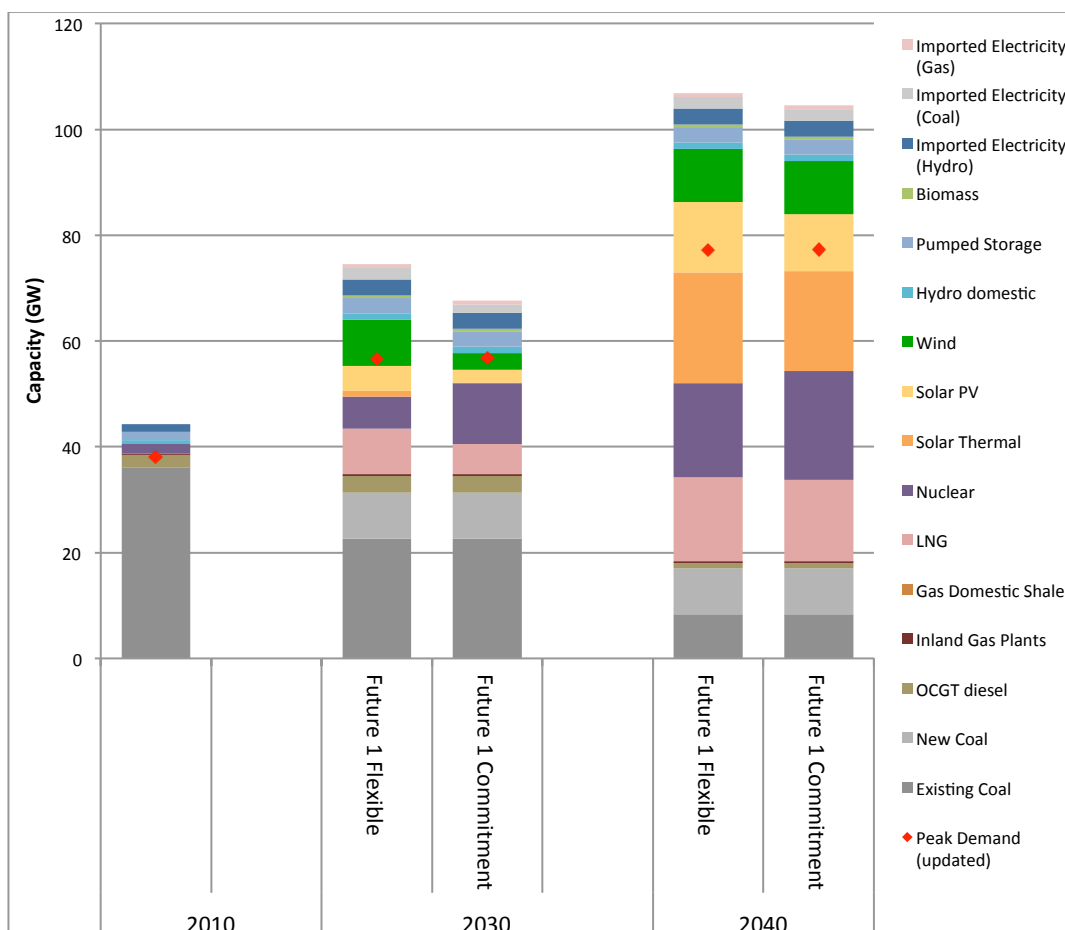
In Future 1, peak demand is similar for both the case where a flexible planning approach is adopted and when there is a firm commitment to 9.6 GW of nuclear power: at 57 GW



in 2030 and 77 GW in 2040, as shown in Figure 10.<sup>30</sup> The installed capacity is higher for the scenario where a flexible planning approach is adopted, because of higher uptake of renewable energy technologies.

When a flexible planning approach is adopted, nuclear capacity does come online but only approximately 4GW of new capacity by 2030, whereas other new capacity is from wind, natural gas-fired plants (using imported liquefied natural gas) and Solar PV generation. This is in contrast to a fixed commitment to 9.6GW of nuclear, which replaces wind and gas capacity in particular by 2030. By 2040, however, we observe similar levels of new capacity for nuclear even in the flexible plan. The flexible planning scenario has 17.8GW of installed nuclear capacity by 2040, and the forced nuclear scenario has 20.6GW.

It is important to note the difference in 2030 between these scenarios, both of which assume more favourable conditions for nuclear power. In the scenario where flexible planning is adopted (i.e. a plan that aims to minimise costs) significantly less nuclear capacity is built by 2030 than in the scenario where nuclear power is forced onto the system. By 2040, the large nuclear capacity being built is a result of the assumptions about higher electricity demand, limitations on new coal capacity, and the relative prices of different supply options (lower nuclear costs and higher renewable energy and gas). This replicates the findings in the *Toward a New Power Plan* (ERC, 2013) report that found that there was no urgent need for nuclear power in South Africa<sup>31</sup>.



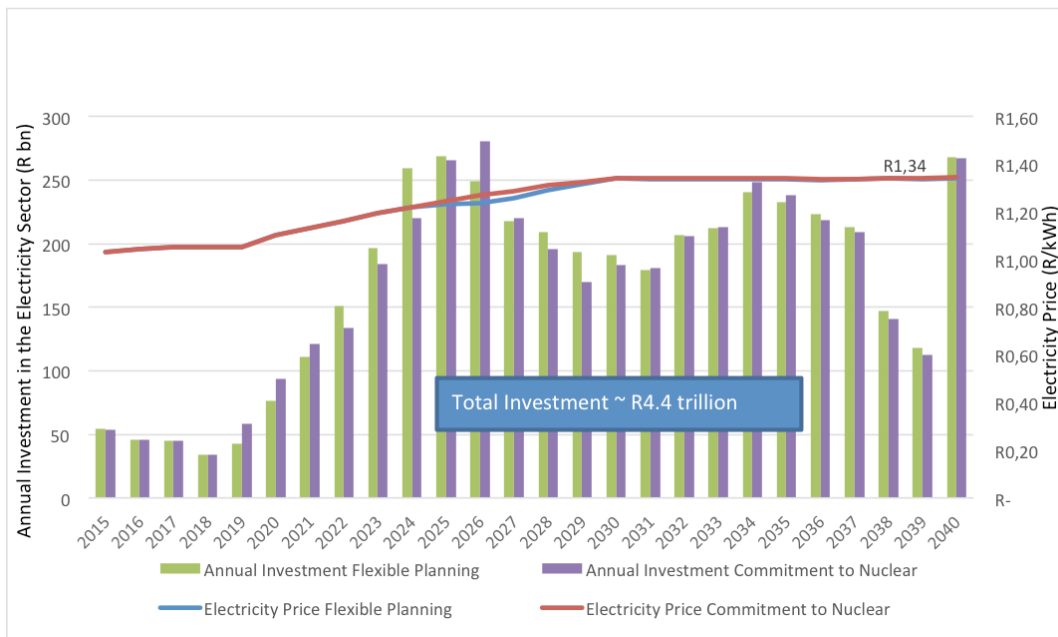
**Figure 10: Electricity sector installed capacity in 2010, 2030 and 2040 for Future 1**

<sup>30</sup> Future one has substantially higher installed capacity by 2040 than Future 2 does – this is in response to a higher demand forecast driven by an assumption of higher economic growth over the period 2015-2040.

<sup>31</sup> The NPP report found that even with low costs for the nuclear build programme and high electricity demand the earliest nuclear power might be required is 2029.

**5.1.1.2 Investment levels and electricity prices**

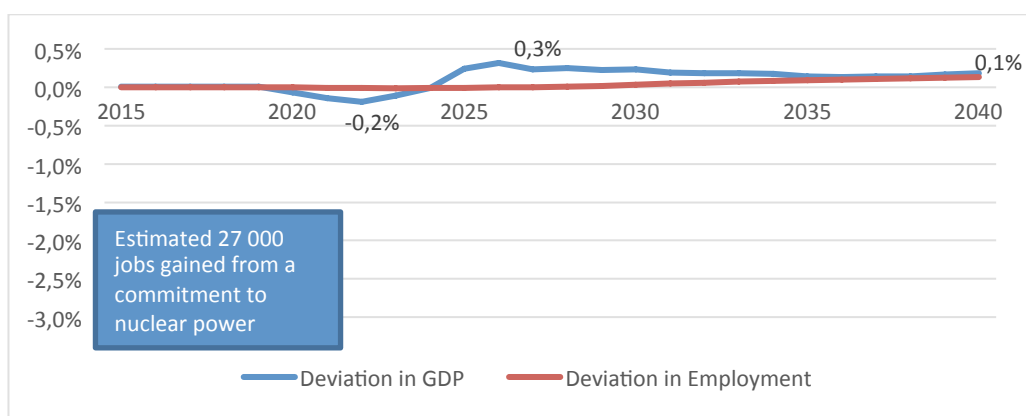
Figure 11 illustrates the annual investment required for a flexible plan versus the forced nuclear scenario, and the resultant electricity price increases. The high growth in electricity demand in Future 1 leads to new installed capacity of 25.2GW and 24.2GW (between 2015 and 2040) for the flexible planning approach and the committed nuclear build cases respectively. Given the low capital cost of nuclear assumed in Future 1, there is no significant difference between the total investment required by the electricity sector in either scenario. A total investment of approximately R4.4 trillion for the electricity sector from 2015 to 2040 is required for both the flexible scenario and the nuclear commitment. The lack of a significant difference in the cost of the electricity build plan translates into a similar electricity price path for both scenarios: R1.34 per kWh (2015 Rands) in 2040 as indicated by the horizontal lines in Figure 11 below.



**Figure 11: Comparison of investment and electricity price for committed nuclear versus flexible planning in Future 1**

**5.1.1.3 Growth and employment**

The deviation in GDP growth and employment between the committed nuclear scenario and a flexible plan is shown in Figure 12. There is a slight decrease in GDP between 2020 and 2024 and then a slight increase in GDP between 2024 and 2035 in the case of the committed nuclear fleet. The deviation has two main causes: firstly, the commitment to nuclear power would require construction of the plants between 2019 and 2030 (factoring in a 6 year lead time), leads to a reduction in the investment available to other sectors of the economy between these years. This has a small negative impact on GDP between 2020 and 2025, after which the nuclear power plants come online and there are returns on these investments. Secondly, there is also a marginal price impact as can be seen in Figure 11 and Figure 12 between 2024 and 2030 when sectors react to slightly higher electricity prices.



**Figure 12: Impact on GDP and employment of the nuclear commitment versus flexible planning approach in Future 1**

The result is an oversupply of affordable electricity, incentivising growth from 2025 onwards. It is essential to understand that this is not a technology specific outcome<sup>32</sup>, but rather the outcome of an overinvestment in electricity supply capacity in an economy with high enough GDP growth to absorb the excess electricity supply. This would not be the case with lower levels of GDP growth and the result would be a larger negative impact on GDP (see Figure 16 on GDP in the results for Future 2).

#### 5.1.1.4 Employment effects by labour category

With an estimated unemployment rate of 25% in South Africa, any potential negative impact on employment is a cause for concern. Table 4 shows total employment (disaggregated by educational attainment) and the potential impact on jobs of the commitment to nuclear power compared to the case where South Africa follows a flexible planning approach. In Future 1, because of the higher growth rate assumed, the effect on employment is marginally positive for all sectors and labour categories for both the flexible and forced nuclear cases.

	Number of employed workers (thousands)			Number of jobs created/(lost) with nuclear commitment	Number of jobs created/(lost) with nuclear commitment as a percentage of employed workers
	2010	Flexible policy in 2040	Nuclear commitment in 2040		
<b>LABOUR</b>	<b>12 369</b>	<b>20 813</b>	<b>20 840</b>	<b>27 298</b>	<b>0.1%</b>
<b>Unskilled labour</b>	<b>5 731</b>	<b>11 081</b>	<b>11 108</b>	<b>27 298</b>	<b>0.2%</b>
Primary	1 942	3 712	3 721	9 030	0.2%
Middle	3 789	7 368	7 387	18 269	0.2%
<b>Skilled labour</b>	<b>6 639</b>	<b>9 732</b>	<b>9 732</b>	-	-
Secondary	3 645	5 697	5 697	-	-
Tertiary	2 994	4 036	4 036	-	-
<b>Electricity sector</b>	<b>37</b>	<b>81</b>	<b>79</b>	<b>-1 460</b>	<b>-1.8%</b>

**Table 4: Employment effects of committed nuclear versus flexible planning in Future 1**

<sup>32</sup> Interestingly, when a similar capacity commitment was made with investment in solar CSP the socioeconomic implications were better than the case with forced nuclear.

### 5.1.1.5 Welfare

The potential impact of the scenarios on welfare in South Africa is also of concern, given South Africa's development imperatives. Households in South Africa are affected either directly through the price of electricity or indirectly through job losses and changing wage rates. The results have shown that by committing to the nuclear build plan, there is less investment available for other sectors, which leads to a slight contraction of the economy in the early 2020s. Some of the sectors that are the main 'losers' of investment are also employment intensive sectors, not only for unskilled, but also for semi-skilled and skilled workers. This is shown below in Figure 13 as household consumption<sup>33</sup> drops for both high and lower income earners before 2024.

In Future 1, once the electricity supply is available from 2023 onwards, there is a small positive impact on all households, (low, middle and high income) (Figure 13). This is an intuitive result because of the higher growth that is assumed in this case and the slight increase in employment caused by the higher growth.

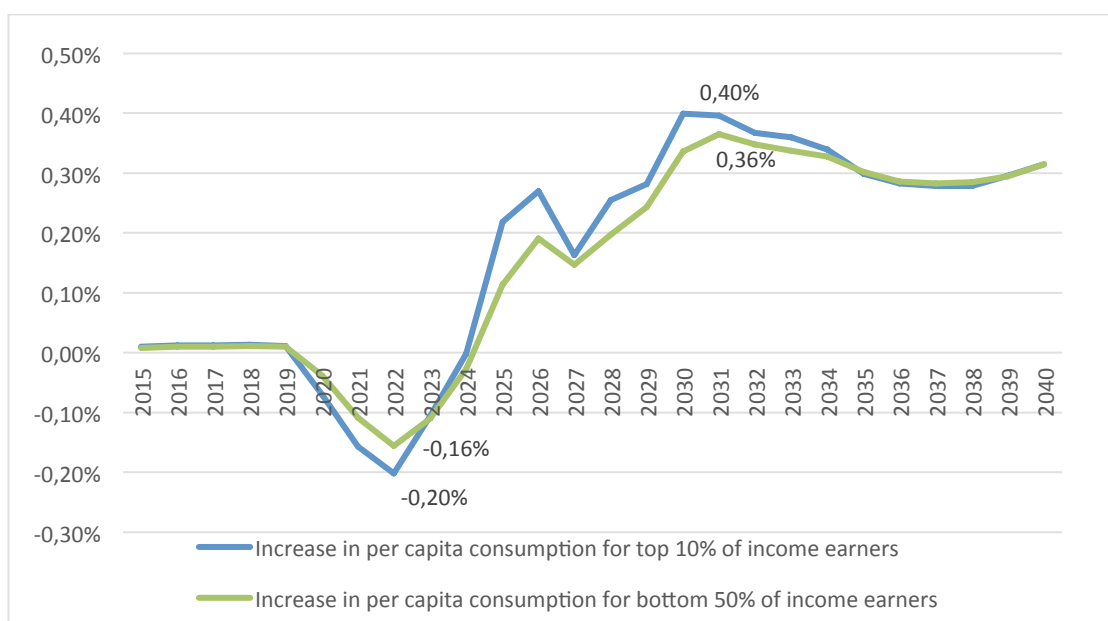


Figure 13: Impacts on household consumption of committed nuclear versus flexible scenario in Future 1

## 5.1.2 Future 2 results: Worst case for nuclear

### 5.1.2.1 Electricity build plan

In Future 2, the demand under the flexible planning scenario peaks in 2030 at 51 GW and grows to 61 GW in 2040, shown in Figure 14. In the scenario where there is a commitment to 9.6 GW of nuclear power, peak demand in 2030 is 50 GW and increases to 58 GW in 2040. The slightly lower demand in the forced nuclear scenario is in response to the higher electricity price in this scenario (see Figure 15 for the electricity price in Future 2). As a result of this price response, peak demand and installed capacity is slightly higher in the flexible planning scenario in both 2030 and 2040 versus the committed nuclear scenario.

<sup>33</sup> Consumption and income are used synonymously because the e-SAGE model is a neo-classical model with fixed savings rates, therefore any increase or decrease in consumption is equal to the increase or decrease in income. Income is used as a proxy for welfare, although there are wider implications on income inequality and poverty that are important and should be explored further.

In Future 2, we see no new nuclear by 2030 and the first committed unit is commissioned in 2031 (a result of an assumed lead time of 12 years). By 2040, we see no new nuclear when the flexible planning approach is adopted, with alternatives such as shale gas, concentrated solar thermal, PV, wind and imported hydro coming online as least cost generation options.

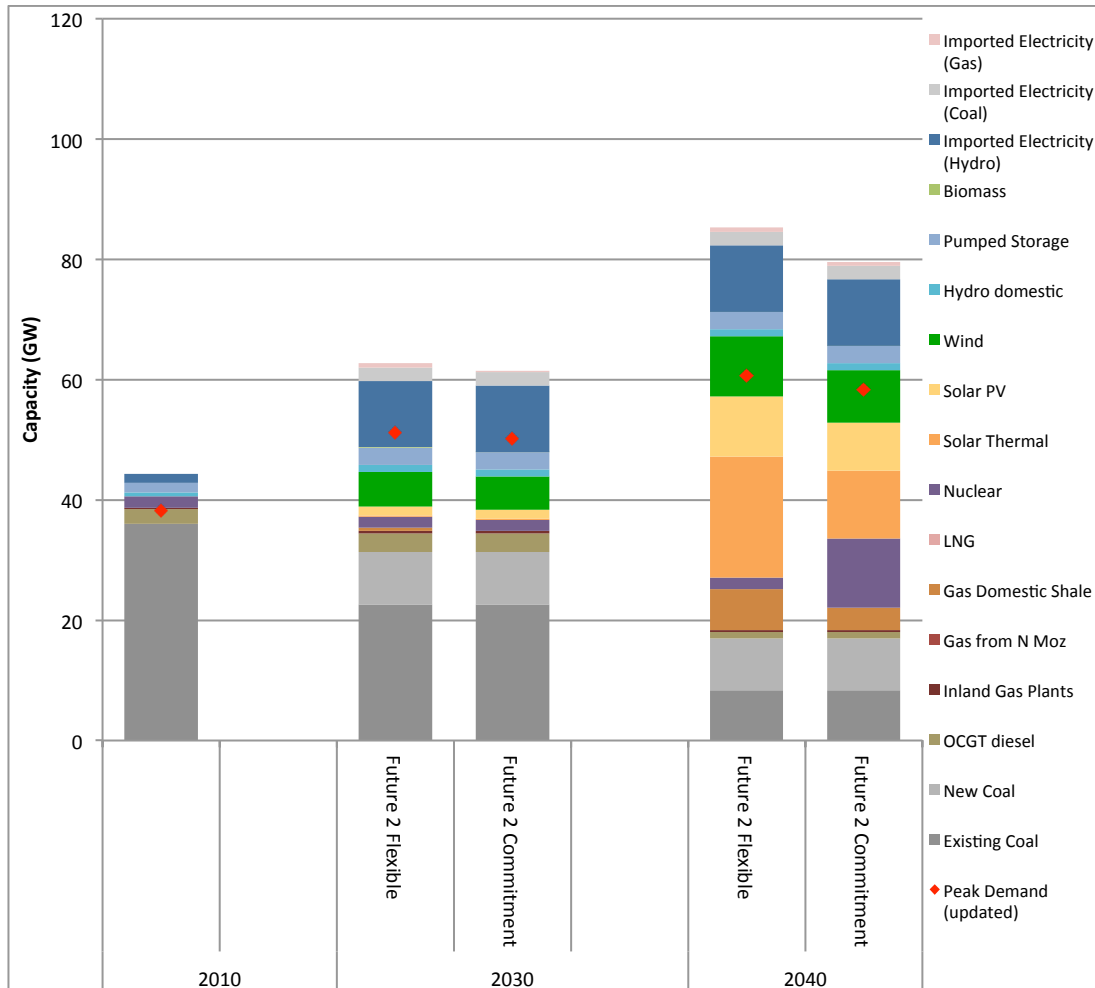


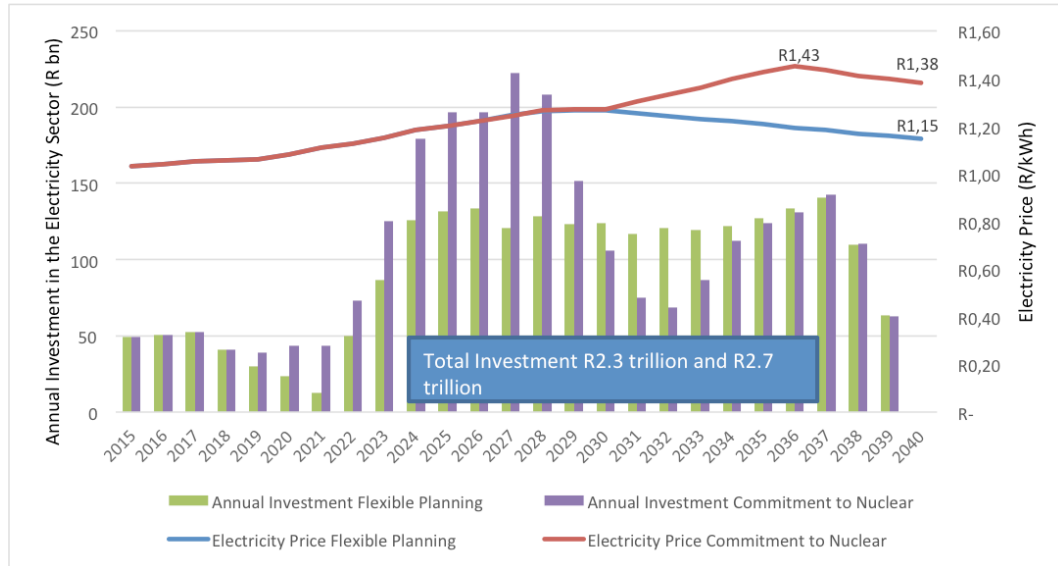
Figure 14: Electricity sector installed capacity in 2010, 2030 and 2040 for Future 2

5.1.2.2 Investment levels and electricity prices

In Future 2, the scenario with lower growth, the commitment to nuclear power produces a significantly higher electricity price than that of a flexible planning approach, which produces the lowest electricity system cost (shown in Figure 15). Despite a lower generation capacity requirement due to lower electricity demand in this scenario, the electricity price increases to R1.38 when nuclear power is forced into the build plan. Since the cost of nuclear is higher (\$7000/kW) this commitment leads to a significant price difference of 23 cents/kWh by 2040. Taken together with the longer lead times required, the nuclear build does not compare favourably with alternative options. Indeed, the commitment to nuclear results in investment costs of R0.4trillion more than the investment required under the flexible planning approach. To put this investment into perspective, in 2027 the additional investment requirement for nuclear power is R102 billion more than the already high investment requirement of R121 billion (when annual electricity investment peaks).

In Future 1, where more favourable conditions for nuclear power are assumed, there is no price difference between the commitment to the fleet and flexible planning. In contrast,

where demand is lower and prices are higher, as in Future 2, the difference in the electricity price would be substantial, with a sustained difference between 2030-2040, leading to 20% higher prices by 2040. Table 5 shows this in more detail with the absolute and percentage divergence in the electricity price under the committed nuclear scenario for Future 2.



**Figure 15: Comparison of investment and electricity price for committed nuclear versus flexible planning in Future 2**

	Electricity price with flexible planning approach (R 2015)	Electricity price with committed nuclear (R 2015)	% Increase in electricity price with the commitment to nuclear power
2030	1.27	1.27	0%
2031	1.26	1.30	4%
2032	1.24	1.33	7%
2033	1.23	1.36	11%
2034	1.22	1.40	14%
2035	1.21	1.43	18%
2036	1.19	1.45	22%
2037	1.18	1.44	21%
2038	1.17	1.41	21%
2039	1.16	1.40	20%
2040	1.15	1.38	20%

**Table 5: Comparison of electricity price divergence between committed nuclear and flexible planning in Future 2**

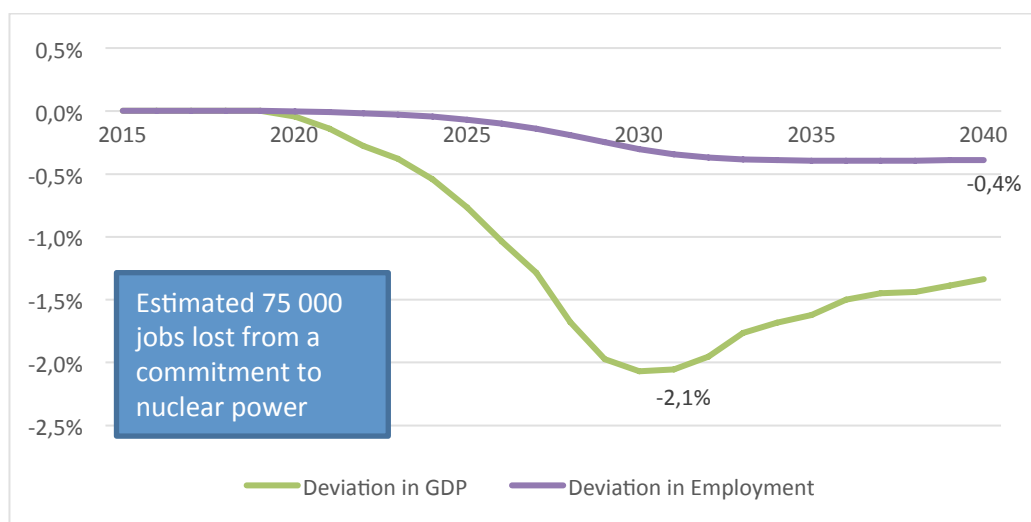
**5.1.2.3 Growth and employment**

The deviation in GDP and employment between the committed nuclear and the flexible planning scenario is substantial as shown in Figure 16. The large effect on GDP is caused by the demand for investment from the electricity sector causing a crowding out effect on

investment available for other sectors between 2020 and 2030. By assuming a lead time of 12 years, there is an investment requirement during the period of construction, so even though the first unit is only commissioned in 2031 the CAPEX payments are made for 12 years before this date. The full impact on the electricity price is reflected once each unit has been commissioned<sup>34</sup>.

Put simply, if South Africa follows a low growth path (average of 2.7% per annum to 2040), nuclear power is expensive and has a long lead time, whereas renewable energy is cheap and shale gas and hydro options are available and competitive. The impact of an increased electricity price has a sustained negative impact on GDP, peaking at 2.1% decrease in 2030 and easing slightly to an annual loss of approximately 1.3% per annum after the units are commissioned. Several sectors are unable to absorb the electricity price hikes and begin to contract due to decreased competitiveness. In this case, the sectors that are the biggest 'losers' are non-ferrous metals (-0.44% per annum), iron and steel (-0.21% per annum) and metals (-0.17% per annum) – all electricity intensive sectors. The electricity sector is also negatively affected (-0.48% per annum) as a result of decreased electricity demand.

The price impact as well as the impact of less available investment for other more profitable sectors has a significant negative impact on employment, with approximately 75 000 jobs lost if South Africa remains committed to an investment in nuclear power. The next section unpacks this result and provides more detail on labour market repercussions.



**Figure 16: Impact on GDP and employment of the nuclear commitment versus flexible planning approach in Future 2**

#### 5.1.2.4 *Employment effects by labour category*

Table 6 below shows the impact of the commitment to nuclear power against a flexible approach in Future 2. The employment effects on unskilled labour are significant. Since high-skilled workers are assumed to be fully employed and able to move between sectors

<sup>34</sup> It is unclear how the nuclear build plan will reflect on Eskom's RAB. If a turnkey model is used where Eskom is allowed to include the nuclear build plan as a capital works in progress (CWIP) as part of their Regulatory Asset Base (RAB), then consumers will bear the construction costs and risk of delays. The impact on the electricity tariff will happen much sooner than is the case in this analysis and is likely to have even more negative socioeconomic implications.

there is no decrease in employment, although the wage rates for skilled labour do decrease. The highest impact is felt on workers who have not completed Matric, with 50 000 jobs potentially at risk due to the slow GDP growth rate.

	Number of employed workers (thousands)			Number of jobs created/(lost) with nuclear commitment	Number of jobs created/(lost) with nuclear commitment as a percentage of employed workers
	2010	Flexible policy in 2040	Nuclear commitment in 2040		
<b>LABOUR</b>	<b>12 369</b>	<b>19 282</b>	<b>19 207</b>	<b>(74 663)</b>	<b>(0.4%)</b>
<b>Unskilled labour</b>	<b>5 731</b>	<b>9 549</b>	<b>9 475</b>	<b>(74 663)</b>	<b>(0.8%)</b>
Primary	1 942	3 204	3 180	(24 393)	(0.8%)
No matric	3 789	6 345	6 295	(50 270)	(0.8%)
<b>Skilled labour</b>	<b>6 639</b>	<b>9 732</b>	<b>9 732</b>	-	-
Secondary	3 645	5 697	5 697	-	-
Tertiary	2 994	4 036	4 036	-	-
<b>Electricity sector</b>	<b>37</b>	<b>66</b>	<b>59</b>	<b>(7 066)</b>	<b>(10.7%)</b>

**Table 6: Employment effects of committed nuclear versus flexible planning in 2040 for Future 2**

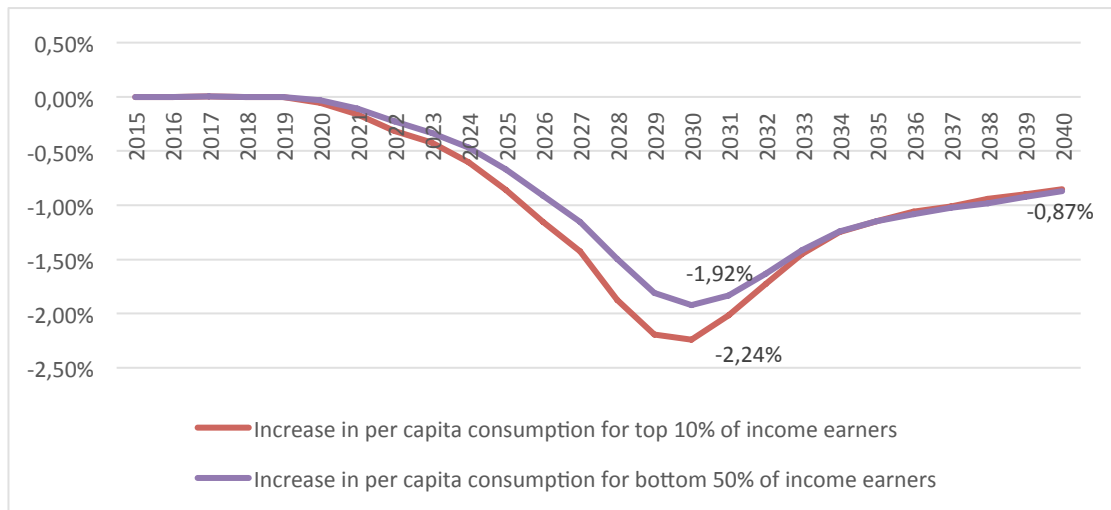
#### 5.1.2.5 Welfare

The combination of lower economic growth rates and a commitment to the nuclear fleet results in a significant increase in the electricity price which in turn results in the contraction of a number of key sectors in South Africa and decreases employment as discussed above. The net result is therefore a negative impact on welfare.

Household income is lower for households of all income levels. Figure 17 shows the impact on household consumption of the nuclear commitment scenario against the flexible planning approach. Consumption of the richest 10% of households falls by up to 2.24% against the consumption in the flexible scenario. Consumption for the poorest 50% of households falls by up to 1.92%.

In essence, a key message from this result is that all consumers are likely to be burdened by the commitment to nuclear power. If consumers are unable to substitute electricity for more affordable energy options, they are likely to have to spend more on electricity and will therefore be forced to forgo the consumption of other goods or decrease their rates of saving. This is of particular concern for low income earners. Although the percentage impact is smaller than for wealthier consumers, poorer households already spend a significant portion of their income on basic energy services, and forgoing other consumption will have serious impacts on their overall welfare.



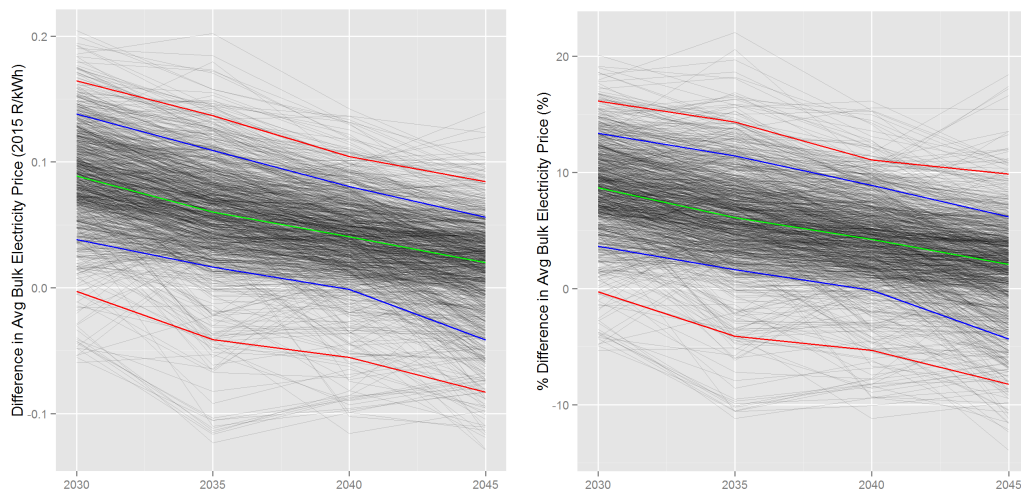


**Figure 17: Impacts on household consumption of committed nuclear versus flexible scenario in Future 2**

## 5.2 Quantifying the risks of a higher electricity price using Monte Carlo Analysis

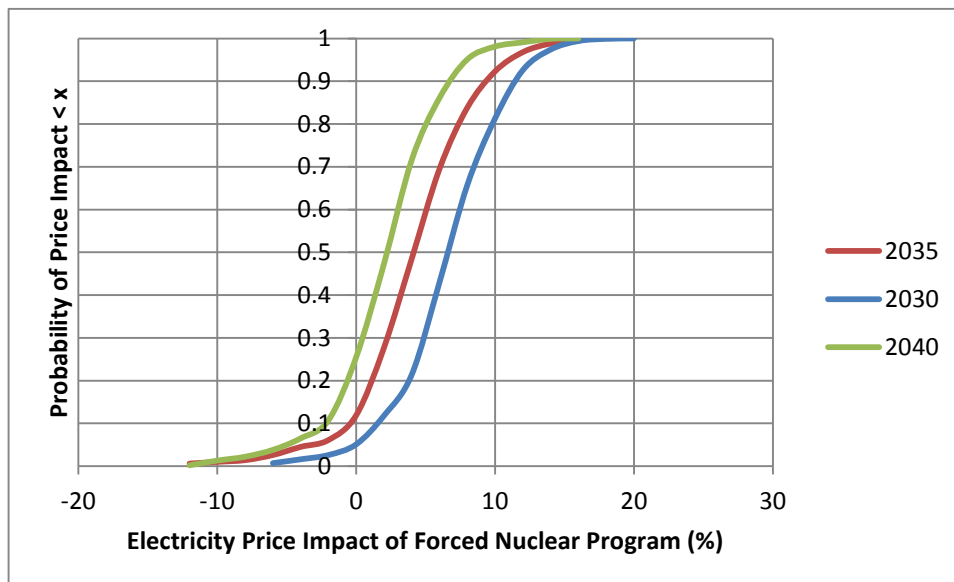
As stated above, the actual future is likely to fall somewhere in between the two extreme, illustrative futures considered above. In this third tier of analysis we move away from these illustrative futures and use a Monte Carlo simulation to model a thousand different ‘futures’ or scenarios, each with an internally consistent set of assumptions from a distribution for each of the uncertain parameters. To relate back to the potential socioeconomic implications explained in the previous section, Future 1 would be closer to the lower bound of the price differences and Future 2 closer to the upper bound shown in Figure 18. Each line represents a possible ‘future’; too many to detail individually. The Monte Carlo simulations enable the estimation of the probability of a future closer to that of Future 1 or Future 2.

The 1000 different combinations are tested with and without the forced nuclear build plan. In each case the electricity price is compared over the modelling horizon. Figure 18 shows the difference in electricity price for all 1000 scenarios in absolute (R/kWh) and in percentage terms. The “green” line shows the median line, starting off at around 10c/kWh in 2030 (10%) and dropping over time as the “committed build” gets absorbed in the system. The blue lines show the 80% confidence interval, which stays above the zero line until 2040. The red line shows the 95% confidence interval.



**Figure 18: Difference in Electricity price between “forced” and “free” in absolute and percentage terms**

The cumulative distribution plots for the difference in percentage terms for 2030, 2035 and 2040 are shown in Figure 19. The x-axis shows the percentage change in electricity price when South Africa is committed to the full fleet of nuclear power. The y-axis shows the probability of the price impact being less than the corresponding x-axis value. Consistent with the charts in Figure 18, the electricity price difference drops over time, however, with a significant risk of sustained higher electricity prices, which would have adverse effects on the economy along the lines of those explained in the results for Future 2, although by varying degrees depending on the magnitude of the electricity price increase.



**Figure 19: Cumulative probability distribution for the price impact of the nuclear program**

Figure 19 shows that in 2030 there is approximately a 94% chance of the electricity tariff being higher with the committed build. In addition there is a 20% chance of the tariff arising from the commitment to nuclear power being 10% greater than that from a flexible planning approach.

The two extreme cases analysed in the previous section fall within the range of results shown here. In the economic analysis of the two extreme cases, the impact of higher electricity prices and the opportunity cost of the capital allocation of the nuclear program

on the economy has been quantified. Monte Carlo simulations using the linked model would have been preferable, but not possible within the time frame and budget available for this project. However, by combining the knowledge gained in the first part of the analysis and the distribution for the electricity price obtained here, one can infer fairly robustly that the risks of a negative impact on the economy of the large commitment being contemplated are very high indeed.

## 6. Discussion

This study was limited to a technical analysis of the risks and potential implications of a commitment to 9.6 GW of nuclear power by 2030. There are a number of interesting and important areas for future work, however, and these areas are briefly outlined after this discussion of the key findings from this study.

If economic growth is high and the costs of nuclear are low, then the negative impact of building nuclear versus other capacity is negligible. In this future, higher demand requires higher installed capacity, and if we are optimistic about nuclear and pessimistic about alternatives, then committing to nuclear power will not impact on the electricity price or investment required compared to a flexible approach (since the capacity will be required and the forced nuclear is relatively cheap). In addition, if this future were to transpire, an overinvestment in electricity capacity before 2030 could lead to favourable outcomes for the economy and facilitate higher growth in later years. When there is higher growth there are marginal positive benefits from the commitment to nuclear power, although these effects are driven directly by the supply of affordable electricity and not by the decision to invest in nuclear power explicitly. In this case, job creation and incomes are driven by higher GDP growth and not directly by the investment in nuclear power.

If South Africa follows a path of lower economic growth, and nuclear costs are high while cheaper alternatives exist, a commitment to a fleet of nuclear power plants will have negative socioeconomic implications. Electricity prices will be higher over the period 2030-2040 and could be 20% higher in 2040 when compared to a flexible planning approach; similarly, there will be negative effects on key sectors as well as on GDP. The investment required for electricity generation infrastructure will be significant, crowding out investment in other sectors and increasing the electricity price. This could lead to a significant number of jobs at risk as the economy contracts in response to higher electricity prices. Given high levels of unemployment amongst unskilled workers and the potential negative impacts on relatively employment intensive industries, unskilled workers are most likely to face the worst impacts of growing unemployment. In turn, household consumption will drop for all consumer groups, with potentially serious ramifications on welfare of all.

The results discussed above are for two illustrative futures, when in reality an infinite number of futures could unfold. The Monte Carlo analysis was used to analyse 1000 of these futures combining different assumptions for the uncertain parameters, drawing from probability distributions for each one of them. This probabilistic approach was used to gain an understanding of the risks associated with committing to 9.6 GW of nuclear by 2030, by comparing in each of the 1000 scenarios the electricity price trajectory when a more flexible approach is taken. The results show that in 2030 there is a 94% chance that electricity prices will be higher if South Africa commits to a full fleet of nuclear instead of adopting a flexible planning approach. They also show that the risks of sustained higher electricity prices are very high. A commitment to 9.6 GW before 2030, when demand is low and more affordable alternatives exist would therefore not be prudent. The investment could have significant socioeconomic implications and the lock-in associated with the investment will result in South Africa foregoing investment in other small scale and more cost effective electricity generation technology options.

However, this does not mean that nuclear power should be completely discarded as an option for South Africa in the longer term, as it may indeed play a role in the SA power system under certain circumstances, some which may not have been considered by the

analysis<sup>35</sup>. Given uncertainty it is preferable to keep all options open, but there is no rush in terms of making this decision, and there is no justification for making a commitment of this scale at this time. These findings are consistent with the New Power Plan (ERC, 2015)

Key areas for future research:

This study is a first pass at a significant piece of work and a number of key areas for future research have been identified.

Macroeconomic, aggregate models such as e-SAGE capture linkages and interactions between all agents and markets in the economy. There are however a number of microeconomic (community and provincial level) impacts that are not adequately captured in these types of models. The impact of localisation, direct job creation at the community level (for instance the potential socioeconomic and environmental impact of a nuclear plant constructed in Thyspunt) should be analysed as the localisation component could be tailored to develop areas such as these. There is potential for skills development at a more micro-level, however an analysis of the potential is heavily reliant on the full disclosure of the localisation plan by the government.

The specifics of how South Africa will finance an investment is another topic that needs to be explored. The high capital cost and risks associated with nuclear power mean that it is likely that government will have to guarantee the build plan, which would put huge pressure on an already constrained fiscus. The lock-in of investing in the full fleet under this funding model will result in South Africa forgoing investment in other electricity generation technologies as well as investment in other sectors of the economy. Our results show that this could have significant negative impacts on the economy and if the procurement should go ahead, a comprehensive financing plan would need to be in place to mitigate these impacts. An alternative could be the procurement of nuclear power under a build, own and operate (BOO) model, which could mitigate some of the risk to the consumer, but it is unclear whether any of the nuclear vendors would be able to supply finance.

An important next step is to run these scenarios through a dispatch model to ensure that there is no threat to the security of supply. However, given that there is evidence that CSP could be capable of providing a stable baseload supply in South Africa, it is unlikely that there would be any threat to security of supply in the least cost scenarios (Pfenninger & Keirstead, 2015).

Lastly, the findings in this report have important implications for the political economy of South Africa, especially for sectors and consumers that are most vulnerable to electricity price increases. While in the modeling framework, the adjustment to a new equilibrium happens without any cost, it is likely that in the real world these sectors will lobby and exert pressure on the government. The impacts of this, along with other elements of the political economy of nuclear power, warrant a separate study and could be an interesting piece of future work.

---

<sup>35</sup> It is not possible to describe all the future uncertainty using probability distributions.

## 7. Conclusion

In conclusion, the results of this study show that the commitment to a large and inflexible nuclear build plan will result in higher electricity prices and furthermore that the socioeconomic impacts of this could be significant.

There is a small chance that a future with low costs for nuclear, high costs for renewable energy, no gas or hydro import alternatives and high electricity demand could arise, but even under these conditions the socioeconomic implications of an investment in nuclear power are similar to that of alternative electricity investment paths. In this future there would be no significant difference between the electricity price from a flexible planning approach or from a commitment to the full nuclear fleet.

It is more likely that the future that will arise is one in which these favourable conditions do not materialize and that the electricity price will be higher with the commitment to nuclear power than they would be were a flexible planning approach adopted instead. In this case the socioeconomic implications would look more like those shown in the illustrative future two scenario. With sustained increases in the electricity prices, economic growth will decrease, jobs are at stake and household welfare could decrease across all income classes.

This study goes further and quantifies the risk of a future with negative socioeconomic implications from the commitment to nuclear power similar to that of future 2 unfolding. We find that there is a 94% chance that electricity prices will be higher in 2030 with the commitment to nuclear power. In addition there is 20% chance of the tariff arising from the commitment to nuclear power being 10% greater than that from a flexible planning approach. From this we can infer, fairly robustly, that the risks of a negative impact on the economy of such a large scale are high.

However, if South Africa's economic growth does pick up in the coming years, then an overinvestment in electricity capacity could lead to more favourable outcomes for the economy in the future, as consumers will be able to take advantage of the over-supply of electricity in later years. This is not driven directly from an investment in nuclear power, however, but is essentially based on the availability of affordable electricity.

There is a balance that must be found between investing in electricity generation capacity and investing in other key areas of the economy. This study clearly shows the trade offs of investment and the potential crowding out effects that could transpire with an overinvestment in the electricity sector, especially in instances of lower growth.

Finally the electricity build plan must reflect and balance the expected electricity demand, consider least-cost alternatives and ensure the provision of affordable electricity to consumers.. Therefore given the risks inherent in long-term electricity planning, government must, if it chooses to procure nuclear power, do so in a way that minimizes the likely risks and negative effects on the economy and consumers in South Africa. Our results show that there is no economic case to be made for a firm commitment to commissioning a full fleet of 9.6GW of nuclear power by 2030. The findings of this study show that in all futures a flexible planning approach is preferred.

## 8. References

- Altieri, K., Trollip, H., Caetano, T., Hughes, A. Merven, B., and Winkler, H. 2015. Pathways to deep decarbonisation, DDPP Country Report: South Africa. Energy Research Centre (ERC).
- Alton, T., Arndt, C., Davies, R., Hartley, F., Makrelov, K., Thurlow, J., Ubogu, D. 2014. Introducing carbon taxes in South Africa, *Applied Energy*, 116(1), 344-354.
- Arndt, C., Davies, R., & Thurlow, J. 2011. *Energy Extension to the South Africa General Equilibrium (SAGE) Model*. United Nations University's World Institute for Development Economics Research (UNU-WIDER).
- Black & Veach 2012. Cost and performance data for power generation technologies. Prepared for the National Renewable Energy Laboratory February 2012.
- Energy Research Centre (ERC). 2013. Toward a New Power Plan. Report prepared for the National Planning Commission, April. Available [http://www.erc.uct.ac.za/Research/publications/13ERC-Towards\\_new\\_power\\_plan.pdf](http://www.erc.uct.ac.za/Research/publications/13ERC-Towards_new_power_plan.pdf)
- Flyvbjerg, B., Bruzelius, N., Rothengatter, W. 2003. *Megaprojects and Risk: An Anatomy of Ambition*. Cambridge University Press, Cambridge.
- International Atomic Energy Agency (IAEA). 2013. Status Report 108 - VVER-1200 (V-491) (VVER-1200 (V-491)). Available: <http://www.iaea.org/NuclearPower/Downloadable/aris/2013/36.VVER-1200%28V-491%29.pdf>
- International Atomic Energy Agency (IAEA). 2015. Power Reactor Information System (PRIS): Reactors Database. International Atomic Energy Agency.
- International Energy Association (IEA). 2014. *Energy Technology Perspectives 2014: Harnessing Electricity's Potential*. Paris, France.
- International Energy Association (IEA). 2015. *Energy Technology Perspectives 2015: Mobilising Innovation to Accelerate Climate Action*. Paris, France.
- Mantshantsha, S. Business Day. 2015. NEWS ANALYSIS: Rosatom cagey about cost of nuclear power stations in SA. *BDlive*, 19 October 2015. Available: <http://www.bdlive.co.za/business/energy/2015/10/19/news-analysis-rosatom-cagey-about-cost-of-nuclear-power-stations-in-sa>
- Merven, B. & Durbach, I. 2015. Obtaining long-term forecasts of the key drivers of greenhouse gas emissions in South Africa" Energy Research Centre. University of Cape Town. September 2015.

- Nell, K. 2003. *Long-run Exogeneity Between Saving and Investment: Evidence from South Africa*. Johannesburg, South Africa: Working Paper 2 - 2003, Trade and Industrial Policy Strategies.
- Oanda. 2015. *Historical exchange rates monthly averages January-September 2015*. Available: <http://www.oanda.com/currency/historical-rates/>
- Pfenninger, S. & Keirstead, J. 2015. Comparing concentrating solar and nuclear power as baseload providers using the example of South Africa. *Energy*, 87, pp. 303-314. Available: <https://dx.doi.org/10.1016/j.energy.2015.04.077>
- Republic of South Africa. Department of Minerals and Energy (DME). 2007. *Energy Security Master Plan - Electricity 2007-2025*. Pretoria.
- Republic of South Africa. 2008. National Energy Act, No. 34 of 2008. Pretoria: Government printer.
- Republic of South Africa. Department of Energy (DoE). 2011. Integrated Resource Plan for Electricity (IRP), 2010-2030. *Government Gazette* No. 34263 6 May 2011. Pretoria. Available: <https://www.energy.gov.za>.
- Republic of South Africa. Department of Energy (DoE). 2013. Integrated Resource Plan for Electricity (IRP) 2010-2030 Update. Pretoria. Available: [http://www.doe-irp.co.za/content/IRP2010\\_updatea.pdf](http://www.doe-irp.co.za/content/IRP2010_updatea.pdf)
- Republic of South Africa. National Planning Commission (NPC). 2013. National Development Plan 2030: Our future – make it work. [https://nationalplanningcommission.files.wordpress.com/2015/02/ndp-2030-our-future-make-it-work\\_0.pdf](https://nationalplanningcommission.files.wordpress.com/2015/02/ndp-2030-our-future-make-it-work_0.pdf), accessed December 2015.
- Russian News Agency (TASS). 2014. *Rosatom to supply 8 nuclear power units to South Africa*. 22 September 2014. Available: <http://tass.ru/en/economy/750722>
- SNEL, AECOM and EDF. 2011. *Etude de Développement du site Hydroélectrique d'Inga et des Interconnexions électriques associées [Study of the Development of Hydroelectric Sites of Grand Inga and Associated Electrical Sites]*. Kinshasa, Democratic Republic of Congo: Société Nationale d'Electricité, AECOM and Electricité de France.
- Steyn, G. 2001. *Governance, finance and Investment: decision-making and risk in the electric power sector*. DPhil Dissertation, University of Sussex.
- Thomas, S. 2010. *The economics of nuclear power: An update*. Heinrich Boell Stiftung, Berlin. [http://www.boell.de/downloads/ecology/Thomas\\_economics.pdf](http://www.boell.de/downloads/ecology/Thomas_economics.pdf)

Thurlow, J. 2004. *A Dynamic Computable General Equilibrium (CGE) Model for South Africa: Extending the Static IFPRI Model*. Pretoria: Trade and Industrial Policy Strategies (TIPS).

Thurlow, J. 2008. *A recursive dynamic CGE model and microsimulation poverty module for South Africa*. Washington, D.C.: International Food Policy Research Institute.

World Nuclear Association (WNA). 2014. *South Africa reports reactor vendor progress*. World Nuclear News. 17 December 2014. Available: <http://www.world-nuclear-news.org/NN-South-Africa-reports-reactor-vendor-progress-17121401.html>.