A Computable General Equilibrium Analysis of the proposed build plans as presented in the Integrated Resource Plan

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I hereby declare that this dissertation is my own work. I understand what plagiarism is, and where I have used the ideas of others, I have referenced these correctly.

Signed: _________________

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ABSTRACT

Global concerns with regard to electricity supply ranged from growing demand, especially in developing countries, energy security, diversity of supply, safety and the global movement towards low-carbon technologies. The Integrated Resource Plan (IRP) is an operational process by which these concerns as well as other policy goals are addressed. This is done with the aim of providing a long-term plan for the electricity sector. The current modelling approach used in the IRP is unable to quantify the effects on various policy goals that the plan is likely to have. This thesis uses a CGE model to analyse the plan in terms of some of these policy goals in an attempt to fill this analytical gap. The base case, revised balanced and policy-adjusted scenarios are simulated in the E-SAGE model developed by Arndt et al. (2008). The model has a top-down structure but employs bottom-up energy information to estimate most of its energy parameters. This approach provides a partial reconciliation of top-down and bottom-up methods, which proves to be very useful for policy analysis. There is an indication from the results that current GDP and demand assumptions in the IRP will lead to over-investment in the electricity sector. Results also indicate that a movement away from coal in the electricity sector will not devastate the mining sector or the economy as a whole. These results suggest that economic growth in the policy-adjusted scenario will remain in line with the AsgiSA goal of between 3% and 6%, marginally less than the base case. All three scenarios from the IRP were found to have a positive impact on employment with the base case producing the highest employment rate. This thesis concluded that the interaction between the energy model and an economy-wide model is useful for policy makers as it allows broader criteria for the decision-making process of the IRP.

“In policy analysis, there is a gap between the realm of pure theory, trade and growth theory in particular, and the real world that faces the policy maker and planner. When it comes to policy debate and policy formulation, more is needed than the qualitative insights that pure theory can yield. Although theoretical reasoning and the insights gained from simplified abstract models must provide the starting point, more elaborate and "realistic" analysis is also required. Intelligent policy debate and policy formulation requires knowledge of the quantitative significance of the various mechanisms analyzed by theory. Furthermore, indirect effects of policies may escape intuition and thus the attention of theorists, whereas empirical modelling can reveal their presence and importance. Finally, sensitivity tests are needed to clarify the role of key behavioural assumptions or important parameter values. Models simple enough for analytic solution can seldom provide the framework for such analysis. Empirical general equilibrium models that can be solved numerically are thus useful to provide a bridge between the theorist, the planner, and the practical policy maker. Theorists will be able to recognize in their specification the fundamental structure of simpler theoretical models and will be able to relate the functioning of the applied models to known theorems and analytical results. Policy makers, on the other hand, will be able to recognize in the questions addressed by the models some of the real-world policy dilemmas they face.”

Dervis, de Melo, & Robinson (1982)

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INTRODUCTION

Global concerns with regard to electricity supply ranged from growing demand, especially in developing countries, energy security, diversity of supply, safety and the global movement towards low-carbon technologies. The Integrated Resource Plan (IRP) was drafted and remains a ‘living plan’, with the main objective of estimating long-term electricity demand and providing an outline for how this demand will be met in terms of generating capacity type, timing and cost. The IRP is an operational process used to produce a plan that should address a number of policy goals. These policy goals include energy security, climate change, economic development, economic growth and decreased unemployment. The bottom-up approach to modelling is currently used in the IRP, however this approach alone is unable to analyse the plan’s ability to address a number of the aforementioned policy goals. Hence, the main motivation for this thesis is addressing this analytical gap which exists in the planning process of the IRP.

The focus of this thesis can be divided into two main parts. Firstly, it aims to motivate and explain the need for this form of economy-wide analysis to be done as part of the planning process, and how the decision-making process will be strengthened with this analysis. Secondly, it aims to present the results of an economy-wide analysis of these scenarios as well as to assess the plan in terms of a number of the IRP’s policy goals.

The first section of this thesis offers a background to the policy-modelling debate. This is an important starting point as it provides an explanation as to what a policy is, what modelling is, and how the gap between these two paradigms can be bridged. This is followed by an examination of the dichotomy which exists in energy modelling approaches. This is then followed by an examination of the integration of these two approaches. The third section is an overview of the first approach to modelling found in the IRP in terms of governance, objectives and scope of the plan and the proposed scenarios. An explanation of the data sources and assumptions used in the modelling is also presented as these are synonymous to that used in the economy-wide modelling which follows. The fourth section presents a comprehensive overview of the standard and dynamic versions of the South African General Equilibrium (SAGE) model developed by James Thurlow et al. (2004). This is followed by a description of Arndt et al.’s (2011) latest energy extension to the SAGE model which is used in the analysis for this thesis. Next is a discussion of the data sources, assumptions, model calibration, parameter initialisation and simulation calibration used in this model. Section five outlines the results from the various IRP scenarios analysed in the model. This thesis will conclude by putting forward the main findings formulated from the results of the economy-wide model as well as an assessment of the plan in terms of a number of the IRP’s policy goals.

A policy in its simplest terms is defined as a 'course of action adopted or proposed by a political party'. It defines a "form of intention, norm or 'decision-rule' a higher level principle" which encompasses the "complex interaction of different decision processes in multiple (and often competing) state agencies" (Marquard, 2006). Policies are governed by an iterative process as they are modified and evolve according to changes in the goals of state agencies and ultimately the goals of the state (Marquard, 2006). Hence, it is important to note that a policy should be viewed, not as an exact moment of decision-making, but rather as a continuously evolving output of a system driven by 'dominant policy paradigms' (Tyler, 2010). Policies are generally portrayed in the form of written policy documents, (i.e. white papers and regulation), statements made by policy makers, strategic documents and actualised policy, amongst others (Tyler, 2010). For the purpose of this thesis, the main policy paper used is the Integrated Resource Plan (IRP) for electricity in South Africa. The purpose of which is to provide a "long-term electricity capacity plan which defines the need for new generation and transmission capacity for the country" (DoE, 2009). A number of stakeholders are involved in the planning process of the IRP and therefore the plan outlines the culmination of a number of strategic and policy objectives. These include: (1) security of supply for electricity; (2) the consideration of potential environmental impacts; (3) cost and feasibility considerations and; (4) climate change commitments. A more detailed discussion on the IRP is provided further on in this thesis. A crucial step in this form of analysis is finding a coherent method by which to bridge the gap between policy and modelling. In the words of Chappin and Dijakema (2010, p. 107):

> *"A policy is a transition instrument if policy makers implement it to cause structural change; in other words, if it is intended to invoke a transition. The policy is effective when it indeed initiates a transition and leads to some optimal end state while additional requirements for the transition path often exist."*

Models provide a tool for researchers as well as policy analysts to quantify the potential and realised transitional effects of policies. In the case of CGE models, for the past five decades their use has enlightened numerous policy debates (Devarajan & Robinson, 2002, p. 1). In some instances critics argue against the use of CGE modelling in policy debate due to the misuse of this form of modelling. Devarajan et. al (2002) highlights a few reasons for this: "(i) pushing the model beyond its domain of applicability; (ii) violating the principle of Occam's razor – i.e., use the simplest model suited to the task; (iii) the black box syndrome – results whose link with the policy change is opaque." In light of this, it is important for modellers to hedge against these risks that could potentially lead to insignificant results and the misuse of CGE models. The 'black-box syndrome' poses a general concern with most models, especially CGE models, due to their perceived complexity. To ensure that this is not a concern in this thesis an in-depth explanation of the linkages, assumptions and data in the model is provided. In order to ensure the model's suitability for policy analysis there are a number of features that should be present in the model. As highlighted by Devarajan, et al. (2002, p. 2) these features include policy relevance, transparency, timeliness, validation and estimation, as well as a diversity of approaches. Firstly, in terms of policy relevance, there should be a clear link between the policy influence on the model and the usefulness of the economic outcomes to policy makers (Devarajan & Robinson, 2002, p. 2). Secondly, these links should be clear and easy to trace, in other words there should be an appropriate level of transparency in the model (Devarajan &

Robinson, 2002, p. 2). Thirdly, the data used in the model should be relevant and up to date if it is to be suitable for an ongoing policy debate (Devarajan & Robinson, 2002, p. 2). Fourthly, the model should be found to provide accurate results for the realm of policy decisions that exist in the policy debate, in other words there should be a level of validation in the results and the reasons for the assumptions used in the model should be evident (Devarajan & Robinson, 2002, p. 2). Lastly, the validity of the results of a model is greatly enhanced when a number of diverse models are used that produce the same result (Devarajan & Robinson, 2002, p. 2). Although with time constraints as well as cost implications, the use of a variety of models in the assessment of policy issues is sometimes not an option for policy analysts. These preceding aspects have been taken into account in this thesis to ensure the models suitability for policy analysis.

An important consideration when using modelling as a tool for policy analysis is identifying the optimal method of construction and use of the CGE model for the policy impact analysis in question. Bohringer, et al. (2006) identify a number of central steps that are involved in attaining this optimal method. The following diagram illustrates these steps:

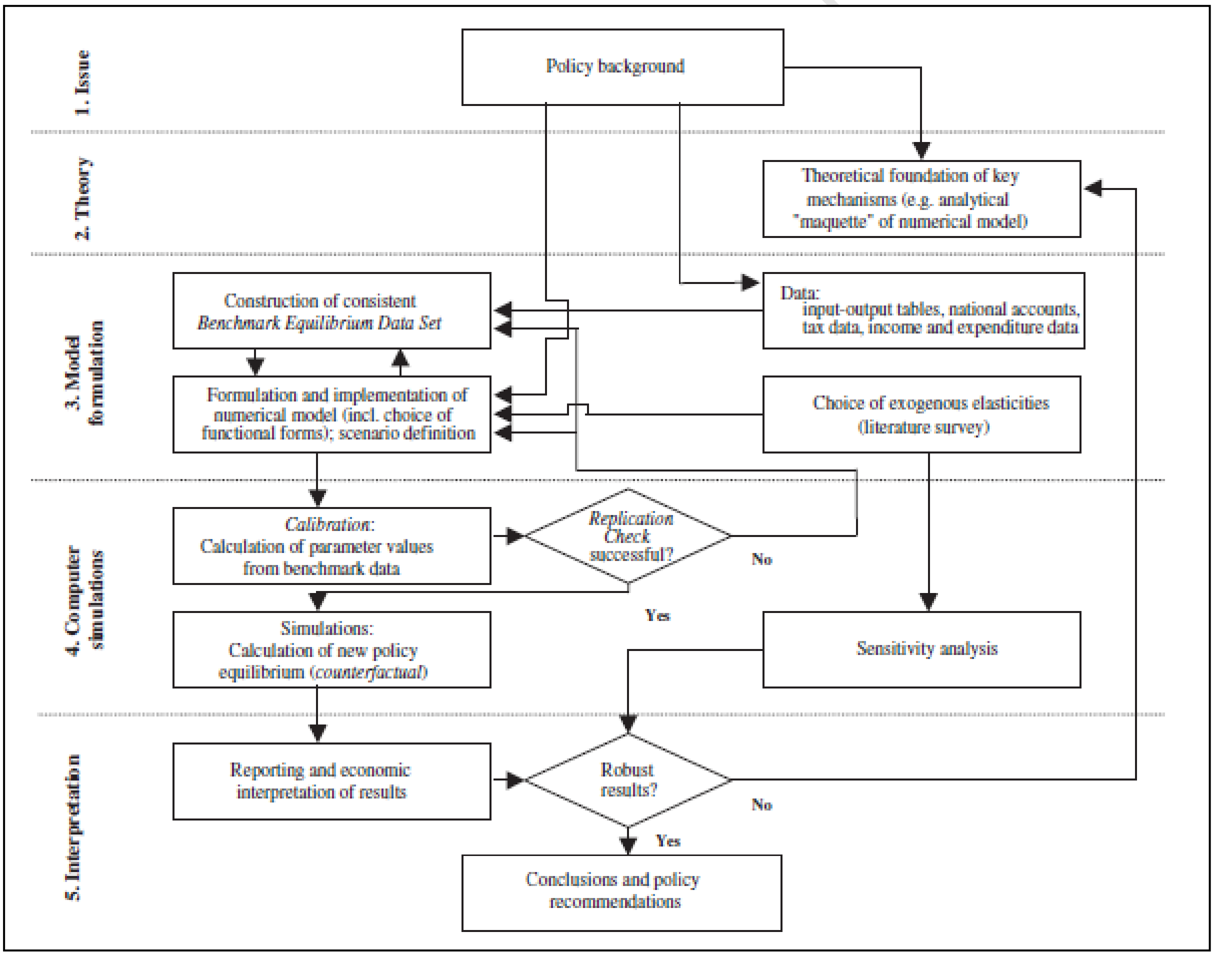

Figure 1: Steps in CGE modelling (Bohringer & Loschel, 2006)

The first step involves an assessment of the policy issue at hand in order to decide on an appropriate model design as well as identifying the data that will be required for modelling purposes (Bohringer & Loschel, 2006). The second step entails a consideration of economic theory. This is a crucial aspect as the economic theory used depicts the 'key economic mechanisms' that will drive the results in the model (Bohringer & Loschel, 2006). It is therefore important that these theoretical assumptions represent sound economic thought. The next step involves the model formulation in terms of the data input and the construction of the benchmark equilibrium which provides the numerical framework for the policy analysis (Bohringer & Loschel, 2006). Following the completion of this step, it is then possible to input simulations into the model which represent the consideration of potential paths that follow a change in policy (Bohringer & Loschel, 2006). The objective of which is to allow a comparison between the results of the model with and without the policy change and therefore to identify the potential impacts of the policy change. The inclusion of a sensitivity analysis is important to ensure the robustness of the model results. This type of analysis allows recognition of the impact that a change in the assumptions and key inputs would have on the model. The final and possibly most challenging step is then to provide conclusions and policy recommendations. The structure of this thesis follows the preceding outline identified by Bohringer, et al. (2006) to ensure a coherent and rational flow for the policy analysis.

ENERGY POLICY MODELLING APPROACH

The preceding section highlighted some of the complexities that surround the policy and modelling debate. Policy and planning decisions are often difficult owing to various uncertainties and generally a fair number of stakeholders involved. Decision making within the energy sector is no exception. The substantial cost of energy technologies, long-term impacts of investment decisions as well as the long lifespan of most energy technologies highlight the needs for long planning horizons and an assessment of the inter-linkages that exist between the energy sector, the economy and the environment (Pandey, 2002). Furthermore, within the energy sub-sector of electricity, the focus of this thesis, complexities regarding operational planning, distribution and pricing exist and influence decision making in the short and medium term (Pandey, 2002). Pandey (2002) expands and identifies how energy policy modellers are faced with these as well as other unique challenges in the context of developing countries. Developing countries, such as South Africa, generally lack the funding, institutions and stability that exists in developed countries. As a result, literature tends to be less abundant within the former – as is the case with literature concerning top-down and bottom-up energy models (Pandey, 2002). Top-down and bottom-up models represent the two broad approaches that are available in terms of modelling the linkages that exist between energy systems, the economy and environmental factors (van der Zwaan, Gerlagh, Klaassen, & Schrattenholzer, 2002). The energy policy modelling approach used in this thesis can be described as the use of bottom-up information for the electricity sector in a top-down economic model. In light of this the taxonomy of models and the explanation of the common dichotomy which exists between these two broad approaches is crucial and will now be discussed.

BOTTOM-UP APPROACH

The bottom-up approach to modelling represents the first category of models used in this thesis. This approach is frequently used in the energy sector to provide an estimate for the 'least cost' method of meeting a given demand for final energy or energy services subject to various systems constraints (Loschel, 2002, p. 107). Models of this nature generally utilise a technology-based treatment of the energy sector and are purely partial models that lack interaction with the economy (Loschel, 2002, p. 107). Bottom-up models are extensively used in energy analysis and planning owing to a number of reasons (Jacobsen, 1998). Arguably, the most important is that they allow for more detail, in terms of both technological as well as economic parameters (Jacobsen, 1998). One of the key advantages of this approach is that it allows for a detailed restructuring of the energy supply sector, which is obviously an important aspect of energy planning. However, along with the positives, this approach has a number of criticisms. Firstly, it is often subjected to criticism by economists for the assumption that a 'single, anticipated estimate of a financial cost indicates the full social cost of technological change' (Jaccard, Murphy, & Rivers, 2004, p. 32) [1]. In line with this, a second criticism is that this approach does not allow the macroeconomic effects of changes in the energy system to be analysed (Jacobsen, 1998). This is generally an issue, and a strong motivation for using bottom-up models in conjunction with top-down models. This is even more so when considering the potential economy-wide impacts that changes in the energy sector could have. In terms of this thesis, the bottom-up approach is utilised in the modelling done for the Integrated Resource Plan (IRP). Data such as costs of generation technologies, annual electricity demand and supply forecasts as well as annual investment costs are crucial in terms of electricity planning. This approach is lacking, however, in terms of the potential economy-wide effects of changes in electricity planning. In the case of the IRP, a number of the policy goals that the planning process is meant to address cannot be quantified using this approach – namely economic growth and development. Quantifying the impact of the IRP on economic growth and development is of obvious importance, therefore the current bottom-up modelling approach is insufficient.

TOP-DOWN APPROACH

Top down models, in contrast, are generally favoured by economists and can be described as models that represent the energy system in a:

" ..highly aggregated way by means of neoclassical production functions that capture substitution possibilities through substitution elasticities." (Loschel, 2002)

Top-down models are considered useful in the analysis of long-term plans as they are based on behavioural relations (Loschel, 2002). However, this approach is vulnerable to criticism as models are generally based on aggregate, historical data that may not necessarily be in-line with future trajectories (Jaccard, Murphy, & Rivers, 2004). This modelling approach has an obvious advantage over the bottom-up approach in terms of enabling the user to gain insight into the interaction between changes in the energy sector and the economy. Although, by the same token, the highly aggregated feature of this approach is limiting in terms of the lack of technological detail when compared to models which follow the bottom-up approach. For instance, top-down models generally do not rely on direct descriptions of technologies, but

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[1] Jaffe and Stavins (Jaffe, 1994), Sutherland (Sutherland, 1996), Stavins (Stavins, 1999)

rather on changes in the cost of production at a commodity or industry level (Loschel, 2002). There are two basic model types which follow the top-down approach - namely macroeconometric models and computable general equilibrium (CGE) models. The former are usually based on long-run time series data and offer a substantial amount of economic detail, although they tend to lack structural detail (Loschel, 2002). In light of this restraint, this thesis uses a computable general equilibrium model in order to model the economy with sufficient structural detail. This form of modelling is useful for the purpose of this analysis, but also has a number of drawbacks that will be discussed further on in this thesis.

INTEGRATION OF TOP-DOWN AND BOTTOM-UP MODELLING PARADIGMS

It is evident that top-down and bottom-up modelling approaches have markedly different strengths and weaknesses which allow and impede them in answering questions in the policy debate. The detailed technological representation associated with bottom-up models allows them to be well suited to the assessment of a number of policy options in the energy sector. These include technology mix, fuel mix, logistics and emissions from sectors and sub-sectors (Pandey, 2002). The limited focus of these models and the absence of factors external to the energy sector also enable detailed representations of the end-use demand patterns and the processes involved in energy supply (Kydes, Shaw, & McDonald, 1995). On the other hand, top-down models are valuable when assessing policy questions that involve impacts on macroeconomic indicators and economy-wide effects. A unique feature of CGE models in particular is their ability to illustrate policy impacts as well as demonstrate the interactions between energy sectors and the rest of the economy (Frei, 2003). Nevertheless, the incapacity of CGE models, as with most top-down models, to deal with a highly disaggregated energy sector is still a drawback of this type of modelling (Frei, 2003). The integration of these two paradigms is more of a necessity for developing countries as they generally need to make a fair amount of their investment decisions prior to their economic growth reaching saturation (Pandey, 2002). The fact that developing markets have not reached their full growth potential results in a more uncertain future with regard to trajectories such as electricity demand growth. Therefore, the need for paradigm integration arises to account for this uncertainty. It is however not always an easy task integrating these two approaches. The integration of these two modelling paradigms is needed to produce a consistency between micro-level decisions and macro-level policies that will enable policy makers to obtain a clearer picture of the energy sector in the future (Koopmans, 2001).

The integration approach attracts even further motivation when viewed in terms of the usefulness of CGE models in the energy policy debate. In the words of Frei (2003, p. 1029):

> *"[The] long-term effects of energy policy measures may cause a structural change in the technology mix going along with the 'natural' emerging and phasing out of technologies. This and the lack of empirical evidence on elasticities determining technological evolution under energy policy constraints are common criticisms about the CGE approach in the context of energy policy analysis. The incorporation of*

> *bottom-up activity analysis, endogenous investment decisions and specific capital stock evolutions increase the empirical evidence of CGE-based energy policy analysis."*

There is a fundamental difference between these two approaches in terms of the flow of information that they contain. In this case, the bottom-up modelling approach in the IRP is based on an energy model, and hence analyses the flow of energy. In contrast, the CGE model represents an economic model and hence analyses the flow of money. This difference is sometimes an obstacle to model integration, although in most cases one is possible to use prices to aid in this integration.

In summary, it is optimal, when assessing policy options for the energy sector, to integrate the economic equilibrium character of the top-down paradigm with the optimization and detail of the bottom-up paradigm (Pandey, 2002). [2] Following this notion, this thesis attempts to provide a clearer picture by utilizing the bottom-up information provided by the modelling done in the Integrated Resource Plan (IRP) in an economy-wide framework supplied in the South African General Equilibrium (SAGE) model. This is done with the intention of analysing the impacts of the plan on a number of policy goals that are not currently available under the current IRP approach. The next section describes the IRP for South Africa in order to provide a background understanding of the governance, modelling, scenarios and assumptions surrounding this plan.

THE INTEGRATED RESOURCE PLAN

GOVERNANCE AND ELECTRICITY POLICY

The electricity sector is regulated by The National Energy Regulator of South Africa (NERSA), a statutory body established under the National Energy Regulatory Act 40 of 2004. Under the Electricity Regulation Act No 4 of 2006, NERSA is required to issue licenses to all players involved in the production and supply of electricity as well as "regulate prices and tariffs" that are supplied by electricity licensees (South Africa, 2004). The Minister of Energy holds the power to determine a desired generation mix and a national electricity plan against which NERSA provides licences for new generation capacity (South Africa, 2004).

> *34. (1) The Minister may, in consultation with the Regulator –*
>
> *(a) determine that new generation capacity is needed to ensure the continued uninterrupted supply of electricity;*

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[2] Wilson and Swisher (Wilson, 1993), Bohringer (Bohringer C. , 1998), and Jacobsen (Jacobsen, 1998) provide examples of the attempts of the integration of these two paradigms in energy policy analysis. Kypreos (Kypreos, 1999) also presents an interesting case where an integrated MARKAL-MACRO model was used for the analysis of long-term energy-environment policies in Switzerland. Bunn et al. (Bunn, 1997) illustrates the use of bottom-up optimization and top-down system dynamics approaches in a complementary manner to analyze different aspects of electricity privatization policy.

(b) determine the types of electricity sources from which electricity must be generated, and the percentage of electricity that must be generated from such sources;

(c) determine that electricity thus produced may only be sold to the persons or in the manner set out in such notice;

(d) determine that electricity thus produced must be purchased by the persons set in such notice;

(e) require that new generation capacity must –

(i) be established through a tendering procedure which is fair, equitable, transparent, competitive and cost-effective;

(ii) provide for private sector participation.

34. (3) The Regulator, in issuing a generation license –

(a) is bound by any determination made by the Minister in terms of subsection (1).[3]

The Ministry of Energy has issued regulations in terms of the Act which specify that Eskom's System Operator, in conjunction with the Department of Energy and the Regulator, is responsible for developing an integrated electricity plan as a basis for investment decisions in the power sector (South Africa, 2006).

3. (1) The process of developing the integrated resource plan shall include the-

- *(a) adoption of the planning assumptions;*
- *(b) determination of the electricity load forecast;*
- *(c) modelling and scenario planning based on the planning assumptions;*
- *(d) determination of a base plan derived from a least cost generation investment*
- *(b) requirement;*
- *(e) risk adjustment of the base plan, which shall be based on –*

    - *i. the most probable scenarios; and*
    - *ii. government policy objectives for a diverse generation mix, including renewable and alternative energies, demand side management and energy efficiency; and*
- *(f) approval and gazetting of the integrated resource plan.*

3. (5) The Minister shall approve the integrated resource plan and publish it in the government gazette for implementation.

3. (6) The regulator -

(a) must consider applications for licences in accordance with the determination in line with sub-regulation (5).[4]

In summary, the system operator is given the task of producing electricity plans for approval by the minister who will publish them as a framework for investment decisions and the regulator's licensing approvals. This herein outlines the process of the IRP, although it is an iterative

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[3] Electricity Regulation Act No 4, 2006

[4] Government Gazette Vol. 530, No. 32378, August 2008

process as it is considered to be a ‘living plan’ as it is amended as new data is obtained (DoE, 2011).

OBJECTIVES AND SCOPE

The primary objective of the IRP is to “determine the long term electricity demand and detail how this demand should be met in terms of generating capacity, type, timing and cost” (DoE, Integrated Resource Plan for Electricity, 2010). The goal is to “develop a sustainable electricity investment strategy for generation capacity and supporting infrastructure for South Africa over the next 20 years” (DoE, Integrated Resource Plan for Electricity, 2010). There are also a number of intentions stated in the IRP. Firstly, the IRP is intended to improve the long-term security of supply for the electricity sector by meeting the adequacy criteria of the required economic growth and development path (DoE, 2009). Secondly, the IRP should present a framework for the derivation of new generation capacity by the Ministry, as is illustrated in the New Generation Capacity regulations (DoE, 2009). Thirdly, to determine the amount of investment in capacity needed in South Africa over the medium term (DoE, 2009). Lastly, the IRP is intended to take into account environmental impacts and other externalities as well as consider the effect of the inclusion of renewables in the electricity planning (DoE, 2009).

The scope of the IRP covers the total demand and supply for the entire South African electricity sector, and therefore takes into account Eskom as well as non-Eskom sources of generation capacity and production (DoE, 2009). As previously mentioned, the plan spans over a 20 year period in order to provide a general idea of the long-term requirements for capacity in the electricity sector. This is motivated by the decommissioning of some of the existing plants and the inclusion of possible emissions target regimes over this period (DoE, 2010).

The initial stage of the IRP requires the generation of a base case, or reference scenario. This base case represents the least cost option and is considered the optimal option in terms of meeting capacity needs when the only limitation is the cost factor (DoE, 2010). There are a number of other scenarios that are then compiled in light of explicit policy and the consideration of risk adjustments that eventually lead to the determination of a proposed electricity build plan for South Africa.

A number of policy requirements govern the IRP. These form the foundation on which the IRP is built. Three particular elements of policy are crucial to the determination of the plan. Firstly, the Energy White Paper (DME, 1998) specified a preference for the movement away from reliance on coal and towards a more diverse electricity generation mix with the inclusion of nuclear, natural gas and renewable options (DoE, 2009). Secondly, in light of potential future international climate change obligations the IRP is considerate of South Africa’s climate change policy (DoE, 2009). With regard to this, the importance of accounting for the environmental impacts of electricity generation technologies is noted and should be accounted for in the IRP. Thirdly, there is a considerable amount of political pressure to ensure that electricity provision remains at the least possible cost to the consumer. In light of this, the purpose of the IRP is to provide a capacity is build plan in order to meet the expected demand growth at the minimum social cost; the cost should include the costs associated with the impact of externalities (DoE, 2009).

In the same light, there are a number of policy goals that influence the IRP. The current process of the IRP is such that the policy goals act as 'inputs' into its operational process. The intention of the IRP is to address these policy goals and propose a plan that will help aid in reaching these goals. There are a number of policy goals, namely: (1) emissions reduction; (2) decreased water usage; (3) cost of plan; (4) regional development; (5) localisation; (6) economic growth or GDP growth; (7) employment; (8) good terms of trade; (9) and low electricity price. The modelling approach used in the IRP is limiting in terms of analysing the plan's ability to address some of these policy goals. The current modelling approach in the IRP is able to quantify the first three policy goals. The fourth policy goal of regional development is estimated, although this is done without any actual form of economic analysis. The suitability of the plan to the remaining five policy goals remains unaccounted for. This is a major gap as these policy goals are important considerations for economic growth and development in the country. The use of a CGE model should aid in analysing the plans influence on these policy goals. The following section describes the current generation capacity in the electricity sector before moving onto the various IRP scenarios.

CURRENT GENERATION CAPACITY

Before embarking on a discussion of the scenarios proposed in the IRP, it is important to outline the current generation capacity which the expansion plan will build upon. Eskom, currently one of the top twenty largest utilities in the world by generation capacity, continues to monopolise the South African electricity supply sector. The utility generates around 96% of South Africa's electricity the remaining contribution being 3% from private generation contributors (predominantly for their own use) and a contribution from municipalities of about 1%. South Africa's electricity sector is highly reliant on coal, with approximately 93% of electricity generation, by GWh, from coal (Eskom, 2011). The remaining electricity generation is mainly from nuclear and hydo-power with approximately 5% from each and a negligible amount from open-cycle gas turbines (OCGT) used for peaking[5]. Along with its operations in South Africa, Eskom also imports and exports electricity in the countries of the South African Development Community (SADC). Imports consist of power from Mozambique and to a lesser extent the Democratic Republic of Congo and Zambia. Electricity is also exported by the utility to a number of neighbouring countries (Namibia, Botswana, Mozambique, Swaziland, Lesotho, Zimbabwe and Zambia), with foreign sales making up 5.9% of Eskom's total electricity sales (Eskom, 2011).

The following scenarios are modelled from 2010 to 2030 and build on the existing electricity generation capacity. The total generation capacity is assumed to have been 43 895 MW in 2010 and to have been split by technology as described above.

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[5] A breakdown of the existing generation capacity plants is provided in the appendix

The IRP modelled a number of initial scenarios, each with regard to a specific stakeholder expectation or constraint. The revised balanced scenario and more recently, after some refinement, the Policy-Adjusted scenario were formed in consideration of these divergent stakeholder's expectations and key constraints. These scenarios were proposed to characterize the "best trade-off between least investment cost, climate change mitigation, diversity of supply, localization and regional development" (DoE, Integrated Resource Plan, 2011). The following table provides a brief outline of the constraints that were considered in the initial scenarios tested within the IRP framework[6]. A brief description of the committed build plan and the three scenarios modelled in this thesis will now follow.

Scenario	**Constraints**
Base Case 0.0	Limited regional development options No externalities (incl. carbon tax) or climate change targets
Emission Limit 1.0 (EM1)	Annual limit imposed on CO_2 emissions from electricity industry of 275 MT CO_2-eq
Emission Limit 2.0 (EM2)	Annual limit imposed on CO_2 emissions from electricity industry of 275 MT CO_2-eq, imposed only from 2025
Emission Limit 3.0 (EM3)	Annual limit imposed on CO_2 emissions from electricity industry 220 MT CO_2-eq, imposed from 2020
Carbon Tax 0.0 (CT)	Imposing carbon tax as per Long Term Mitigation Strategy (LTMS) values (escalated to 2010 ZAR)
Regional Development 0.0 (RD)	Inclusion of additional regional projects as options
Enhanced DSM 0.0 (EDSM)	Additional DSM committed to extent of 6 TWh energy equivalent in 2015
Balanced Scenario	Emission constraints as with EM 2.0, Coal costs at R200/ton; LNG cost at R80/GJ, Import Coal with FGD, forced in Wind earlier with a ramp-up (200 MW in 2014; 400 MW in 2015; 800 MW from 2016 to 2023; 1600 MW annual limit on options throughout)
Revised Balanced Scenario	As with Balanced Scenario, with the additional requirement of a solar programme of 100 MW in each year from 2016 to 2019 (and a delay in the REFIT solar capacity to 100 MW in each of 2014 and 2015). CCGT forced in from 2019 to 2021 to provide backup options. Additional import hydro as per the Regional Development scenario

Table 1: Summary of the IRP Scenarios (DoE, Integrated Resource Plan, 2011)

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[6] It is interesting to view the differences in results for the various initial scenarios and therefore a brief description of these scenarios is provided in Appendix I

COMMITTED BUILD PLAN

There are a number of projects considered committed to in the IRP and therefore are modelled into all the IRP scenarios. A table of these committed projects is presented below.

	Coal	Coal	Coal	Hydro	Gas	Coal	Renewables	Renewables	Hydro	Renewables	Coal
	RTS Capacity	**Medupi**	**Kusile**	**Ingula**	**DOE OCGT IPP**	**Cogeneration, Own Build**	**Wind**	**Solar CSP**	**Landfill, hydro**	**Sere**	**Decommissioning**
2010	380					260					
2011	679					130	200				
2012	303	722					200		100	100	
2013	101	722		333	1 020		300	100	25		
2014		1 444		999				100			
2015		722	1 446								-180
2016		722	723								-90
2017			1 446								
2018			723								
2019											
2020											
2021											-75
2022											-1 870
2023											-2 280
2024											-909
2025											-1 520
2026											
2027											
2028											-2 850
2029											-1 128
2030											

Table2: Committed schedule for the IRP

One can see from the table above that much of the immediate investment programme in new generation capacity is based on coal. The Return to Service (RTS) capacity represents three previously mothballed coal stations; namely Camden, Grootvlei and Komati, that are being brought back into service. The construction of two new supercritical coal fired power stations, Medupi and Kusile, is included in the committed plan. Currently the construction of both plants is underway with the commissioning of the first units expected in 2012 and 2015 respectively – assuming no delays. Ingula is a pumped-storage plant currently under construction in the lower Drakensberg in Kwa-Zulu Natal with full completion expected in 2014. A further 1020 MW of open-cycle gas turbine (OCGT) capacity is planned to come online in 2013. A number of renewable energy projects have also been included in the IRP committed build plan, although due to the lack of information in the Eskom committed build plan the details of these projects are unclear. There is no nuclear capacity included in the committed build plan, however the Integrated Resource Plan (DoE, Integrated Resource Plan, 2011) identified the need for a firm commitment to at least 3 GW of nuclear in the near future. This is due to the long lead times associated with nuclear builds – shown at a later stage in this thesis as being an estimated lead time of 16 years[7].

BASE CASE

The first scenario modelled is the base case, which represents the business-as-usual growth path. In other words, the scenario where there are no restrictions on the build plan and therefore the 'cheapest' build plan is chosen. There are three versions of the base case that are given to account for the effect of a delay in Kusile and Medupi and for the potential cancelling of Kusile. A discussion of the case where Kusile is committed on time according to the initial commitment schedule will follow. In addition to the committed builds there is approximately 19450 MW of coal in various forms planned to come online by 2030 – 1 750MW from fluidised bed combustion (FBC), 1 200MW imported coal and 1 6500MW from pulverized coal plants with flue gas desulphurisation (FGD). The base case also plans for 3 680MW of open-cycle gas turbines (OCGT), 3 318MW of closed-cycles gas turbines powered by gas and 1 959MW of imported hydropower. Carbon Dioxide (CO_2) emissions are not constrained and continue to grow to a level of 381million tons at the end of 2030. In this scenario, a planned 42GW will come online over the period, at a total cost of R 789bn in present value terms (excluding the capital costs for plants under the committed schedule). The introduction of newer dry-cooled coal power stations attributes to a decline in water usage in this scenario from 336 420 million litres in 2010 to 266 721 million litres in 2030.

REVISED BALANCED SCENARIO

The revised balanced scenario (RBS) is chosen with consideration of the expectations from the various stakeholders as well as the key constraints governing the IRP. An emission target similar to that of the emissions 2 scenario is enforced. These scenarios contain the same committed schedule as already illustrated and introduce various Medium-Term Power Purchase Programmes (MTPPP) and Renewable Energy Feed-in Tariff (REFIT) commitments. There is some diversification with a number of renewable options, nuclear, gas and imported capacity in these scenarios, and only 2 750 MW of coal planned much later in the period. There is a substantial amount of wind that is to come online from 2014 onwards, as it is seen as the cheapest renewable option. There is also an interest in the potential for localisation in the manufacturing sector for wind. Capacity expansion in concentrated solar power is present in the plan and its potential for localisation is also recognised. Renewable technologies were lumped together from 2020 in the RBS as to allow for diversification of the plan when more was known about the costs, local knowledge and experience concerning the specific renewable technologies.

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[7] The lead time is based on a full nuclear build of six 1600MW nuclear units, with one unit commissioned every 18 months after a lead time of 12 years.

The IRP is considered a ‘living plan’, one that undergoes an iterative process of continuous revision and updating. In light of this it is expected that the proposed electricity build plan will be reviewed at least every two years by the Department of Energy (DoE). In October 2010, the Revised Balanced Scenario (RBS) was presented as the proposed build plan, although it has been reviewed and after a consultation process the Policy-Adjusted IRP illustrates the proposed electricity build plan to 2030 (DoE, 2011). The figure below displays the differences in the form of the total additional capacity until 2030 between the RBS and the Policy-Adjusted IRP.

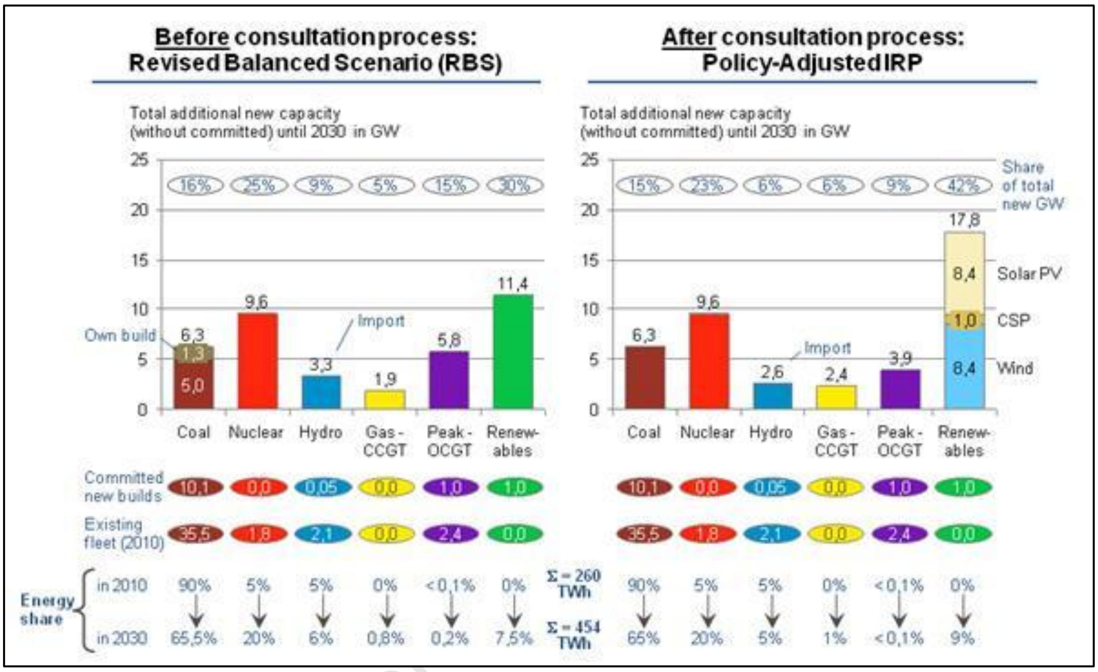

Figure 2: Output mix of the RBS and Policy-Adjusted IRP scenarios (DoE, 2011)

It is evident from figure 2 that there is a movement towards a higher proportion of investment in renewable. Renewables increased from 11.4 GW to 17.8 GW, a 12% increase in the share of renewables in the total new capacity build. There is more planned solar power, with a an addition of 8.4 GW of solar PV and 1 GW of CSP by 2030. The total new coal and nuclear capacity remain the same in the new scenario. There is a 0.7 GW decrease in imported hydro, a decrease of 0.9 GW of OCGT and an increase in CCGT of 0.5 GW.

A COMPARISON OF THE SCENARIOS

A brief description of the three main scenarios modelled in this thesis has now been discussed. It is also important to understand the differences between the scenarios to aid in the interpretation of the results presented in this thesis. The figure below illustrates a few key differences between the base year and the three scenarios in 2020 and 2030.

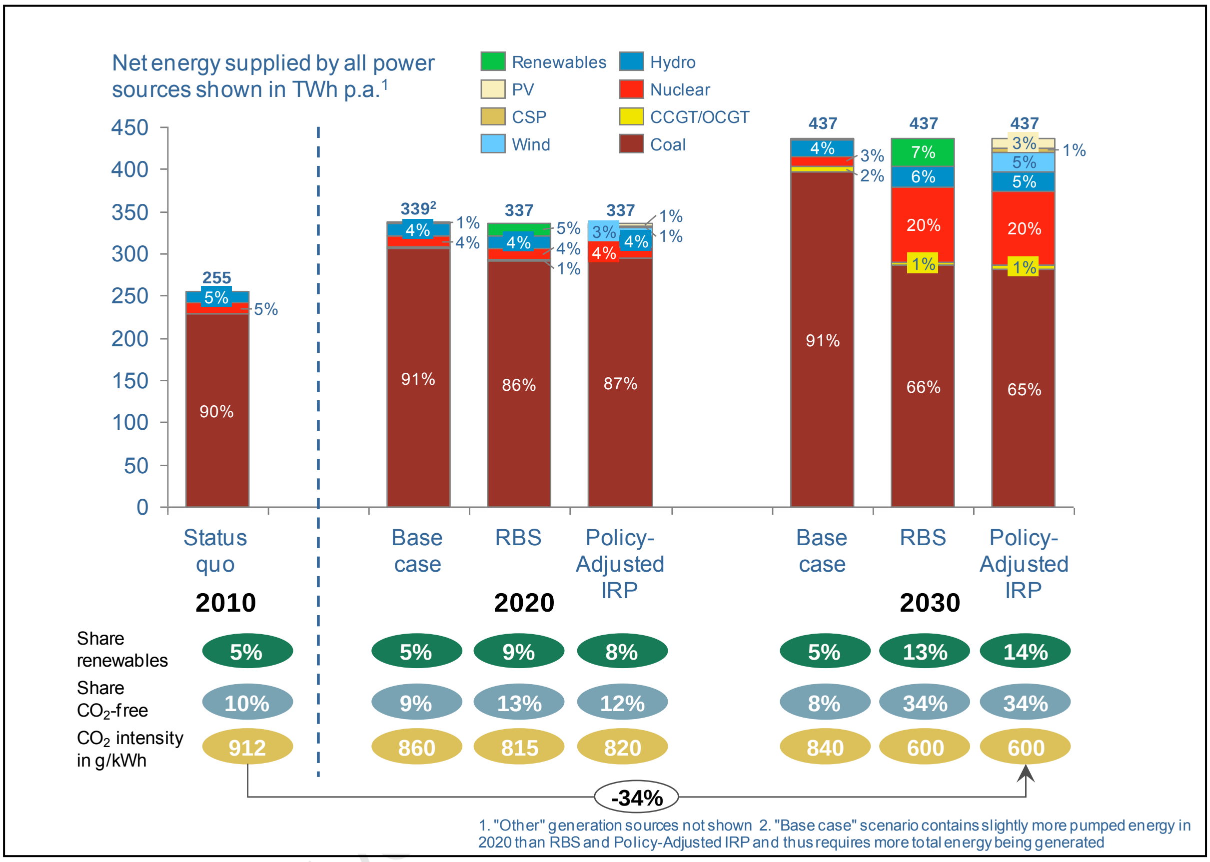

Figure 3: Comparing the Base Case with the RBS and Policy-Adjusted IRP (DoE, 2011)

The base year highlights South Africa's high reliance on coal for electricity generation and the negative effect this is having on the climate with a carbon intensity of 912g/kWh. The share of renewables is significantly low at 5% of total capacity – main contributors being nuclear at 4% and hydropower at 1%. The base case maintains this reliance on coal at 91% of net energy supplied over the period. The RBS and policy-adjusted IRP are similar to the base case in 2020 with a high reliance on coal, no nuclear capacity at this stage and only 4% and 5% of the renewable capacity has come online for the respective scenarios. By 2030 the RBS and policy-adjusted IRP paint a very different picture to that of the base case with a reliance on coal of 66% and 65% respectively and 20% reliance on nuclear. CCGT and OCGT represent a slightly higher share in the base case than the other two scenarios with a corresponding share of 2% and 1%. The main update through the consultation period prior to the policy-adjusted scenario was the provision of a split in the renewable capacity portion of the plan. It is therefore difficult to compare the composition of renewables in 2030, other than to say that the policy-adjusted scenario contains 1% more renewable capacity.

There is a substantial difference between the scenarios in terms of emissions intensity. As the figure shows there is a decrease of 34% in CO_2 intensity between the base year and 2030 for the RBS and policy-adjusted scenarios. This compared to the 8% decline over the period for the base case.

DATA SOURCES AND ASSUMPTIONS

This section will provide a brief overview on the data used in the IRP as well as a number of the key assumptions used in the modelling of the IRP. Highlighting these aspects is crucial as one must ensure the accuracy and validity of both data sources and the assumptions made given their impact on the outcome of the model.

DEMAND

Electricity demand forecasts, as with most forecasts, are very difficult to predict. This is due to, among other things, their particularly strong correlation with GDP. Given the difficulty associated with the prediction of the demand path there is a risk of either over-investment in capacity in the event of supply exceeding the actual demand, or a shortage in electricity in the case of actual demand exceeding supply. The IRP attempts to hedge against this risk by estimating a number of growth paths based on high, moderate and low economic growth forecasts, illustrated below in figure 4.

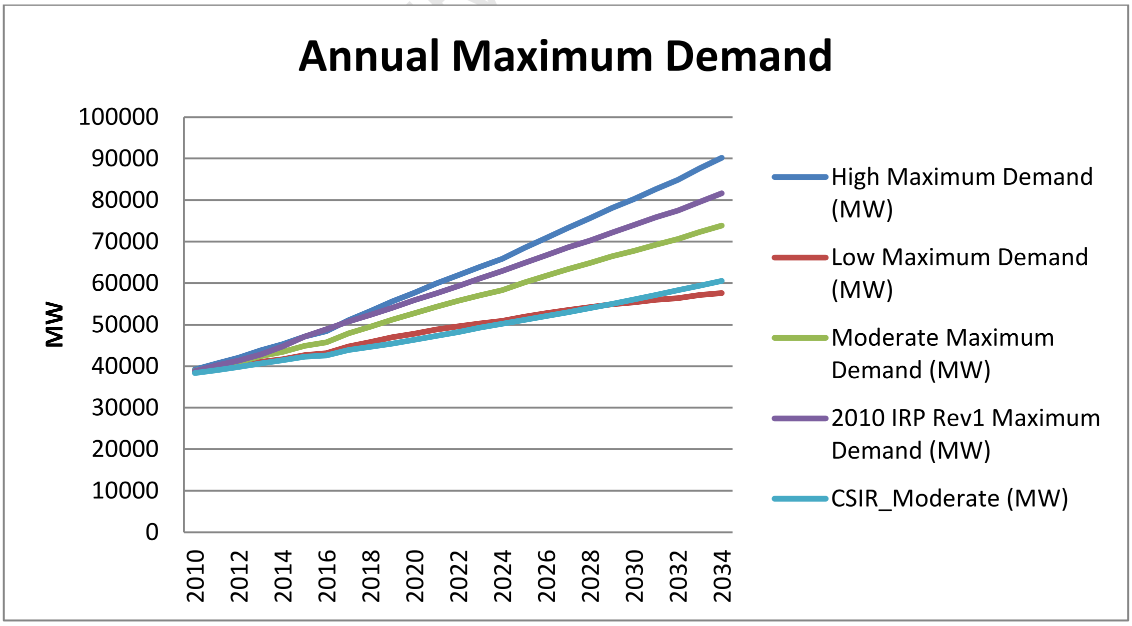

Figure 4: Annual Maximum Demand Paths from the IRP

[Data Source: (DoE, 2011)]

In recent IRP (DoE, 2011) identified that the demand forecast was at the higher end of the spectrum, which is an advantage in terms of ensuring security of supply. A disadvantage though, is that it could lead to a repeat of the over-investment in electricity capacity that occurred in South Africa in the 1970's (Steyn, 2006). The figure below illustrates that an overinvestment in electricity capacity is likely. Total capacity exceeds the highest maximum demand by a fair margin throughout the period, even with the inclusion of the decommissioned plants.

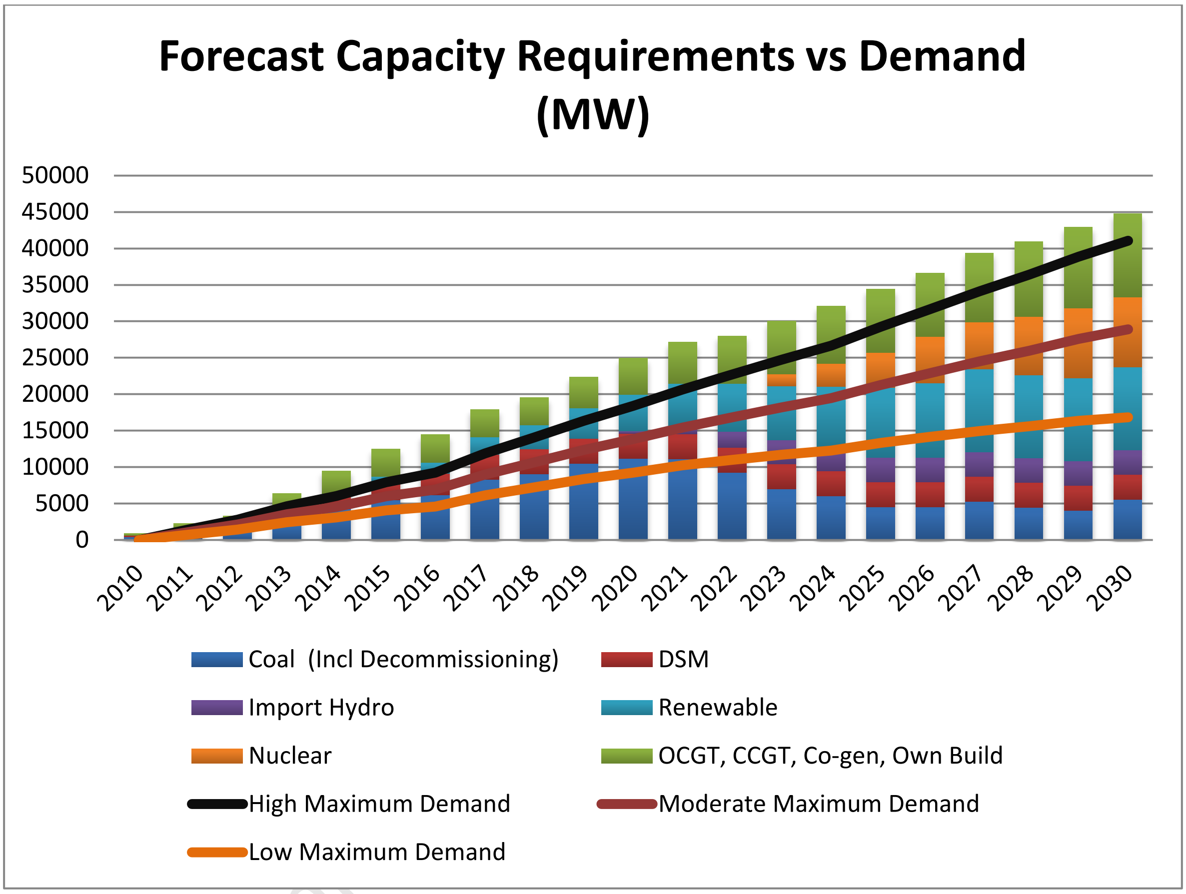

Figure 5: Forecast Capacity Requirements[8]

COSTS

Electricity generation expansion plans require a significant amount of financing and seem to be prone to running over budget as has been witnessed in South Africa's experience. Uncertainty surrounds the cost of and it is sometimes difficult to estimate these, especially for capacity builds in the future. The real cost of most generation technologies is highly debated, especially in the case of nuclear power. There are a number of reasons for this – unreliability of data, difficulties of forecasting, learning, scale economics, technical progress and construction time, to

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[8] Based on a similar graph by Gaunt (2010)

name a few (Thomas, 2005). The IRP based its modelling costs on the comprehensive EPRI report (2010), compiled for use in the IRP. The table below presents a brief outline of the costs of the different generation technologies as well as a breakdown of the expected investment schedule, both sourced from the EPRI Report (2010).

Unit build costs			
	Overnight cost	***Capacity, rated net***	***Unit cost***
	R/kW	*MW*	*Rbn*
Pulverized Coal	17 785	750	13.3
Integrated Gasification Combined Cycle	24 670	644	15.9
Fluidized Bed Combustion	14 965	250	3.7
Nuclear	26 575	1 600	42.5
Combined Cycle Gas Turbine	5 780	711	4.1
Open Cycle Gas Turbine	3 955	115	0.5
Wind	14 445	100	1.4
Solar Thermal	37 425	125	4.7
Solar Photovoltaic	37 225	10	0.4
Biomass	50 085	25	1.3

Table 3: IRP Unit Build Costs

Years	***1***	***2***	***3***	***4***	***5***	***6***
Pulverized Coal	10	25	45	20		
Integrated Gasification Combined Cycle	10	25	45	20		
Fluidized Bed Combustion	10	25	45	20		
Nuclear	15	15	25	25	10	10
Combined Cycle Gas Turbine	90	10				
Open Cycle Gas Turbine	40	50	10			
Wind	5	5	5	25	60	
Solar Thermal	10	25	45	20		
Solar Photovoltaic	10	90				
Biomass	10	25	45	20		

Table 4: IRP Investment Schedule

EMISSIONS AND WATER USAGE

The data used in the IRP for emissions as well as water usage was also sourced from the EPRI report. The following table provides a brief overview of these figures for various technologies:

	CO2 Emissions	**Water Usage**
	kg/MWh	l/MWh
Pulverized Coal	936,2	229,1
Integrated Gasification Combined Cycle	857,1	256,8
Fluidized Bed Combustion	976,9	33,3
Nuclear		6000 (sea)
Combined Cycle Gas Turbine	376	12,8
Open Cycle Gas Turbine	622	19,8
Wind		
Solar Thermal		245
Solar Photovoltaic		
Biomass	1287	210

Table 5: IRP Emissions and Water Usage

THE SOUTH AFRICAN ENERGY (SAGE) MODEL

For the purpose of this thesis only a brief overview of what CGE modelling is will be provided to give the reader a general understanding of this type of modelling. Dervis et al's (1982) seminal work 'General Equilibrium Models for Development Policy' provides a comprehensive expanation of the neoclassical modelling tradition from which the standard model for South Africa (Thurlow & van Seventer, September 2002) was derived. Thurlow (2004) presents the dynamic SAGE model - the basic core for the model used in the analysis for this thesis. The model used is the energy extension to the SAGE model from Arndt, Davies, & Thurlow (2011).

AN INTRODUCTION TO CGE MODELLING

Economy-wide policy analysis in South Africa has experienced a significant increase in the use of computable general equilibrium (CGE) models (Thurlow & van Seventer, September 2002). A number of these models have contributed to the local policy making process in areas including trade strategy, income distribution, and structural change in the economy. There are several features of CGE modelling that contribute to its suitability for such analysis (Arndt, Davies, & Thurlow, 2011). Firstly, CGE models are structured so that 'all economy-wide constraints are respected' and therefore provide a 'theoretically consistent framework for welfare and distributional analysis' (Arndt, Davies, & Thurlow, 2011). Secondly, CGE models 'simulate the functioning of a market economy', and provide a platform for analysis on how different economic conditions affect markets and prices (Arndt, Davies, & Thurlow, 2011). Thirdly, the way in which these models are structured allows for the addition of ‘new phenomena and technologies’, for example the inclusion of a biofuels sector in Mozambique (Arndt, Benfica, Tarp, Thurlow, & Uaiene, 2008). Lastly, CGE models ‘contain detailed sectoral breakdowns and provide a “simulation laboratory” for qualitatively examining how different impact channels influence the performance and structure of the economy’ (Arndt, Davies, & Thurlow, 2011). The economy-wide aspect and the fact that CGE models allow for highly detailed interaction effects made this type of modelling more suitable than econometric models for the purpose of this thesis. However, it must be noted that CGE models, due to their complex nature and various assumptions, are regarded as less suitable than the latter for predictions over long periods of time. CGE models are considered useful, in the same way that Sadoulet, et al (1995) explain for input-output models, for “providing guidelines to potential linkage effects...[rather] than predictive models” (Pauw, 2007). In light of this the results of the CGE model should be viewed as a guideline for the effects of a shock and not the actual predicted future. The main reason for the use of a CGE model in this thesis was its usefulness in terms of providing a framework to analyse shocks. A baseline, or reference case, exists and is compared to other scenarios where certain variables are altered, or shocked, and the resulting changes in the economy are assumed to be caused by these shocks (Pauw, 2007).

THE STANDARD SOUTH AFRICAN GENERAL EQUILIBRIUM MODEL

The dynamic CGE model used in this analysis is the South African General Equilibrium (SAGE) model developed by James Thurlow for Trade and Industrial Policies (TIPS) (Thurlow, 2004). The SAGE model, which is described in detail below, is based on the neoclassical tradition that was originally presented by in the seminal work by Dervis, de Melo, & Robinson (1982). According to Thurlow (2004), there are a number of extensions and adaptations that have been made to this framework including ‘the ability of producers to produce more than one commodity, the explicit treatment of transaction costs and the home consumption of non-marketed goods’ (Lofgren, Harris, & Robinson, 2001). For the purpose of this thesis, the energy extension to the SAGE model, developed by Channing Arndt, Rob Davies and James Thurlow (2011), was used. This extension allowed the SAGE model to reflect the structure and workings of South Africa’s energy sector, which was crucial for the analysis done in this thesis.

The SAGE model is a dynamic recursive model and therefore contains two main components; one that involves the model updates ‘within-the-period’ and one that involves updates ‘between-the-periods’. An understanding of distinction between the two is important as dynamic-recursive modelling is essentially a static model that is run a number of times to simulate the economy over a number of years. The static, or core, model is solved ‘within-the-period’ with the use of non-linear equations that are solved simultaneously to capture linkages that exist in the real economy. The ‘between-the-period’ component updates the economic effects of the static model into the next period (Kearney, 2010). The most important effect that is captured between-the-periods is the process of capital accumulation (Thurlow, 2004). In the SAGE model investments are financed by a national pool; in which all savings are collected (Arndt, Davies, & Thurlow, 2011). These investments are converted into capital stocks in order to calculate the total rate of capital accumulation (Arndt, Davies, & Thurlow, 2011). According to Thurlow (2008), the allocation of new capital to all sectors is based upon each sectors current share of capital stocks, as well as the capital depreciation rate and the sectors relative profit rates. In light of this sectors with above average capital returns are allocated a greater share of investible funds than their share in capital income, and the converse is true (Thurlow, 2008).

As previously mentioned, the SAGE model captures 'linkages', these include the 'linkages between sectoral and national growth' as well as 'household incomes and poverty' (Arndt, Davies, & Thurlow, 2011). South Africa's unique economic structure determines the 'various direct and indirect transmission channels that exist between sector-level growth and household incomes' (Arndt, Davies, & Thurlow, 2011). Both production and consumption linkages are captured within the SAGE model when analysing the effects of 'policies and sector growth on national growth and household incomes' (Arndt, Davies, & Thurlow, 2011).

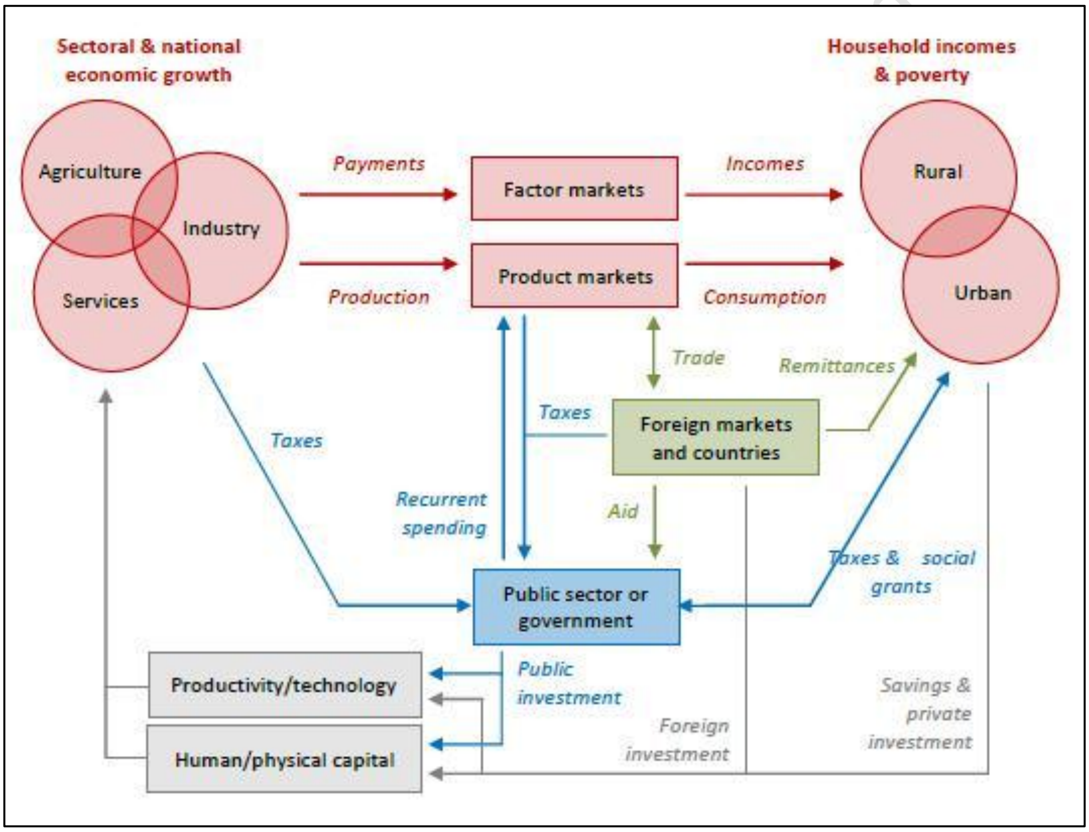

Figure 6: Economy-Wide Framework (Arndt, Davies, & Thurlow, 2011)

The figure above illustrates the linkages that exist in the economy and hence in the SAGE model. A number of 'blocks' in the economy can be identified; namely industry, government, foreign markets, factor markets, product markets and households. The interactions, or linkages, between these blocks are shown in the figure. Production linkages and consumption linkages represent the two main types of linkages. In simple terms, production linkages describe the flows between sectors and the technologies, whereas consumption linkages describe the flows between household incomes and product markets. The interactions and flows between the various blocks in the economy are important for CGE modelling. The economic equations that govern the model may seem daunting at first, but they are merely representations of these flows in the economy. The following sections will delve further into these equations and functional forms.

FUNCTIONAL FORMS

The SAGE model, as with all CGE models, is governed by a number of production functions – of which various functional forms impose certain behaviours on the model. This section will briefly describe the different modelling functional forms that are used in the SAGE model.

The Leontief Function

The Leontief specification is represented by:

$$q_j = \min[a_i x_i] \qquad i = 1 \dots \dots n \tag{1}$$

This specification represents an elasticity of substitution of zero. In other words the input quantity, for example technology, is specified by fixed shares and is unaffected by changes in price.

Constant Elasticity of Substitution (CES) Functions

$$q = A\left[a_1 x_1^{-p} + a_2 x_2^{-p}\right]^{-\frac{1}{p}} \tag{2}$$

$$A > 0 \quad scaling\ factor$$

$$a_i\ share\ parameter \quad 0 < a_i < 1 \quad a_1 + a_2 = 1$$

$$P\ elasticity\ parameter$$

$$Elasticity\ of\ substitution\ on\ \sigma = \frac{1}{1+p}$$

$$-1 < p$$

The CES function, as the name implies, represents a specification where the quantity of a variable has a constant elasticity of substitution, or an elasticity of substitution equal to one. Constant Elasticity of Transformation (CET), an application of CES, works in the same regard, except that outputs are used instead of inputs as arguments and there is a negative CES.

Armington Function

Standard trade theory assumes domestic and foreign goods are perfect substitutes. Armington (A Theory of Demand for Products Distinguished by Place of Production, 1969), suggested that they might not be perfect substitutes and that there should be an allowance for 'brand' or 'source' preferences. The Armington function uses CES to model aggregation of imports and domestic goods into a composite good:

$$q = A[\delta M^{-p} + (1-\delta)D^{-p}]^{1/p} \tag{3}$$

$$\frac{M}{D} = \left(\frac{\delta}{1-\delta} \cdot \frac{P_d}{P_m}\right)^{\sigma} \tag{4}$$

$$P_q q = (P_d D + P_m M)(1 + t_q) \tag{5}$$

PRODUCTION AND PRICES

There are 46 productive sectors, or *activities*, identified within the model; a list of which is provided in [TABLE: sectors, commodities and factors in the 2005 SAM]. The six factors of production, also shown in the table, are capital, crop land and labour - labour is disaggregated into four factors by level of education. Figure [insert figure number] illustrates the technology underlying production as depicted for a sole producer as well as how a single producer can supply more than one commodity (Thurlow, 2004).

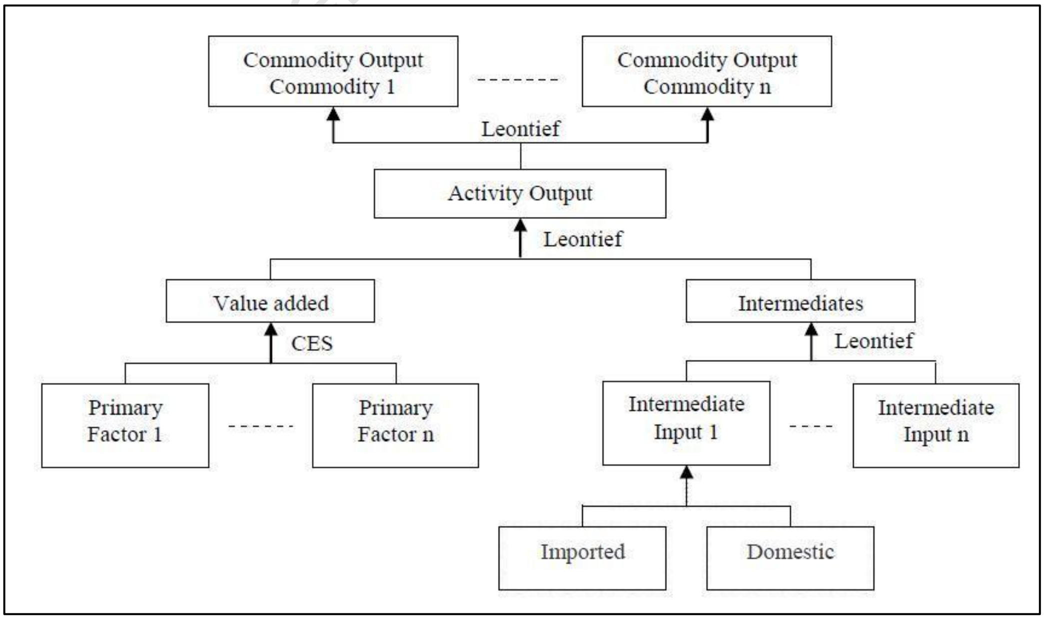

Figure 7: Production Technology (Thurlow, 2004)

The view of the production schedule for a sole producer is provided for simplicity, although in reality, the SAGE model contains 46 sectors, each of which are assigned a representative producer. The behaviour of the representative producer is such that they will maximize profits subject to a given set of input and output prices (Thurlow, 2004). The model follows neoclassical theory, and assumes constant returns to scale and hence a constant elasticity of substitution (CES) function is used to determine production (Arndt, Davies, & Thurlow, 2011):

$$QA_i = \alpha_i^p \left(\sum_f \delta_{if}^p \cdot QF_{if}^{-p_i^p} \right)^{-1/p_i^p} \tag{6}$$

where QA is the output quantity of sector i, α^p is the shift parameter reflecting total factor productivity (TFP), QF is the quantity demanded of each factor f (i.e., labour and capital) and δ^p is a share parameter of factor f employed in the production of good i. The elasticity of substitution between factors σ is a transformation of ρ^p.

The use of a CES function allows producers to respond to changes in relative factor returns by smoothly substituting between available factors to derive a final value-added composite (Thurlow, 2004).

Profits π in each sector i are defined as the difference between revenues and total factor payments (Arndt, Davies, & Thurlow, 2011):"

$$\pi_i = PV_i \cdot QA_i - \sum_f (WF_f \cdot QF_{if}) \tag{7}$$

where PV is the value-added component of the producer price, and WF is factor prices (e.g., labour wages and returns on capital). Profit maximization implies that factors will receive an income where marginal revenue is equal to marginal cost, based on endogenous relative prices (Thurlow, 2004). Maximizing sectoral profits subject to Equation 6, and rearranging the resulting first order condition provides the system of factor demand equations used in the model (Arndt, Davies, & Thurlow, 2011):

$$QF_{if} = {\propto_i^p}^{\frac{p_i^p}{1+p_i^p}} \cdot QA_i \left(\delta_{if}^p \cdot \frac{PV_i}{WF_f} \right)^{1/(1+p_i^p)} \tag{8}$$

According to Arndt et al. (2011), the SAGE model assumes a Leontief specification for technology when calculating the intermediate demands of individual goods as well as when merging aggregate factor and intermediate inputs. This use of fixed shares is due to the belief that technology, and not the decision making of producers, determines the mixture of intermediates per unit of output, and the ratio of intermediates to value-added (Thurlow, 2004). In light of this the complete producer price PA is (Arndt, Davies, & Thurlow, 2011):

$$PA_i = PV_i + \sum_j (PQ_j \cdot io_{ij}) \qquad (9)$$

Where io_{ij} represents the fixed input-output coefficient used in the demand for intermediates, which defines the quantity of good *j* used in the production of one unit of good *i* (Arndt, Davies, & Thurlow, 2011).

The SAGE model is constructed to allow a distinction between an *activity* and a *commodity.* This distinction allows each activity to produce multiple commodities as well as each commodity to be produced by a number of activities. The latter is seen as more controversial, although there are cases in which this occurs in the real economy. For instance, an example is put forward by Thurlow (2004), where the agricultural sector produces some processed goods as well as their primary output of agricultural goods. Processed goods are also produced by the processed foods sector and therefore the good would need to be produced by more than one activity in the model. The figure below illustrates the way in which the supply of a single commodity from multiple producers is combined to obtain an aggregate commodity output (Thurlow, 2004). A CES function is used to govern this aggregation, which results in the agents demanding the good to substitute between the different producers supplying the good; in order to maximize consumption with regard to the relative supply prices (Thurlow, 2004).

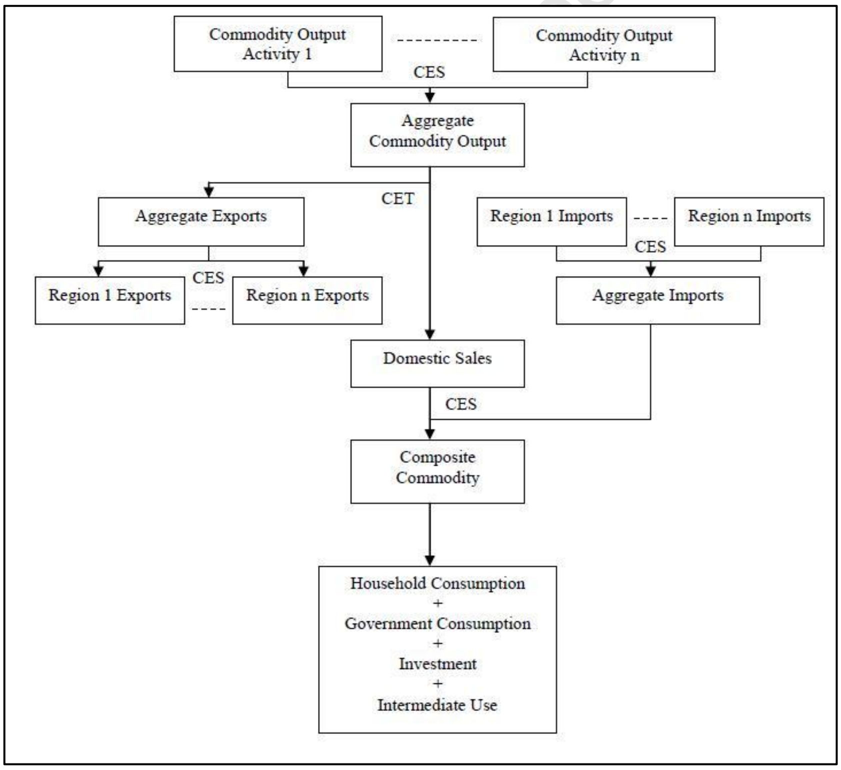

Figure 8: Commodity Flows (Thurlow, 2004)

The SAGE model represents an open-economy and hence the model recognizes the two-way trade that exists between countries for similar goods (Arndt, Davies, & Thurlow, 2011). Substitution possibilities, governed by a CET function, exist between the production for domestic and for foreign markets, (Thurlow, 2004). A CET function is used to allow the distinction between domestic and imported goods in terms of differences in time and/or quality that may exist between them (Thurlow, 2004). This relationship is presented below (Arndt, Davies, & Thurlow, 2011):

$$QA_i = a_i^e \left[\delta_i^e \cdot QD_i^{p_i^e} + (1 + \delta_i^e) \cdot QE_i^{p_i^e}\right]^{1/p_i^e} \tag{11}$$

$$PA_i . QA_i = PD_i \cdot QD_i + PE_i \cdot QE_i \tag{12}$$

$$PE_i = (1 - te_i) \cdot pwe_i \tag{13}$$

where QE is the quantity of good i that is exported, te is the export tax rate (negative if a subsidy), and pwe is the exogenous world export price

Maximizing $PQ_iQQ_i - PD_iQD_i - PM_iQM_i$ subject to Equation 11 and rearranging the resulting first order condition gives the following equation defining the ratio of QD and QM (Arndt, Davies, & Thurlow, 2011):

$$\frac{QD_i}{QM_i} = \left(\frac{\delta_i^m}{1-\delta_i^m} \cdot \frac{PM_i}{PDi}\right)^{1/(1+p_i^m} \tag{14}$$

Producers are, once again, driven by profit maximization and therefore choose to sell in the market that offers the highest returns (Thurlow, 2004). Exported commodities are disaggregated further using a CES according to the specific region under a CES specification (Thurlow, 2004). The assumption that the substitution between regions is governed by a CES specification is fair as one would expect that producers would react to changes in relative prices across regions. This would therefore change the geographical composition of their exports accordingly (Thurlow, 2004).

The import market is treated in the same regard. Substitution possibilities exist between imported and domestic goods under a CES Armington specification (Armington, 1969). This is true in the use of both final and intermediate goods (Arndt, Davies, & Thurlow, Energy Extension to the South Africa General Equilibrium (SAGE) Model, 2011):

$$QQ_i = a_i^m \left[\delta_i^m \cdot QD_i^{-p_i^m} + (1 + \mu_i) \cdot QM_i^{-p_i^m}\right]^{-1/p_i^m} \tag{15}$$

$$(1 - tq_i) \cdot PQ_i \cdot QQ_i = PD_i \cdot QD_i + PM_i \cdot QM_i \tag{16}$$

$$PM_i = (1 + tm_i) \cdot pwm_i \tag{17}$$

where tq is an indirect sales tax, QQ is the composite good consumed domestically, QD and QM are domestically supplied and imported quantities, and PD is the price of domestic good QD.

Under the small country assumption, South Africa is assumed to face almost perfectly elastic world supply at world prices (Thurlow, 2004). Hence, the import price PM is determined exogenously by world imports prices pwm and import tariffs tm (Arndt, Davies, & Thurlow, 2011).

Minimizing $PA_iQA_i - PD_iQD_i - PE_iQE_i$ subject to Equation 11 gives the ratio of QD and QE (Arndt, Davies, & Thurlow, 2011):

$$\frac{QD_i}{QE_i} = \left(\frac{\delta_i^e}{1-\delta_i^e} \cdot \frac{PD_i}{PE_i}\right)^{1/(pf-1)} \qquad (18)$$

INSTITUTIONAL INCOMES AND DOMESTIC DEMAND

Figure 9 illustrates and summarizes the interactions between the institutions that exist in the model. The SAGE model distinguishes between different institutions that exist in the South African economy; namely, households, government and enterprises. Households are disaggregated according to income deciles, except for the top decile, which is divided into five income categories (Thurlow, 2004).

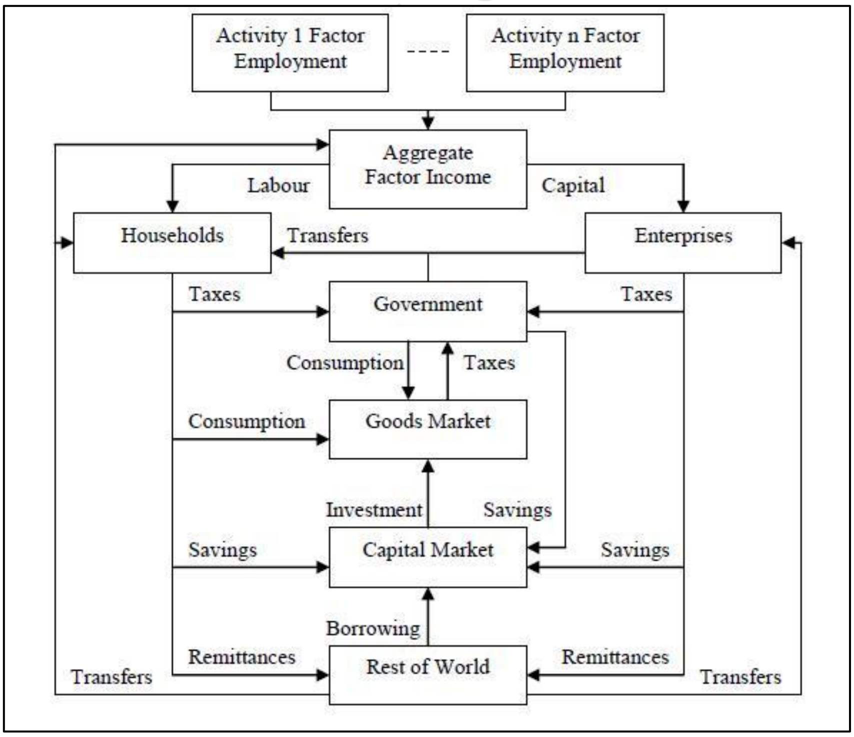

Figure9: Institutional Figures and Domestic Demand (Thurlow, 2004)

The factor income generated from production forms the primary source of income for households and enterprises (Thurlow, 2004). In addition, due to the model representing an open economy, household incomes consist of transfers from the government, other domestic institutions as well as from the rest of the world. Factor returns in South Africa have been found to differ across both occupations and sectors. In this light, the SAGE model utilizes a fixed activity-specific wage-distortion term combined with the economy-wide wage to generate activity-specific wages that are paid by each activity (Thurlow, 2004). There are a number of assumptions governing the factor market. Firstly, the supply of capital is fixed over a specific time-period, ie. fully employed, and is considered immobile across sectors (Thurlow, 2004). Hence, capital earns activity-specific returns. Secondly, all categories of labour are assumed to face upward-sloping labour supply curves, with wage elasticities determining supply adjustments that are caused by changes in real wages (Arndt, Davies, & Thurlow, 2011). Remittances are also received by factors from the rest of the world and therefore also contribute to factor incomes (Thurlow, 2004).

The SAGE model follows general equilibrium theory in that households within a certain income category are assumed to share identical preferences, and are therefore modelled as 'representative consumers' (Thurlow, 2004). According to this theory, equilibrium is reached when the representative household maximizes their utility subject to a budget constraint. The Stone-Geary utility function is used to define the consumer problem (Thurlow, 2004):

$$\text{Max}_i\, U_h = \prod_i (QH_{hi} - \gamma_{hi})^{\beta_{hi}} \qquad (19)$$

$$\text{Subject to} \qquad \sum_i (PQ_i \cdot QH_{hi}) = (1 - sh_h - th_h) \cdot YH_h \qquad (20)$$

In the model, each representative household has its own utility function, in which *QH* is the level of consumption of good *i*, γ is a committed (income-independent) level of consumption of good *i,* and β is the households' marginal budget share (Arndt, Davies, & Thurlow, 2011). Utility is maximized for the consumer subject to a budget constraint, in which *PQ* is the market price of each good, *YH* is total household income, and *sh* and *th* are marginal savings and direct income tax rates, respectively (Arndt, Davies, & Thurlow, 2011). By maximizing the above utility function subject to a household budget constraint, a linear expenditure system (LES) of demand is derived (Arndt, Davies, & Thurlow, 2011):

$$QH_{hi} = \gamma_{hi'} + \beta_{hi}\left[(1 - sh_h - th_h) \cdot YH_h - \sum_j (PQ_j \cdot \gamma_{hj)})\right] \cdot PQ_i^{-1} \text{ where } j \approx i \qquad (21)$$

The LES of demand represents the consumer preferences captured in the model, given prices and incomes. These demand functions define households' real consumption of each commodity (Thurlow, 2004). The LES specification is used in the model as it allows the identification of excess household income and therefore ensures a minimum level of consumption (Thurlow, 2004).

The government is considered to be a separate agent with income and expenditure, although it isn't considered to have any behavioural functions (Arndt, Davies, & Thurlow, 2011). Most of the income earned by the government is from direct and indirect taxes and its expenditure is assumed to be on consumption and household transfers (i.e., grants) (Thurlow, 2004). Total government revenue YG is shown below as the sum of all the individual taxes[9]:

$$YG = \sum_i (tq_i \cdot PQ_i \cdot QQ_i + tm_i \cdot pwm_i \cdot QM_i + te_i \cdot pwe_i \cdot QE_i + \sum_h (th_h \cdot YH_h) + \sum_{if} (tf_f \cdot WF_f \cdot QF_{if}) \qquad (22)$$

In the SAGE model, as in most CGE models, the tax rates are normally exogenous in order for them to be used to simulate policy changes (Arndt, Davies, & Thurlow, 2011).

The government's expenditure equation is given below, minus the transfers to households and firms for simplicity (Arndt, Davies, & Thurlow, 2011):

$$YG + wg = \sum_i (PQ_i \cdot QG_i) + GS \qquad (23)$$

where *QG* is consumption spending from equation 27 and *GS* is the government's recurrent fiscal surplus (or deficit if negative). *QG* is assumed to be found exogenously, which then implies that an increase in government revenues causes an expansion of the fiscal surplus (or deficit) (Arndt, Davies, & Thurlow, 2011).

Household and enterprise savings are collected into a 'savings pool' from which investment in the economy is financed (Thurlow, 2004). It is assumed in the model that government borrowing can diminish this supply of loanable funds and that capital inflows from the rest of the world are able to increase it (Thurlow, 2004). There is no specified behavioural function governing the level of investment demand in the model, although the model assumes that the total value of investment spending must equate the total amount of investible funds TI in the economy (Arndt, Davies, & Thurlow, 2011). It is assumed that there is no real compositional shift in investment following the changes in relative commodity prices (Thurlow, 2004):

$$TI = \sum_i PQ_i \cdot QI_i = \sum_i PQ_i \cdot qinv_i \cdot IA \qquad (24)$$

where *qinv* is the initial investment quantity for each good *i, PQ* is the market price derived from the equilibrium conditions in Equation 27, and *IA* is the endogenous proportional adjustment factor (Arndt, Davies, & Thurlow, 2011). The value of *QI* for each good *i* is assumed to be in fixed proportion to the initial quantity of investment (Arndt, Davies, & Thurlow, 2011).

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[9] A list of the various tax rates is provided in Appendix II

EQUILIBRIUM CONDITIONS

The SAGE model assumes full employment and factor mobility across sectors. Thus the following factor market equilibrium holds (Arndt, Davies, & Thurlow, 2011):

$$\sum_i QF_{if} = QFS_f \tag{25}$$

where *QFS* is fixed total factor supply. Assuming all factors are owned by households, household income *YH* is determined by (Arndt, Davies, & Thurlow, 2011):

$$YH_h = \sum_{if} \omega_{hf}(1 - tf_f) \cdot WF_f \cdot QF_{if} \tag{26}$$

where ω is a coefficient matrix determining the distribution of factor earnings to individual households, and tf is the direct tax on factor earnings (e.g., corporate taxes imposed on capital profits).

Lastly, commodity market equilibrium requires that the composite supply of each good *QQ* equals total demand as shown below (Arndt, Davies, & Thurlow, 2011):

$$QQ_i = \sum_h QH_{hi} + QI_i + QG_i + \sum_j (io_{ji} \cdot QA_i) \tag{27}$$

MACROECONOMIC CLOSURES AND ASSUMPTIONS

The model is set up with a number of closures that govern the macro adjustments in the model. The selection of appropriate closures should ensure that the model reacts to shocks in a way that is representative of the real economy under investigation. There are considered to be three broad macroeconomic accounts in the SAGE model: the current account, the government balance and the savings and investment account (Thurlow, 2004). The macroeconomic balance in the SAGE model is governed by a number of closure rules, which provide a mechanism through which adjustments are made to maintain this balance, or equilibrium (Arndt, Davies, & Thurlow, 2011).

According to Arndt, et al. (2011), the current account is considered to be the most important of these macro accounts. A substantial amount of research pours into this topic, although in this case due to the single-country open economy CGE model it is considered an exogenous variable (Arndt, Davies, & Thurlow, 2011). It is assumed that a flexible exchange rate adjusts in order to maintain a fixed level of foreign borrowing for the current account macro closure rule (Thurlow, 2004). South Africa's firm commitment to a flexible exchange rate system and idea that foreign borrowing is unlimited ensure that the chosen closure rule is realistic (Thurlow, 2004).

The second closure rule concerns the government balance. The government consumption spending in the SAGE model is considered to be exogenous. In response to this the fiscal balance, or government savings are flexible and adjust accordingly (Arndt, Davies, & Thurlow, 2011).

The third closure rule, perhaps the least obvious, involves the choice of a savings-investment closure (Thurlow, 2004). The relationship between savings and investment continues to be a highly debated and controversial topic in macroeconomics (Nell, 2003). Neo-classical along with 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), recent works have 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, Davies, & Thurlow, 2011). Although, the addition of dynamics increases the complexity of this relationship to an extent; a more detailed description of the dynamics will follow.

Along with these three macroeconomic accounts, a factor market closure exists in the model. The various factors in the economy require specification in terms of how they are to be treated in the model. The SAGE model assumes full employment for high-skilled labour and unemployment amongst low-skilled labour with labour being mobile across sectors - a suitable closure for the South African context (Pauw, 2007). Capital stock is assumed to be fully-employed and activity-specific, as the simulations impose a structural shift on production capacity. Land is assumed to be fixed and immobile as it is generally treated.

The consumer price index is assumed to be the numeraire in the SAGE model (Arndt, Davies, & Thurlow, 2011). In other words, all prices are considered 'relative to the weighted unit price of household's initial consumption bundle' (Arndt, Davies, & Thurlow, 2011).

BETWEEN-PERIOD SPECIFICATION/ DYNAMIC MODEL

The preceding chapter described the country specific static model for South Africa in detail. This model, however, is unable to account for inter-temporal iterations and is therefore too limited on its own for the purpose for this thesis. The between-period specification, as previously mentioned, outlines the dynamic component of the SAGE model. The static model is extended to a dynamic recursive model in which a number of parameters update according to exogenous behavioural changes over time as well as the results from previous periods (Arndt, Davies, & Thurlow, 2011). This differs from the static model which is endogenously dependent on past outcomes and does not take into account future expectations (Thurlow, 2004).

There are a number of exogenous behavioural trends that are imposed on the SAGE model. According to Arndt, et al. (2011), factor supplies and productivity, represented by QFS and α^p respectively, are considered to be the most important of these trends. These exogenous variables are updated in the SAGE model using the following dynamic equations (Arndt, Benfica, Tarp, Thurlow, & Uaiene, 2008):

$$QFS_{ft+1} = QFS_{ft} \cdot (1 + grf_{ft}) \text{ where } f \neq k \qquad (28)$$

$$\alpha^p_{it+1} = \alpha^p_{it} \cdot (1 + grp_{it}) \qquad (29)$$

$$QG_{it+1} = QG_{it} \cdot (1 + grg_t) \qquad (30)$$

where *t* represents time (in the case years), *k* is a subset of *f* that contains the capital factor, *grf* is the change in supply for factor *f* in time period *t, grp* is the rate of change in government recurrent spending (Arndt, Davies, & Thurlow, 2011).

Capital supply is excluded from the above equation for factor supply as it is assumed to be based on previous period results. According to Thurlow (2004), the process of capital accumulation is modelled endogenously as investment levels from previous time periods generate new capital stocks. Capital is considered to be immobile and sector-specific in the SAGE model. This in turn implies that the returns on capital in each sector are allowed to differ (Arndt, Davies, & Thurlow, 2011). Therefore a sector-specific wage distortion term was introduced into the SAGE model. This term is attached to the factor return variable *WF,* therefore changing equations 8, 22 and 26 by including this term (Arndt, Davies, & Thurlow, 2011). The wage distortion term is an adjustment factor, at first it is assigned the value of one, although an increase in sectoral capital demand would cause *WD* to rise above one and a decrease would cause a drop below one (Arndt, Davies, & Thurlow, 2011).

The capital stock updating equation is therefore defined at sector level and given by:

$$QF_{ikt+1} = (1 - d) \cdot QF_{ikt} + QK_{ikt} \quad \text{where} \quad NK_{ikt} = SK_{ikt} \cdot \frac{TI_t}{PK_t} \qquad (31)$$

The new capital allocation parameter, *SK,* denotes the amount of new investment that is allocated to each sector *QK* and thus sums to one (Arndt, Davies, & Thurlow, 2011). The approach of Dervis et al. (1982) is adopted in the SAGE model, defining SK as:

$$SK_{ikt} = SP_{ikt} + \tau \cdot SP_{ikt} \left(\frac{WD_{ik} \cdot WF_k - AR_t}{AR_t} \right) \qquad (32)$$

where *SP* is the current sectoral share of aggregate profits and AR represents the economy-wide average profit rate (Arndt, Davies, & Thurlow, 2011). According to this specification, new capital across sectors is determined by each sector's initial share of aggregate capital income, and adjusted by the capital depreciation rate and by previous period sectoral profit-rate differentials (Thurlow, 2004). Hence, sectors that boast above average capital returns are allocated a larger share of investible funds than their share of capital income, the converse is true for sectors with below average capital returns (Dervis, de Melo, & Robinson, 1982). Investment allocation in the SAGE model is 'known as a "putty-clay" specification, since new capital is mobile, but once invested becomes sector specific' (Arndt, Davies, & Thurlow, 2011).

Growth projections for population are exogenously calculated and imposed onto the SAGE model. Population growth is assumed to increase the level of consumption demand which in turn results in higher 'supernumerary' income levels of household consumption (Thurlow, 2004). The new consumers that enter the market through this population growth are assumed to have the same preferences as the existing consumers in the market (Thurlow, 2004).

Real government consumption growth and transfer spending are determined exogenously and updated every period based on exogenous trends (Arndt, Davies, & Thurlow, 2011). Factor specific productivity growth is also calculated exogenously from observed trends for labour and capital and forced on the model (Thurlow, 2004). Apart from the aforementioned, the rest of parameters in the SAGE model are either fixed values or fixed proportions of endogenous variables in the dynamic model (Arndt, Davies, & Thurlow, 2011).

The components of the SAGE dynamic model have now been explained in detail. The recursive dynamic system involves the model being solved as a 'series of equilibriums'. Each equilibrium in this case corresponding to a specific year (Thurlow, 2004). This series of equilibriums produces an anticipated growth path that is assumed to be the baseline growth path of the model. By altering certain exogenous parameters in the model and re-solving the model for a new series of equilibriums one can simulate specific policy changes in the economy and present their corresponding simulated growth paths. The differences between the baseline and the simulated growth paths can be viewed as the economy-wide impact of the simulated policy (Thurlow, 2004).

THE ENERGY EXTENSION OF THE SAGE MODEL

The dynamic SAGE model has now been explained in detail. Although this is a core model that was put forward with the intention of policy makers and individual researchers adapting it according to their specific policy and research needs, respectively (Thurlow, 2004). The energy extension to the SAGE model, presented by (Arndt, Davies, & Thurlow, 2011) provides one such adaptation of the SAGE model. The core SAGE model was adapted to mirror the structure and workings of the South African energy sector (Arndt, Davies, & Thurlow, 2011). The core model was extended in two main areas for this to be done. Firstly, the energy sector was disaggregated in order to follow the complete life cycle of fuels within the economy; in other words to enable one to model the 'flow of primary fuels to the transformation subsectors, and from distribution to final energy users' (Arndt, Davies, & Thurlow, 2011). The second extension allows firms to switch to investing in lower energy-intensive technologies in an attempt to adapt to higher energy prices (Arndt, Davies, & Thurlow, 2011).

The SAGE model was disaggregated to replicate the structure of the South African energy sector, as illustrated below:

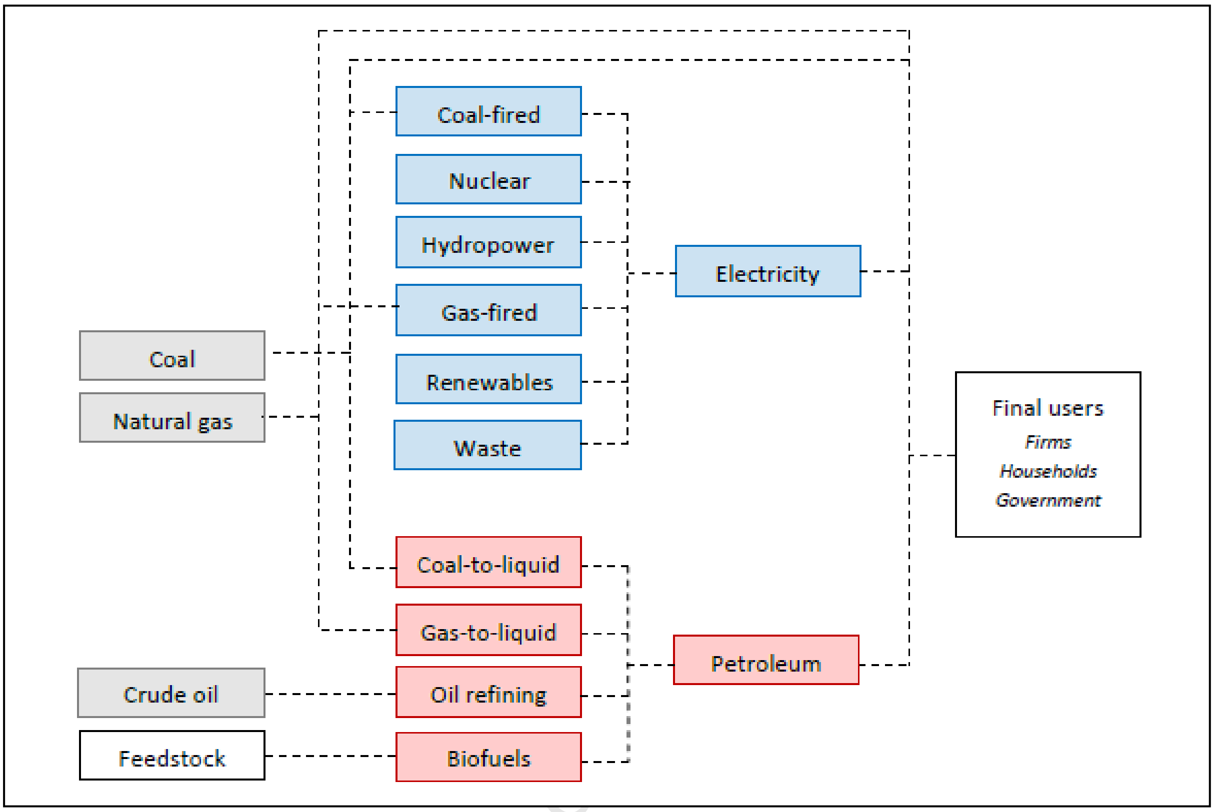


Figure 10: Structure of the energy sector in the energy extension to the SAGE model (Arndt, Davies, & Thurlow, 2011)

One can see from the diagram above that South Africa's three main primary fossil fuels are coal, natural gas and crude oil. Coal and natural gas already exist as separate accounts in the SAGE model and oil crude oil is assumed to be imported and supplied to the petroleum sector for refining (Arndt, Davies, & Thurlow, 2011). Three main sectors are identified in the SAGE model as the demanders of these primary fuels: the electricity sector, the refined petroleum sector and the final users (Arndt, Davies, & Thurlow, 2011). The electricity and refined petroleum sectors are disaggregated as shown in the figure above in order for the model to realistically simulate the energy sector. From table [] it can be seen that the bulk of South Africa's non-exported coal is used in the electricity sector to produce electricity, although a small amount is used directly by producers and households. In terms of natural gas, a quarter of natural gas is imported and approximately a third of the total usage is in the electricity and petroleum sectors.

Electricity is defined as a single commodity in the SAGE model comprised of each electricity subsector's (i.e. nuclear, hydropower, etc.) separate supply onto the national grid. Table [] compiles the amounts of electricity produced by each of these six electricity subsectors. The model assumes that each of these subsectors has their own distinctive production technology, based on estimates from an earlier study by Kallie Pauw (2007). It is also assumed that each subsector requires a different mix of factor inputs (Arndt, Davies, & Thurlow, 2011). Hence, there are a number of different electricity 'activities' and a sole electricity commodity. This is a realistic assumption as consumers in South Africa are not able to demand certain 'types' of electricity as it all comes from the national grid, electricity subsectors have very different supply processes and costs.

In terms of the petroleum sector, four potential sources of petroleum product and one petroleum commodity is assumed, using the same logic as was explained for the electricity sector (Arndt, Davies, & Thurlow, 2011). Table 6 shows that most refined petroleum is produced from imported crude oil, although a significant amount is gained from the "coal-to-liquids" (CTL) and "gas-to-liquids" (GTL) conversion processes (Arndt, Davies, & Thurlow, 2011). Although, no biofuels were produced in 2005, a biofuels sector was included in the extension to the SAGE model to allow for potential future biofuels production (Arndt, Davies, & Thurlow, 2011).

There are a number of adjustments that were made in order to allow multiple energy subsectors to produce the same commodity. The production functions from equation 6, the updated dynamic version of equation 8 and equation 9 are adapted to:

$$QAS_{is} = \alpha_{is}^{p} \left(\sum_f \delta_{isf}^{p} \cdot QF_{isf}^{-p_{is}^{p}} \right)^{-1/p_{is}^{p}} \tag{33}$$

$$QF_{isf} = \alpha_{is}^{p^{\frac{p_{is}^{p}}{1+p_{is}^{p}}}} \cdot QAS_{is} \left(\delta_{isf}^{p} \cdot \frac{PV_{is}}{WD_{isf} \cdot WF_f} \right)^{1/(1+p_{is}^{p})} \tag{34}$$

$$PAS_{is} = PV_{is} + \sum_j PQ_j io_{ijs} \tag{35}$$

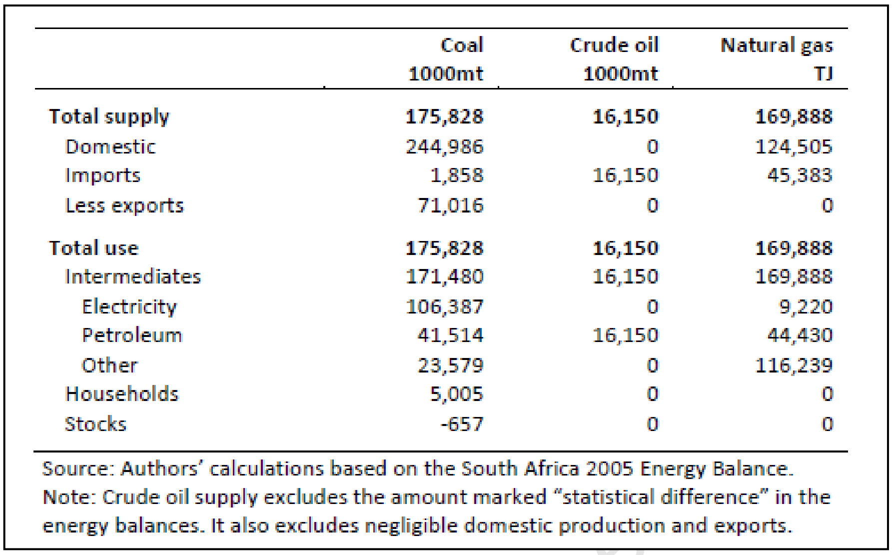
where *QAS* is the output of subsector s within aggregate sector *i, PAS* is the subsector producer price, and *io* reflects each subsector's unique production technology. Factor demands *QF* are also defined at sector level.

In order to replicate the economy, 'total sector output *QA* is governed by a CES aggregation function, which favours subsectors that are capable of producing the energy commodity at a lower price than other subsectors' (Arndt, Davies, & Thurlow, 2011). The aggregation function, as well as its corresponding first order conditions, is shown below:

$$QA_i = \alpha_i^{s} \left(\sum_s \delta_{is}^{s} \cdot QAS_{is}^{-p_i^{s}} \right)^{-1/p_i^{s}} \tag{36}$$

$$PAS_{is} = PA_i \cdot QA_i \cdot \sum_{s'} \left(\delta_{is'}^{s} \cdot QAS_{is'}^{-p_i^{s}} \right) \cdot \delta_{is}^{s} \cdot QAS_{is}^{-p_i^{s}-1} \tag{37}$$

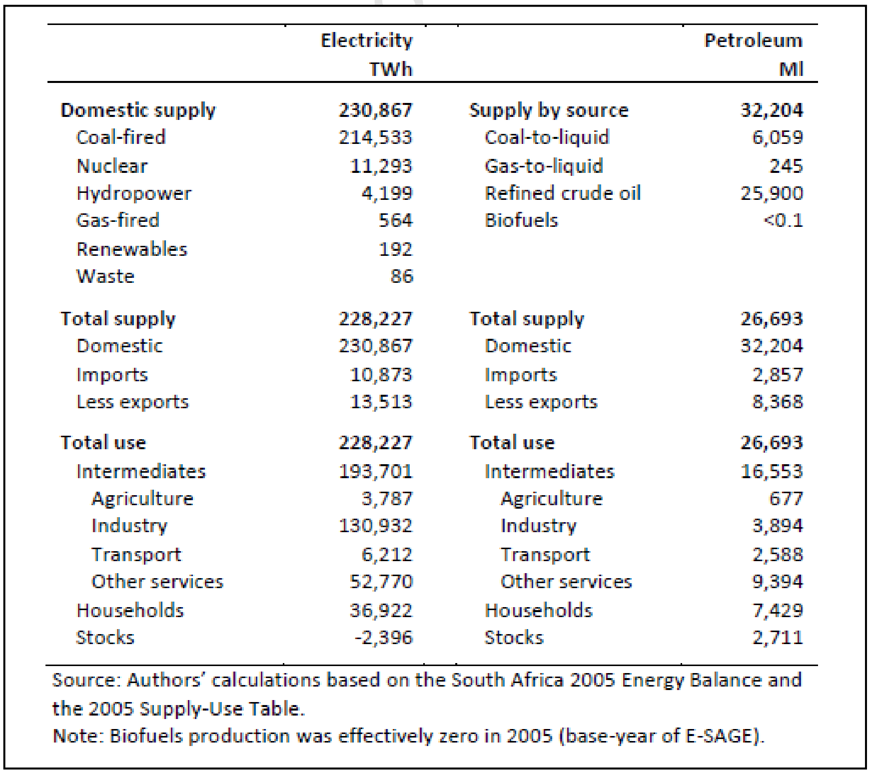
A high elasticity of substitution is assumed to exist between energy subsectors in order to replicate their product homogeneity (Arndt, Davies, & Thurlow, 2011). However, switching between different energy subsectors is constrained by the fixed installed capital in each subsector, due to the immobility of this capital (Arndt, Davies, & Thurlow, 2011). The speed at which South Africa can exchange between energy sources is determined by new capital investment as installed capital is assumed to depreciate at a fixed rate (Arndt, Davies, & Thurlow, 2011). In the current extension to the SAGE model, new investment in each subsector is determined exogenously and follows the Integrated Resource Plan (IRP) (Arndt, Davies, & Thurlow, 2011).



	Coal 1000mt	Crude oil 1000mt	Natural gas TJ
Total supply	**175,828**	**16,150**	**169,888**
Domestic	244,986	0	124,505
Imports	1,858	16,150	45,383
Less exports	71,016	0	0
Total use	**175,828**	**16,150**	**169,888**
Intermediates	171,480	16,150	169,888
Electricity	106,387	0	9,220
Petroleum	41,514	16,150	44,430
Other	23,579	0	116,239
Households	5,005	0	0
Stocks	-657	0	0

Source: Authors' calculations based on the South Africa 2005 Energy Balance.
Note: Crude oil supply excludes the amount marked "statistical difference" in the energy balances. It also excludes negligible domestic production and exports.

Table 6: Supply and use of primary fuels in the energy extension to the SAGE model in 2005 (Arndt, Davies, & Thurlow, 2011)



	Electricity TWh		Petroleum Ml
Domestic supply	**230,867**	**Supply by source**	**32,204**
Coal-fired	214,533	Coal-to-liquid	6,059
Nuclear	11,293	Gas-to-liquid	245
Hydropower	4,199	Refined crude oil	25,900
Gas-fired	564	Biofuels	<0.1
Renewables	192		
Waste	86		
Total supply	**228,227**	**Total supply**	**26,693**
Domestic	230,867	Domestic	32,204
Imports	10,873	Imports	2,857
Less exports	13,513	Less exports	8,368
Total use	**228,227**	**Total use**	**26,693**
Intermediates	193,701	Intermediates	16,553
Agriculture	3,787	Agriculture	677
Industry	130,932	Industry	3,894
Transport	6,212	Transport	2,588
Other services	52,770	Other services	9,394
Households	36,922	Households	7,429
Stocks	-2,396	Stocks	2,711

Source: Authors' calculations based on the South Africa 2005 Energy Balance and the 2005 Supply-Use Table.
Note: Biofuels production was effectively zero in 2005 (base-year of E-SAGE).

Table 7: Supply and use of electricity and petroleum in the energy extension to the SAGE model in 2005 (Arndt, Davies, & Thurlow, 2011)

Lastly, labour is assumed to be mobile across sectors, as well as subsectors, which implies that the previously given factor market equilibrium must be revised to equate subsector demands QF with total factor supply QFS. In the same regard, total household incomes are updated to be the sum of subsector earnings. These two modifications are given below:

$$\sum_{is} QF_{isf} = QFS_f \tag{38}$$

$$YH_h = \sum_{isf} \omega_{hf}(1 - tf_f) \cdot WF_f \cdot WD_{isf} \cdot QF_{isf} \tag{39}$$

ENDOGENOUS ENERGY INPUT DEMAND

The core SAGE model has been extended so that non-energy producers are able to respond to changes in energy prices by switching investment to less-energy intensive capital and production technologies between-periods (Arndt, Davies, & Thurlow, 2011). The following equation is included in the model to allow this behaviour:

$$io_{iset+1} = \left[1 - \left(1 - \frac{PQ_{et}^{-p_e^k}}{pq_e^o}\right) \cdot \mu_{ist}\right] \cdot io_{iset} \tag{40}$$

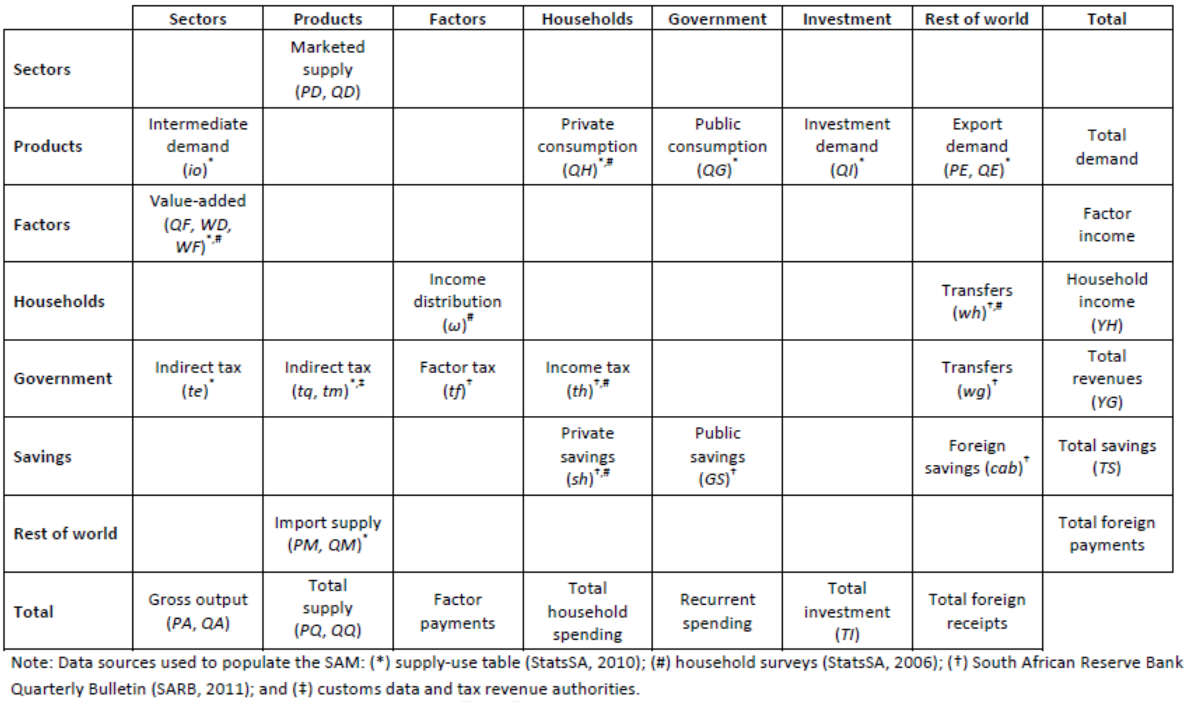
$$\mu_{ist} = \sum_k QK_{ikst} / \sum_k QF_{iskt} \tag{41}$$

where a producers' current intermediate demand *io* for energy commodity *e* depends on previous period energy demand adjusted for changes in energy market prices PQ relative to the base year energy price pq^0 (Arndt, Davies, & Thurlow, 2011). A sector's responsiveness to fluctuations in energy prices depends on the share of new investment QK in the sector's total capital stock. As previously explained, the allocation of new capital was determined in eq 22' and 23 (Arndt, Davies, & Thurlow, 2011). The adjustment of more energy-intensive technologies in a specific sector therefore necessitates new capital investments. In light of this, sectors that have slower growth rates and are less profitable find it harder to adjust to higher energy prices (Arndt, Davies, & Thurlow, 2011).

DATA SOURCES, ASSUMPTIONS AND MODEL CALIBRATION

According to Arndt, et al (2011), one of the main advantages that CGE models hold over theoretical models is that they can be calibrated to detailed empirical data. In other words, the model's parameters and variables can be assigned values using real observed country-specific data. Although, it is crucial to analyse the data that is used as input into any model, as a model can only be as accurate as the data it is based on.

In CGE modelling the main data source is the social accounting matrix (SAM). This is true for the SAGE model, where the values of almost all the variables and parameters are currently drawn from a 2005 SAM (Arndt, Davies, & Thurlow, 2011). A SAM is a comprehensive, economy-wide data framework. It is a square matrix in which each account is represented by a row and a column and it 'captures all income and expenditure flows between producers, consumers, the government and the rest of the world over a particular year' (Arndt, Davies, & Thurlow, 2011).



	Sectors	Products	Factors	Households	Government	Investment	Rest of world	Total
Sectors		Marketed supply (*PD*, *QD*)						
Products	Intermediate demand (*io*)*			Private consumption (*QH*)$^{*,\#}$	Public consumption (*QG*)*	Investment demand (*QI*)*	Export demand (*PE*, *QE*)*	Total demand
Factors	Value-added (*QF*, *WD*, *WF*)$^{*,\#}$							Factor income
Households			Income distribution (ω)$^{\#}$				Transfers (*wh*)$^{\dagger,\#}$	Household income (*YH*)
Government	Indirect tax (*te*)*	Indirect tax (*tq*, *tm*)*,‡	Factor tax (*tf*)†	Income tax (*th*)$^{\dagger,\#}$			Transfers (*wg*)†	Total revenues (*YG*)
Savings				Private savings (*sh*)$^{\dagger,\#}$	Public savings (*GS*)†		Foreign savings (*cab*)†	Total savings (*TS*)
Rest of world		Import supply (*PM*, *QM*)*						Total foreign payments
Total	Gross output (*PA*, *QA*)	Total supply (*PQ*, *QQ*)	Factor payments	Total household spending	Recurrent spending	Total investment (*TI*)	Total foreign receipts	

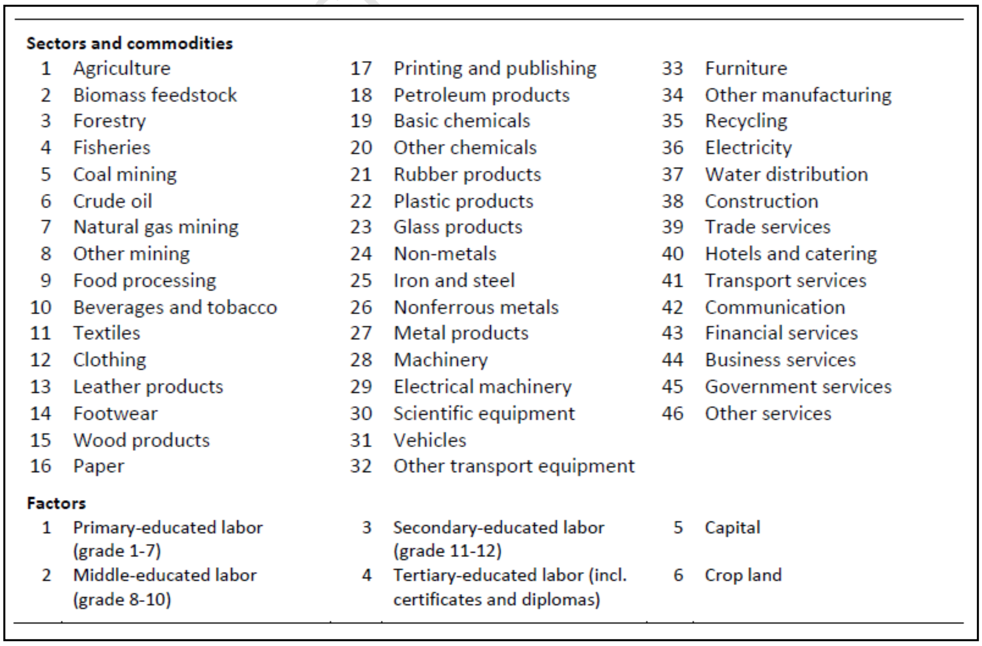
Note: Data sources used to populate the SAM: (*) supply-use table (StatsSA, 2010); (#) household surveys (StatsSA, 2006); (†) South African Reserve Bank Quarterly Bulletin (SARB, 2011); and (‡) customs data and tax revenue authorities.

Table 8: Structure of the core social accounting matrix (Arndt, Davies, & Thurlow, 2011)

The SAM is a representation of all the monetary flows in the economy. There are 'accounts' in the SAM that correspond to the different 'actors' in the economy. Namely, sectors (producers), factors, government, and the rest of the world. The rows and the columns in the SAM represent incomes and payments, respectively, from one account to another (Arndt, Davies, & Thurlow, 2011). The SAM also represents an equilibrium whereby, as with double-accounting, payments must be equal to the receipts – the row totals must be equal to the column totals. In light of this, the SAM is considered the base year equilibrium state for the SAGE model.

In terms of constructing the SAM used in the SAGE model, there were three main data sources. Firstly, the national supply-use table produced by Statistics South Africa (2010). The supply-use table provides balanced commodity demand and supply for the base year, 2005, including 'disaggregated government and investment demand across products' (Arndt, Davies, & Thurlow, 2011). The technical coefficients are used to calculate 'intermediate demand based on sectors' level of gross output' (Arndt, Davies, & Thurlow, 2011). The table also provides 'detailed information on imports and exports' as well as data on trade margins (Arndt, Davies, & Thurlow, 2011). Secondly, the national accounts produced by the South African Reserve Bank (2010) are used in constructing the SAM. The national accounts are used to complete specific cells that are not covered in the supply-use tables, such as data on tax rates, government revenues and expenditures, as well as detailed information on GDP (Arndt, Davies, & Thurlow, 2011). The balance of payments is utilized in compiling the 'rest-of-the-world account, which includes information on the current account, transfer receipts and payments (Arndt, Davies, & Thurlow, 2011). Lastly, the nationally representative 2005 household income and expenditure survey (IES) is used in compiling the SAM. The household survey provides detailed information that allows the disaggregation of labour into different education groups for use in the SAM. The survey, along with the government account, is used to establish the 'level and distribution of social transfers' (Arndt, Davies, & Thurlow, 2011). Information on household's expenditure patterns as well as the distribution of factor incomes is also captured from these surveys (Arndt, Davies, & Thurlow, 2011). The household account is highly disaggregated in the SAGE model, with '14 household groups represented based on their level of per capita consumption spending' (Arndt, Davies, & Thurlow, 2011) . Hence the IES is the foremost determinant of 'differential income and distributional effects across household groups in the SAGE model' (Arndt, Davies, & Thurlow, 2011).

Data compilation represents the first stage in constructing the SAM. The second stage is to balance the SAM, as there are inevitably discrepancies between the incomes and expenditures from the household surveys (Arndt, Davies, & Thurlow, 2011). Arndt, et al. (2011), used the Bayesian approach, which essentially describes a method of decision making in light of incomplete or imperfect information (Robinson, Cattaneo, & El-Said, 2001). Mathematical assumptions are made about the likely content in the absence of data and as this data is gathered the Bayesian approach reiews the assumptions and decision making accordingly. In this case, a 'cross-entropy distance measure' was used to 'minimise the deviation in the balanced SAM from the unbalance initial SAM containing the original data' (Arndt, Davies, & Thurlow, 2011).



Sectors and commodities					
1	Agriculture	17	Printing and publishing	33	Furniture
2	Biomass feedstock	18	Petroleum products	34	Other manufacturing
3	Forestry	19	Basic chemicals	35	Recycling
4	Fisheries	20	Other chemicals	36	Electricity
5	Coal mining	21	Rubber products	37	Water distribution
6	Crude oil	22	Plastic products	38	Construction
7	Natural gas mining	23	Glass products	39	Trade services
8	Other mining	24	Non-metals	40	Hotels and catering
9	Food processing	25	Iron and steel	41	Transport services
10	Beverages and tobacco	26	Nonferrous metals	42	Communication
11	Textiles	27	Metal products	43	Financial services
12	Clothing	28	Machinery	44	Business services
13	Leather products	29	Electrical machinery	45	Government services
14	Footwear	30	Scientific equipment	46	Other services
15	Wood products	31	Vehicles		
16	Paper	32	Other transport equipment		
Factors					
1	Primary-educated labor (grade 1-7)	3	Secondary-educated labor (grade 11-12)	5	Capital
2	Middle-educated labor (grade 8-10)	4	Tertiary-educated labor (incl. certificates and diplomas)	6	Crop land

Table 9: Sectors, commodities and factors in the 2005 social accounting matrix (Arndt, Davies, & Thurlow, 2011)

The aforementioned data sources provide nearly all of the data needed to calibrate the SAGE model, only the 'behavioural elasticities' are not provided by these data sources (Arndt, Davies, & Thurlow, 2011). The following section will discuss how these behavioural elasticities are determined.

BEHAVIOURAL ELASTICITIES AND OTHER EXTERNAL DATA

As previously noted, the consumption, production and trade functions all require behavioural elasticites. Behavioural elasticities can be thought of as the quantification of the responsiveness of a variable to a change in another variable. For example, the responsiveness of consumers to changes in the price of a good.

The factor subtitution elasticities that are found in the production functions, _ in equation 2 for example, are difficult to estimate in developing countries, as there generally are no 'reliable country-specific estimates' in existence (Arndt, Davies, & Thurlow, 2011). In light of this Arndt et al (2011) chose to assume that there was an elastic factor subtitution for most activities. This methodology is analogous to the recent findings from the 'meta-analyses of econometrically estimated elasticities' (Boys & Florax, 2007) as well as with the general methodology used in cross-country econometric analysis (Arndt, Benfica, Tarp, Thurlow, & Uaiene, 2008)

The responsiveness of producers and consumers to movements in relative prices when choosing whether or to source goods to and from foreign markets is governed by trade elasticities. When foreign and domestically produced goods are considered homogenous, agents in the market are less likely to have differences in preferences between foreign and domestically produced goods. In light of this the higher elasticities are expected for these types of goods, for example metals and grains. The converse is true for goods, such as motor vehicles, that are considered to be highly differentiated, and therefore these goods are assigned low elasticities. In the SAGE model the trade elasticities, one for imports and one for exports, were determined using the global estimates found in Dimaranan (2006).

In terms of income elasticities, the SAGE model utilised income elasticities that were derived as econometric estimates (Case, 2000). The estimated income elasticities are used, in combination with the average budget shares that are taken directly from the SAM, to determine the 'marginal budget shares' that are used in the SAGE model.

INITIALISING THE MODEL PARAMETERS

The SAGE model is initialized using the aforementioned data sources and therefore, due to the use of a 2005 SAM, the base run of the static model represents the South African economy in 2005.This section provides a brief overview of the economy and the electricity sector linkages that exist in the base year, 2005.

South Africa’s electricity sector, was in 2005 and still remains highly reliant on the burning of fossil fuels for electricity generation, far more so than the global reliance – as shown below in figure 10. This is due to the fact that investment in power generation in South Africa has, historically, always been orientated towards coal for two main reasons. Firstly, it was the cheapest option and secondly South Africa has large resources of coal and therefore this option presented a form of energy security (Eberhard, 2004).In 2005 coal-fired plants accounted for approximately 93% of electricity generation, compared to the global figure of 40%. The remaining 7% comprised of 5% nuclear, under 2% of hydo-power and a negligible amount of renewables, waste and gas.

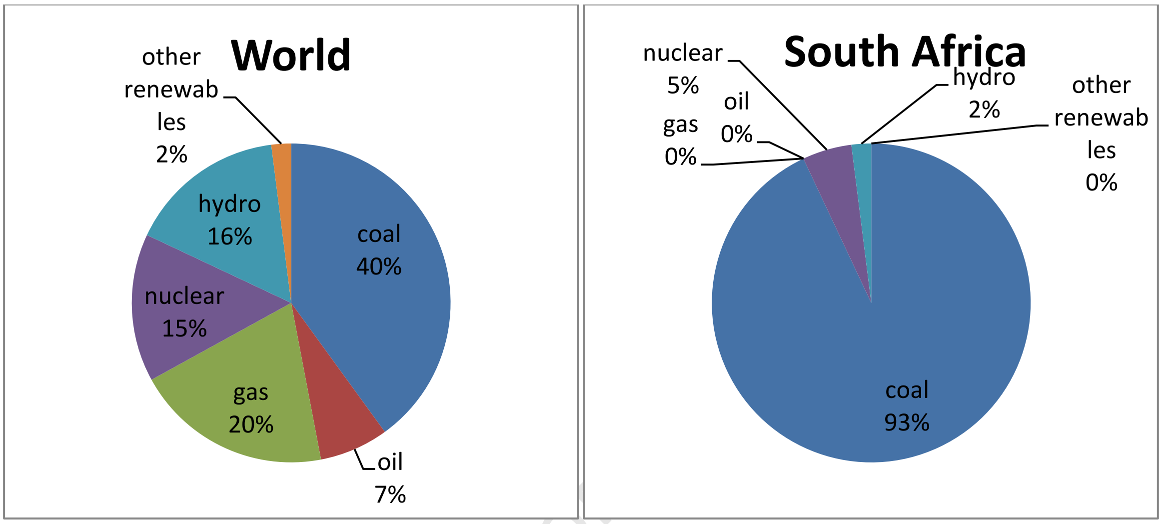
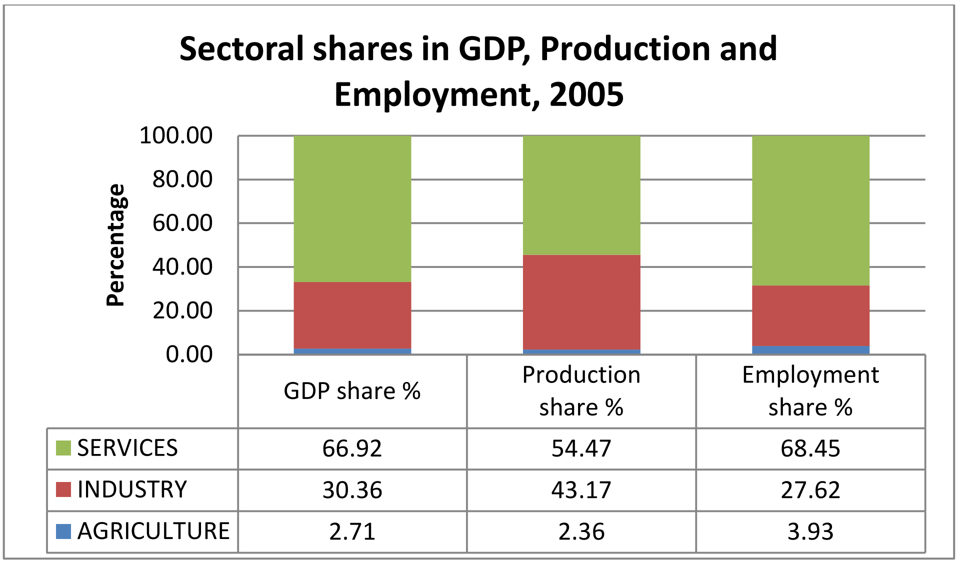


Figure 11: Sources of Electricity of the World and for South Africa

[Data Source: IEA, cited in the Stats SA Energy Reports for South Africa, 2005]

KEY SECTORAL INDICATORS

South Africa has historically been industry orientated as a consequence of historic regimes and incentives. These incentives consisted of South Africa’s relatively cheap electricity as well as other financial incentives. The service industry, however, gained momentum and as is shown in the figure below, contributed a higher share to GDP than the industrial sector in 2005, with 66,9% and 30,4% respectively. The service industry possess a 54,47% share of production, slightly higher than that of the industrial sector. In terms of employment, the service sector trumps the industrial sector once again with a 68,5% share of employment compared to the industrial sector with 27,62%. The agricultural sector is rather insignificant in comparison with a 2,7% contribution to GDP, 2,4% share in production, and due to the sector’s labour intensity 3,9% employment share.



	GDP share %	Production share %	Employment share %
🟩 SERVICES	66.92	54.47	68.45
🟥 INDUSTRY	30.36	43.17	27.62
🟦 AGRICULTURE	2.71	2.36	3.93

Figure 12: Sectoral shares in GDP, production and employment in 2005

PRODUCTION LINKAGES

The production linkages in the SAGE model are determined using the 2005 SAM, as previously explained. Acquiring an understanding of the production linkages that exist within the model is crucial as it provides a base when analysing the results of the model. The proportions of these linkages, found in the SAM, provide the basis for which the endogenous growth of sectors in the economy is determined, in the absence of an exogenous shock. This section will provide a brief overview of the backward and forward production linkages that exist in the electricity sector in the base year 2005.

BACKWARD LINKAGES

Backward linkages can be defined as the flow of inputs into the production process of a sector, or in this case the share of inputs into the production of electricity. There are very few significant inputs into the electricity sector, apart from the proportion of coal that is sold to the electricity sector. The electricity sector purchased 62% of the total industry sales of coal in 2005, which represents 43% of the total output value for the coal sector. The electricity sector also required 9,2% of the total electricity provided to industries, equivalent to 7% of the sectors total output. The purchases of natural gas by the electricity sector accounts for 5,4% of the sectors total industry sales and 5% of its output in the base year. The final significant backward linkage is between the electricity sector and the electrical sector. In the base year purchases of electrical machinery from the electricity sector corresponded to 6% of the total industry's output and 9,2% of total industry sales.

	Electricity % of total industry sales	Electricity % share sector totals	Electricity % share domestic sales
Coal	62.0%	43%	61%
Natural gas	5.4%	5%	5%
Petroleum	0.8%	0%	0%
Metal products	0.6%	1%	1%
Machinery	0.6%	0%	0%
Electrical machinery	9.2%	6%	6%
Electricity	8.4%	7%	7%
Trade services	1.7%	0%	0%
Financial services	1.3%	1%	1%

Table 10: Electricity sector purchases as a percentage of total industry sales, sector totals and domestic sales.

FORWARD LINKAGES

Forward linkages represent the flow of output from one sector into other sectors, in this case illustrated as the share of electricity in the cost structure of other sectors. The share of electricity in the total cost of sectors in South Africa is in no way trivial in the base year, although with the recent electricity prices increases this proportion is likely to be more substantial and representative of sectoral reliance on electricity. That being said, there are a number of sectors in the base year that allocated a significant portion of their expenditure to electricity. The basic chemicals sector allocated 9,8% of their total expenditure to electricity, which represents 12,5% of the sectors spending on intermediate inputs. The amount spent on electricity by the electricity sector itself represents 7,1% of the sector's total expenditure, a substantial 13,8% of the sector's purchase value for intermediate inputs. The iron and steel sector as well as the nonferrous metals sector contributed a significant proportion of their expenditure on intermediate inputs on electricity, equating to 6,4% and 8,5% respectively. The glass products sector also spent a significant proportion on electricity at 7,3% of their total expenditure on intermediate inputs and 5,1% of their total costs. The coal mining sector allocated 3,5% and 1,5% of total expenditure on intermediate inputs, and total sectoral expenditure, respectively, to electricity. Intuitively this value seems quite low for this sector, although, as previously mentioned, this may be due to the low cost of electricity in the base year, 2005. These sectors mentioned above are likely to be most affected by electricity price hikes due to their relatively high proportions of expenditure on electricity.

	Coal	Basic Chemicals	Glass Products	Iron and Steel	Non-Ferrous Metals	Electricity
Electricity % of total cost	1.5%	9.8%	5.1%	5.1%	6.1%	7.1%
Electricity % of intermediates cost	3.5%	12.5%	7.3%	6.4%	8.5%	13.8%

Table 11: Purchases of electricity as a percentage of total sector costs

ELECTRICITY DEMAND

Electricity demand in South Africa is mainly comprised of intermediate demand for the production of goods and provision of services. Electricity demand in the base year was broken up into 80 % of demand from commodities, or intermediate sectors, 15% from households and 5% from the rest of the world, in terms of export demand.

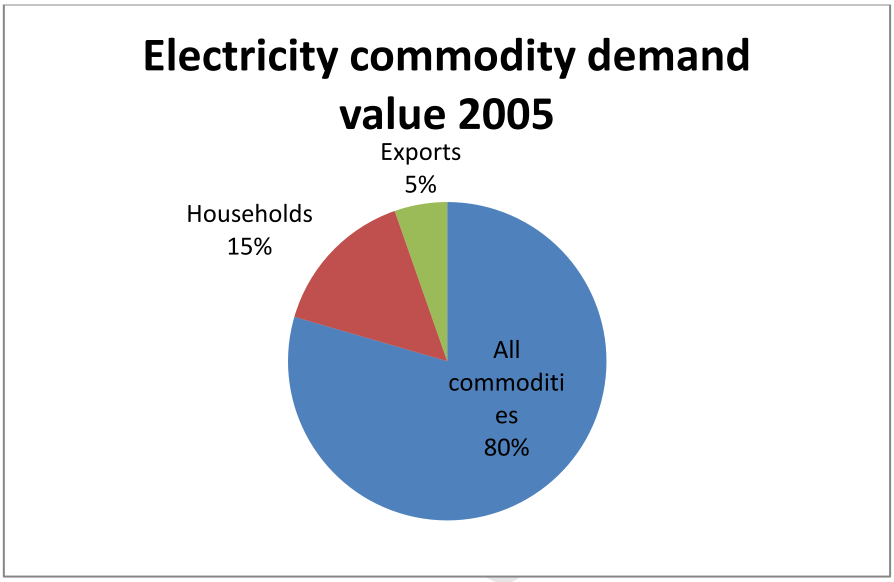


Figure 13: Electricity demand split, 2005

The 80% allocated to the intermediate demand for electricity can be broken down further. Industry accounts for nearly 68% of total intermediate demand for electricity. Manufacturing is the main contributor with almost two-thirds of the industry demand. This demand is mainly from the chemical and metal sectors. The remaining third is mainly comprised of mining and electricity, each with almost equal shares. The service sector demand accounts for just over 30% of total intermediate demand in electricity, approximately half of which stems from the business services sector.

ELECTRICITY SECTOR INVESTMENT GOODS

The electricity sector is assumed to have an investment split over a number of investment goods as is illustrated in figure 11. Construction accounts for the biggest proportion of investment in the electricity sector with 37,7%, followed by the machinery sector with 25,3% and vehicles with 15,7%. The remainder of the total investment, less than 22%, allocated to the remaining 5 sectors, as illustrated in the diagram above. It is important to note that these proportions are likely to change over the period as investment in the dynamic model is determined according to profit-rate differentials.

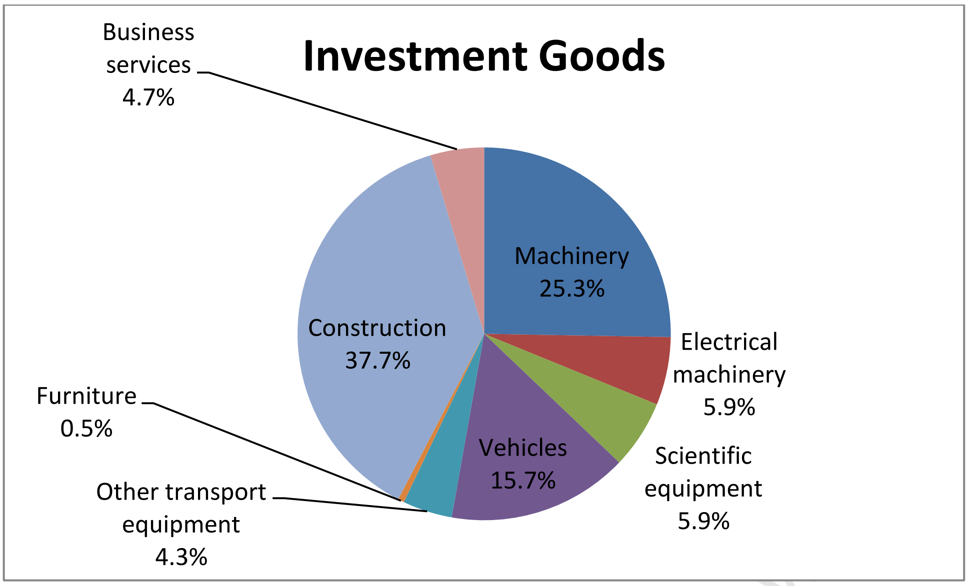


Figure 14: Electricity sector investment goods split

SIMULATION CALIBRATION

The simulations in this model are set-up to allow one to impose the proposed electricity generation build plans as proposed by the IRP. The use of an economy-wide model that takes into account complex interactions is crucial, as previously mentioned, to the analysis of these simulations. It is often with great difficulty when modelling for one to decipher the result of one change in the economy, this becomes even more so when introducing a number of changes in the economy. This method of modelling is useful in this regard, as it allows a 'hybrid comparative static-dynamic' framework in which to shock the economy (Pauw, 2007). In other words, the model allows a relocation of capital stock, which is considered a key element of dynamic modelling where, as previously explained, the link between current period investment and changes in capital stock is explicitly modelled (Pauw, 2007). The aforementioned represents the dynamic component of the hybrid. In terms of the comparative static model, the base as well as the scenarios are modelled on the same inputs, except for the specific shocks to the model, namely a structural shift and an investment shock, which allows a *ceteris paribus* environment for one to analyse these shocks. Ceteris paribus being the economic terms used to indicate when all other factors in the economy are kept constant. The simulations in this model contain two of said 'shocks' that allow the electricity generation build plans to accurately be imposed onto the model

STRUCTURAL CHANGE SIMULATION

The first type of shock used is a structural change in the electricity sector. This structural change involves the shift between the different subsectors of the electricity sector, namely coal-fired, nuclear, hydropower, renewable, waste-based and gas powered electricity generation. This is an important modelling aspect as each method of power generation comprises of different inputs, in terms of labour intensities, skill compositions and intermediates demand, to name a few. The structural change is simulated by means of imposing an exogenous growth path for the quantity of each activity (QA) in the electricity sector. The figure below illustrates the different compositions of electricity supply in GWh for the three scenarios over the period to 2030:

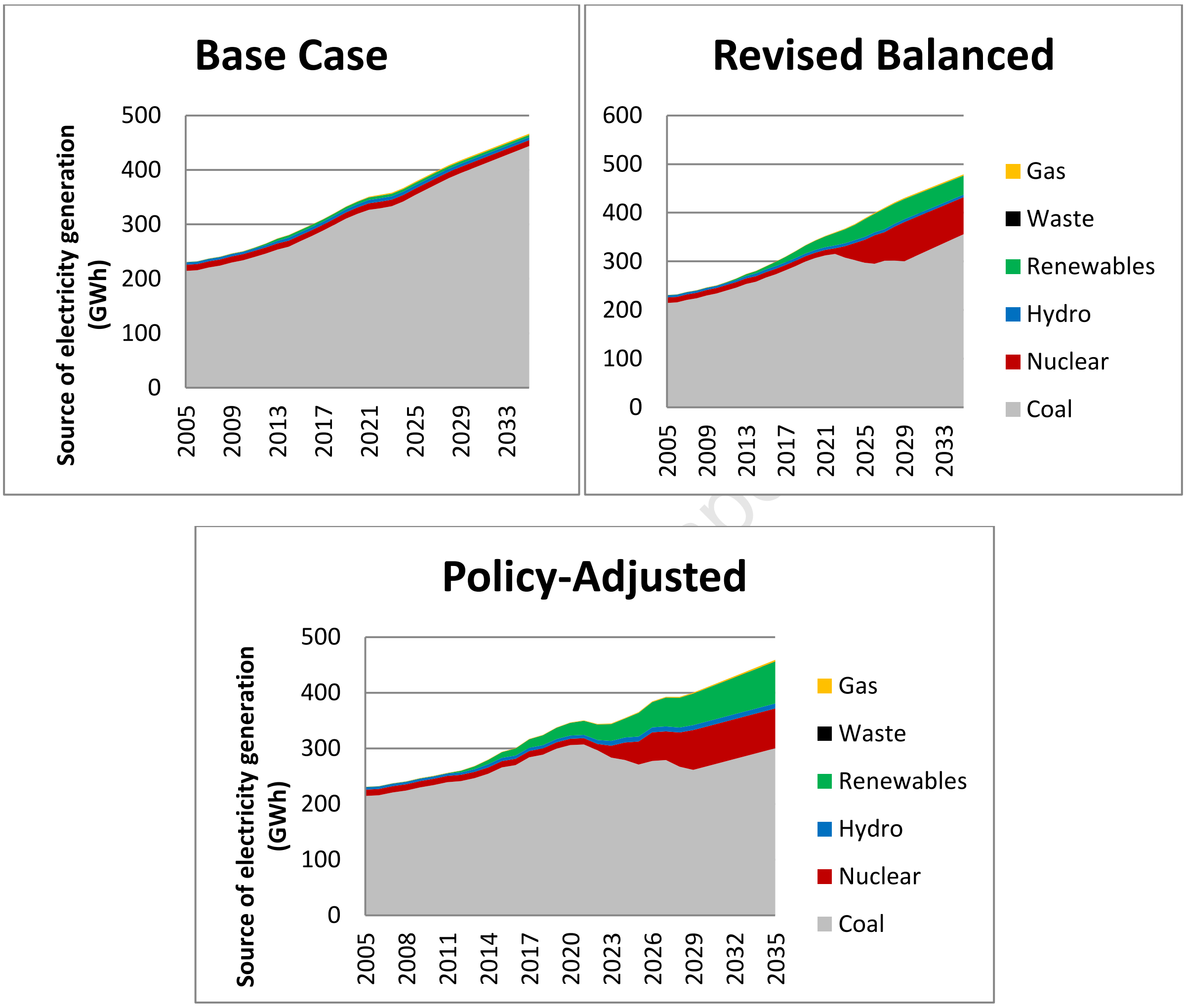


Figure 15: Base Case, Revised Balanced and Policy-Adjusted Scenarios source of electricity generation to 2030

EXOGENOUS ELECTRICITY INVESTMENT SIMULATION

The second shock represents the imposition of exogenously determined investment in the electricity sector in order to analyse the effects of this investment on the economy. An increase in investment leads to an increase in the amount of investment funds that need to be raised. In the case of this study, the closures chosen assume that this is achieved through increased savings – from households as well as enterprises. It has been found that these investment effects observed in a comparative static general equilibrium model usually have small compositional effects (Pauw, 2007). On one hand household demand declines which leads to reduced final demand, and on the other hand increased investment leads to an increase in final demand. The aforementioned compositional effects occur from the fact that the structures differ between that of household and investment demand in terms of the selection of commodities that are consumed (Pauw, 2007). Hence the observed changes in GDP, welfare and employment are contributed to by these differences in the structures of production that exist in the declining sectors, versus those that exist in the growing sectors (Pauw, 2007). The preceding economic theory holds for the base case as well as the revised and policy-adjusted scenarios. Although, in the case of the revised and policy-adjusted scenarios, the additional financing that is needed, over and above that in the base case, is assumed to be borrowed from abroad, incurring 5% interest annually. These interest payments are assumed to be removed from the total amount of investable funds on an annual basis (Arndt, Davies, & Thurlow, 2011). It is assumed that no principal payments are made on this electricity sector debt within the period modelled (Arndt, Davies, & Thurlow, 2011). This assumption could be criticised as it does not allow the full effect of the extra investment to filter though the economy. This is a valid criticism, although it is plausible that the generation technologies could be funded by a foreign loan. This calibration does cause a certain rigidity in the model and running the model with various other financing assumptions in order to do a comparison would be useful. However this is beyond the scope of this thesis. The figure below illustrates the exogenous electricity investment projections, consistent with the IRP, that are imposed on the model. The cumulative costs calculated over the period 2005 to 2030 for the committed build plan was approximately R237 billion. The cost over the period for the baseline, revised and policy-revised plans were R657 billion, R807 billion and R1096 billion.

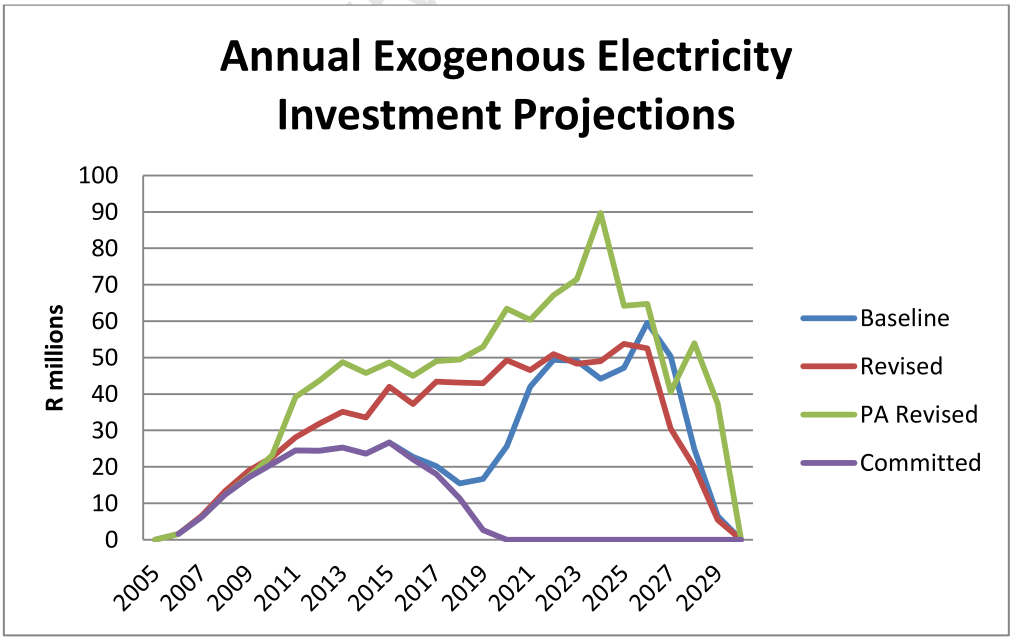


Figure 16: Annual Exogenous Electricity Investment Projections

RESULTS AND ANALYSIS

This section presents the results from the three scenarios simulated in the CGE model. The results with regard to the baseline, or rather the 'business-as-usual' scenario will be presented and briefly analysed first. This will be followed by a presentation and analysis of the revised and policy-adjusted scenarios. As previously discussed, CGE modelling is considered a useful tool with regards to providing a framework for comparison between baseline and simulated runs and not a predictive model as such. In light of this the results of the scenarios will be explained in comparison to the base run, to indicate the actual result of the shocks rather than the values of the variables.

BASELINE SCENARIO

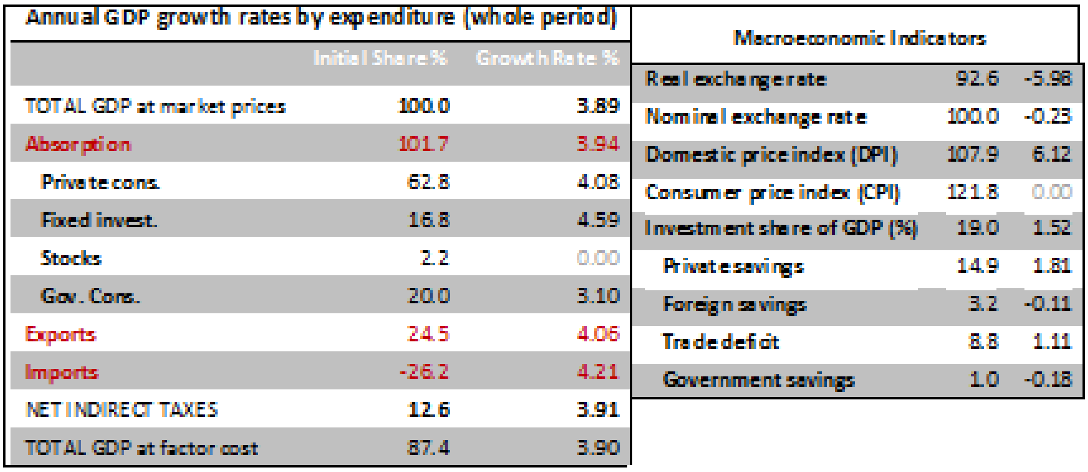
The baseline growth path is produced first with the assumption that South Africa's economy continues to grow over the period in line with its recent performance. The IRP's base case scenario for electricity expansion is imposed on this scenario and the simulation therefore illustrates South Africa's growth path assuming a 'business-as-usual' build plan. In other words, a scenario where there are no constraints and the electricity build plan follows a plan similar to past experience with large investments in coal-fired plants. The table below highlights the annual growth rates of GDP disaggregated by sector and displays a few of the best performing sectors in the baseline. It should be noted that the annual growth rates are relative to each industry's initial share of GDP. The agricultural sector grew by 3,6%, slightly less than the industrial and service sectors that grew by approximately 3,9% annually over the period. The sectors that were previously listed as the key investment sectors for the electricity sector were amongst the best performers over the period. The construction sector, which was estimated to receive 37,7% electricity sector investment grew at an average annual rate of 4,48%. The machinery sector also received a large portion of investment from the electricity sector and grew at an annual average of 4% over the period. The vehicles sector received the third highest proportion of investment from electricity and grew at an average of 3,6% annually until 2030. The mining sector grew substantially over the period, considering its already high initial share of GDP, at an average annual rate of 4,18%. The coal mining and natural gas mining sectors grew at an average annual rate of 3,5% and 6,12% respectively, over the period. The high growth experienced by these mining sectors is in line with expectations considering the large amount of coal-fired and CCGT capacity in the base case. The electricity sector as a whole grew by 2,65% over the period with coal-fired, hydropower, renewables and gas growing at 2,55%, 1,26%, 8,26%, and 13,8% respectively. There was no growth in the nuclear power and waste generation sectors of electricity which one would expect considering that no capacity was allocated to these sectors in the base case.

Total GDP at factor cost

	Initial Share %	Growth Rate%
TOTAL GDP at factor cost	100.00	3.90
AGRICULTURE	**2.71**	**3.60**
INDUSTRY	**30.36**	**3.90**
Mining	7.60	4.18
Coal mining	1.30	3.50
Natural gas mining	0.05	6.12
Manufacturing	18.25	3.80
Petroleum refining	1.61	4.11
Crude oil based petrol	1.21	3.73
Coal to liquid petrol	0.39	5.04
Gas to liquid petrol	0.02	5.59
Biofuels	0.00	4.85
Machinery	1.64	4.00
Machinery	0.89	4.02
Electrical machinery	0.50	4.05
Scientific equipment	0.25	3.83
Vehicles and transport equip.	1.73	3.39
Vehicles	1.50	3.61
Other manufacturing	1.03	4.49
Furniture	0.22	3.51
Other industry	4.51	3.79
Electricity	1.91	2.65
Coal-fired	1.74	2.55
Nuclear	0.12	0.00
Hydropower	0.02	1.26
Renewables (solar/wind)	0.02	8.26
Waste	0.00	0.00
Gas	0.00	13.80
Water distribution	0.51	4.39
Construction	2.10	4.48
SERVICES	**66.92**	**3.91**
Hotels and catering	0.99	5.01
Transport services	5.56	4.11
Communications	3.97	4.59
Financial services	9.27	4.15
Business services	10.26	4.31

Table 12: Base case industry contribution to GDP at factor cost

Following the discussion on the total GDP growth by factor cost for the base case attention will now be given to annual growth rates of GDP by expenditure over the period – illustrated in table 13. The key economic variables show a positive growth impact from the baseline scenario on the economy as a whole. The absorption[10] results indicate a negative balance of payments and hence a trade deficit in the base year followed by an increase in the deficit over the period with an average annual growth rate of 3.94% over the period to 2030. This is mirrored by the higher value of imports in comparison to the value of exports in the base year, and a growth rate of 4.21% and 4.06% respectively. The increase in the growth of imports is attributed to the appreciation of the Rand that occurs over the period – an average annual appreciation of 0,2% in nominal terms. The closure rule chosen in this model for the 'savings-investment' closure was one of 'savings-driven' investment. Hence, private savings increased with an average annual increase of 1.81% over the period, and investment followed suit as shown by the 1.52% average annual increase of the investment share of GDP. Fixed investment growth also increased over the period with an average annual growth rate of 4.59%, gaining on average, 1.52% annually as a share of GDP. One would expect this result since the simulations imposed a high amount of fixed investment growth in the electricity sector, which led to knock-on effects of investment by the electricity sector in other industries within the economy. Private consumption increases over the period with an average annual growth rate of 4.8%, which is likely to be attributed to the appreciated value of the Rand as well as the increased demand spurred on by the economic growth over the period.



Annual GDP growth rates by expenditure (whole period)	Initial Share %	Growth Rate %
TOTAL GDP at market prices	100.0	3.89
Absorption	101.7	3.94
Private cons.	62.8	4.08
Fixed invest.	16.8	4.59
Stocks	2.2	0.00
Gov. Cons.	20.0	3.10
Exports	24.5	4.06
Imports	-26.2	4.21
NET INDIRECT TAXES	12.6	3.91
TOTAL GDP at factor cost	87.4	3.90

Macroeconomic Indicators		
Real exchange rate	92.6	-5.98
Nominal exchange rate	100.0	-0.23
Domestic price index (DPI)	107.9	6.12
Consumer price index (CPI)	121.8	0.00
Investment share of GDP (%)	19.0	1.52
Private savings	14.9	1.81
Foreign savings	3.2	-0.11
Trade deficit	8.8	1.11
Government savings	1.0	-0.18

Table 13: Base case annual GDP growth rates by expenditure and other macroeconomic indicators

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[10] Absorption is the total demand for all final marketed goods and services of all economic agents resident in the economy. It is equal to the sum of domestically produced goods consumed in the country and imports. Hence an increase in absorption signifies an increase in total demand in the economy.

REVISED AND POLICY-ADJUSTED SCENARIOS

This section outlines a number of results using key economic indicators for the economy. An analysis of the performance of the scenarios against the baseline scenario will follow.

KEY ECONOMIC INDICATORS

The table below provides a summary for the breakdown of GDP in terms of expenditure as well as the annual growth rates for a few macroeconomic indicators. One can see that the overall effect of the new scenarios is a decrease in the economic growth rates for the economy as a whole, more so for the policy-adjusted IRP. This decrease in the growth rate is attributed to the financing option assumed for the excess investment required for these scenarios as opposed to the requirement for the baseline scenario. The additional investment requirement was assumed to be obtained using a foreign loan, of which only the 5% interest payment was paid annually over the period. Hence none of the principal payments were made. The interest payments were assumed to be taken out of the 'savings pool'. A result of this assumption is the opportunity cost of investment in other sectors forgone. The impact of which is a slight decrease in the overall growth rates of the economy - as seen in these results,. However, it should be noted that even though there is a decrease in the economic growth rates, there is still an increase in the overall value of economic growth in these two scenarios. A more detailed discussion of the sectors attributing to this economic growth (GDP) will follow in the next section.

Annual GDP growth rates by expenditure (whole period)

			% deviation from baseline	
	Initial Share %	Baseline % growth	Revised	PA-IRP
TOTAL GDP at market prices	**100.0**	**3.89**	**-0.10**	**-0.12**
Absorption	101.7	3.94	-0.10	-0.14
Private cons.	62.8	4.08	-0.07	-0.10
Fixed invest.	16.8	4.59	-0.30	-0.40
Gov. cons.	20.0	3.10	0.00	0.00
Exports	24.5	4.06	-0.10	-0.11
Imports	-26.2	4.21	-0.12	-0.19
NET INDIRECT TAXES	**12.6**	**3.91**	**-0.12**	**-0.15**
TOTAL GDP at factor cost	87.4	3.90	-0.08	-0.10

Macroeconomic Indicators

	Initial Share %	Baseline	Revised	PA-IRP
Real exchange rate	92.6	-5.02	-0.46	0.22
Nominal exchange rate	100.0	-0.55	-2.04	-1.54
Domestic price index (DPI)	107.9	4.70	-1.64	-1.85
Investment share of GDP (%)	19.0	0.58	-0.97	-1.28
Private savings	14.9	0.80	-0.85	-0.86
Foreign savings	3.2	-0.08	0.02	0.06
Trade deficit	8.8	0.97	-0.19	-0.54
Government savings	1.0	-0.14	0.02	0.03

Table 14: Annual GDP growth rates, macroeconomic indicators for the RBS and policy-adjusted scenarios as a percentage deviation from the baseline

The growth rate of absorption for the economy declined slightly for both the revised and policy-adjusted scenarios with a deviation of 0.1% and 0.14%, respectively, from the average annual growth rate. The fall in the real value of investment due to the interest repayment on the electricity loan places a downward pressure on absorption. A trade deficit remained in both scenarios at the end of the period, with a greater decrease in the deficit from the policy-adjusted scenario. This is due to the slight increase in the average annual growth rate for the exchange rate experienced in this scenario in comparison to the baseline - a slightly more depreciated Rand. The relative depreciation of the Rand resulted in a more pronounced decrease in imports and hence a larger decrease in the trade deficit in comparison to the revised scenario. The growth rates for private savings and the investment share of GDP declined slightly for both scenarios, however the annual growth rates for foreign and government savings increased in both scenarios. The former as a result of the assumption for the difference in the investment requirements, as previously discussed. In addition, the annual average growth rates of fixed investment also declined over the period due to this assumption.

IMPACT ON GDP

GDP is an important key variable in the analysis of an economy-wide model as it provides insight into whether the shock was detrimental or beneficial to the growth of the economy. The baseline scenario gave an average annual increase of 3.89% in total GDP at market prices. The figure below illustrates the year-on-year growth rate projection for the revised scenario and the policy-adjusted scenarios in comparison to the baseline scenario. The GDP growth rates are identical for all scenarios leading up to 2010. This is expected as the electricity build plans, and therefore the shocks, are only imposed from 2010 onwards. The main divergence of GDP growths for the different scenarios occurs around 2015 as the GDP growth rates for the new scenarios remains lower than that of the baseline scenario, more so for the policy-adjusted scenario. The growth rates follow a similar path, albeit at different levels. This is probable as the industry investment that is taken out of domestic savings, bar the 5% loan interest payment, is similar in both scenarios. Hence, the GDP growth rates in both instances follow analogous industry growth patterns. The scenarios do result in a lower GDP in comparison to the base case with the percentage deviation from total real GDP at the end of the period at -1,8% and -2,3% for the revised and the policy-adjusted scenarios respectively. The decline in the growth rate, however, is not substantial and the annual GDP growth for both scenarios remains in line with the AsgiSA goal of between 3% and 6% annual GDP growth.

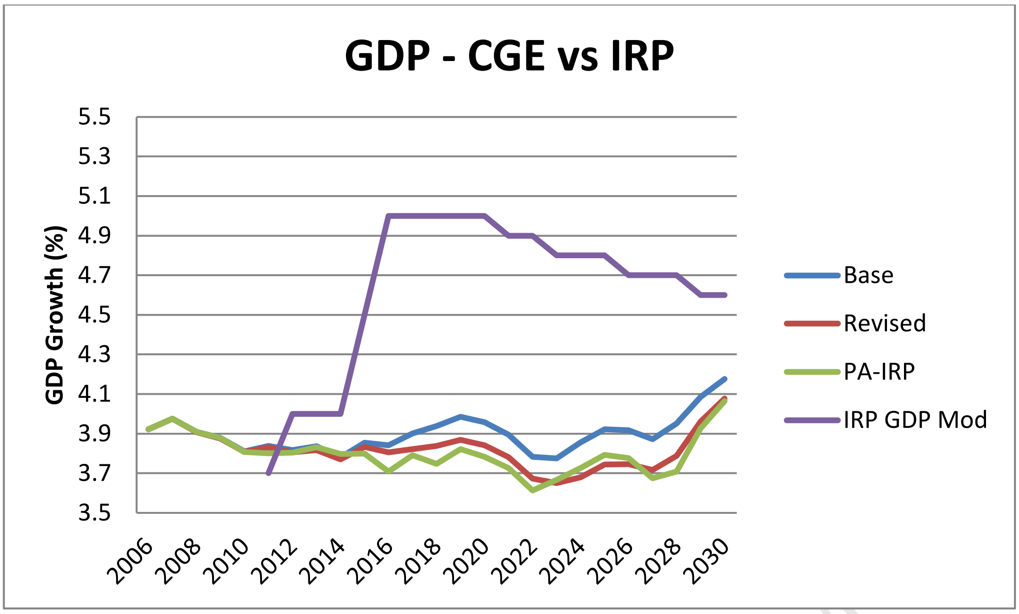


Figure 17: GDP growth rate for the IRP scenarios from the CGE model vs the forecasted IRP moderate GDP growth rate

The figure above illustrates the GDP growth path determined using the CGE model in comparison to the moderate GDP forecast used in the modelling process of the IRP. GDP forecasts are notoriously difficult to predict, especially over the long-term. The IRP assumed that the growth of the electricity demand was correlated with that of demand. This is a realistic assumption, as economic growth tends to stimulate electricity demand growth in the economy. The GDP forecast is therefore crucial to the modelling in the IRP, as an overestimate of demand will cause an inflated electricity demand figure leading to over-supply of electricity. The converse is also true as an underestimate of demand will ultimately lead to an under-supply of electricity. In light of this, the results of the CGE model indicate that the IRP is likely to have overestimated economic growth in the economy. It is unclear as to what the assumptions were for the GDP growth forecast as provided by the System Operator (SO, 2010). The high growth rate in 2015 especially is questionable. Given that the electricity demand forecast is already likely to cause an overinvestment in capacity, as discussed earlier in this thesis, this seemingly high estimate of growth is a concern. The interaction between GDP and electricity demand growth forecasts provides a complex problem, although the solving of this problem is beyond the scope of this thesis, and further research is needed.

IMPACT ON INDUSTRIES

The table below provides a breakdown of the deviation from the base of the revised and policy-adjusted scenarios in terms of the annual GDP growth rates per sector. The overall impact of the scenarios is a decline in the growth rates of all sectors in the economy except for the electricity sector. The revised scenario causes a 1.29% deviation from the baseline value of 2.65% average annual growth rate of the electricity sector, compared to a slightly higher deviation of 1.5% from the policy-adjusted scenario. As is expected, the coal-fired growth rate is less for the revised and policy-adjusted scenarios with a deviation of -1.07% and -1.66% from the baseline. Coal-mining, as a result also takes a knock and declines by -0.53% and -0.69% with the respective scenarios. Nuclear power sees a substantial increase in the scenarios compared to the baseline as the baseline assumed no new capacity of nuclear power. The deviation from the baseline is 8.14% and 7.66% for the revised and policy-adjusted scenarios respectively, a slightly lower growth for the latter even though the capacity increases are the same in both scenarios. Hydropower growth is slightly lower than the base with a deviation of 0.02% for the revised scenario and higher than the base with a deviation of 1.83% for the policy-adjusted scenario. In terms of renewable there is a substantial growth in both scenarios with a deviation of 10.43% and 12.22% for the revised and policy-adjusted scenarios. This is due to the latter's higher capacity of renewable technologies included in the build plan.

Average Annual Industry Growth Rate				
			% deviation from baseline	
	Initial Share %	Baseline % growth	Revised	PA-IRP
AGRICULTURE	**2.71**	**3.60**	**-0.12**	**-0.13**
of which: Biomass feedstock	0.00	4.85	-0.31	-0.29
INDUSTRY	**30.36**	**3.90**	**-0.05**	**-0.07**
Mining	7.60	4.18	-0.16	-0.20
of which: Coal mining	1.30	3.50	-0.53	-0.69
of which: Natural gas mining	0.05	6.12	-0.13	-0.45
Manufacturing	18.25	3.80	-0.11	-0.13
of which: Petroleum refining	1.61	4.11	-0.16	-0.19
Other industry	4.51	3.79	0.33	0.38
of which: Electricity	1.91	2.65	1.29	1.50
Coal-fired	1.74	2.55	-1.07	-1.66
Nuclear	0.12	0.00	8.14	7.66
Hydropower	0.02	1.26	-0.02	1.83
Renewables (solar/wind)	0.02	8.26	10.43	12.22
Waste	0.00	0.00	0.00	0.00
Gas	0.00	13.80	0.31	-0.51
SERVICES	**66.92**	**3.91**	**-0.09**	**-0.11**

Table 15: Industry growth rates as a percentage deviation from the baseline

The table below shows presents the effect of the revised balanced and policy-adjusted scenarios on a few of the industries in the economy. The industry that benefited most from these simulations is the electricity sector as shown below by the year-on-year growth rate deviation from the base of the new scenarios. The electricity sector experienced growth in the baseline scenario, and even more so in these scenarios as more investment and capacity was added to this sector. The mining, and specifically the coal-mining, sector performed the worst under the new scenarios. This in an intuitive result given the high proportion of total output from the coal mining sector that is purchased by the electricity sector; 62% of total industry sales in the base year. The amount of capacity allocated to coal-fired power stations was substantially less than the base in the two scenarios which resulted in the decline in the growth of the coal-fired portion of electricity generation. The growth rates of the manufacturing and machinery sectors, along with all other sectors in the economy except for electricity, declined over the period. This is likely to be caused by the decrease in fixed investment in these scenarios and the resource competition that exists between sectors due to the limited amount of investment.

Year-on-year Growth Rate Deviation from Baseline

	2002-2010	2011-2015	2016-2020	2021-2025	2026-2030
Mining					
Revised	-0.51%	-3.49%	-6.75%	-3.11%	-4.74%
PA-IRP	-0.42%	-6.91%	-8.67%	-3.59%	-4.65%
Coal Mining					
Revised	-0.56%	-5.25%	-17.07%	-21.47%	-34.45%
PA-IRP	-0.31%	-13.18%	-18.23%	-29.01%	-42.84%
Manufacturing					
Revised	-0.12%	-0.99%	-3.67%	-5.05%	-3.85%
PA-IRP	-0.13%	-1.79%	-5.48%	-4.80%	-5.20%
Machinery					
Revised	0.90%	3.54%	-5.60%	-17.23%	-2.89%
PA-IRP	1.01%	2.92%	-3.96%	-13.02%	-11.63%
Electricity					
Revised	0.00%	12.36%	70.98%	147.54%	22.66%
PA-IRP	0.00%	44.52%	57.99%	101.16%	80.56%
Electricity-Coal					
Revised	0.00%	-6.13%	-18.36%	-130.92%	-68.35%
PA-IRP	0.00%	-8.33%	-18.19%	-216.11%	-107.39%

Table 16: Industry growth rates for a few industries that performed best and worst under the scenarios

EFFECT ON TRADE

The key indicators presented in the beginning of this chapter included the average movement of growth in exports and imports over the period, and illustrated that these growth rates declined in relation to the baseline in both the revised and the policy-adjusted scenarios. The decline in export and import growth rates was present in almost all industries over the period. The electricity sector experienced a substantial increase in annual export growth rates over the period with an average growth rate of 1.4% and 1.19% for the revised and policy-adjusted scenarios respectively. The other sectors benefited in terms of an increase in the rate of export growth, namely the non-ferrous metal and basic chemicals sectors. This is likely to be a result of the high proportion of exports in the total outputs of these sectors with exports representing 47% and 18% of total output, respectively, for these sectors.

Average Annual Export Growth Rate				
			% deviation from baseline	
Exports	Initial Share %	Baseline % growth	Revised	PA-IRP
ALL COMMODITIES	**100.00**	**4.06**	**-0.10**	**-0.11**
AGRICULTURE	**2.65**	**3.47**	**-0.24**	**-0.12**
INDUSTRY	**82.98**	**3.94**	**-0.07**	**-0.09**
Coal mining	2.41	3.49	-0.47	-0.44
Manufacturing	54.28	3.73	-0.04	-0.06
Chemicals	6.50	2.82	0.35	0.25
Metals	16.83	3.94	0.15	0.07
Other industry	0.81	0.88	1.40	1.19
Electricity	0.81	0.88	1.40	1.19
SERVICES	**14.38**	**4.79**	**-0.25**	**-0.24**

Table 17: Exports as a percentage deviation from baseline for the RBS and policy-adjusted scenarios

A decline in most industry growth rates was also found for industry imports for both scenarios. Natural gas mining was the only exception with an increase in the sectors annual growth rate for imports in both the revised and the policy-adjusted scenario with 0.32% and 0.26% respectively.

Average Annual Import Growth Rate				
			% deviation from baseline	
Imports	Initial Share %	Baseline % growth	Revised	PA-IRP
ALL COMMODITIES	**100.00**	**4.21**	**-0.12**	**-0.19**
AGRICULTURE	**1.36**	**3.54**	**-0.04**	**-0.16**
INDUSTRY	**82.65**	**4.24**	**-0.14**	**-0.21**
Mining	10.94	3.76	-0.14	-0.18
Coal mining	0.06	3.50	-0.64	-1.15
Crude oil	9.49	3.77	-0.16	-0.20
Natural gas mining	0.11	5.13	0.32	0.26
Manufacturing	71.09	4.30	-0.14	-0.21
Food processing	3.54	3.44	-0.06	-0.12
Other industry	0.62	4.67	-0.36	-0.33
Electricity	0.62	4.67	-0.36	-0.33
SERVICES	**15.99**	**4.13**	**-0.01**	**-0.08**

Table 18: Imports as a percentage deviation from baseline for the RBS and policy-adjusted scenarios

The table below summarizes the changes in average wages, profits and returns (less tax on factor income and transfers) for all factors in the economy over the period. Wages increased by a fair amount in the base case, an average growth rate of 4,11% annually, for the labour sector as a whole. There is a slight negative deviation from the baseline for both the revised and policy-adjusted scenarios in terms of wages for labour factors other than tertiary labour. Therefore, wages for these factors still increase, as in the base year, although by a lesser amount. This is more evident for the policy-adjusted scenario. Wages in the tertiary labour sector increase to a greater extent in the new scenarios than they did in the baseline. This is a result of the closure chosen as an increase in the demand for labour, met by a fixed supply, will result in an increase in the wage rate.

Change in average wages

			% deviation from baseline	
	Initial Value	Baseline % growth	Revised	PA-IRP
LABOUR (mil of workers)	**61 678**	**4.11**	**-0.08**	**-0.12**
Primary (g1-7)	28 729	3.51	-0.13	-0.18
Junior secondary (g8-10)	41 787	3.97	-0.15	-0.20
Senior secondary (g11-12)	79 418	4.23	-0.13	-0.17
Tertiary	135 144	4.52	0.01	0.01

Table 19: Average wages as a percentage deviation from the baseline for the RBS and policy-adjusted scenarios

The supply of labour increased in the base case. Classic theory would predict this result as an increase in the real wage rate leads to an increase in the labour supply and therefore an increase in employment and vice versa. The factor supply growth rates experienced a negligible negative deviation from the baseline for both the revised and the policy-adjusted scenarios for labour factors other than tertiary labour. This is likely to have been caused by the decrease in the wage rates in these scenarios. The macro closures chosen for labour assumed that tertiary labour was fully employed and that other labour factors faced an upward-sloping supply curve, therefore this result is intuitive.

Factor supply growth rates (QFS)

			% deviation from baseline	
	Initial Value	Baseline % growth	Revised	PA-IRP
LABOUR (mil of workers)	**11 333**	**1.32**	**-0.01**	**-0.01**
Primary (g1-7)	3 185	1.48	-0.01	-0.02
Junior secondary (g8-10)	3 447	1.32	-0.01	-0.01
Senior secondary (g11-12)	3 086	1.23	0.00	-0.01
Tertiary	1 616	1.12	0.00	0.00

Table 20: Factor supply growth rates as a percentage deviation from the baseline for the RBS and policy-adjusted scenarios

EFFECT ON PRICES

The table below outlines the average annual price growth rates for a number of the commodities in the economy as well as the deviations in these growth rates found in the revised and policy-adjusted scenarios. There was an increase in the annual price growth rates found in all three scenarios, however, there was a decline in the growth rates in the revised and policy-adjusted scenarios compared to the base year. The lower price growth paths are associated with the slower GDP growth found in the scenarios, relative to the baseline.

Average Annual Price Growth Rate (%)

		% deviation from baseline	
	Baseline % growth	Revised	PA-IRP
ALL COMMODITIES	0.20	-0.07	-0.06
AGRICULTURE	**-0.13**	**-0.03**	**-0.03**
of which: Biomass feedstock	0.08	-0.07	-0.07
INDUSTRY	**0.20**	**-0.12**	**-0.09**
Mining	-0.16	0.13	0.24
of which: Coal mining	-0.04	-0.08	-0.10
of which: Crude oil	-0.02	-0.08	-0.06
of which: Natural gas mining	-0.14	-0.03	0.02
Manufacturing	0.01	-0.05	-0.04
of which: Petroleum refining	-0.84	0.16	0.20
Other industry	1.38	-0.71	-0.66
of which: Electricity	3.60	-1.78	-1.52
SERVICES	**0.21**	**-0.01**	**-0.02**
of which: Transport	-0.07	-0.03	-0.04

Table 21: Average annual price growth rates as a percentage deviation from the baseline for the RBS and policy-adjusted scenarios

The endogenous electricity price path increased over the period in all the scenarios, although to a lesser extent in the revised and policy-adjusted cases than in the baseline.

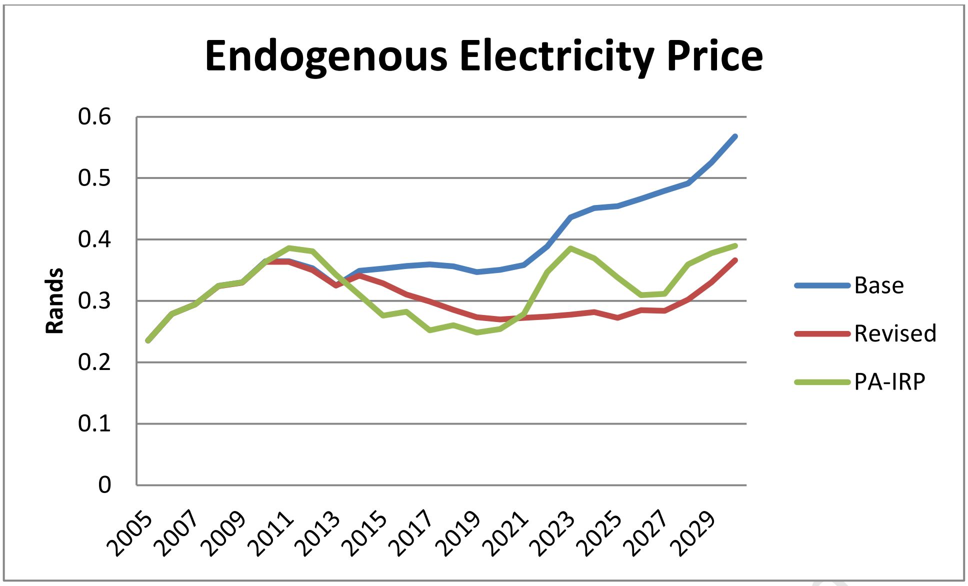


Figure 18: Endogenous electricity price

This result seems counter-intuitive in two main regards. Firstly, one would expect the price of electricity to increase along with the increase in investment to act as a funding mechanism. However, this is a result of the assumptions made in the model. Secondly, the electricity price is regulated in South Africa and therefore is unlikely to respond to the market as shown above. In the case of the model though, price acts as a mechanism to maintain equilibrium in the electricity sector. The simulations effectively control the supply of electricity in the model by fixing the amount of capital available to the sector – as determined in the IRP scenarios. An increase in the capacity leads to an increase in the capital stock in the electricity sector. The effect of this is an increase in the output or generation capacity, which in turn represents an increase in the supply of electricity. Electricity demand grows at a rate that is determined by population growth as well as economic growth. Initially supply will outpace demand and the price of electricity will drop to a new equilibrium. The lower price will increase demand and the price will rise again accordingly. The way in which the electricity price reacts is synonymous to economic price theory in this way. Forcing alternative financing options on the model would result in different responses from the electricity price. The comparison of these responses in price would provide for an interesting debate on regulation and pricing. However, this is beyond the scope of this thesis and is a potential for future research.

EMISSIONS

The emissions calculated using the CGE model were very similar to those calculated in the IRP, as shown in the figure below. The CGE path for emissions is slightly lower in most cases, especially for the policy-adjusted scenario.

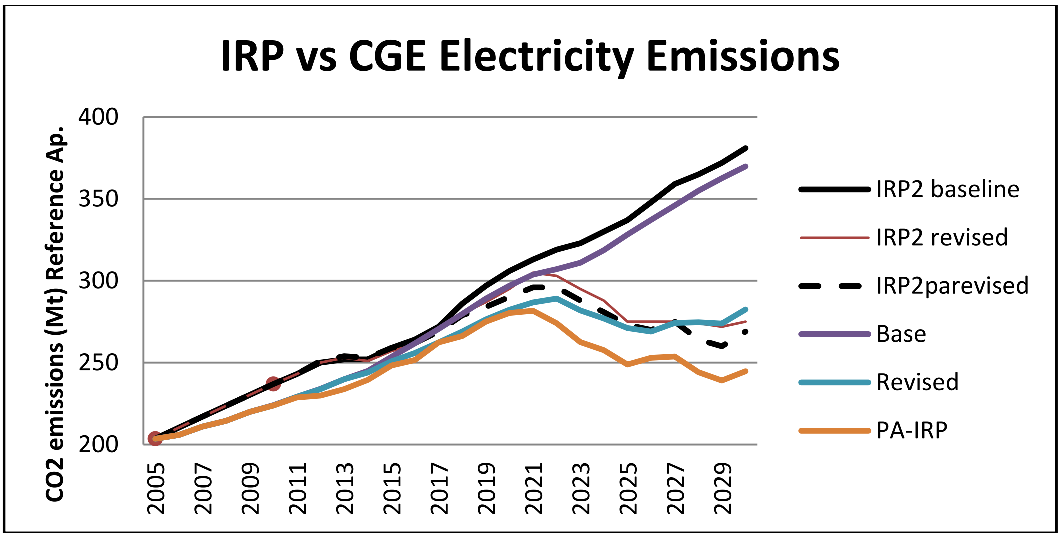
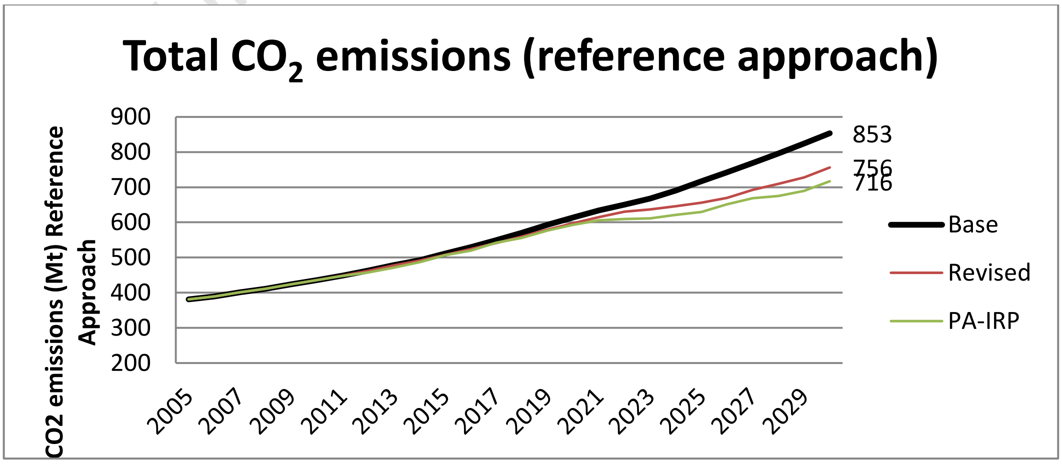


Figure 19: IRP vs CGE estimates of emissions

Two main approaches exist for estimating carbon emissions in an economy. The first approach is the Reference Approach, which is a top-down approach, which calculates CO_2 emissions from the combustion of fossil fuels, or primary fuels, using a country's energy supply data (Garg & Pulles, 2006). The sectoral approach is less straightforward and involves the use of secondary fuels in the estimation of CO_2 emissions. It is useful to calculate emissions based on both these approaches, as this provides two independent estimates of emissions and is considered '*good practice'* by the IPPC (2006) to:

> *"...apply both a sectoral approach and the reference approach to estimate a country's CO_2 emissions from fuel combustion and to compare the results of these two independent estimates."*

In light of this, the total CO_2 emissions using both the sectoral and reference approaches are illustrated below in figure 20.



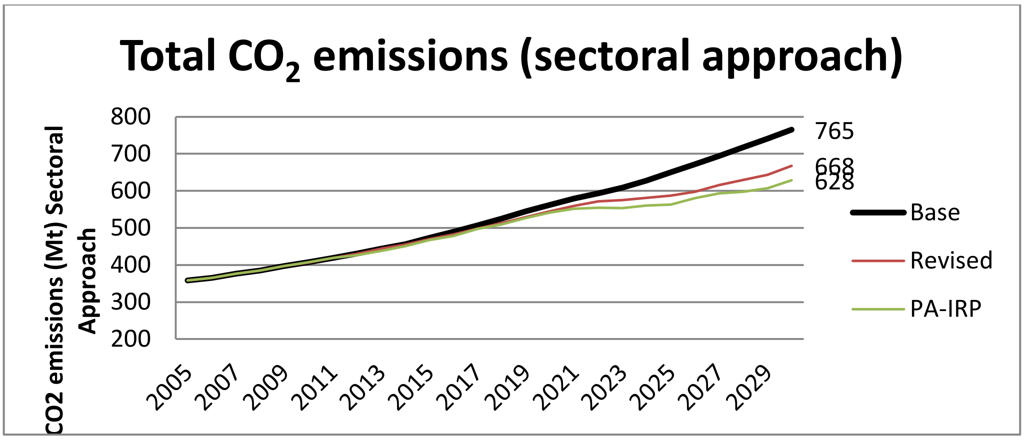


Figure 20: Total CO_2 emissions using the sectoral and reference approach

The above figures illustrate that the total emissions using the sectoral approach are slightly lower over the period than when the reference approach is used. It is often the case that there is a slight difference between the results of these approaches. In this case the difference of less than 5% is not problematic. The importance of the above figures is to highlight the contribution of the scenarios to the mitigation of CO_2 in the context of the country's total emissions. The pursuit of climate change targets is one of the policy goals of the IRP. These climate change targets are based on the cabinet approved emissions growth path from the Long Term Mitigation Scenarios (LTMS) (DEAT, 2008). The approved path of emissions followed a 'peak, plateau and decline' formation. The path illustrates a peak of total emissions at 2020 of just under 600 Mt of CO_2-eq. Both the reference and the sectoral approach yield emissions of around 600 Mt CO_2-eq in 2020. The emissions growth path above does not include other mitigation efforts therefore these efforts are likely to decrease the emissions in the figures above. From the electricity sector's mitigation efforts alone, it is not possible to conclude as to whether or not the preferred IRP will result in reaching the climate change policy goal. However, one can reiterate what is said in the IRP that the revised and policy-adjusted scenarios result in a decrease in CO_2 emissions.

SUMMARY OF RESULTS

The table below provides a summary of some of the key economic variables, discussed above in the results section, for the various scenarios defined in this thesis.

	Baseline		Revised Balanced	Policy-Adjusted IRP
Economic Variables	**Initial Value**	**% Growth**	**Deviation from baseline**	
Total GDP (at market prices)	100.0	3.89	-0.10	-0.12
Absorption	101.7	3.94	-0.10	-0.14
Private cons.	62.8	4.08	-0.07	-0.10
Fixed invest.	16.8	4.59	-0.30	-0.40

Gov. cons.	20.0	3.10	0.00	0.00
Exports	24.5	4.06	-0.10	-0.11
Imports	-26.2	4.21	-0.12	-0.19
Net Indirect Taxes	12.6	3.91	-0.12	-0.15
Sector Growth:				
Agriculture	2.71	3.60	-0.12	-0.13
Industry	30.36	3.90	-0.05	-0.07
Services	66.92	3.91	-0.09	-0.11
Wages:				
Labour (mil of workers)	61 678	4.11	-0.08	-0.12
Factor Supply:				
Labour (mil of workers)	11 333	1.32	-0.01	-0.01
Prices:				
All Commodities	-	0.20	-0.07	-0.06
Agriculture	-	-0.13	-0.03	-0.03
Industry	-	0.20	-0.12	-0.09
Services	-	0.21	-0.01	-0.02

Table 22: Summary of results

SENSITIVITY OF RESULTS

FACTOR MARKET CLOSURE

Changing the factor market closure to that used in the LTMS economy-wide input (Pauw, 2007) has a positive effect on growth in the baseline scenario in terms of total GDP at factor cost. The average annual growth rate is 6.93% in this case, compared to the growth rate of 3.95% experienced with the factor market closures set at upward-sloping supply curves for labour. Industry growth rates for all sectors experienced an increase accordingly, except for the electricity sector. This is as a result of the model imposing an endogenous investment and capacity growth path in the simulations. In terms of factor contribution to economic growth, as based on the Solow growth decomposition[11], labour contributions increase substantially as one would intuitively expect. The contribution of labour to economic growth is 35%, an increase of 21% from the baseline scenario with the previous factor closure setting. The shares of capital and land contributions to economic growth remain unchanged and as a result the total factor productivity (TFP) bears the brunt of a lowered share of contributions from 20% to 3%. The Solow growth decomposition is relatively similar for the three scenarios, with small changes due to slight increases in capital contribution from increased investment in the revised and policy-adjusted scenarios. The table below illustrates the differences between the factor supply growth rates and the average wage differentials between the two factor closures. The factor supply growth for labour, except for tertiary labour as its supply is assumed to be fixed, more than triple under the new factor closure as one would expect. Capital supply also increased to nearly twice that of the previous factor closure. In terms of average wages, the wages for all

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[11] The Solow decomposition highlights the contribution of factors and total factor productivity (TFP) to economic growth

labour types, except for tertiary, decrease below the initial value of average wages in 2005. This is a reasonable result as, in the presence of unemployment and therefore no constraints on the supply of labour, an increase in labour supply leads to a decrease in the price of labour, or rather the wage.

Factor Supply Growth Rates		**Previous Factor Closure**			**New Factor Closure**		
	Initial Value	***Baseline***	***Revised***	***PA-IRP***	***Baseline***	***Revised***	***PA-IRP***
LABOR (mil of workers)	11 333	1.37	-0.01	-0.01	5.76	-0.23	-0.23
Primary (g1-7)	3 185	1.56	-0.02	-0.02	6.05	-0.26	-0.26
Junior secondary (g8-10)	3 447	1.38	-0.01	-0.01	6.23	-0.24	-0.24
Senior secondary (g11-12)	3 086	1.27	-0.01	-0.01	6.25	-0.23	-0.21
Tertiary	1 616	1.14	0.00	0.00	1.00	0.00	0.00
CAPITAL (calib. units)	3 269	4.28	-0.19	-0.27	7.56	-0.45	-0.49
LAND	4	1.00	3.09	0.00	1.00	6.11	0.00
Change in Average Wages, Profits and Returns (less taxes)	***Initial Value***	***Baseline***	***Revised***	***PA-IRP***	***Baseline***	***Revised***	***PA-IRP***
LABOR (mil of workers)	61 678	4.03	-0.08	-0.09	2.80	-0.04	0.07
Primary (g1-7)	28 729	3.40	-0.10	-0.16	-0.10	0.05	0.06
Junior secondary (g8-10)	41 787	3.91	-0.12	-0.18	-0.05	0.03	0.03
Senior secondary (g11-12)	79 418	4.17	-0.12	-0.15	-0.06	0.01	0.02
Tertiary	135 144	4.47	-0.02	0.03	10.39	-0.32	-0.15
CAPITAL (calib. units)	200	-4.22	0.37	0.50	-4.47	0.72	0.93
LAND	200	-4.22	0.37	0.50	-4.47	0.72	0.93

Table 23: Factor supply growth rates under the previous and new factor closure

MAIN FINDINGS, POLICY RECOMMENDATIONS AND CONCLUSIONS

MAIN FINDINGS AND POLICY RECOMMENDATIONS

This thesis set out with two main aims. Firstly, it aimed to evaluate the need for economy-wide analysis to be done in the planning process according to the current literature. As well as how the decision making process will be strengthened with this analysis. Secondly, it aimed to present the results from an economy-wide analysis of these scenarios in order to provide policy recommendations for the electricity sector. In fulfilling these aims a number of findings were mentioned in the discussion. This is an important section as it outlines a number of the key findings as well as interprets them. The linkages to policy recommendations are also provided where applicable.

MODELLING AND POLICY DEBATE

The substantial cost of electricity generation technologies, the long-term impacts of investment decisions as well as the long lifespan of most generation technologies highlights the need for long planning horizons and an assessment of the inter-linkages that exist between the energy sector, the economy and the environment. An integration the economic equilibrium character of the top-down approach with the optimization and detail of the bottom-up paradigm provides a more comprehensive method of assessing policy options for the energy sector. The important question of 'where does policy fit into the modelling process?' was discussed using the central steps for optimally using modelling as a tool for policy analysis identified by Bohringer, et al. (2006). It was found that policy should influence the modelling process throughout, from providing a policy background on which the model is based to identifying policy recommendations at the end of the modelling process. In the same light modelling should influence policy throughout the decision making process. A key finding in terms of this debate is that modelling is a tool and should therefore aid in policy discussion; however, it should, not be the policy discussion. It should be used iteratively to provide a framework for assessing different policy options. An iterative process is necessary because as policies change and more data is obtained models should be updated accordingly.

There are a number of features that an economy-wide model should contain to ensure the model's suitability for policy analysis. Devarajan, et al (2002) identified these features as including policy relevance, transparency, timeliness, validation and estimation, as well as a diversity of approaches. The model for the analysis completed in this thesis was found to be suitable for policy analysis in this way. The use of the most recent IRP scenarios in the model ensured the relevance and timeliness of the model to the policy debate. In terms of transparency and validation, a comprehensive overview of the model data, functional forms and assumptions were provided along with a motivation for their use. Lastly, a diversity of approaches was beyond the scope of this thesis as the intention was to provide the analysis based on a CGE model specifically. The suitability and drawback of the approach chosen was discussed in this thesis and the potential for the use of more approaches exists in future research.

THE INTEGRATED RESOURCE PLAN SCENARIOS

Three scenarios were modelled in this thesis; the base case, revised balanced (RBS) and policy-adjusted scenarios from the IRP. A description of the electricity sector in 2010 highlighted South Africa's high reliance on coal for electricity generation and the negative effect this is having on meeting climate change policy goals with a carbon intensity of 912g/kWh. The share of renewables was significantly low at 5% of total capacity. The base case, the least-cost projection, maintains this reliance on coal at 91% of net energy supplied over the period. The RBS and Policy-Adjusted IRP are quite similar to the base case in 2020 as there is still a high reliance on coal, no nuclear capacity has been committed at this stage and only 4% and 5% of the renewable capacity has come online for the respective scenarios. By 2030 the RBS and Policy-adjusted IRP paint a very different picture to that of the base case with a reliance on coal of 66% and 65% respectively and 20% reliance on nuclear. CCGT and OCGT represent a slightly higher share in the base case than the other two scenarios with a corresponding share of 2% in the RBS and 1% in the policy-adjusted scenarios.

There is a substantial difference between the scenarios in terms of emissions intensity. There is a decrease of 34% in CO_2 intensity between the base year and 2030 for the RBS and Policy-

Adjusted scenarios. This compared to the 8% decline in emissions intensity in 2030 for the base case.

The cumulative cost for the base case scenario was R657 billion over the period until 2030. The cumulative cost for the RBS and policy-adjusted scenarios were significantly higher at R807 billion and R1096 billion over the period. These cumulative costs were calculated from the cost estimates used in the IRP.

POLICY GOALS OF THE INTEGRATED RESOURCE PLAN

The current modelling approach used in the IRP process was unable to assess the plan with regard to a number of the policy goals the plan is meant to address. The bottom-up modelling approach used in the IRP enabled the assessment of the plan in terms of emissions reduction, decreased water usage and the cost of the plan. Regional development was estimated in the IRP, although there was no actual economic analysis in this estimation of development. The effects on regional development need to be revised, although this is beyond the scope of the model used in this paper. A regional CGE model would have to be developed to sufficiently assess the IRP and regional development goals. The CGE model provided the examination of the plan in terms of a number of the remaining economic growth and development policy goals. These include economic growth, employment, terms of trade and electricity price. Although important, an analysis of the localisation impacts is beyond the scope of this thesis. The current CGE model contains static assumptions with regard to the investment in electricity capacity that would have to be revised to analyse localisation. In addition, there are a number of data constraints that exist for in this area. The importance of localisation is noted and it remains an area that needs to be explored.[12] The use of a CGE model adds tremendously to the process of the IRP as it allows for a more comprehensive analysis of potential build plans. An assessment of the plan in terms of a number of the economic growth and development goals will now be briefly discussed.

ECONOMIC GROWTH

The results from the baseline run gave an average annual increase of 3.89% in total GDP at market prices. GDP growth rates were found to be slightly lower for the RBS and policy-adjusted scenarios with a deviation of 0,1% and 0,12% in the average annual GDP growth rate, respectively. The decrease in the growth rate is intuitive, given that the interest payments on the foreign loan have an opportunity cost of investment in other sectors. A key finding was that there was this decline in the growth rate, however, it was not substantial and the annual GDP growth for both scenarios remains in line with the AsgiSA goal of between 3% and 6% annual GDP growth. The financing option is conservative; however, it is a possible option for a number of the generation builds and therefore this is a relevant finding. It is important to note that the choice of financing assumption is likely to have a substantial impact on the effect that the investment plan will have on economic growth. Under the financing assumption made in this model, one can conclude that the policy-adjusted IRP is unlikely to lead to a substantial decrease in economic growth. In other words, the policy-adjusted plan will still aid in South Africa reaching the policy goal of economic growth, just a slightly lower economic growth than was found in the base case. This highlights the importance of modelling various policy options throughout the decision-making process to ensure that the resulting plan is optimal.

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[12] A more detailed examination of localisation is provided in the 'further research potential' section.

EMPLOYMENT

The results of the labour response to the IRP scenarios followed classic economic theory – an increase in the wage rate leads to an increase in labour supply, therefore employment and vice versa. The labour assumptions chosen in the model were that tertiary labour was fully employed and that all other labour factors faced an upward-sloping supply curve. The average wage rates for all labour groups increased substantially in the base case, with an average aggregate labour wage rate of 4,52% annually over the period. The higher wage rate lead to an increase in the supply of labour, and therefore employment, with an average increase in the aggregate labour supply of 1,32% annually over the period. The supply of low-skilled workers increased by the highest amount with an average annual increase of 1,48%. One can conclude from this result that the base case produced employment opportunities in all labour sub-sectors, especially in terms of the low-skilled labour. The average wage and supply growth rates declined slightly in the RBS and policy-adjusted scenarios compared to the base year for all labour sub-sectors. However, the average wage rate for labour in the policy-adjusted scenario still increased by an average of 3.99% annually over the period. This slight decrease from the base case is the labour market's response to a decrease in industry investment in these simulations. This is due to the financing assumption made in the model. In terms of the policy goal of employment, one can conclude that the policy-adjusted IRP will increase employment as well as wage rates for all labour subsectors and aid in achieving this policy goal, although to a slightly lesser extent than the base case. This result may seem to contradict the findings in existing studies that have been completed using the bottom-up approach to employment potentials for renewable energy. These studies illustrate the potential for significant job creation from the diversification of South Africa's electricity supply through renewable energy. However the decreased employment growth in the policy-adjusted case in comparison to the base case is not a result of the number of jobs created by each generation technology. This is result is attributed to the response of the labour market to a 'contraction' of the industries in relation to the base case that is caused by the financing option chosen in the model.

TERMS OF TRADE

The results indicate that both exports and imports increased in the base case in terms of annual growth rates over the period, at 4,06% and 4,21% respectively. There was a slight decline in both imports and exports in the RBS and policy-adjusted scenarios and was present in almost all industries in the economy.

The electricity sector experienced a substantial increase in annual export growth rates over the period with an average growth rate of 1.4% and 1.19% for the RBS and policy-adjusted scenarios respectively. There were other sectors that benefited in terms of an increase in the rate of export growth, namely the basic chemicals and non-ferrous metal sectors. This is likely to be due to the high proportion of exports in total output of these two sectors.

In terms of import growth, it was found that there was a decline in most of the industry import growth rates. Natural gas mining was the only exception with an increase in the sectors annual growth rate for imports in both the revised and the policy-adjusted scenarios of 0.32% and 0.26% respectively.

These results indicate that there are a number of sectors that performed better in terms of export growth in the policy-adjusted scenario and there is still import and export growth in this scenario for all industries. However, a trade deficit is maintained in all scenarios, meaning import value remains higher than that of exports. This is not necessarily a problematic result, as many developing and some developed countries maintain trade deficits. In terms of the policy goal, the policy-adjusted scenario includes two interesting export growth opportunities in the basic chemicals and non-ferrous metal sectors. The results from the model also indicate that the policy-adjusted scenario does not have a substantial negative impact on the terms of trade.

ELECTRICITY PRICE

The response of the electricity price in the model was based on the assumptions that the electricity price responds to the market directly. The electricity price is however a regulated price in reality. The results obtained from this model therefore provide for an interesting discussion in terms of the possible inefficiencies of regulation. Regulation, in theory, attempts to ensure that the price is reflective of the market. However, if the price of electricity was deregulated would it respond by decreasing and follow a behaviour similar to that in this model? The model may be telling us that there is an inefficient use of resources and that there is indeed an overinvestment in the electricity sector. This result therefore raises a number of questions concerning the interaction between regulation and price and whether or not a deregulated price would increase efficiency in the electricity sector.

Forcing alternative financing options on the model would result in different responses from the electricity price. It was noted that the comparison of these responses in price would provide for an interesting debate. In terms of the policy goal of a low electricity price one could deduce from the model that the policy-adjusted IRP would be the best option for maintaining this goal as it produces the lowest price path. However, this inference is likely to be highly debated and highlights the need for further research in electricity pricing policy.

THE ELECTRICITY SECTOR AND THE ECONOMY

A number of key linkages were identified from the 2005 SAM on which the CGE model is based. In terms of backward linkages there were a number of findings. The electricity sector purchased 62% of the total industry sales of coal in 2005, which represents 43% of the total output value for the coal sector. The electricity sector also required 9,2% of the total electricity provided to industries, equivalent to 7% of the sectors total output. The purchases of natural gas by the electricity sector accounts for 5,4% of the sectors total industry sales and 5% of its output in the base year. The final significant backward linkage is between the electricity sector and the electrical machinery sector. In the base year purchases of electrical machinery from the electricity sector corresponded to 6% of the total industry's output and 9,2% of total industry sales.

A number of forward linkages were also identified. It was found that the proportion of spending on electricity in 2005 was quite small, although with recent electricity price hikes this proportion is likely to have increased somewhat. A number of sectors did however allocate a substantial portion of spending to the electricity sector. The basic chemicals and electricity sectors were found to allocate the largest portion of their intermediate input expenditure on electricity, 12,5% and 13,8% respectively. The iron and steel sector and the nonferrous metals sectors also contributed a significant proportion of their expenditure on intermediate inputs of electricity, equating to 6,4% and 8,5% respectively. The glass products sector also spent a significant proportion on electricity at 7,3% of its expenditure on intermediate inputs. The coal mining sector allocated 3,5% of total expenditure on intermediate inputs to electricity. This proportion seemed quite low intuitively, although, as previously mentioned, this may be due to the low cost of electricity in the base year, 2005. One can conclude that the sectors mentioned would be the most affected by electricity price hikes due to the large proportions of their spending being attributed to electricity.

This thesis identified a number of key investment goods for the electricity sector. Construction was found to account for the biggest proportion of investment in the electricity sector with 37,7%. This was followed by the machinery sector with 25,3% and vehicles with 15,7%. The remainder of the total investment, less than 22% is allocated to the remaining 5 sectors: business services, scientific equipment, electrical machinery, other transport equipment and furniture. These proportions were likely to change over the period as investment in the dynamic model is determined according to profit-rate differentials[13]. One can conclude however that these sectors are allocated the bulk of electricity investment over the period and should benefit from this increased investment.

WINNERS AND LOSERS

The sectors that were previously listed as the key investment sectors for the electricity sector were found to be amongst the best performers over the period; as one would have expected. Growth in the base case scenario was such that the construction sector grew by an average of 4,48%, the machinery sector by 4%, and the vehicles sector by 3,6% annually over the period. The mining sector grew substantially over the period, considering its already high initial share of GDP, at an average annual rate of 4,18%. The coal mining and natural gas mining sectors grew at an average annual rate of 3,5% and 6,12% correspondingly, over the period. The high growth experienced by these mining sectors is intuitive given the large amount of coal-fired and CCGT capacity in the base case. The electricity sector as a whole grew by 2,65% over the period with coal-fired, hydropower, renewables and gas growing at 2,55%, 1,26%, 8,26%, and 13,8% respectively. There was no growth in the nuclear power and waste generation sectors of electricity which is expected considering that no capacity was allocated to these sectors in the base case.

It was found that the overall impact of the scenarios was a decline in the growth rates of all sectors in the economy except for the electricity sector. This is a result of the financing option chosen in the model. There is a trade-off in the RBS and the policy-adjusted scenarios between further investment in the electricity sector and the investment in all other sectors in the economy. The repayment of the interest on the loan reduces the amount of funds available for investment in all other sectors of the economy. This therefore leads to a slight contraction of these sectors relative to the base case. However sector growth for all sectors was still positive in both the RBS and the policy-adjusted scenarios. This was expected due to the opportunity cost of investment from the funding option used. The electricity sector grew by 1,29%, and 1,5% more in the revised and policy-adjusted scenarios respectively in comparison to the base case. The mining, and specifically coal-mining, sectors performed the worst under the new scenarios. As is expected, the coal-fired growth rate is less for the revised and policy-adjusted scenarios

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[13] Profit-rate differentials refer to differences in the relative profitability of sectors in the economy.

with a deviation of -1.07% and -1.66% from the baseline. Coal-mining, as a result also takes a knock and growth declined by -0.53% and -0.69% in the respective scenarios. However, growth in the coal mining sector was still 2,97% and 2,81% for the revised and the policy-adjusted scenarios. Growth in the nuclear power subsector was found to increase substantially in the scenarios compared to the baseline. This is intuitive as the baseline assumed no new capacity from nuclear power. The deviation from the baseline is 8.14% and 7.66% for the revised and policy-adjusted scenarios respectively, a slightly lower growth for the latter even though the capacity increases are the same in both scenarios. Hydropower growth is slightly lower than the base with a deviation of 0.02% for the revised scenario and higher than the base with a deviation of 1.83% for the policy-adjusted scenario. In terms of renewable energy there was a substantial growth in both scenarios with a deviation of 10.43% and 12.22% for the revised and policy-adjusted scenarios. This is due to the latter's higher capacity of renewable technologies included in the build plan.

In conclusion, there were a number of best and worst performing industries, or rather 'winners' and 'losers' from the simulations. A movement away from coal-fired generation will have negative effects on the coal mining sector. However there is still growth in this sector as with the other sectors in the economy. Therefore a decrease in the reliance of the electricity sector on coal is unlikely, as some argue, to devastate the coal mining sector. The successful pursuit of a more diverse electricity build plan, like the policy-adjusted IRP, would entail a closer look at the sectors that perform best and worst under the scenario. More research into the linkages that exist between the electricity sector and other sectors in the economy would also allow a broader analysis.

FURTHER RESEARCH POTENTIAL

The E-SAGE model provides a framework for economy-wide research in the energy sector that is currently unparalleled in South Africa. As with all models though, there is still a potential for further research and improvement.

IMPORTS AND LOCALISATION

Firstly, allowing an investment split between local and foreign goods would allow further research into localisation effects. Currently, the model uses a static assumption in terms of the investment splits, as they are estimated from the base year, specified in the 2005 SAM. In light of this, the research potential of the model would be heightened if localisation effects could be accounted for. A number of data constraints exist in this area and there is a need for localisation to be explored further. The distinction between investment in import content and domestic content is very important (Pauw, 2007). Increased investment demand for imported goods causes funds to leave South Africa and therefore will ultimately impact negatively on the GDP. Investment in nuclear power and renewable energies, especially, are likely to have very high demands for imported goods. Hence, the addition of fixed import shares of investment for capacity builds is likely to result in a more accurate imitation of the economy by the model. One would be able to analyse the knock-on effects of localisation from different simulations – and in this way gain insight into South Africa's potential to become an industry leader in the production of generation technologies. For instance, the localisation effects of expanding the nuclear build plan would be interesting to analyse considering South Africa's high deposits of uranium. If enough nuclear plants were built in South Africa there could be huge localisation potential in terms of revamping the nuclear procurement industry in the country. It would be of interest to be able to analyse the knock-on effects of this for a number of reasons – including profitability and identifying the industry 'winners' and 'losers'.

FINANCIAL SECTOR

The financing for the electricity build plan is a highly debated topic. The question of which financing options will be used in itself presents important policy questions that need to be explored. A number of financing avenues exist for the expansion plan - including capital from shareholders, government guaranteed bonds, increasing the electricity price and foreign loans. The option chosen in the model might be criticised as a very modest approach. The foreign loan is a possible option, although admittedly might not illustrate the full impact of such a large investment plan. An expansion of the model to include a full financial 'block' would enable further research into the effects of using different financing options.[14] This would add to the policy debate by allowing a framework to assess different financing options, alone as well as in mixed portfolios, to outline the best and worst policy options.

EXOGENOUS ELECTRICITY PRICE

The electricity price is currently an endogenous variable in the model and is, therefore determined by the model. The introduction of an exogenous growth path for the electricity price would be extremely useful in light of the recent electricity price hikes. Users would be able to simulate electricity price paths and the effect this could have on the demand for electricity. This would provide useful information for policy makers and parties within the electricity sectors and would aid in their decision-making.

HYBRID MODEL

The general finding in this discussion is that there is a need for a closer interaction between the modelling done in the IRP and an economy-wide model. The ultimate goal should be to 'endogenize' the build plan within the CGE model which would allow the use of broader criteria in the IRP process.[15]. A hybrid model is one option of achieving this. Another option would be to link an energy model with a CGE model. Both approaches would allow continuous interaction between the build plan and the economy over the period. This continuous interaction would yield more accurate results. For instance, energy demand in the IRP is based on a

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[14] The Development Bank of South Africa (DBSA)'s Macromodel provides an example of where a complete financial block has been added to the core CGE model (Gibson, 1996). This allows users to simulate shocks to financial variables such as private sector portfolios and government fiscal balance.

[15] There is currently joint research between the Energy Research Centre and the United Nations University's World Institute for Development Economics Research (UNU-WIDER) from which they hope to produce such a hybrid.

predetermined growth path. The process of shocking the model by adding a specified electricity supply path changes the economic growth path. The build plan should be based on an updated growth path for the following years and change accordingly. This highlights the need for the modelling to follow an iterative approach and the use of either of these approaches would lead to this result.

CONCLUSION

This thesis has discussed the need for a computable general equilibrium (CGE) model to assess the Integrated Resource Plan (IRP) in order to provide information that will enable improved decision-making in the electricity sector. An economy-wide framework for examining the macroeconomic and distributional consequences of an electricity supply shock on the South African economy was presented. Through this, simultaneous quantitative expressions were provided for the impact of an external shock on macro aggregates including: (1) GDP; (2) total absorption; (3) exports and imports; (4) real exchange rate; (5) sector prices; (6) and factors of production. This was done by integrating two modelling approaches to research in the electricity sector. The first approach used the data, assumptions and scenarios found in the IRP, which followed a bottom-up approach to modelling. The second top-down approach used Arndt, et al. (2011)'s highly disaggregated CGE model that captured crucial economy-wide impacts of relative price and income effects as well as the response of the labour market to external shocks imposed on the economy.

A number of key findings were identified in terms of the policy-modelling debate as well as deduced from the results of the CGE model. One key finding was that policy should influence modelling and modelling should influence policy in order for a successful integration of these two paradigms.

The main finding from the modelling of the IRP was that the policy-adjusted scenario would have a slightly negative effect on the growth of the economy overall, in comparison to the base case. However, this is only a slight negative impact and the economy still performs well under a number of key indicators. There is still potential industry growth in new as well as historically-favoured industries. This result is influenced by the assumptions made in the model and is likely to change according to changes in these assumptions. A number of research areas were identified that are beyond the scope of this thesis. Areas such as localisation need to be explored as an inclusion of these aspects is likely to change the results of the model.

The E-SAGE model used in the analysis provided an adequate framework for the purpose of this thesis. The use of this CGE model allowed an analysis of the scenarios using a number of key policy goals that the IRP was unable to quantify under its current modelling approach. These policy goals included economic growth measured using GDP, employment, terms of trade and electricity price. The aforementioned analysis of the plan contributes to a more comprehensive decision-making process in the IRP. There are a large number of policy goals, some of which this thesis did not assess and in light of this a few areas for potential research were identified. These include an expansion of the model to include a breakdown of imports as a portion of investment, localisation, a financial sector, an exogenous electricity price growth path and to ultimately create a hybrid energy-CGE model.

Referring back to the definition of policy by Chappin and Dijakema (Chappin & Dijkema, 2010): 'a policy is effective when it indeed initiates a transition and leads to some optimal end state while additional requirements for the transition path often exist'. This thesis concludes that the current policy-adjusted scenario is a movement in the right direction in terms of reaching a number of the policy goals of the IRP. There will be winners and losers, as is normally the case with change, but considering current global supply concerns new avenues for growth must be explored.

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APPENDIX I

DESCRIPTION OF THE INITIAL IRP SCENARIOS

EMISSIONS 1

In this scenario an emissions limit of 275million tons of CO2 is enforced over the whole period. Under these constraints nuclear, wind and gas are considered preferred base-load options to coal. The total amount of coal commissioned in the period drops to 3700MW, more than 15GW less than in the base case. A nuclear fleet of 6 units of 1600MW each comes online with the first unit commissioned in 2022. Due to the nuclear lengthy build period, a substantial amount of wind, 11000MW, is commissioned from 2017 to 2027. In addition, the introduction of nearly 2000MW of imported hydro, 4140MW of OCGT and 4266MW of gas powered CCGT is also scheduled. The total cost of this build plan where approximately 35GW of electricity is brought online is R860bn, in present value terms. Hence this scenario is significantly more costly than the base case requiring R71bn more financing. Water usage however, is less than that of the base case with a decline over the period to 241 785 million litres in 2030.

EMISSIONS 2

The emissions 2 scenario calls for an emissions limit of 275 million tons of CO2 as was the case in emissions 1, although the constraint only applies from 2025 onwards. Therefore this allows a delay in the shift from coal-fired plants to lower carbon emitting technologies. Wind and nuclear builds are delayed 5 years and 1year respectively. A build plan similar to that in base case is used until 2022 where low –carbon technologies are favoured in light of the constraint. The decommissioning of old coal-fired plants also attributes to maintenance of this carbon emissions limit. The total cost of this scenario, in present value terms, is slight lower than that of emissions 1 at R835bn.

EMISSIONS 3

This scenario introduces a more severe emissions limit of 220 million tons of CO2 from 2020. Hence, apart from the coal-fired power stations commissioned in the committed build plan, no coal comes online over the period. The first wind farm is commissioned in 2015 followed by a substantial number of turbines over the rest of the period, to the total of 17600MW of wind by 2030. There is a fleet of 6 nuclear power plants that follow the same build plan at in emissions 1. 11 250 MW of centralised solar panels are commissioned over the period, along with 1110MW of imported hydro, 6440MW of OCGT and 4266MW of CCGT. Water usage is considerably lower than other scenarios at 218 970 million litres in 2030. The total cost of this scenario is substantially higher than the other scenarios due to the high investment costs of renewable technologies. The total cost is R1 250bn, 50% higher than the total cost of the base case, although if a carbon was introduced the cost of these two scenarios could merge as the base case would decrease in affordability due to its high emissions.

CARBON TAX

This scenario imposes a tax on carbon emissions, at the level proposed by the Long Term Mitigation Scenarios LTMS, of R165/MWh in 2010, increasing to R332/MWh in 2020 and remaining constant to the end of the period, 2030. Under the constraints of this tax there is a shift to lower-carbon emitting technologies. A nuclear fleet of 6 units is commissioned, along with 17 600 MW of wind, 1959 MW of imported hydro, 4255 MW of OCGT, 4266MW of CCGT and 1750MW of coal. The total cost of this build plan, in present value terms, is R852bn, excluding the carbon tax. The total CO2 emissions increase to a level of 260 million tons and the water usage declines over the period to 238 561 million litres.

REGIONAL DEVELOPMENT

The regional development scenario allows the inclusion of all potential import options within the region. Although these import options present lower generation cost options, they also involve an expansion of the current transmission capacity which in itself if quite costly. The total cost of this scenario, in present terms and excluding transmission expansion costs, is R783bn – slightly cheaper than the base case. A total of 3349MW of imported hydro is introduced as well 2200MW of imported coal, although local OCGT and CCGT options are favoured over imported gas options.

ENHANCED DSM

This scenario represents a experimental scenario that was produced to examine the effect on the IRP of additional demand side management (DSM). A further 6TWh of DSM is introduced by 2015 which led to a cost reduction of R12.8bn, in present terms. Therefore it was deduced that a 6TWh DSM programme that would cost less than the cost reduction would be beneficial.

ADJUSTED EMISSIONS SCENARIO

The recent publication of the IRP included a number of new scenarios after a number of input changes were recognised – including increasing the cost of nuclear, including learning rates (mainly effecting solar and wind inputs), and the disaggregation of solar technologies following acquired data and studies regarding solar technologies. An Adjusted Emissions scenario was modelled to include these changes in inputs using the foundation of the previously explained Emission 2 scenario. From this scenario another five scenarios were developed, the results of which will be briefly discussed below. The cost-optimisation of the Adjusted Emissions scenario phased out nuclear from the build plan due to the combined effect of the higher input cost of nuclear, the new data on solar, as well as the effect of the inclusion of learning rates on renewable technologies. The scenario includes 6 GW of coal, 16 GW of wind, 8 GW of OCGT, 4 GW of CCGT, 3GW of hydro and 9 GW each of CSP and PV. Total CO2 emissions, as with the emission 2 scenario, level at 275 million tons. The total cost, in present value terms, is estimated at R827bn, R38bn higher than the original base case scenario presented in the draft IRP (DoE, 2010). Water usage in this scenario decreases over the period to 256 026 million litres on 2030.

HIGH EFFICIENCY

The High Efficiency scenario is an update to the previous Enhanced DSM scenario with an increase to 6298 MW of DSM from the formerly modelled 3420 MW of DSM (DoE, 2011). The generation capacity build plan is similar to that of the Adjusted Emission scenario, with the only changes being a decrease in CSP and wind to 8 GW and 14 GW respectively. However the total cost, in present value terms, is approximately R25bn less at R802bn. The total CO2 emissions are marginally less at a level of 274 million tons, and water usage is the same.

LOW GROWTH

The low growth scenario takes into account the uncertainty of the demand forecast and models on the projected demand growth path from the CSIR-Low forecast. This scenario plans an additional 31 GW to come online by 2030, substantially less than the 55 GW planned for the Adjusted Emission scenario. The breakdown of the new capacity is 6 GW of coal, 3 GW of hydro, 4 GW of CCGT, 10 GW of OCGT, 4 GW of wind and 3 GW of solar PV. The total cost is considerably lower, as one would expect, at R703bn. Total carbon emissions remain level at 275 million tons in 2030 and water usage is lower at 243 572 million litres in 2030.

RISK AVERSE

This scenario restricts the capacity allowed from renewables and import options, and as a result of the emissions target, 8 GW of nuclear capacity was introduced. The amount of coal capacity was reduced to 4 GW, CCGT to 3 GW, OCGT to 6 GW, CSP to 4 GW, wind to 10 GW and PV to 7 GW, with hydro remaining unchanged at 3 GW. The total CO2 emissions were marginally lower at a level of 271 million tons in 2030, and water usage decreased over the period to 248 617 million litres. The total cost of this scenario is R871bn, R44bn higher than the Adjusted Emissions scenario.

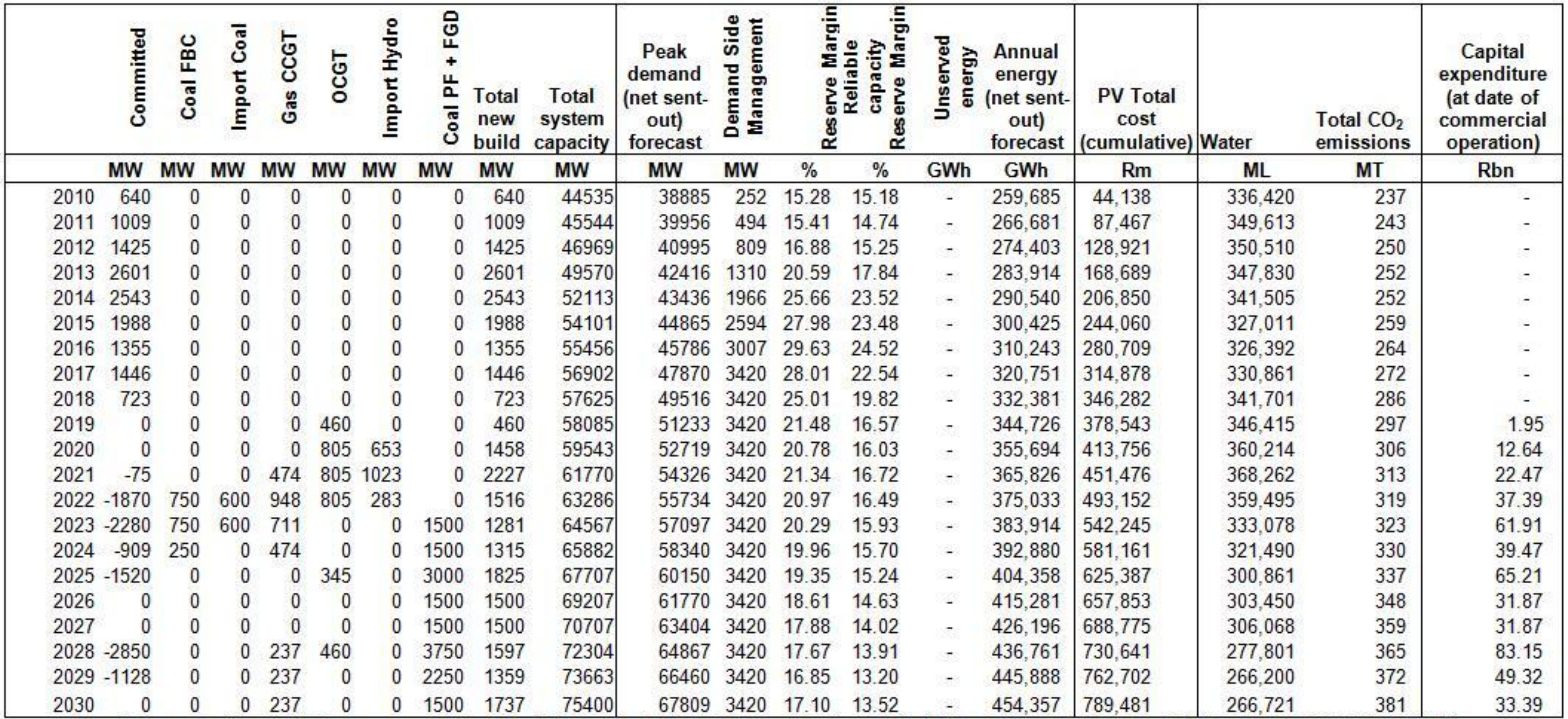
PEAK OIL

The ‘Peak Oil’ scenario models a build plan with higher costs for gas, coal and diesel. This results in an increase in the amount of new nuclear capacity to 9.6 GW, a decrease in coal to 4 GW, a decrease in OCGT to 7GW, a decrease in wind to 13 GW, a decrease in solar PV to 6 GW and no allowance for new CSP and CCGT. The reason for this counterintuitive result in terms of CSP and CCGT, is that in the model used for the IRP CSP and CCGT were combined as CCGT provides a backup for the CSP capacity, and in this way presents a base-load alternative to nuclear. The levelised cost for nuclear, even after the price increase in the new IRP was lower than the CSP and CCGT combination, therefore nuclear was the least cost option in this scenario. The total CO2 emissions are much lower than the limit at a level of 259 in 2030, due to the decrease in demand for fossil fuels as a result of the increase prices. The total cost, in present value terms, of this capacity build plan is R884bn, R57bn higher than the Adjusted Emissions scenario.

EARLIER COAL

In the 'Earlier Coal' scenario the emissions level is increased to a limit of 287 million tons per year from 2025 to allow for a slightly larger coal programme. The total new coal generation capacity increases by 2 GW to 8GW by 2030, capacity in renewable technologies decrease marginally to 8 GW, 14 GW and 7 GW for PV, wind and CSP respectively. OCGT and hydro remain at 8 GW and 3 GW respectively, and CCGT decreases to 3 GW. This scenario is slightly less expensive than the Adjusted Emission scenario at an estimated total cost of R824bn.

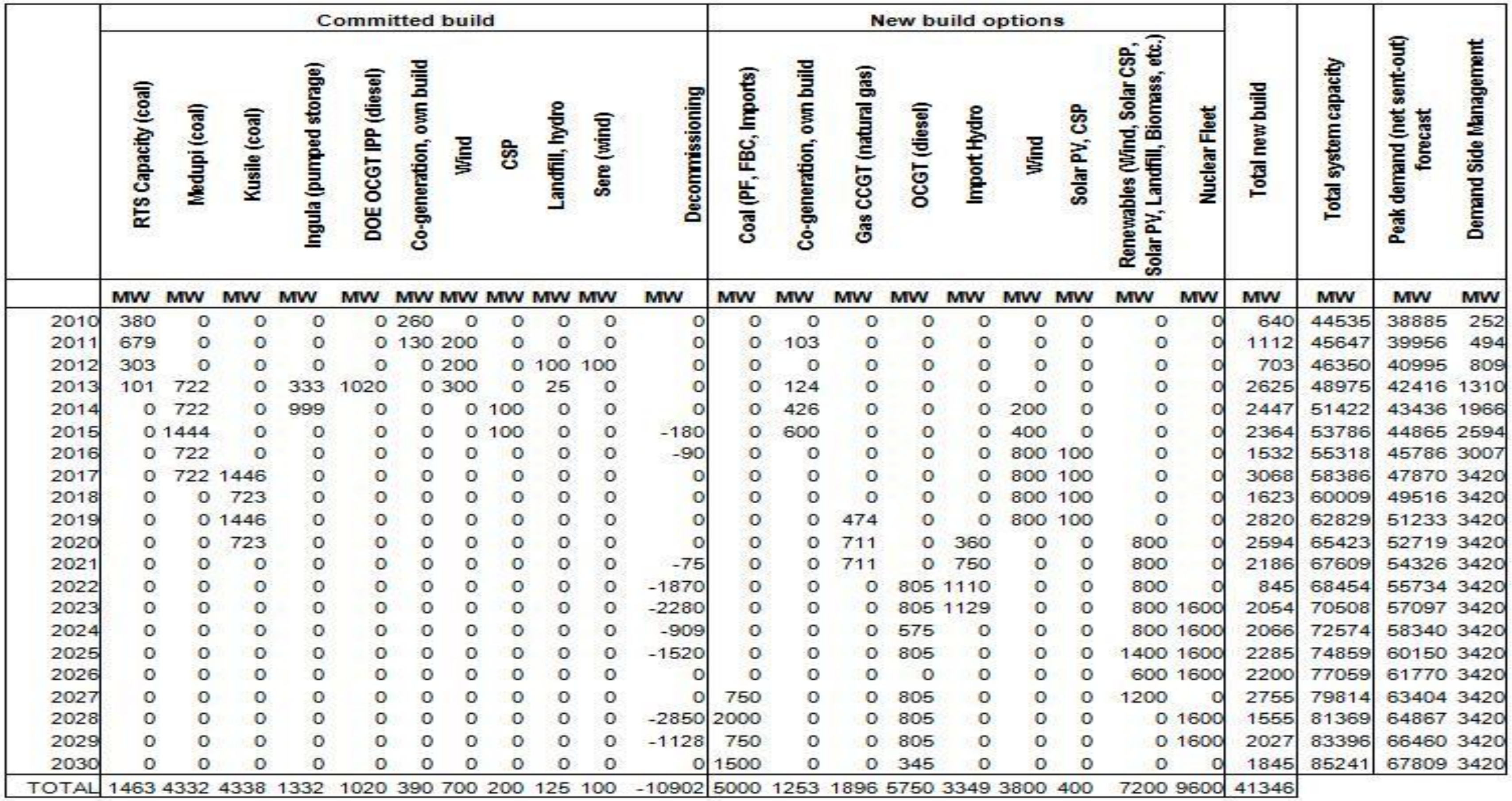
Source: (DoE, 2010)



	Committed	Coal FBC	Import Coal	Gas CCGT	OCGT	Import Hydro	Coal PF + FGD	Total new build	Total system capacity	Peak demand (net sent-out) forecast	Demand Side Management	Reserve Margin	Reliable capacity Reserve Margin	Unserved energy	Annual energy (net sent-out) forecast	PV Total cost (cumulative)	Water	Total CO_2 emissions	Capital expenditure (at date of commercial operation)
	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	%	%	GWh	GWh	Rm	ML	MT	Rbn
2010	640	0	0	0	0	0	0	640	44535	38885	252	15.28	15.18	-	259,685	44,138	336,420	237	-
2011	1009	0	0	0	0	0	0	1009	45544	39956	494	15.41	14.74	-	266,681	87,467	349,613	243	-
2012	1425	0	0	0	0	0	0	1425	46969	40995	809	16.88	15.25	-	274,403	128,921	350,510	250	-
2013	2601	0	0	0	0	0	0	2601	49570	42416	1310	20.59	17.84	-	283,914	168,689	347,830	252	-
2014	2543	0	0	0	0	0	0	2543	52113	43436	1966	25.66	23.52	-	290,540	206,850	341,505	252	-
2015	1988	0	0	0	0	0	0	1988	54101	44865	2594	27.98	23.48	-	300,425	244,060	327,011	259	-
2016	1355	0	0	0	0	0	0	1355	55456	45786	3007	29.63	24.52	-	310,243	280,709	326,392	264	-
2017	1446	0	0	0	0	0	0	1446	56902	47870	3420	28.01	22.54	-	320,751	314,878	330,861	272	-
2018	723	0	0	0	0	0	0	723	57625	49516	3420	25.01	19.82	-	332,381	346,282	341,701	286	-
2019	0	0	0	0	460	0	0	460	58085	51233	3420	21.48	16.57	-	344,726	378,543	346,415	297	1.95
2020	0	0	0	0	805	653	0	1458	59543	52719	3420	20.78	16.03	-	355,694	413,756	360,214	306	12.64
2021	-75	0	0	474	805	1023	0	2227	61770	54326	3420	21.34	16.72	-	365,826	451,476	368,262	313	22.47
2022	-1870	750	600	948	805	283	0	1516	63286	55734	3420	20.97	16.49	-	375,033	493,152	359,495	319	37.39
2023	-2280	750	600	711	0	0	1500	1281	64567	57097	3420	20.29	15.93	-	383,914	542,245	333,078	323	61.91
2024	-909	250	0	474	0	0	1500	1315	65882	58340	3420	19.96	15.70	-	392,880	581,161	321,490	330	39.47
2025	-1520	0	0	0	345	0	3000	1825	67707	60150	3420	19.35	15.24	-	404,358	625,387	300,861	337	65.21
2026	0	0	0	0	0	0	1500	1500	69207	61770	3420	18.61	14.63	-	415,281	657,853	303,450	348	31.87
2027	0	0	0	0	0	0	1500	1500	70707	63404	3420	17.88	14.02	-	426,196	688,775	306,068	359	31.87
2028	-2850	0	0	237	460	0	3750	1597	72304	64867	3420	17.67	13.91	-	436,761	730,641	277,801	365	83.15
2029	-1128	0	0	237	0	0	2250	1359	73663	66460	3420	16.85	13.20	-	445,888	762,702	266,200	372	49.32
2030	0	0	0	237	0	0	1500	1737	75400	67809	3420	17.10	13.52	-	454,357	789,481	266,721	381	33.39

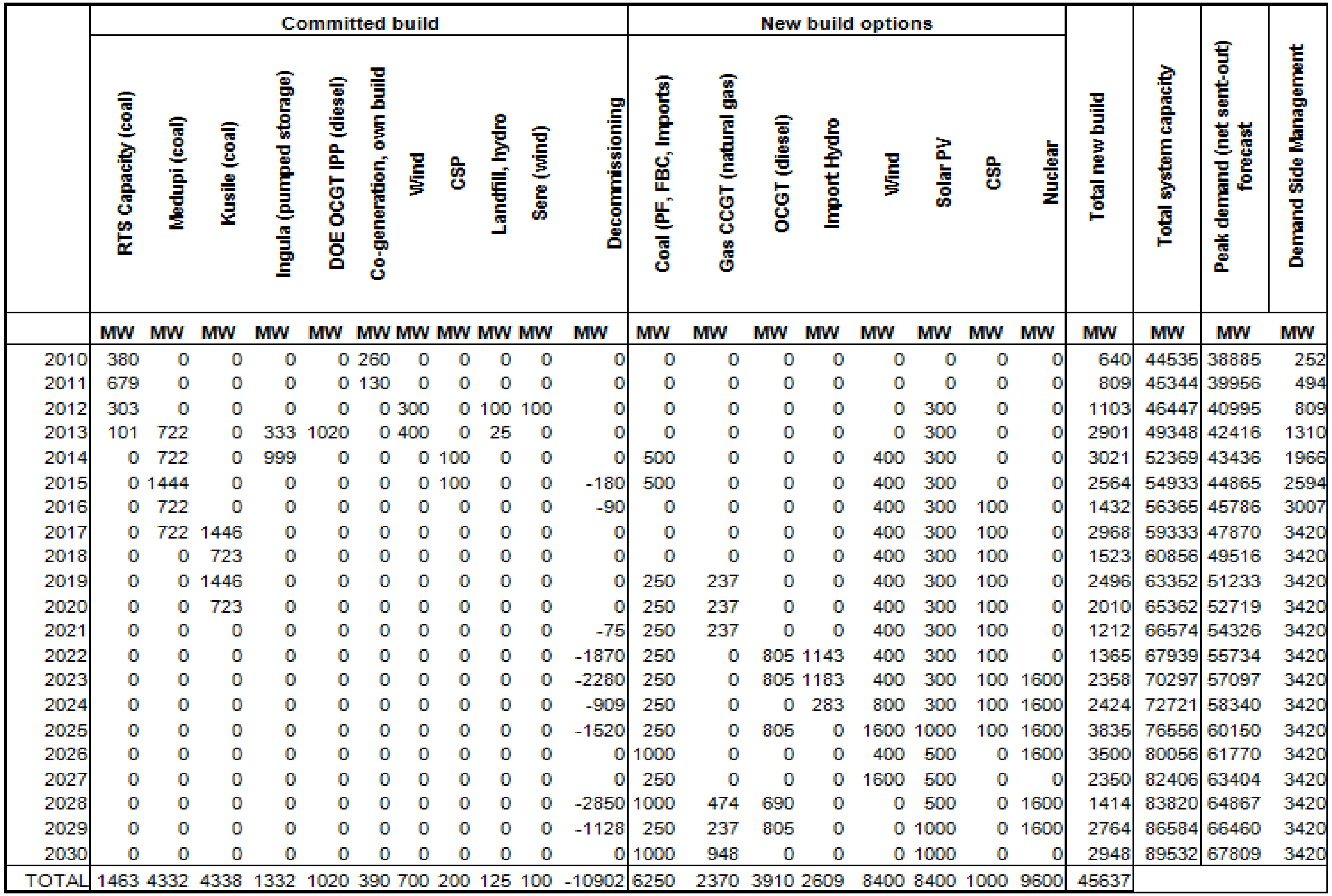
No emission constraints; committed programme includes Medupi, Kusile, Ingula, Sere and Return to Service capacity (all from Eskom), 1025MW from REFIT, 1020MW OCGT IPP; 390MW from MTPPP; maximum wind 1600MW per year; EEDSM as per Eskom MYPD2 application, max 3420MW

Source; : (DoE, 2010)



	Committed build											New build options												
	RTS Capacity (coal)	Medupi (coal)	Kusile (coal)	Ingula (pumped storage)	DOE OCGT IPP (diesel)	Co-generation, own build	Wind	CSP	Landfill, hydro	Sere (wind)	Decommissioning	Coal (PF, FBC, Imports)	Co-generation, own build	Gas CCGT (natural gas)	OCGT (diesel)	Import Hydro	Wind	Solar PV, CSP	Renewables (Wind, Solar CSP, Solar PV, Landfill, Biomass, etc.)	Nuclear Fleet	Total new build	Total system capacity	Peak demand (net sent-out) forecast	Demand Side Management
	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW
2010	380	0	0	0	0	260	0	0	0	0	0	0	0	0	0	0	0	0	0	0	640	44535	38885	252
2011	679	0	0	0	0	130	200	0	0	0	0	0	103	0	0	0	0	0	0	0	1112	45647	39956	494
2012	303	0	0	0	0	0	200	0	100	100	0	0	0	0	0	0	0	0	0	0	703	46350	40995	809
2013	101	722	0	333	1020	0	300	0	25	0	0	0	124	0	0	0	0	0	0	0	2625	48975	42416	1310
2014	0	722	0	999	0	0	0	100	0	0	0	0	426	0	0	0	200	0	0	0	2447	51422	43436	1966
2015	0	1444	0	0	0	0	0	100	0	0	-180	0	600	0	0	0	400	0	0	0	2364	53786	44865	2594
2016	0	722	0	0	0	0	0	0	0	0	-90	0	0	0	0	0	800	100	0	0	1532	55318	45786	3007
2017	0	722	1446	0	0	0	0	0	0	0	0	0	0	0	0	0	800	100	0	0	3068	58386	47870	3420
2018	0	0	723	0	0	0	0	0	0	0	0	0	0	0	0	0	800	100	0	0	1623	60009	49516	3420
2019	0	0	1446	0	0	0	0	0	0	0	0	0	0	474	0	0	800	100	0	0	2820	62829	51233	3420
2020	0	0	723	0	0	0	0	0	0	0	0	0	0	711	0	360	0	0	800	0	2594	65423	52719	3420
2021	0	0	0	0	0	0	0	0	0	0	-75	0	0	711	0	750	0	0	800	0	2186	67609	54326	3420
2022	0	0	0	0	0	0	0	0	0	0	-1870	0	0	0	805	1110	0	0	800	0	845	68454	55734	3420
2023	0	0	0	0	0	0	0	0	0	0	-2280	0	0	0	805	1129	0	0	800	1600	2054	70508	57097	3420
2024	0	0	0	0	0	0	0	0	0	0	-909	0	0	0	575	0	0	0	800	1600	2066	72574	58340	3420
2025	0	0	0	0	0	0	0	0	0	0	-1520	0	0	0	805	0	0	0	1400	1600	2285	74859	60150	3420
2026	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	600	1600	2200	77059	61770	3420
2027	0	0	0	0	0	0	0	0	0	0	0	750	0	0	805	0	0	0	1200	0	2755	79814	63404	3420
2028	0	0	0	0	0	0	0	0	0	0	-2850	2000	0	0	805	0	0	0	0	1600	1555	81369	64867	3420
2029	0	0	0	0	0	0	0	0	0	0	-1128	750	0	0	805	0	0	0	0	1600	2027	83396	66460	3420
2030	0	0	0	0	0	0	0	0	0	0	0	1500	0	0	345	0	0	0	0	0	1845	85241	67809	3420
TOTAL	1463	4332	4338	1332	1020	390	700	200	125	100	-10902	5000	1253	1896	5750	3349	3800	400	7200	9600	41346			

Source: (DoE, 2011)



	Committed build											New build options											
	RTS Capacity (coal)	Medupi (coal)	Kusile (coal)	Ingula (pumped storage)	DOE OCGT IPP (diesel)	Co-generation, own build	Wind	CSP	Landfill, hydro	Sere (wind)	Decommissioning	Coal (PF, FBC, Imports)	Gas CCGT (natural gas)	OCGT (diesel)	Import Hydro	Wind	Solar PV	CSP	Nuclear	Total new build	Total system capacity	Peak demand (net sent-out) forecast	Demand Side Management
	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW
2010	380	0	0	0	0	260	0	0	0	0	0	0	0	0	0	0	0	0	0	640	44535	38885	252
2011	679	0	0	0	0	130	0	0	0	0	0	0	0	0	0	0	0	0	0	809	45344	39956	494
2012	303	0	0	0	0	0	300	0	100	100	0	0	0	0	0	0	300	0	0	1103	46447	40995	809
2013	101	722	0	333	1020	0	400	0	25	0	0	0	0	0	0	0	300	0	0	2901	49348	42416	1310
2014	0	722	0	999	0	0	0	100	0	0	0	500	0	0	0	400	300	0	0	3021	52369	43436	1966
2015	0	1444	0	0	0	0	0	100	0	0	-180	500	0	0	0	400	300	0	0	2564	54933	44865	2594
2016	0	722	0	0	0	0	0	0	0	0	-90	0	0	0	0	400	300	100	0	1432	56365	45786	3007
2017	0	722	1446	0	0	0	0	0	0	0	0	0	0	0	0	400	300	100	0	2968	59333	47870	3420
2018	0	0	723	0	0	0	0	0	0	0	0	0	0	0	0	400	300	100	0	1523	60856	49516	3420
2019	0	0	1446	0	0	0	0	0	0	0	0	250	237	0	0	400	300	100	0	2496	63352	51233	3420
2020	0	0	723	0	0	0	0	0	0	0	0	250	237	0	0	400	300	100	0	2010	65362	52719	3420
2021	0	0	0	0	0	0	0	0	0	0	-75	250	237	0	0	400	300	100	0	1212	66574	54326	3420
2022	0	0	0	0	0	0	0	0	0	0	-1870	250	0	805	1143	400	300	100	0	1365	67939	55734	3420
2023	0	0	0	0	0	0	0	0	0	0	-2280	250	0	805	1183	400	300	100	1600	2358	70297	57097	3420
2024	0	0	0	0	0	0	0	0	0	0	-909	250	0	0	283	800	300	100	1600	2424	72721	58340	3420
2025	0	0	0	0	0	0	0	0	0	0	-1520	250	0	805	0	1600	1000	100	1600	3835	76556	60150	3420
2026	0	0	0	0	0	0	0	0	0	0	0	1000	0	0	0	400	500	0	1600	3500	80056	61770	3420
2027	0	0	0	0	0	0	0	0	0	0	0	250	0	0	0	1600	500	0	0	2350	82406	63404	3420
2028	0	0	0	0	0	0	0	0	0	0	-2850	1000	474	690	0	0	500	0	1600	1414	83820	64867	3420
2029	0	0	0	0	0	0	0	0	0	0	-1128	250	237	805	0	0	1000	0	1600	2764	86584	66460	3420
2030	0	0	0	0	0	0	0	0	0	0	0	1000	948	0	0	0	1000	0	0	2948	89532	67809	3420
TOTAL	1463	4332	4338	1332	1020	390	700	200	125	100	-10902	6250	2370	3910	2609	8400	8400	1000	9600	45637			

APPENDIX II

Table A1: Model Indices, Variables and Parameters (Arndt, Davies, & Thurlow, Energy Extension to the South Africa General Equilibrium (SAGE) Model, 2011)

Indices			
c	Commodities and activities	e	Energy commodities and activities ($e \subset c$)
f	Factors (land, labor and capital)	h	Representative households
k	Capital ($k \subset f$)	s	Subsectors producing the same commodity
l	Land and labor ($l \subset f$)	t	Time periods
Exogenous parameters			
α^a	Sector aggregation function shift parameter	ci	Capital price index weights
α^p	Production function shift parameter	cm	Import transaction cost coefficients
α^q	Import function shift parameter	cpi	Consumer price index
α^t	Export function shift parameter	cw	Consumer price index weights
β	Household marginal budget share	d	Capital depreciation rate
γ	Non-monetary consumption quantity	ga	Government consumption adjustment factor
δ^a	Sector aggregation function share parameter	gh	Per capita transfer from government
δ^p	Production function share parameter	grf	Land and labor supply growth rate
δ^q	Import function share parameter	grh	Population growth rate
δ^t	Export function share parameter	grg	Government consumption growth rate
θ^i	Intermediate share of gross output	grp	Rate of technical change
θ^v	Value-added share of gross output	grc	Foreign savings inflows growth rate
π	Foreign savings growth rate	io	Intermediate input coefficients
ρ^a	Sector aggregation substitution elasticity	pop	Household population
ρ^k	Energy price-demand elasticity	pwe	World export price
ρ^p	Production function substitution elasticity	pwm	World import price
ρ^q	Import function substitution elasticity	qfs	Total factor supply
ρ^t	Export function substitution elasticity	$qgov$	Base government consumption quantity
τ	Capital allocation adjustment factor	$qinv$	Base investment demand quantity
ω	Factor income distribution shares	rf	Factor foreign remittance rate
μ	Share of new capital in sector capital stock	sh	Marginal propensity to save
cab	Current account balance	$tco2$	Carbon tax rate (rand per ton of CO$_2$ equiv.)
cc^d	Carbon content of domestic good (direct only)	tf	Factor direct tax rate
cc^e	Carbon content of exported good (indirect)	th	Personal direct tax rate
cc^m	Carbon content of imported good (indirect)	tm	Import tariff rate
cd	Domestic transaction cost coefficients	tq	Sales tax rate
ce	Export transaction cost coefficients	wh	Net transfer from rest of world
Endogenous variables			
AR	Average capital rental rate	QF	Factor demand quantity
FS	Fiscal surplus (deficit)	QG	Government consumption quantity
IA	Investment demand adjustment factor	QH	Household consumption quantity
PA	Aggregate sector output price	QI	Investment demand quantity
PAS	Subsector output price	QK	New capital stock quantity
PD	Domestic supply price with margin	QM	Import quantity
PE	Export price	QN	Aggregate intermediate input quantity
PM	Import price	QQ	Composite supply quantity
PN	Aggregate intermediate input price	QT	Transaction cost demand quantity
PQ	Composite supply price	QV	Composite value-added quantity
PS	Domestic supply price without margin	WD	Sector distortion in factor return
PV	Composite value-added price	WF	Economywide factor return
QA	Aggregate sector output quantity	YF	Total factor income
QAS	Subsector output quantity	YG	Total government revenues
QD	Domestic supply quantity	YH	Total household income
QE	Export quantity	X	Exchange rate

Table A2: Model Equations (Arndt, Davies, & Thurlow, Energy Extension to the South Africa General Equilibrium (SAGE) Model, 2011)

Prices	
$PM_{ct} = pwm_c \cdot (1 + tm_c) \cdot X + \sum_{c'} PQ_{c't} \cdot cm_{c'c} + tco2 \cdot cc_i^m$	A1
$PE_{ct} = pwe_c \cdot X_t - \sum_{c'} PQ_{c't} \cdot ce_{c'c} + tco2 \cdot cc_i^e$	A2
$PD_{ct} = PS_{ct} + \sum_{c'} PQ_{c't} \cdot cd_{c'c}$	A3
$PQ_{ct} \cdot \left(1 - tq_c\right) \cdot QQ_{ct} - tco2 \cdot cc_i^d \cdot QQ_i = PD_{ct} \cdot QD_{ct} + PM_{ct} \cdot QM_{ct}$	A4
$PA_{ct} \cdot QA_{ct} = PS_{ct} \cdot QD_{ct} + PE_{ct} \cdot QE_{ct}$	A5
$PN_{cst} = \sum_{c'} PQ_{c't} \cdot io_{cc's}$	A6
$PAS_{cst} \cdot QAS_{cst} = PV_{cst} \cdot QV_{cst} + PN_{cst} \cdot QN_{cst}$	A7
$cpi = \sum_{c} cw_c \cdot PQ_{ct}$	A8
$DPI = \sum_{c} cp_c \cdot PA_{ct}$	A9
Production and trade	
$QV_{cst} = \alpha_{cst}^p \cdot \sum_f \left(\delta_{fcs}^p \cdot QF_{fcst}^{-\rho_{cs}^p}\right)^{-1/\rho_{cs}^p}$	A10
$WF_{ft} \cdot WD_{fcst} = PV_{cst} \cdot QV_{cst} \cdot \sum_{f'} \left(\delta_{f'cs}^p \cdot QF_{f'cst}^{-\rho_c^p}\right)^{-1} \cdot \delta_{cs}^p \cdot QF_{fcst}^{-\rho_{cs}^p - 1}$	A11
$QN_{cst} = \theta_{cs}^i \cdot QAS_{cst}$	A12
$QV_{cst} = \theta_{cs}^v \cdot QAS_{cst}$	A13
$QA_{ct} = \alpha_c^s \cdot \sum_s \left(\delta_{cs}^s \cdot QAS_{cst}^{-\rho_{cs}^s}\right)^{-1/\rho_{cs}^s}$	A14
$PAS_{cst} = PA_{ct} \cdot QA_{ct} \cdot \sum_{s'} \left(\delta_{cs'}^s \cdot QAS_{cs't}^{-\rho_c^s}\right)^{-1} \cdot \delta_{cs}^s \cdot QAS_{cst}^{-\rho_c^s - 1}$	A16
$QA_{ct} = \alpha_c^t \cdot \left(\delta_c^t \cdot QE_{ct}^{\rho_c^t} + (1 - \delta_c^t) \cdot QD_{ct}^{\rho_c^t}\right)^{1/\rho_c^t}$	A17
$\frac{QE_{ct}}{QD_{ct}} = \left(\frac{PE_{ct}}{PS_{ct}} \cdot \frac{(1 - \delta_c^t)}{\delta_c^t}\right)^{1/\left(\rho_c^t - 1\right)}$	A18
$QQ_{ct} = \alpha_c^q \cdot \left(\delta_c^q \cdot QM_{ct}^{-\rho_c^q} + (1 - \delta_c^q) \cdot QD_{ct}^{-\rho_c^q}\right)^{-1/\rho_c^t}$	A19
$\frac{QM_{ct}}{QD_{ct}} = \left(\frac{PD_{ct}}{PM_{ct}} \cdot \frac{(1 - \delta_c^q)}{\delta_c^q}\right)^{1/\left(1 + \rho_c^t\right)}$	A20
$QT_{ct} = \sum_{c'} \left(cd_{cc'} \cdot QD_{c't} + cm_{cc'} \cdot QM_{c't} + ce_{cc'} \cdot QE_{c't}\right)$	A21
Incomes and expenditures	
$YF_{ft} = \sum_c WF_{ft} \cdot WD_{fct} \cdot QF_{fct}$	A22

Table A2 continued: Model Equations (Arndt, Davies, & Thurlow, Energy Extension to the South Africa General Equilibrium (SAGE) Model, 2011)

Incomes and expenditures continued	
$YH_{ht} = \sum_{f} \omega_{hf} \cdot \left(1 - tf_{f}\right) \cdot \left(1 - rf_{f}\right) \cdot YF_{ft} + gh_{h} \cdot pop_{ht} \cdot cpi + wh_{h} \cdot X$	A23
$PQ_{ct} \cdot QH_{cht} = PQ_{ct} \cdot \gamma_{ch} + \beta_{ch} \cdot \left((1 - sh_{h}) \cdot (1 - th_{h}) \cdot YH_{ht} - \sum_{c'} PQ_{ct'} \cdot \gamma_{c'h} \right)$	A24
$QI_{ct} = IA_{t} \cdot qinv_{c}$	A25
$QG_{ct} = ga_{t} \cdot qgov_{c}$	A26
$YG_{t} = \sum_{h} th_{h} \cdot YH_{ht} + \sum_{f} tf_{f} \cdot YF_{ft} + \sum_{c} \left(tm_{c} \cdot pwm_{c} \cdot QM_{ct} \cdot X + tq_{c} \cdot PQ_{ct} \cdot QQ_{ct}\right)$ $+ \sum_{i} tco2 \cdot \left(cc_{i}^{d} \cdot QQ_{i} + cc_{i}^{m} \cdot QM_{i} - cc_{i}^{e} \cdot QE_{i}\right)$	A27
Equilibrium conditions	
$qfs_{ft} = \sum_{cs} QF_{fcst}$	A28
$QQ_{ct} = \sum_{c's} io_{c'cs} \cdot QN_{c'st} + \sum_{h} QH_{cht} + QG_{ct} + QI_{ct} + QT_{ct}$	A29
$\sum_{c} pwm_{c} \cdot QM_{ct} + \sum_{f} \left(1 - tf_{f}\right) \cdot rf_{f} \cdot YF_{ft} \cdot X_{t}^{-1} = \sum_{c} pwe_{c} \cdot QE_{ct} + \sum_{h} wh_{h} + cab_{t}$	A30
$YG_{t} = \sum_{c} PQ_{ct} \cdot QG_{ct} + \sum_{h} gh_{h} \cdot pop_{ht} \cdot cpi + FS_{t}$	A31
$\sum_{h} sh_{h} \cdot (1 - th_{h}) \cdot YH_{ht} + FS_{t} + cab_{t} \cdot X_{t} = \sum_{c} PQ_{ct} \cdot QI_{ct}$	A32
Capital accumulation and allocation	
$AR_{kt} = \frac{YF_{kt}}{qfs_{kt}}$	A33
$QF_{kct+1} = (1 - d) \cdot QF_{kct} + QK_{kct}$	A34
$QK_{kct} = \frac{QF_{kct}}{qfs_{kt}} + \tau \cdot \frac{QF_{kct}}{qfs_{kt}} \cdot \left(\frac{WF_{kt} \cdot WD_{kct}}{AR_{kt}}\right) \cdot \left(\sum_{c'} PQ_{c't} \cdot QI_{c't}\right) \cdot \left(\sum_{c'} PQ_{c't} \cdot ci_{c'}\right)^{-1}$	A35
Land and labor supply, technical change, population growth, and other dynamic updates	
$qfs_{lt+1} = qfs_{lt} \cdot \left(1 + grf_{lt}\right)$	A36
$\alpha_{ct+1}^{p} = \alpha_{ct}^{p} \cdot \left(1 + grp_{ct}\right)$	A37
$pop_{ht+1} = pop_{ht} \cdot \left(1 + grh_{ht}\right)$	A38
$ga_{t+1} = ga_{t} \cdot \left(1 + grg_{t}\right)$	A39
$cab_{t+1} = cab_{t} \cdot \left(1 + grc_{t}\right)$	A40
Intermediate energy demand adjustment	
$io_{iset+1} = \left[1 - \left(1 - \frac{PQ_{et}^{-\rho_{e}^{k}}}{pq_{e}^{0}}\right) \cdot \mu_{ist}\right] \cdot io_{iset}$	A41
$\mu_{ist} = \sum_{k} QK_{ikst} \Big/ \sum_{k} QF_{iskt}$	A42

Table A3: Classification of Sectors (Arndt, Davies, & Thurlow, Energy Extension to the South Africa General Equilibrium (SAGE) Model, 2011)

SAGE model sector	SIC (revision 3)	SAGE model sector	SIC (revision 3)
Agriculture	11	Non-metals	342
Biomass feedstock	11	Iron and steel	351
Forestry	12	Nonferrous metals	352, 353
Fisheries	13	Metal products	354, 355
Coal mining	21	Machinery	356, 357, 358, 359
Crude oil extraction	221	Electrical machinery	36
Natural gas mining	221	Scientific equipment	37
Other mining	23, 24, 25, 29	Vehicles	381, 382, 383
Food processing	301, 302, 303, 304	Other transport equip.	384, 385, 386, 387
Beverages and tobacco	305, 306	Furniture	391
Textiles	311, 312, 313	Other manufacturing	392
Clothing	314	Recycling	395
Leather products	315, 316	Electricity	411, 412, 413
Footwear	317	Water distribution	42
Wood products	321, 322	Construction	501, 502, 502, 503, 504
Paper	323	Trade services	61, 62, 63
Printing and publishing	324, 325, 326	Hotels and catering	64
Petroleum products	331, 332, 333	Transport services	71, 72, 73, 74
Basic chemicals	3341, 3343,	Communication	75
Other chemicals	3342, 335, 336	Financial services	81, 82, 83
Rubber products	337	Business services	505, 84, 85, 86, 87, 88
Plastic products	338	Government services	91, 92, 93, 94
Glass products	341	Other services	95, 96, 99, 01, 02, 09