

South African Energy Model: A System Dynamics Approach

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Abstract

This paper provides a South African energy model that was developed as a first step towards a comprehensive Threshold 21 model for South Africa. The energy sector consists of five sub-models, which are structured around the supply and demand of electricity, coal, oil, and natural gas in the sector. The model was used to examine a set of policies that the South African government is currently considering, e.g. expansion of nuclear energy production and implementation of more stringent energy efficiency measures. The analyses show that energy efficiency measures are indeed the best option to curb the supply and demand constraints, which the energy sector faces, in the short term. In general, the paper demonstrates how a system dynamics approach can be utilized effectively to support understanding of energy-related issues and clarify the advantages and disadvantages related to the options available to government and the private sector. The paper also highlights potential pitfalls that may be encountered when building such a model. Future developments include extending the model to incorporate the linkages between the energy sector and the economy, society and environment, which would complete the T21

framework for South Africa, and extending the model, with models for other countries in the region, to the Southern African Development Community.

Keywords: energy modeling, policy analysis, South Africa

1. Introduction

Energy is central to sustainable development and poverty reduction efforts; its availability influences the lives of poor people and their ability to escape poverty. As a developing economy, South Africa faces the dual challenge of pursuing economic growth and environmental protection. The economy of the country is mainly structured around large-scale, energy-intensive mining and associated beneficiation industries, pushing its energy intensity levels to above world average levels (Hughes et al., 2002); even when compared to developed countries (DME, 2005a). From an economic growth perspective the energy sector is critical as it contributes about 15% of the country's gross domestic product (GDP).

Large deposits of coal in South Africa, with government policies, have made for low cost electricity supply by international standards. While the cost of electricity in South Africa is still among the lowest, strong economic development, rapid industrialization, and a mass electrification program have led to demand for power outstripping supply in early 2008. The recent power supply crisis has accelerated the recognition for the need to diversify the energy mix, and move towards alternative energy sources such as nuclear power, natural gas, and various forms of renewable energy, as well as exploring a range of energy demand options.

As an example, two niche renewable energy technologies, namely solar and biofuels, have been identified that can make a significant contribution towards poverty alleviation by improving the general welfare of households as well as creating employment (Visagie and Prasad, 2006). South Africa has high levels of solar radiation and an established manufacturing infrastructure for solar water heaters (SWHs). SWHs can contribute to a reduction in greenhouse gas emissions and their manufacturing and installation can contribute to job creation and skills development. High initial capital cost of SWHs, however, presents an obstacle to the development of a SWH market in South Africa. On the other hand, biofuels have the potential to contribute to job creation and socio-economic development in disadvantaged rural communities, energy security in the light of rising oil prices, and reducing greenhouse gas emissions. However, the key challenges to the development of a biofuels market are food security and limited water resources.

Given such challenges, the establishment of alternative energy systems is not a simple one. This is mostly due to the intricacy of social, economic and environmental factors coupled with the implementation of alternative energy policies and programs. As a consequence, the complexity in policy planning raises the need for decision support tools that are based on detailed modelling of the different interrelationships between the economic sectors, energy supply and demand sub-sectors, and the natural resource base and society at large. Threshold 21 (T21) provides a framework for such an analysis (Bassi, 2006).

T21 is a planning tool that integrates the economic, social, and environmental dimensions of a country into a single, comprehensive, transparent, user-friendly analytical framework. It is a dynamic macro-model, based on the systems thinking approach to modeling. This approach is most suited for studying complex inter-connected systems with numerous feedback loops. Since the inception of the system dynamics (SD) field in the mid-1950s, the span of application of this methodology has grown to encompass work in corporate planning and policy design, biological and medical modeling, public management, energy and the environment, and economic research (Bassi, 2006).

This study provides an initial step towards the development of a South African T21 model by focusing on the energy modules of the T21 framework, and testing the key questions arising from various energy-related public and private strategies. The study aims at developing a customized South Africa-T21 model to provide a better understanding of the potential of a system dynamics approach in addressing issues related to energy portfolio diversification, specifically the introduction of alternative energy systems, in the context of South Africa and the region.

2. The South African energy sector

Energy supply is generally divided into two parts, i.e. primary supply and secondary supply. Primary supply is obtained through the extraction or collection of energy resources, e.g. coal mining, the drilling for oil, or the production of biomass. Primary energy can be used directly, but in most cases it is converted into other forms for final energy use. Secondary energy supply, such as electricity, is obtained from the conversion of the primary resources, e.g. coal, nuclear, natural gas, oil, biomass, or other renewables, as well as secondary resources such as waste material. The following sub-sections provide a brief description of the main energy supply and consumption patterns in the South African economy.

2.1 Coal

South Africa has rich reserves of coal and its energy sector is dominated by it; coal constitutes about 75% of the country's primary energy and fuels 93% of its electricity generation (DME, 2005). Much of the coal that is mined for consumption in the South African economy is of low quality, i.e. bituminous thermal grade, and it needs to be beneficiated (DME, 2004a). High grade coal is primarily for export purposes.

Production and consumption of coal in South Africa have grown steadily over the past two and half decades, at an average annual rate of 2.7 percent (EIA, 2008). National coal reserves are plentiful and pressure on supplies is only likely to be felt around 2012, due to underinvestment, with the peak of production being expected around 2070 (Dutkiewicz, 1994). Currently, 33% of the coal mined in South Africa is exported. The industrial, commercial, transport and residential sectors all consume coal directly. Figure 1 shows the aggregate domestic consumption, production and export of coal for the period 1992-2004.

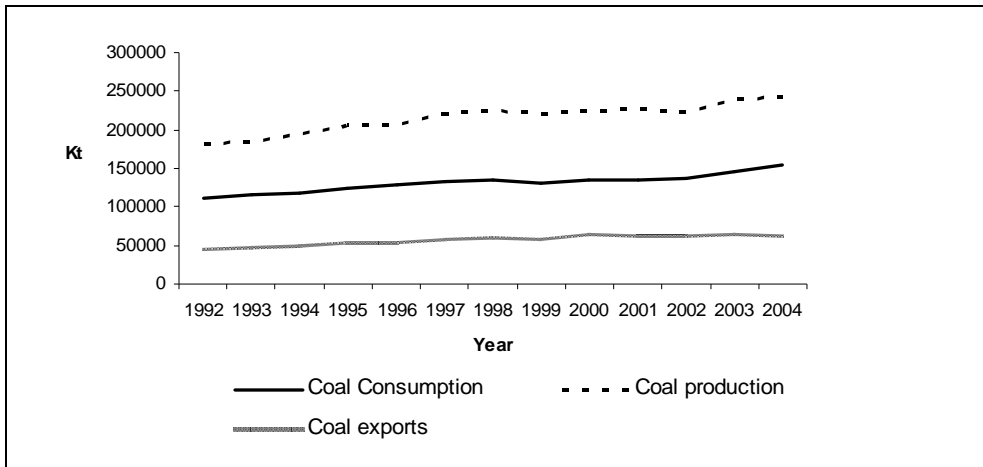


Figure 1: Annual coal production, domestic coal consumption and exports
Source: DME (2006)

2.2 Gas

South Africa's prospects for natural gas production were boosted in 2000 with the discovery of offshore reserves close to the Namibian border. The reserve, named the Ibhubezi Prospect, contains proven reserves of 0.27 to 0.3 trillion cubic feet of hydrocarbons (Dewar and Gasson, 2006). Gas field reserves in South Africa are, however, limited and the Moss gas gas-to-oil installation, the only one of its kind in the Western Cape Province of South Africa, is unlikely to continue operations beyond 2010.

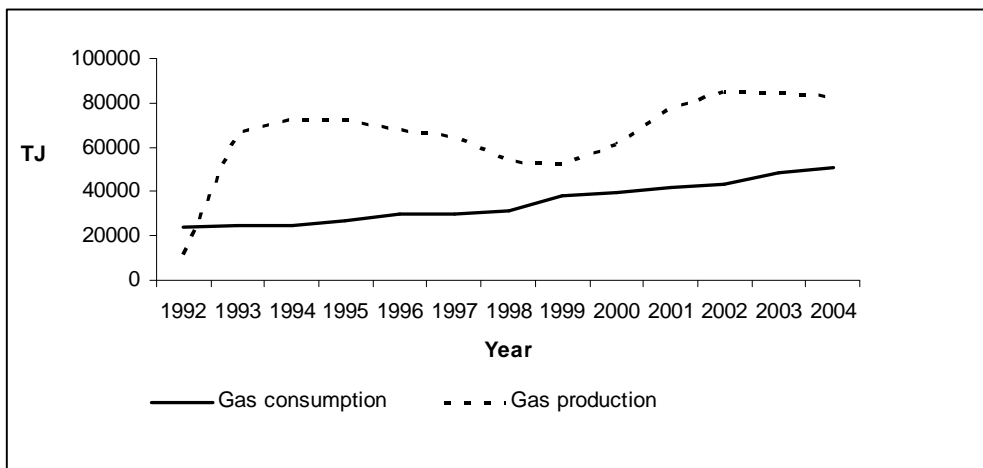


Figure 2: Annual gas production and domestic gas consumption
Source: DME (2006)

Gas consumption plays only a small part in the South African energy mix, accounting for 2% of primary energy supply and 1% of final consumption (DME, 2005b). The natural gas supply is almost exclusively used by the Moss gas gas-to-oil plant and most of the gas

consumed directly is produced by coal gasification. Figure 2 shows gas production and domestic consumption.

2.3 Oil

Liquid fuels in South Africa are derived from refined crude oil, liquefied natural gas, and from coal via the Sasol (Fischer-Tropsch) coal-to-oil process. Products are sold in local markets and exported, mainly to East Africa. About 36% of liquid fuel demand is met by synthetic fuels, which are produced locally from coal and gas, while the remaining 64% is met from locally refined imported crude oil (DME, 2005b).

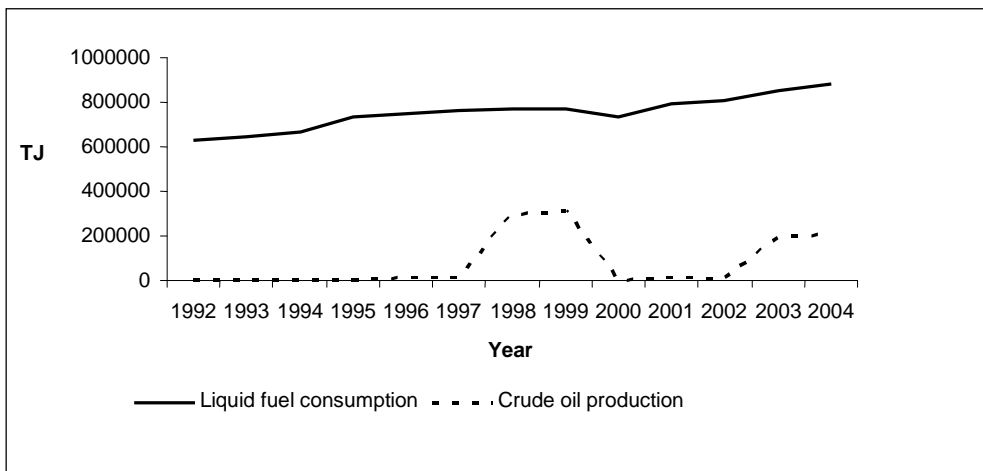


Figure 3: Annual crude oil production and liquid fuel consumption
Source: DME (2006)

2.4 Electricity generation – conventional and alternative

Electricity is an important energy source in all aspects of development including industry, agriculture, environment and the socio-economy at large. As shown in Figure 4, the gap between electricity generation and consumption in South Africa has been steadily decreasing over the years. To respond to the declining gap between the supply and demand for electricity, it is necessary to understand the behavior in the electricity consumption in the coming years and how the planned development in the electricity production responds to the growing demand.

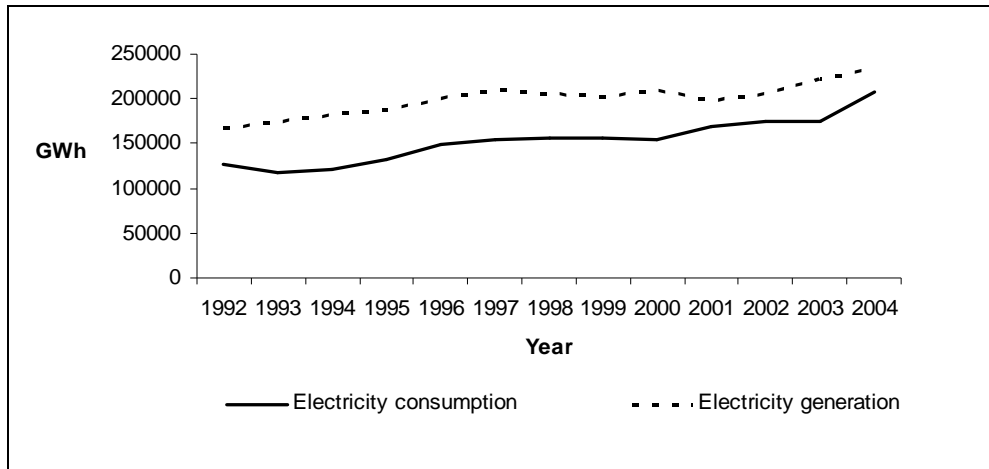


Figure 4: Annual Electricity generation and consumption
 Source: DME (2006)

There are three groups of electricity generators in South Africa (NERSA, 2005): the national public electricity utility, Eskom; municipal generators and auto generators; and industries that generate electricity for their own use (EIA, 2008a). Eskom generates 95% of South African electricity and two-thirds of its network is made up of more than 300,000 km of power lines, of which 27,000 km constitute the national transmission grid (EIA, 2008). The main generating stations are located in the Mpumalanga Province, where there is vast coal reserves (refer to Figure 5 that shows the locations of all the power stations). There are 13 coal-fired power stations with an installed capacity of 37,698 MW. Three of these power stations, with an installed capacity of 3,780 MW, were mothballed in 1990 and are currently being re-commissioned (ESKOM, 2008).

There is one nuclear power station (Koeberg) with an installed capacity of 1,800 MW and four gas turbine power stations with an installed capacity of 1,378 MW. Two of the gas turbine generators (2 X 171 MW) run on kerosene and the other two are newer, run by diesel, and were commissioned in March 2007. In addition, there are two conventional hydroelectric plants with limited potential for expansion, and two pumped storage stations (NERSA, 2005).



Figure 5: Map of South Africa showing the location of all the power stations
Source: ESKOM (2008)

The South African government has a number of electricity generation expansion plans, including (ESKOM, 2008; ESKOM, 2009; and Flak, 2009):

- (i) Construction of two coal-fired power stations namely: (a) 4,788 MW Medupi power station, which is proposed to be progressively commissioned from 2012 (798 MW in 2012, 1,596 MW in 2013, 798 MW in 2014 and 1,596 MW in 2015); and (b) 3,212 MW Bravo power station proposed to be progressively commissioned in 2013 (803 MW in 2013, 1,606 MW in 2014 and 803 MW in 2015);
- (ii) Re-commissioning previously mothballed power stations providing 3,600 MW;
- (iii) Construction of Ingula pumped storage hydro scheme with four 1,352 MW turbines; to be commissioned in 2013;
- (iv) Construction of fourteen 149 MW open-cycle gas units for a total of 2,086 MW installed capacity. Seven units were commissioned between March 2007 and June 2007; the other seven are expected to be commissioned in 2009;
- (v) A 100 MW wind farm (fifty times 2 MW). The plant could, potentially, be operational by the middle 2010.

- (vi) Construction of a 6,000 MW nuclear power plant. A 3,200 MW generating capacity is proposed to be commissioned in 2019.

The implication of the proposed electricity expansion plan is an increase in the availability of electricity, which would consequently reduce the (potential) electricity price volatility. However, the reduction in the volatility in price also largely depends on demand side management, which requires the electricity users to be energy efficient. In 2002, Eskom, the electricity utility, indicated that demand side management could reduce the demand by up to 11,000 MW.

2.5 Biomass

With South Africa being a dry country, the conditions to build up sustainable biomass for energy generation are limited (Davidson et al., 2006). However, this is an important energy source for households' domestic use and for industry, i.e. sugar refining, and pulp and paper. The annual sugarcane production is approximately 20 million tons per year of which 7 million tons is bagasse with a heating value of 6.7MJ/kg (Davidson et al., 2006). Most of the bagasse is used in the sugar refineries to generate steam for electricity and for process heat.

Biomass can also be used to yield biodiesel, -ethanol, -methanol and -hydrogen. Biodiesel is mostly produced from sunflower and soya oil, while bioethanol is generated from maize, sugar beet and cane, and sweet sorghum (Brent et al, in Press). Biofuels options have potential for generating income for the rural areas through biomass plantations that can create jobs. However, the prospects of the biomass plantations have raised the concern of food supplies and the impact of planting mono-cultural crops on biodiversity (EDRC, 2003). Canola has been identified as a suitable crop in South Africa for biodiesel production and a canola refinery plant is underway to be established in the Eastern Cape Province, to produce biodiesel for export to the European market.

3. South Africa energy policy

The Energy White Paper of 1998 (DME, 1998) spells out the major objectives of the energy policy as: (i) increasing access to affordable energy services; (ii) improving energy governance; (iii) stimulating economic growth; (iv) managing energy-related environmental impacts; and (v) securing supply through diversity.

Securing energy supply through diversity is the goal that relates to renewable energy as a source of a diverse energy supply (Winkler, 2005). Renewable energy has played a small role due to its limited access, marginalized to the particular niche of off-grid electrification. In mid-2002 the Department of Minerals and Energy (DME) published a White Paper on the 'promotion of renewable energy and clean energy development', which supplements the Energy Policy White paper of 1998 (DME, 2002).

The energy strategy of 2005 (DME, 2005a) allows for immediate implementation of low-cost and no-cost interventions, as well as the higher-cost measures with short payback periods. It acknowledges the significant potential of energy efficiency measures in all energy use sectors. The energy efficiency improvements are planned to be achieved

through enabling instruments and interventions, which include among others: economic and legislative instruments, efficiency labels and performance standards, efficiency management activities and energy audits, and promotion of efficiency practices (DME, 2005a).

The T21 South African energy model is intended to be a tool for an integrated energy policy formulation and evaluation. Since investments in nuclear and renewable resources in South Africa depend heavily on government support and their social, economic and environmental impact, there is need to use such a comprehensive and integrated policy planning tool.

4. The South Africa energy modules of the T21 model

The South Africa energy sector of the T21 model, focusing on national energy strategies, endogenously calculates national energy demand and supply. The causal loop diagram (CLD) in Figure 6 represents, in a simplified manner, the most relevant interconnections underlying the calculation of energy supply and demand in the T21 model. The CLD shows that with increasing economic activity, energy demand grows. Further, higher demand is normally translated into higher energy supply, therefore increasing production requirements, which also account for losses.

Actual energy consumption is calculated as the minimum between energy produced and energy demanded, and the ratio of energy demand and supply is assumed to influence investments in conventional and alternative energy. The allocation of investments into new infrastructure, especially renewable energy, creates jobs and improves economic performance (GDP), but creates what can be considered a side effect: higher GDP leads to increased energy demand, assuming that energy prices do not increase considerably, leading to higher needs for the expansion of production capacity. The availability of energy, e.g. demand supply balance, and eventual pricing policies can influence energy prices, which in turn influence energy demand, as well as energy efficiency mandates. Renewable energy and nuclear energy policy influence energy supply from non-conventional and conventional sources respectively, as well as average energy prices and emissions.

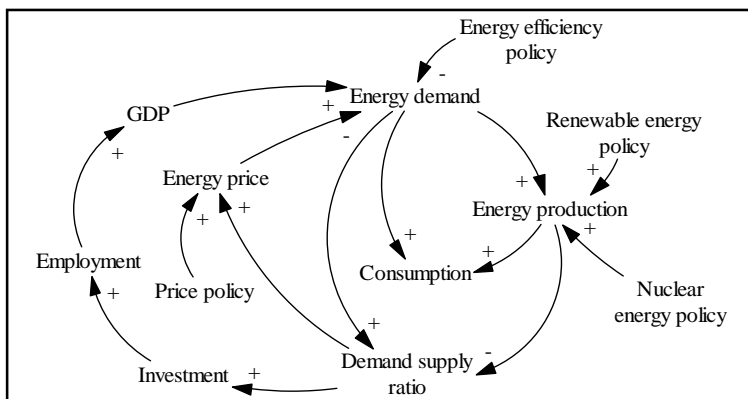


Figure 6: Causal loop diagram

The energy sources included in the model are: renewable (non-hydro), nuclear, hydroelectric, coal, oil and gas. Electricity, coal, gas and oil were considered as energy use. The South African T21 energy model centers on the understanding of the national energy demand and supply of the different energy sources and assumes GDP and prices as exogenous variables at this stage. The following sub-sections describe the different energy supply and demand sub-models.

4.1 Electricity sub-model

The demand for electricity is calculated for the industry, transport, agriculture, commerce, and residential sectors (DME, 2006), the key energy users in South Africa. Electricity demand is modeled as an endogenous variable and is influenced by changes in GDP and energy prices, which in turn affect electricity production from the different sources. Electricity price and GDP are, however, exogenously determined, since the price of electricity in South Africa is regulated by NERSA (National Energy Regulator of South Africa) and GDP is based on the projections made in 2008 (Appel, 2008)). The electricity supply is from six sources, namely: hydro, nuclear, pumped storage, coal, wind, gas turbines and bagasse (DME, 2006).

Electricity supply is calculated based on energy demand and installed electricity generation capacity. In building the electricity sub-model, the planned electricity production targets such as the construction of the 4,788 MW coal fired station, the re-commissioning of 3,600 MW of mothballed power stations, the construction of 1,352 MW of pumped storage hydro, the construction of 2,086 MW open cycle gas turbines and the construction of a 100 MW wind farm were incorporated. It was also assumed that a 1% year-on-year energy efficiency improvement for all the sectors would take place.

The key stock variables in the energy sub-model are *hydro-power plant capacity*, *coal plant capacity*, *nuclear plant capacity*, *wind plant capacity*, *gas turbine capacity*, *solar capacity* and *pumped storage capacity*. Since the differential equations for all these electricity are more or less similar, *coal plant capacity* (CPC) stock is used to illustrate the differential function of these stock variables, which is given as:

$$\frac{dCPC}{dt} = r_{cpc} - r_{cpd}$$

Where r_{cpc} is the coal plant construction and r_{cpd} is coal plant depreciation. The coal plant construction is based on coal plant construction table of the South Africa government plans to put up the coal plants in the country. On the other hand, coal plant depreciation is expressed as

$$r_{cpd} = CC * dr_{cpc}$$

Where CC is coal capacity and dr_{cpc} is depreciation rate of coal plant capacity

The electricity that is generated from coal (EG_C) is therefore given as:

$$EG_C = (CC * cft(time)) * E_{cds}$$

Where cft is the conversion factor table and E_{cds} is the effect of coal demand supply balance on electricity generation from coal. The effect of coal demand supply balance on electricity generation from coal is given as:

$$E_{cds} = E_{dst}(dsr_C)$$

Where E_{dst} is the effect of demand supply table and dsr_C is demand supply ratio for coal. This demand supply ratio for coal is determined by the *total demand for coal plus coal exports* divided by the *annual coal production*.

Since electricity generation from coal in South Africa forms the largest share, the electricity requirements from coal is therefore an important variable. *Electricity required from coal* (ER_C) is treated as the residual of all other available energy sources for electricity production and it is calculated as the difference between the *demand for production in GWh* (DP) and *electricity generation from non-coal sources* (EG_{NC}) (i.e. hydro, nuclear, pumped storage, wind and solar):

$$ER_C = DP - EG_{NC}$$

The demand for electricity generation in GWh is a sum of *power sector electricity use* (PS), *final electricity demand* (FD_E) both net (retail sales) and gross, including losses in generation, transmission and distribution (EL).

Final electricity demand equals retail sales, while the *power sector electricity use* represents the sum of electricity used by the energy sectors, i.e. coal mines, oil refineries and pumped storage. The overall demand can then be calculated as follows:

$$DP = EL + PS + FD_E$$

Tables A1 to A6 of the Appendix show the parameters used in the calculation of electricity demand and supply, both inputs and outputs.

4.2 Coal sub-model

The coal sub-model is divided into two stocks, namely, remaining coal reserves and proven coal reserves (PCR).

$$\frac{dPCR}{dt} = r_{cd} - r_{acp}$$

Where r_{cd} is coal discovery and r_{acp} is the annual coal production in ton. Discovery of coal results in the increase in the proven coal reserves while coal is production depletes it. Coal discovery is determined by the annual discovery fraction and the remaining coal reserves. On the other hand, annual coal production is calculated as the minimum between the sum of domestic demand for coal and exports, and the annual coal production fraction multiplied by the proven coal reserves:

$$r_{acp} = \text{Min}(TD_C + E_C), PCR * f_{acp}$$

Where, E_C is the coal exports in tons; f_{acp} is the annual coal production fraction; and TD_C is the total demand for coal, which is the amount of coal required for consumption in any given year and it includes both direct use (FD_C) (industry, transport, agriculture, domestic, and commerce) and demand for electricity generation and gas, coke and liquification (SD_C). The total demand for coal is given as follows:

$$TD_C = SD_C + FD_C$$

The *total coal demand* also influences *coal demand supply ratio*, which is the ratio between the *total coal demand in kt* and the *annual coal production*, which finally has an effect on the electricity generation from coal.

Again, in the coal sub-model, GDP is the key exogenous input that affects the coal sub-model. The parameters used in the model, the inputs and outputs, are shown in Tables A7 to A9 of the Appendix.

4.3 Gas sub-model

This sub-model is also divided into two stocks, namely, remaining gas reserves and proven gas reserves (PGR).

$$\frac{dPGR}{dt} = r_{gd} - r_{gp}$$

Where r_{gd} is gas discovery and r_{gp} is gas production. The discovery increases the proven reserves while production depletes it. Domestic gas production is mostly driven by the available proven reserves of natural gas. Also, gas production is influenced by the planned production (PP_G), which is calculated as:

$$r_{gp} = \text{IF THEN ELSE}(PGR > 0, PP_G, 0)$$

In South Africa, all the domestic gas produced is liquefied. The liquefied gas therefore increases the liquid fuel supply in the oil sub-model. Domestic demand by the key sectors (transport, industry, commerce, residential and non-specified gas use) is therefore provided by the conversion of coal to gas, which is a variable from the coal sub-model, and also from gas imports. The *net gas import* (I_G) variable is the difference between *total gas demand* (TD_G) and *gas production from coal* (GP_C):

$$I_G = IF THEN ELSE (TD_G > GP_C, TD_G - GP_C, 0)$$

The *total gas demand* is the sum of all sector gas users mentioned above. GDP is similarly the main exogenous variable used in the calculation of gas demand. The parameters, inputs, outputs and the model structure are described in Tables A10 to A12 of the Appendix.

4.4 Oil sub-model

In a similar manner to coal and gas sub-models, the oil sub-model is also divided into two stocks, namely, remaining oil reserves and proven oil reserves (POR).

$$\frac{dPOR}{dt} = r_{od} - r_{aop}$$

Where r_{od} is oil discovery and r_{aop} is annual crude oil production. Domestic crude oil production is calculated as the *annual production fraction* multiplied by proven oil reserves. Before 1996, domestic crude oil was equal to zero (EIA, 2008b). The equation used for domestic crude oil production is therefore given as:

$$r_{aop} = IF THEN ELSE ((Time < 1996), 0, f_{aop} * POR)$$

Where, f_{aop} is the annual oil production fraction. Most of the crude oil consumed in South Africa is imported and, as a consequence, net import (I_O), the difference between what is demanded locally and the amount of oil that is produced domestically is key:

$$I_O = DR_O - r_{aop}$$

Where, I_O is crude oil imports, DR_O is the demand requirements from crude oil. The liquid fuel demand requirement is the sum of oil consumed by different economic sectors, that is: industry, agriculture, mining, transport, residential, commerce, non-energy, and non-specified oil use, and the direct combustion of crude oil. GDP and oil prices were used as the main exogenous variables driving oil consumption in different sectors. The parameters, inputs and outputs used are shown in Tables A13 to A15 of the Appendix.

5. Model validation and scenario definition

The ultimate objective of the model validation is to establish the validity of the structure of the model, and to evaluate the accuracy of the model behaviour's reproduction of the real

system (Barlas, 1996). To validate the South African energy model, the historical data series for the years 1992 to 2004 was used. Direct structure tests (refer Barlas, 1996) such as elasticities were estimated based on the available historical data. This included estimating energy use (e.g. electricity) by a specific sector (e.g. residential, industry) as a function of price and GDP. A logarithm functional form was estimated using STATA software and the coefficients obtained provided the elasticity values, that is, the percentage change in energy use (electricity) by a specific sector, given a 1% change in price and GDP respectively.

The behavioral pattern test (refer Barlas, 1996) of the developed South African energy model was assessed by comparing the baseline simulation results with the historical data, and providing a comparison of the summary statistics of the historical data and the baseline simulation results. In addition, in order to support the comparison of the baseline simulation results with targets and goals in the energy sector, a set of scenarios was defined (see Table 1) to test the model response to changes in nuclear (alternative energy) production, energy efficiency, and prices. Another reason to analyze these scenarios was to demonstrate the capability of the energy model to simulate relevant energy management scenarios. For instance, the energy efficiency exemplifies a demand side energy management approach to lower the level of energy use. On the other hand, the nuclear production illustrates the supply side management to increase the availability of electricity.

Table 1: Scenarios analyzed in the South Africa energy model

Scenario	Energy efficiency (EE)	Yearly price change (after 2011)	Nuclear energy expansion
Baseline	1% yearly EE for the period 2005-2030	3%	Not accounted for
<i>Nuclear energy expansion</i>	1% yearly EE for the period 2005-2030	3%	Accounted for
<i>Energy efficiency1</i>	2% yearly EE for the period 2005-2030	2%	Not accounted for
<i>Energy efficiency2</i>	1.5% yearly EE for the period 2005-2015	2.5%	Not accounted for

6. Results

6.1 Baseline results

The baseline scenario is driven by two main exogenous variables, GDP and energy price. In 2005, GDP growth was 5.09% (World Bank, 2008). The South African Government set a target GDP growth of 6% a year by 2010, which is later projected to decline to 4% by 2030 (Taviv et al., 2008). These optimistic projections for South Africa were recently revised downwards to 3.7% and 3% GDP growth for 2008 and 2009 respectively (Creamer, 2008), due to the global economic crisis. At present, GDP is expected to increase above a 4% growth rate in 2010, because of the Soccer World Cup, that brings about a variety of infrastructure investments. The baseline simulation accounts for the most recent projections of GDP for 2008 to 2010 and assumes a 4% yearly growth rate for the period 2011 to 2030.

Concerning energy prices, Eskom electricity nominal prices have historically followed yearly changes observed in the consumer Price Index (CPI). On the other hand, the average year-on-year increase in electricity price from 1987 to 2002 has been slightly lower than the domestic inflation rate. In June 2008, NERSA allowed Eskom to increase electricity prices by 13.3% in addition to the 14.2% increase granted in December 2008, due to the inability of Eskom to generate enough power to meet soaring energy needs. These price increases resulted in a 27.5% nominal price increase with respect to 2007 (Lesova, 2008)). Currently NERSA projects an annual electricity price increase of 20% to 25% over the next three years (Lesova, 2008), in order to cut down the energy consumption levels, especially by the industrial sector, which is the largest electricity consumer.

6.1.1 Electricity demand and supply baseline simulation results

Gross electricity demand, which includes generation efficiency and losses, is strongly related to retail sales (industry, transport, agriculture, commerce and residential) and the primary users (coal mines, pumped storage, oil refineries). The values for this parameter represent the total electricity requirements in South Africa and provide information on the effort that is required by the electricity suppliers in order to ensure that the demand is met, i.e. the production capacity that needs to be in place to satisfy demand. The effects of energy efficiency and prices are endogenously represented in the electricity sector and contribute to a reduction in energy demand.

The baseline projections for the electricity demand and supply are shown in Figure 7. The historical data used to calibrate the model and test its validity are available for the years 1992 to 2004 and the simulation runs until 2030. Electricity demand is projected to increase over the simulation period reaching approximately 342,723 GWH/year by 2030, which is approximately a 27.5% increase with respect to 2008. Electricity supply is projected to be outpaced by growing demand for electricity starting from 2005 and the demand is likely to continue throughout the simulation period. This result is consistent with the power crisis that started undermining energy availability in South Africa in 2005. Since the electricity supply measures discussed in section 2.4 were taken into account in the baseline scenario, electricity supply is projected to stabilize from the year 2009 until the year 2024, where once again, the demand exceeds the supply from the year 2025. More research would be needed to understand future possible development of the power sector in South Africa.

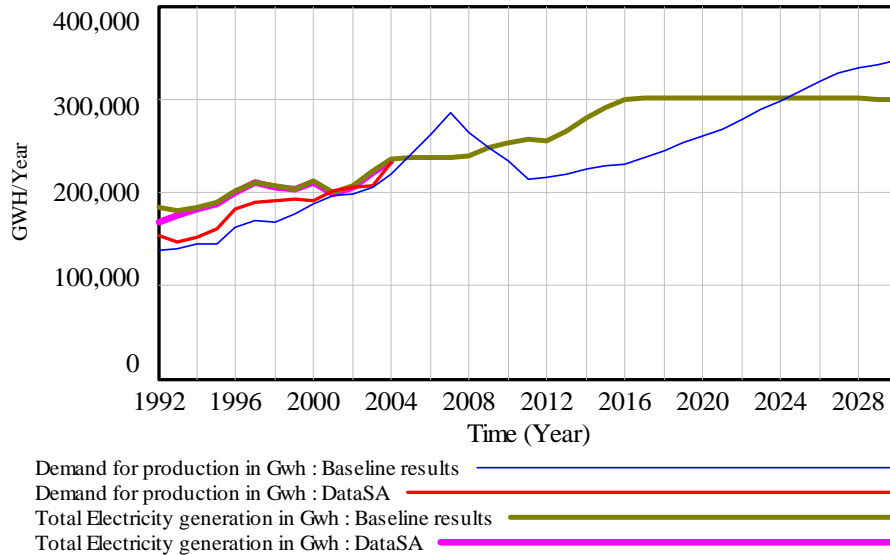


Figure 7: Comparing electricity demand and supply in SA energy model to historical data

The projected increase in electricity price contributes to the relative decline in electricity demand shown from 2008 to 2012. The higher the price, the more conservation and energy efficiency measures are expected to be taken, thereby reducing electricity consumption. The decline in electricity demand is also attributed to the financial crisis, which was accounted for in the GDP projections. The lower the real GDP, the lower the demand for electricity use by the different final users. The strength of the response in electricity consumption due to changes in GDP (elasticity, calculated using STATA, based on the data from DME, 2006) plays a major role in explaining the changes in electricity demand by final users.

As one of the different ways of validating the baseline simulation results, its summary statistics were compared with the historical data as provided in Table 2. The R^2 was computed using the historical data as the first dataset. As it can be observed in Table 2, the electricity sub-model simulation results best fits the historical data

Table 2: Summary statistics for electricity sub-model

Variable	Count	Mean	Std dev (norm)	R^2	#points
Demand for production GWh - Baseline	39	185,057	0.1313	0.6729	13
Demand for production GWh - Data	13	236,190	0.2425	1	13
Total electricity generation in GWh - Baseline	39	200,113	0.0882	0.9265	13
Total electricity generation in GWh - Data	13	255,156	0.1699	1	13

6.1.2 Coal demand and supply baseline simulation results

Coal demand represents the amount of kilotons (Kt) of coal used by the secondary users, i.e. the amount of coal that is transformed to electricity, gas, coke and liquification, and final coal users (industry, transport, agriculture, domestic and commerce) and is one of the main factors driving coal supply in South Africa. Other determinants include the available proven reserves and the annual coal production fraction, which is an exogenous parameter based on historical data (see Table A7 in the Appendix). The results of the baseline scenario for coal demand and supply are shown in Figure 8. The simulation results show that the total demand and supply of coal by 2030 will be about 300,000 Kt and 360,000 Kt respectively.

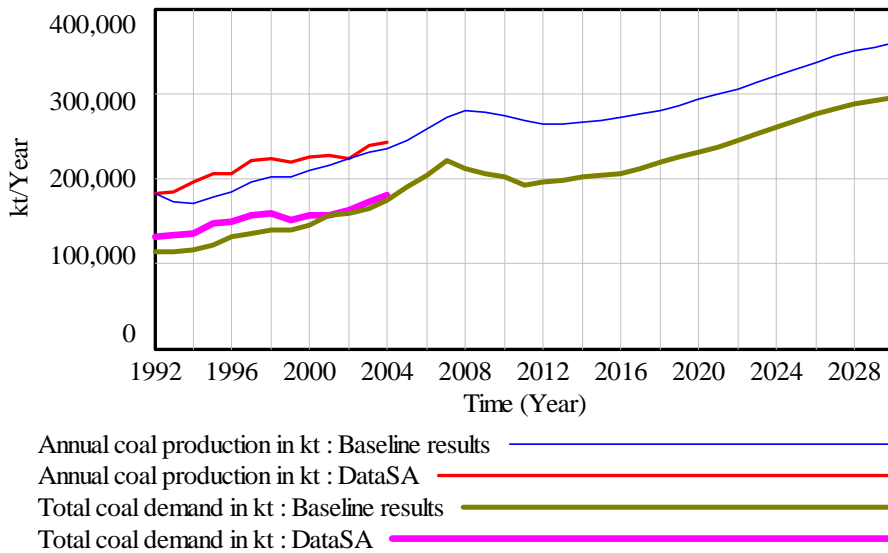


Figure 8: Comparing coal demand and supply in SA energy model to historical data

Coal demand is therefore projected to be met throughout the simulation as South Africa is endowed with rich coal reserves. The simulation results slightly differ from Dutkiewicz (1994), who projected an initial pressure on coal supply around the year 2012 and peak production expected in 2070. The behavior of coal demand follows a similar trend as the one of electricity demand, although the projected decline in demand, due to increasing prices in the case of electricity, is not as significant. This is due to the fact that coal fuels 93% of electricity production and a decline in the demand for electricity is expected to result in a decline in the demand for coal.

Comparing the fit for the baseline results with the historical data, the coal sub-model did not provide a best fit as shown by the low values of the R^2 in Table 3.

Table 3: Summary statistics for coal sub-model

Variable	Count	Mean	Std dev (norm)	R ²	#points
Annual coal production in kt - Baseline	39	215,350	0.0852	0.0788	13
Annual coal production in kt - Data	13	263,081	0.2025	1	13
Total coal demand in kt - Baseline	39	153,484	0.0902	-0.2909	13
Total coal demand in kt - Data	13	200,778	0.2614	1	13

6.1.3 Gas demand and supply baseline simulation results

Natural gas demand consists in final users' demand (transport, industry, and commerce, residential and non-specified users). Since South African gas resources are limited, gas demand drives imports, while additional supply is obtained through coal gasification.

The results of the baseline scenario for gas demand, supply and imports are shown in Figure 8. Challenges were found in analyzing the data on proven resource and reserve, due to inconsistency between stocks and flows. Amidst this challenge, the results of the simulation show increasing demand for gas for the various sectors. Domestic natural gas production is projected to remain close to zero starting from 2004, hence the need to increase imports to meet the demand. This is evident in Figure 8 where the gas imports jumps from zero in 2003 to 43,200 TJ in 2004. This is based on the information provided by EIA (2008b), which shows the decline in the South Africa proven reserves to only 1 BCF by 2004.

Historically a drastic jump was observed in gas production from 1992-1993. PetroSA, which converts natural gas to liquid fuels, came on stream in the fourth quarter of 1992, explaining the drastic increase in production.

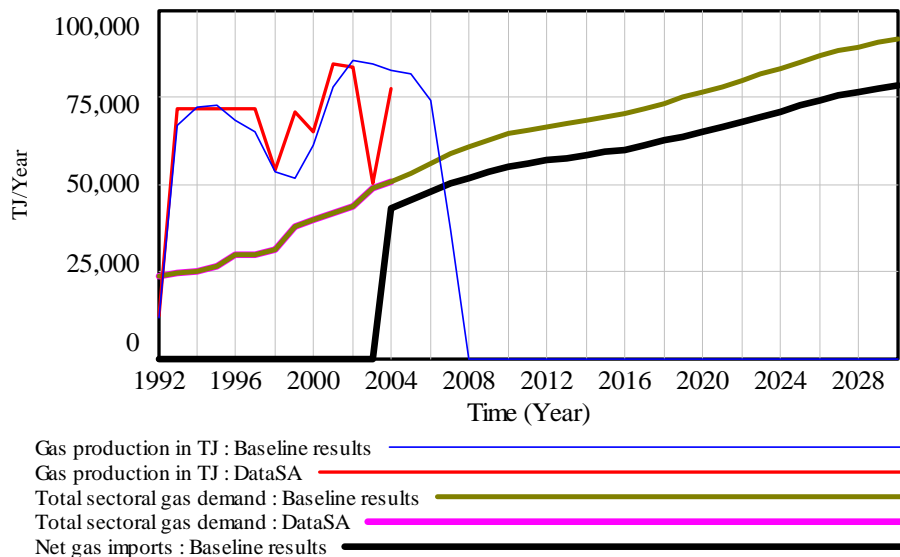


Figure 9: Comparing gas demand and supply in SA energy model to historical data

In contrary with the coal sub-model summary statistics, the R^2 values for gas sub-model indicates a better fit for the baseline simulation results for the *gas production in TJ* provides and the *total sectoral gas demand*. In fact, *total sectoral gas demand* simulation results matches with the historical data as given by a R^2 value of one in Table 4.

Table 4: Summary statistics for gas sub-model

Variable	Count	Mean	Std dev (norm)	R^2	#points
Gas production in TJ - Baseline	39	65,869	0.2756	0.6017	13
Gas production in TJ - Data	13	26,834	1.280	1	13
Total sectoral gas demand - Baseline	39	34,800	0.2599	1	13
Total sectoral gas demand - Data	13	60,687	0.3466	1	13

6.1.4 Oil demand and supply baseline simulation results

Oil demand in the model is defined as the amount of liquid fuel consumed by different economic sectors (industry, agriculture, mining, transport and residential). Oil price and GDP influence liquid fuel demand and since oil resources in South Africa are limited, liquid fuel demand strongly influences crude oil imports. Data consistency issues were also encountered for proven oil reserves. It was therefore assumed that the annual production fraction for the period 2005 to 2030 would follow the 2004 production fraction, which was 0.18%. In addition, the annual discovery fraction was assumed to be 1%.

The results of the baseline scenario for liquid fuel demand, crude oil imports and crude oil production are shown in Figure 9. The demand for liquid fuel is observed to increase up to 2.1 million TJ by 2030, which corresponds to an approximately 82% increase with respect to 2008. The increase in demand on the other hand influences the crude oil imports which increase by approximately 99.4% with respect to 2008.

Given the assumption made for the constant annual production fraction for the period 2005 to 2030, and the discovery fraction, which is relatively higher than the annual production fraction, the crude oil production in TJ appears to be relatively constant for the simulation period 2005 to 2030 (see Figure 10).

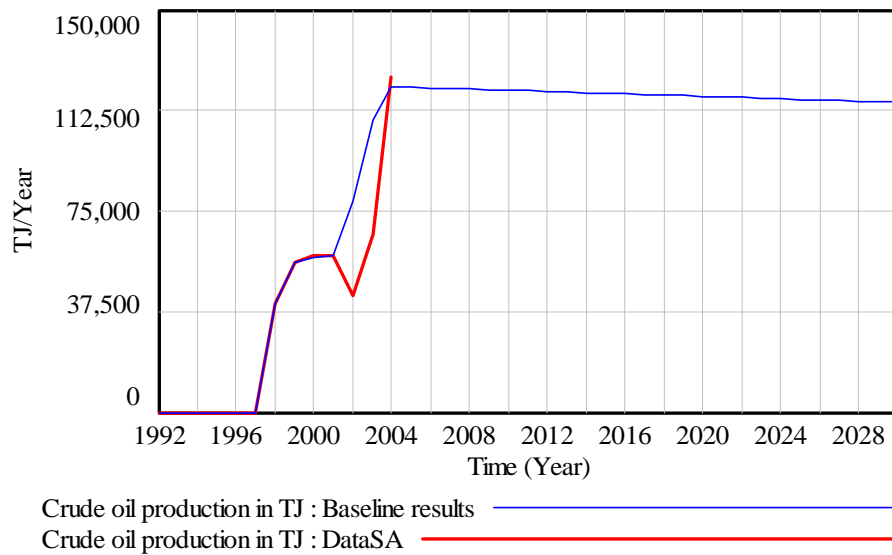
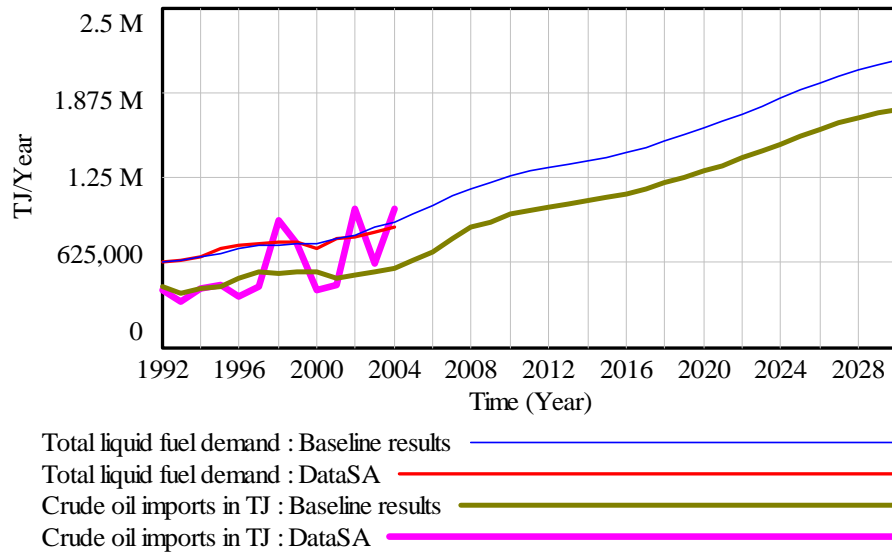


Figure 10: Comparing oil demand and supply in SA energy model to historical data

Analyzing the fit for the oil sub-model, the *liquid fuel demand* baseline simulation results fits well with the historical data while this is not the case for the *crude oil imports* as observed in the low value of R^2 in Table 5.

Table 5: Summary statistics for oil sub-model

Variable	Count	Mean	Std dev (norm)	R ²	#points
Liquid fuel demand - Baseline	39	1.280M	0.3619	0.8987	13
Liquid fuel demand - Data	13	753,043	0.0955	1	13
Crude oil imports in TJ - Baseline	39	986,327	0.4315	0.1094	13
Crude oil imports in TJ - Data	13	591,286	0.4107	1	13

6.2 Scenario Analysis

This section presents the analysis of the scenarios provided in Table 1

6.2.1 Nuclear energy expansion

In early 2007, Eskom approved a plan to boost South African electricity production to 80 GW by 2025. At present, the total electricity generating capacity in South Africa is 49.8 GW of which 41.3 GW is coal fired. The nuclear reactors in South Africa generate 5% of the total electricity, and the planned expansion aims at increasing the nuclear generation capacity to 20 GW. This would therefore increase nuclear energy contribution from 5% to more than 25% of energy supply, and coal contribution would fall from almost 90% to 70%. The new program indicates the construction of up to 4 GW (4,000 MW) of nuclear electricity generation capacity from 2010, with the first unit commissioned in 2016. Eskom, however, dropped its plan to build this nuclear plant due to the financial woes and the government decided to take over and proceed with its implementation (Flak, 2009). The government's plan is to construct a nuclear plant with a total capacity of 6,000 MW. It targets to commission 3,200 MW of the total planned capacity by 2019.

The results of the simulated *nuclear energy expansion* policy, influenced by the delay or lag in the implementation and the realization of the plant, show an increase in the amount of electricity generation for the period 2019-2030 (see Figure 11). It has to be noted that this policy helps cope with demand until 2027 only, when electricity consumption outpaces domestic production. In the baseline results, the demand for production exceeded the total supply in the year 2024. Hence, the *nuclear energy expansion* policy only stabilizes the electricity supply for three years.

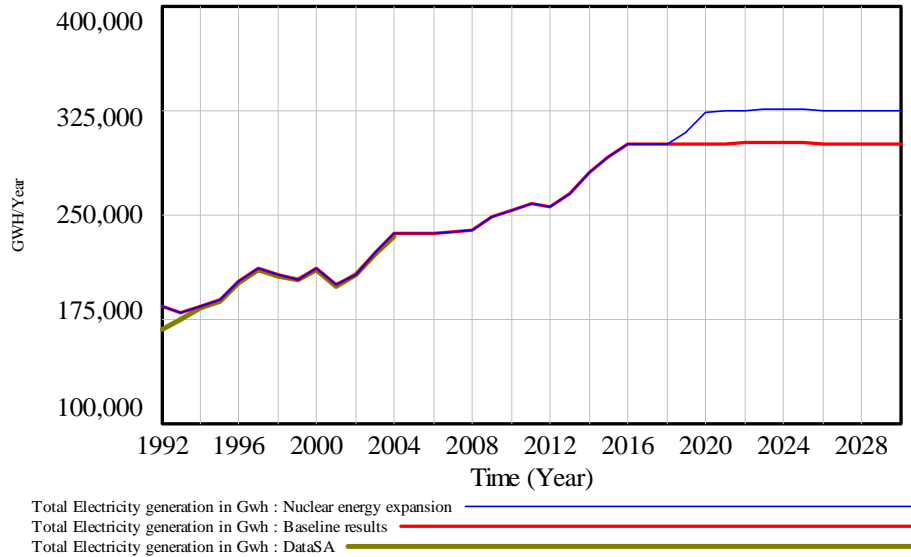
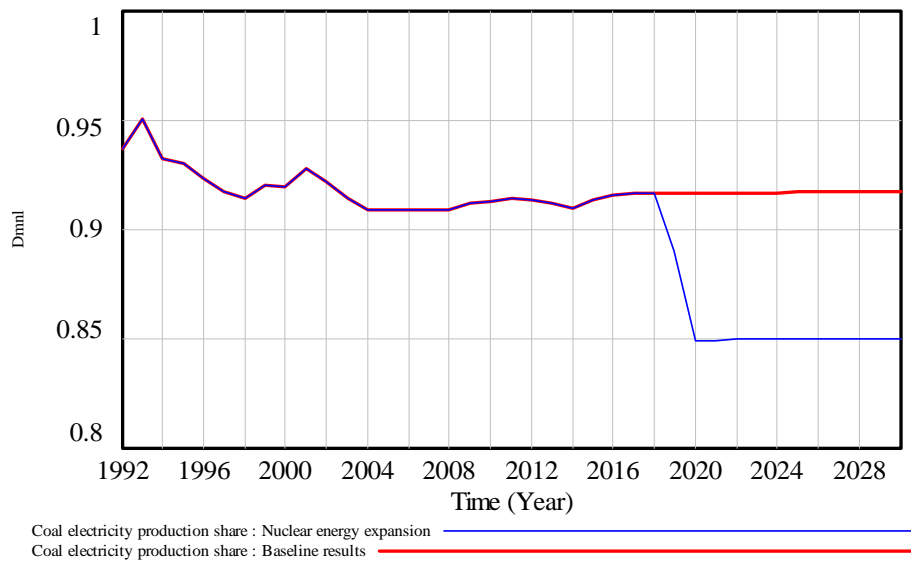


Figure 11: Nuclear energy expansion scenario results

An increase in nuclear energy generation reduces electricity generation requirements from coal. This is clearly observed in the simulation results (see Figure 11), which show an increase in the nuclear electricity production share from 5% in 1992 to about 11.5% in 2030 and a decline in the coal electricity production share from 93.7% in 1992 to about 85% in 2030. The remaining 2,800 MW of nuclear installed capacity, as per the government plan, were not included in the model.



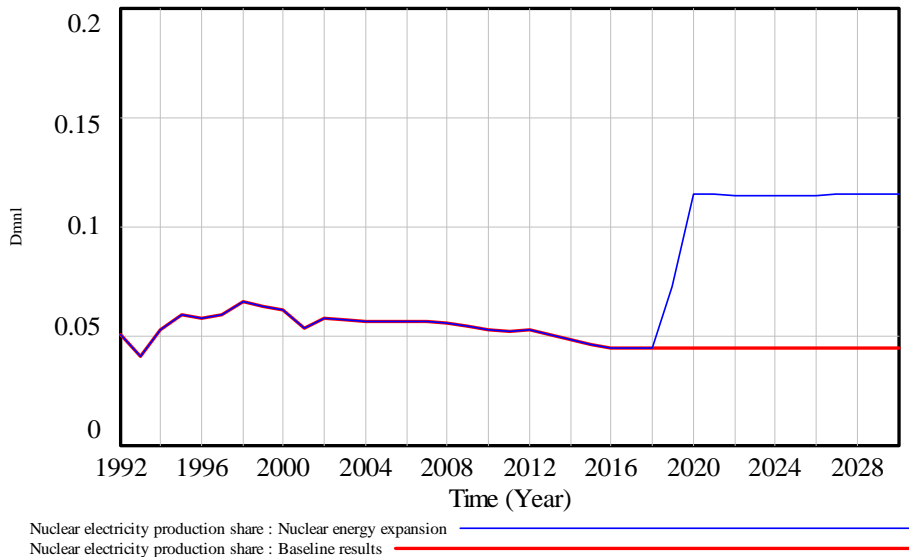


Figure 12: Scenario analysis for nuclear energy expansion – share of electricity production

6.2.2 Energy efficiency

Energy efficiency scenarios were tested and simulated based on a number of specific efficiency targets. It is assumed that interventions at no (or low) cost, such as better energy management and good housekeeping could result in up to 15% reduction in energy consumption when fully implemented by 2015. This implies that, on average, a 1.5% annual increase in energy efficiency would allow the target to be achieved, given that the period in which this target is expected to be met is 10 years, i.e. 2005 to 2015. In addition, an annual 1.5% reduction of energy consumption within the power sector is assumed.

Energy efficiency directly influences the level of energy use. Increasing energy efficiency reduces electricity consumption by final users and results in the generating sector to reduce its pressure on producers. In a similar manner, by reducing demand, higher energy efficiency helps mitigating energy price increases, which allow demand to stay strong relative to earlier conditions. Two energy efficiency scenarios were simulated and analyzed, *energy efficiency1* and *energy efficiency2*, as shown in Table 1.

Energy efficiency1 entails a 2% increase in efficiency, a 2% increase in price, and the *nuclear energy expansion* is not taken into account. The gross electricity supply results for the *energy efficiency 1* scenario are shown Figure 12, for the purpose of comparison together with the *baseline* and *nuclear energy expansion* scenarios. In *energy efficiency1*, total supply is lower than is observed in the baseline and in the *nuclear energy expansion* scenarios, because of higher energy efficiency improvements, which have a stronger impact on demand than changes in electricity prices. Concerning demand and supply and the risk

of power outages and rationing, as observed in the baseline scenario, supply will meet demand only in the *energy efficiency1* scenario.

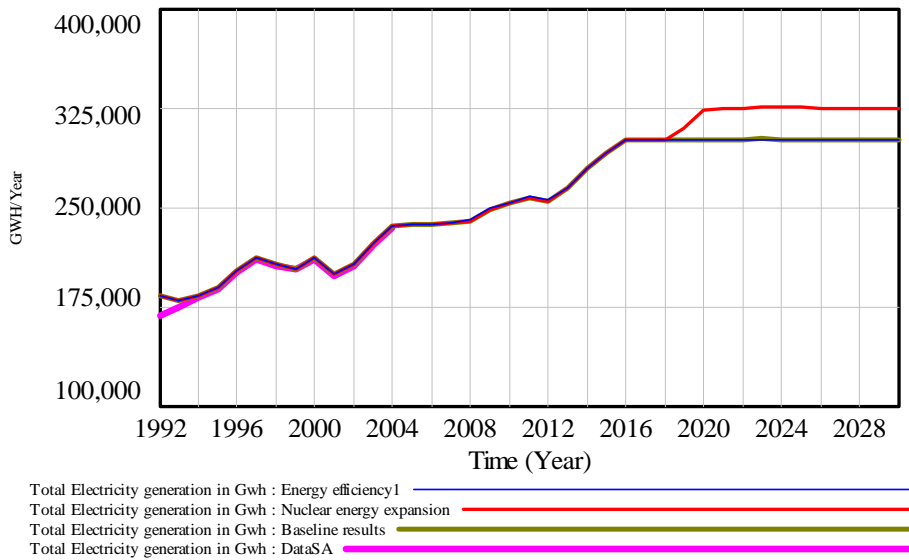
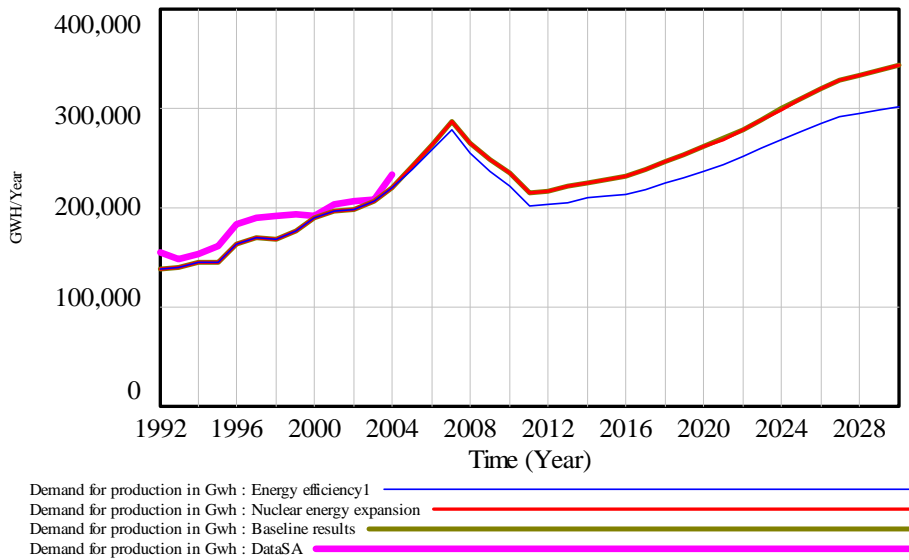
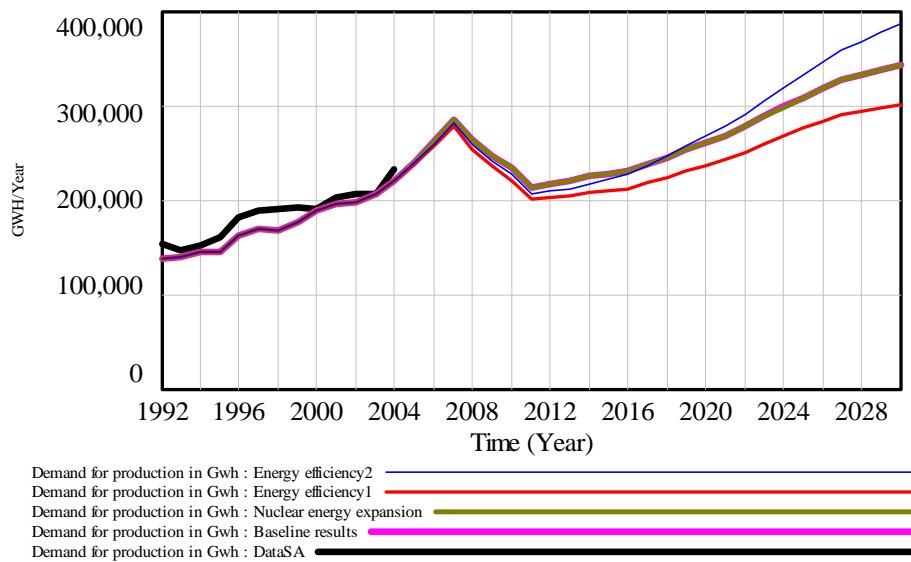


Figure 13: *Energy efficiency1* results – demand for electricity production and total electricity generation

For the case of the *energy efficiency2* scenario, a 1.5% increase in energy efficiency and 2.5% increase in price are tested. The *nuclear energy expansion* is not taken into account. In addition the energy efficiency targets are only simulated through to 2015 when the target

is expected to be achieved. The lower efficiency improvement in the *energy efficiency2* scenario results in higher electricity demand than in the *energy efficiency1* scenario. This is partially offset by a simulated more significant electricity price increase compared to the *energy efficiency1* scenario (see Figure 13).

Electricity demand for the *energy efficiency2* scenario is projected to be lower than the baseline scenario, starting from 2005, but is higher than the results observed in the *energy efficiency1* scenario (see Figure 14). From 2018, the demand for production for the *energy efficiency2* scenario is, however, higher than what is projected in the baseline, *nuclear energy expansion* and *energy efficiency1* scenarios. This is because the achievement of the efficiency measure target is intended by 2015. As in the previous cases, demand for production exceeds supply in the year 2005 but stabilizes in the year 2009. However, for the *energy efficiency2* scenario, the demand once again exceeds the supply in 2023, which is a year earlier than what is projected for the baseline scenario.



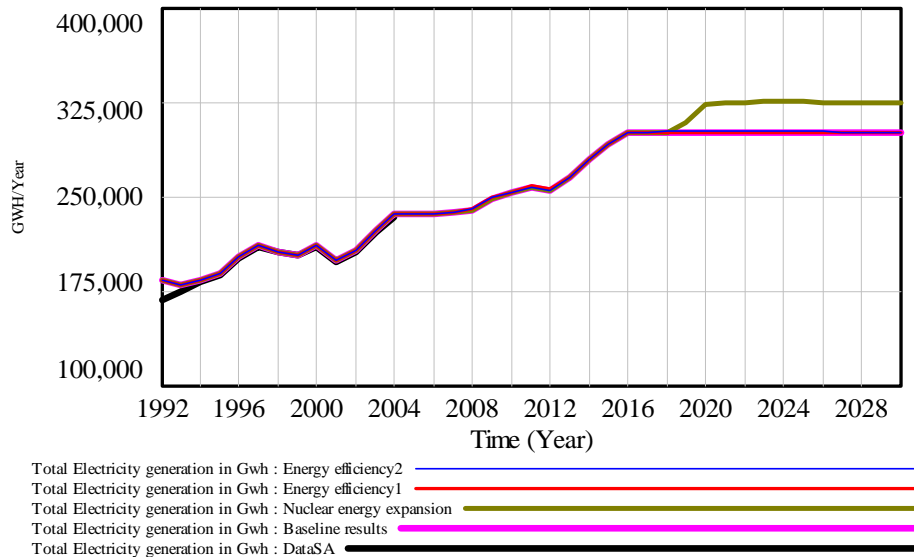


Figure 14: *Energy efficiency2 results* – demand for electricity production and total electricity generation

7. Conclusions

The study summarized in this paper has developed the energy modules of the T21 framework, as an initial step towards developing a South African T21 model as an integrated, comprehensive planning tool for the implementation of alternative energy systems. The aim of the modeling study was to improve the understanding of key drivers and feedback loops underlying the energy sector and to run pilot simulations of a few selected scenarios.

The baseline simulation results were examined for the demand and supply of different energy sources such as electricity, coal, gas, and oil. The baseline results were further validated by comparing the summary statistics with the historical data. The electricity and gas sub-models results did fit the data when compared using the historical data as the first dataset. For coal sub-model, the results on the best fit for the different variables did not fit well with the historical data, while in oil sub-model, only *liquid fuel demand* baseline result fit the historical data.

In addition, the model was used to examine a set of scenarios based on the energy policies currently being considered by the South African Government. These policies include the nuclear energy production expansion and energy efficiency measures. The scenarios that were analyzed demonstrated the capability of the energy model to simulate relevant energy management scenarios. For instance, the energy efficiency exemplified a demand side energy management approach to lower the level of energy use. On the other hand, as can be expected, the nuclear production scenario illustrated the supply side management approach

to increase the availability of electricity. However, the scenario analysis results indicate that a stringent energy efficiency measure may be the best option for enabling the South African energy sector to meet its short term energy requirements. This is best achieved through the *energy efficiency1* scenario whereby energy supply remains above energy demand up to 2030.

The model developed was however not without some limitations. The key major limitation was the sparse data for oil and gas in South Africa, especially on the supply side of these energy sources. The results for these two sub-models should therefore be taken with caution. Nevertheless, the current South African energy model can be extended to account for renewable energy production, especially bioenergy production, which was not taken into account in the current study. This is because in order to account for a renewable energy strategy in South Africa, there is a need to incorporate other sectors such as agriculture. This is currently a larger research focus.

Further research also involves improving the energy model to capture more dynamic components, a better analysis of the policies currently being considered by the Government, and the incorporation of the energy model into a more integrated framework that accounts for society, economy and the environment, to better understand the South African energy context. By combining different T21 modeling efforts across the region, another aim is to develop a more comprehensive T21 model for the Southern African Development Community (SADC) to understand the implications of alternative energy systems in the region.

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APPENDIX

Table A1 Parameters used in electricity demand

Parameter	Value	Units	Source
Initial industry electricity use	76084	GWH	DME (2006)
Initial transport electricity use	4000	GWH	DME (2006))
Initial agriculture electricity use	4038	GWH	DME (2006)

Initial commerce electricity use	15000	GWH	DME (2006))
Initial residential electricity use	22000	GWH	DME (2006)
Initial real GDP	7.458* 10 ⁹	Rand	Calculated ¹
Elasticity GDP to industry demand	2.7	Dimensionless	Estimated ²
Elasticity GDP to transport demand	1.6	Dimensionless	Estimated
Elasticity GDP to agriculture demand	-1.2	Dimensionless	Estimated
Elasticity GDP to commerce demand	3.74	Dimensionless	Estimated
Elasticity GDP to residential demand	2.09	Dimensionless	Estimated
Elasticity price to industry demand	-0.37	Dimensionless	Estimated ³
Elasticity price to transport demand	-0.05	Dimensionless	Estimated
Elasticity price to agriculture demand	0.68	Dimensionless	Estimated
Elasticity price to commerce demand	-0.7	Dimensionless	Estimated
Elasticity price to residential demand	-0.2	Dimensionless	Estimated

Table A2 Parameters used in electricity supply

Parameter	Value	Units	Source
Initial hydro installed capacity	668	MW	DME (2006)
Initial nuclear installed capacity	1800	MW	DME (2006))
Initial pumped storage installed capacity	1580	MW	DME (2006))
Initial wind installed capacity	0	MW	Assumption
Initial solar installed capacity	1580	MW	Assumption
Life of hydro	100	Years	Assumption

Table A3: Input variables used in electricity demand

Input variable name	Module of origin
Oil refineries crude oil in TJ	Oil sub-model
Annual coal production in Kt	Coal sub-model
Total electricity generation in GWh	Electricity supply sub-model
Pumped storage electricity generation	Electricity supply sub-model

Table A4: Input variables used in electricity supply

Input variable name	Module of origin
Demand for production in GWh	Electricity demand sub-model
Demand supply ratio coal	Coal sub-model

Table A5: Output variables in electricity demand

Output variable name	Module of destination
Demand for production in GWh	Electricity supply sub-model

¹ Nominal GDP data was obtained from WDI

² The elasticities were estimated using STATA

³ The elasticities were estimated using STATA

Total electricity generation in GWh	Electricity demand sub-model
Pumped storage electricity generation	Electricity demand sub-model

Table A6: Output variables in electricity supply

Output variable name	Module of destination
Total electricity generation in GWh	Electricity demand sub-model
Pumped storage electricity generation	Electricity demand sub-model
Electricity required from coal	Coal sub-model

Table A7: Parameters used in coal demand and supply

Parameter	Value	Units	Source
Initial coal remaining reserve	$1.15 * 10^{11}$	Ton	EIA
Initial coal proven reserve	$5.5 * 10^{10}$	Ton	EIA
Annual coal discovery fraction	0.06%	Yr-1	Estimated
Annual coal production fraction	2.7%	Yr-1	EIA

Table A8: Input variables used in coal sub-model

Input variable name	Module of origin
Electricity required from coal	Electricity supply sub-model

Table A9: Output variables in coal sub-model

Output variable name	Module of destination
Annual coal production	Electricity demand sub-model
Demand supply ratio	Electricity supply sub-model
Liquification from coal in TJ	Oil sub-model
Gas from coal	Gas sub-model

Table A10: Parameters used in gas demand and supply

Parameter	Value	Units	Source
Initial gas remaining reserve	0	BCf	Data not available
Initial gas proven reserve	943	BCf	EIA (used 1993 data)
Annual gas discovery fraction	0.01	Yr-1	Assumption

Table A11: Input variables used in gas sub-model

Input variable name	Module of origin
Gas from coal	Coal sub-model

Table A12: Output variables in gas sub-model

Output variable name	Module of destination
Liquification from gas in TJ	Oil sub-model

Table A13: Parameters used in oil demand and supply

Parameter	Value	Units	Source
Initial non-energy liquid fuel use	28938	TJ	DME (2006)
Initial transport liquid fuel use	458436	TJ	DME (2006))
Initial agriculture liquid fuel use	57421	TJ	DME (2006)
Initial mining liquid fuel use	16000	TJ	DME (2006))
Initial residential liquid fuel use	28832	TJ	DME (2006))
Initial real GDP	$7.458 * 10^9$	Rand	Calculated (WDI)
Initial real price	52.54	Cent/litre	Calculated, DME 2006
Elasticity GDP to non-energy demand	-0.81	Dimensionless	Estimated ⁴
Elasticity GDP to transport demand	1.79	Dimensionless	Estimated
Elasticity GDP to agriculture demand	0.8	Dimensionless	Estimated
Elasticity GDP to mining demand	1.24	Dimensionless	Estimated
Elasticity GDP to residential demand	1.8	Dimensionless	Estimated
Elasticity PRICE to Non-energy demand	0.07	Dimensionless	Estimated
Elasticity PRICE to transport demand	-0.12	Dimensionless	Estimated
Elasticity PRICE to agriculture demand	-0.17	Dimensionless	Estimated
Elasticity PRICE to mining demand	0.11	Dimensionless	Estimated
Elasticity PRICE to residential demand	-0.1	Dimensionless	Estimated
Initial oil remaining reserve	0	Barrels	Assumption
Initial oil proven reserve	$4.1 * 10^7$	Barrels	EIA
Annual oil discovery fraction	0.01	Yr-1	Assumption
Annual oil production fraction	0.02	Yr-1	Calculated

Table A14: Input variables used in oil sub-model

Input variable name	Module of origin
Liquification from coal in TJ	Coal sub-model
Liquification from gas	Gas sub-model

Table A15: Output variables in oil sub-model

Output variable name	Module of destination
Oil refineries crude oil in TJ	Electricity demand sub-model

⁴ The elasticities were estimated using STATA