Developing an Integrated Energy Plan for South Africa Using the Energy Models LEAP and MARKAL

by

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PREFACE

Submitted to the University of Cape Town in fulfilment of the requirements for the degree of Master of Science in Engineering.

DECLARATION

I, Mavo Solomon, submit this thesis in fulfilment of the requirements for the degree of Master of Science in Engineering. I claim that this is my original work and that it has not been submitted in this or in a similar form for a degree at any other University.

MAVO SOLOMON
April 2003

ACKNOWLEDGEMENTS

In performing this research and analysis, a number of people have made a valuable input into this work. Firstly, I would like to thank Professor Kevin F. Bennett for believing in me and giving me this most wonderful opportunity, and exposure. His right hand man, Mark Idwall Howells, has been instrumental in my understanding of the bigger picture of the energy sector and the finer details of energy modelling.

I am grateful to Steve McFadzean, and his colleagues at the ISEP department, of ESKOM, for their role in making sure I had a thorough understanding of the difficult concepts of electricity demand forecasting and capacity planning, and the economics involved. Many thanks also go to ENGEN's Peter Ayers and Dave Wright for their time, concerning their views of the Liquid Fuels Industry.

In addition I am honoured and humbled by the contribution my research has made to the Department of Minerals and Energy's planning process.

I also wish to express my gratitude to the rest of the Energy Research Institute's (ERI) staff and students, for making the ERI a wonderful research environment. I also want to thank ESKOM for funding my studies.

Last but not least, I am forever indebted to the unwavering technical support and model assessment of the modelling software developers, Gary Goldstein for MARKAL and Charlie Heaps for LEAP

ABSTRACT

The South African Government has long committed itself to developing an Integrated Energy Plan. The Energy White Paper on Policy since back in 1995 established IEP as being one of the most important tasks for the Department of Minerals and Energy. In the context of today's climate, with South Africa hosting the World Summit on Sustainable Development in 2002, the development of an IEP has never been more relevant.

The development of an energy plan encompasses the development of scenarios to put the utilisation of energy in its proper context. It was felt that there was not enough time and data available to produce results for more than one scenario and as such one scenario was developed for analysis. Four cases were chosen in the scenario to cover a range of important issues currently relevant in the country. These issues include the need for diversification away from coal and to find an economic ground for introducing natural gas into the country.

To achieve a base for comparing the different studies, the literature review for this thesis takes the approach of assessing the current status of energy utilisation in South Africa. It looks at new technologies to help the country diversify away from coal. The relevant modelling tools that have been used in the analysis and modelling data that was collected are described.

One of the weaknesses in the modelling work is the lack of external cost data to help quantify the impact of burning fossil energy carriers. As such, the foremost conclusion made from the results is that the cheapest strategy for the country is the continued use of coal. Diversifying away from coal to gas was found to be only marginally more expensive than the continued use of coal and even the added expense of switching to gas can be tempered with energy efficiency. Renewable energy technologies for grid electricity generation still remain expensive and the recommendation is made that an effort should be made to investigate ways to lessen the cost of these technologies.

The models have found great usefulness and it was found that the expertise that was achieved by the ERI should be sustained with the continued use of these and new modelling tools.

GLOSSARY OF TERMS

CCGT	– Combined Cycle Gas Turbine
CFL	– Compact Fluorescent Light
CONV	– Conversion technology as classified in MARKAL
CSIR	– Council for Scientific and Industrial Research
DME	– Department of Minerals and Energy
EFOM	– Energy Flow Optimisation Model
ESI	– Electricity Supply Industry
ETSAP	– Energy Technology Systems Analysis Programme
FX	– Fixed bound on capacity as set in MARKAL
GDP	– Gross Domestic Product
GHG	– Greenhouse Gases
GWh	– Gigawatt hours
IEP	– Integrated Energy Planning
IER	– Institute of Economics and Rational Use of Energy
IPCC	– Intergovernmental Panel for Climate Change
IRP	– Integrated Resource Plan
LEAP	– Long-range Energy Alternatives Planning system
LO	– Lower bound on capacity as set in MARKAL
LP	– Linear Programming
LPG	– Liquid Petroleum Gas
MARKAL	– MARKet-ALlocation
MESAP	– Modular Energy Systems Analysis and Planning
NER	– National Electricity Regulator
PBMR	– Pebble Bed Modular Reactor
PRE	– Process set as classified in MARKAL
PVC	– Present Value Cost
RES	– Reference Energy System
SACU	– Southern African Customs Union
SADC	– Southern African Development Community
SEI	– Stockholm Environmental Institute
SWH	– Solar Water Heater
TIMES	– The Integrated MARKAL-EFOM Systems
UP	– Upper bound on capacity as set in MARKAL

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CHAPTER 1: INTRODUCTION TO ENERGY MODELS

1.1. Integrated Energy Planning (IEP) and Energy Models

It is important to comprehend what the Integrated Energy Planning process means, and then be able to appreciate the role played by energy modelling. IEP presents itself as a complex problem by the very nature of energy use in human society. As with many real life problems, energy related problems treated in isolation might seem trivial to solve. However, when all the economic, social and the political constraints of a region are considered, the complexity of the problem reveals itself. Integrated Energy Planning is the combined account of both the economics and technology of energy. It is the co-ordinated discussion of the demand and supply balances for the different energy carriers. [9]

It is said that no country is an island unto to itself. Thus, globalisation of the energy markets places a huge responsibility for individual countries to appreciate their role in the total scale of their use of energy resources. Presented with this responsibility, it is easy to observe that energy problems are global in nature. As an example, an increase in price of crude oil will have a significant impact on economies that are heavily reliant on imported oil. The year 2001 saw the attack on the twin towers of The World Trade Centre, in the United States of America. The surprising resulting effect; an increase in the strength of the US dollar against many other currencies; combined with the drop of the crude oil price and a weakening of the South African rand, which all meant that it became more expensive to purchase crude oil for South Africa.

It is difficult to explain the relationship of the events mentioned above. An attempt can be made to correlate the attacks on the US, and subsequent strengthening of the US economy, to the South African economy. A conclusion can be made that the overall effect of the continuing weakening of the SA rand versus the strengthening of the US dollar, and the instability of the crude oil price, results in the cost increase of all imported products for South Africa. South African exporters do benefit, but the overall impact to the South African economy is negative.

1.2. South Africa's Energy Responsibility

The South African government has to realise that it needs to cushion its economy from the impact of an unstable global economy, similar to that described above. In Section 8.1 of the White Paper on energy, [6], the Government recognises that Integrated Energy Planning (IEP) requires many skills that, a few years ago, were not available in South Africa. Data gathering and processing is one such skill, and over the years computing tools have been devised to help in the processing of energy statistics. These tools have been instrumental in developing energy utilisation strategies the world over. The tools are called energy models. The results of these models can be used to assess policy on energy related matters.

In this report the emphasis is on the modelling tools themselves; how they take in input of data, their data structure, and the results they generate. Chapter 1 serves to put energy models in proper perspective and highlight the fact that they are not the solution but an aid (or tool) for analysis, and only serve to provide added insight into the dynamics of the energy markets/sector. In fact, it is necessary to first develop, with the help of government policy, an energy plan, and then use the modelling tools to analyse the economic viability of the plan.

The results of the tools can then be used to assess the strategies for the implementation of energy policies. Some policies might need to be revised after analysis, but robust policies should prove themselves to be so even through vigorous sensitivity analyses.

1.3. History of Integrated Energy Planning

The low cost of oil in the period 1950-73, led to the reliance on imported oil for most countries. With the increased crude price since 1973, there has been an awareness of the importance of indigenous supplies. The power shortages experienced recently in the California energy crisis are a sore reminder of what can happen when thorough planning is overlooked. [26] Other issues, such as the growing concern of global warming, have become a priority and care is needed to help foster a mentality of cleaner and efficient use of energy carriers.

The Kyoto Protocol, having been ratified by several country stakeholders, presents countries with the challenge to develop strategies to make better use of global energy resources, and thus minimise the impact of the energy sector on the environment. [29]

To study the impact of energy use on the environment, separate climate and emissions models can be used. In the case of South Africa, with an abundance of cheap fossil energy resources, there has been little incentive to improve on the efficient use of energy. However, with pressure from the developed world, on the developing nations to make better and more efficient use of their energy resources, integrated energy planning provides the platform for analysis of the economic feasibility of clean and renewable energy technologies

In South Africa, the Energy Research Institute, at the University of Cape Town has in the past developed desktop energy models, and used the results in their Sustainable Development Energy reports. [4] Other attempts by the Council for Scientific and Industrial Research (CSIR) in the 1980's to develop a national energy plan were less successful due to the lack of data. The South African Department of Minerals and Energy (DME) has committed itself to develop an Integrated Energy Plan for South Africa, and this report forms a small part of that planning process.

1.4. Philosophy of Energy Modelling

Integrated Energy Planning serves to provide a means to evaluate large-scale investments, and with some optimisation, can predict least cost options for energy supply. IEP modelling also provides important insights about deployment strategies and niche markets for the commercial introduction of new energy technologies.

Energy problems are complex but can be simplified for analysis with the use of energy models. Energy models create a simplified structure (fig. 1.1) that divides the problem into segments. First is the analysis of the energy ***demand*** or consumption in the various economic sectors, and this energy accounting is normally referred to as energy forecasting. This can be influenced by certain factors such as the growth rates of a country's GDP, population, world energy prices, etc.

The analysis then requires the consideration of ***supply*** factors. This means being able to assess the role of the different energy carries for supply, such as the future of nuclear energy technologies, the abundance of hydrocarbons, gas, coal and the role of renewable energy.

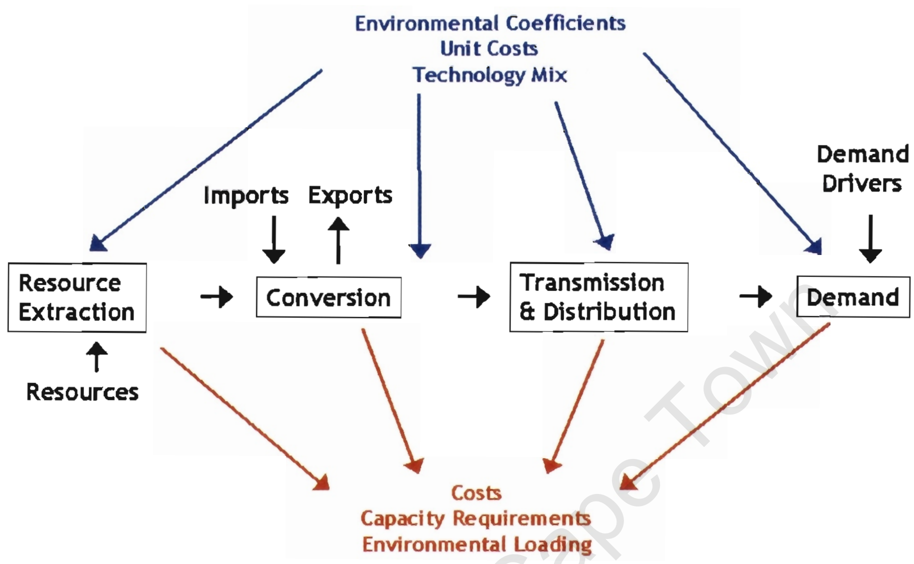

Figure 1.1. Structure of an energy model.

The results apply within the restrictions of the assumptions on GDP growth, population growth, stability of energy prices, rate of exchange of currencies, etc. Should the assumptions change, the results will no longer be valid.

The analysis becomes integrated when all the economics and technology of the total energy activity are considered. Fig. 1.2 shows that the economics involve more than just the cost of buying the energy from the supply sector. They also involve the cost of using or supplying preferred forms of energy. These costs are often referred to as Externality Costs or externalities. Externalities are still a matter of controversy. They do, however, provided insight as to the real cost of energy. An example of external costs is the life of a human being, as is observed from the high number of deaths per year of infants and children from the use of coal and paraffin in the South African residential sector. [23]

Based on these externalities, there is a strong case in favour of safer and cleaner forms of energy and making these accessible to the poor majority in South Africa.

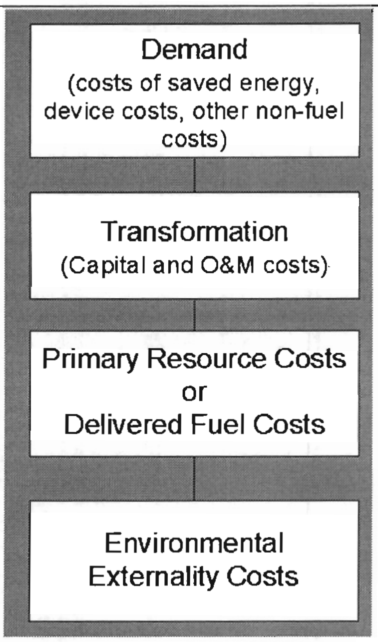

Figure 1.2. Cost accounting in energy models.

Figures 1.1 and 1.2 also show how the models cater for the loading of environmental data, such as emission factors to calculate emissions from the use of energy carriers, and allow for loading of the different costs for the mix of demand and supply technologies.

The model structure can further be disaggregated to whatever level of data required, as demonstrated by fig.1.3. Here the energy service to be addressed is the need for space heating. Differently insulated buildings will have different final energy requirements for the amount of heat required to warm up the space. In the example illustrated in fig.1.3, there could be several technologies required to meet the demand for heat. The technologies themselves might require different types of energy carriers, to convert final energy to the energy service (useful energy) for heating the area space.

What energy modelling tools attempt to do is to simplify the amount of calculations required to process this data, and develop standard sets of results, which can easily be understood and be interpreted. The greatest advantage for the tools is the database of information that can accrue from the *input parameters* and the *output variables*. This database of information can be refined as new and better data become available.

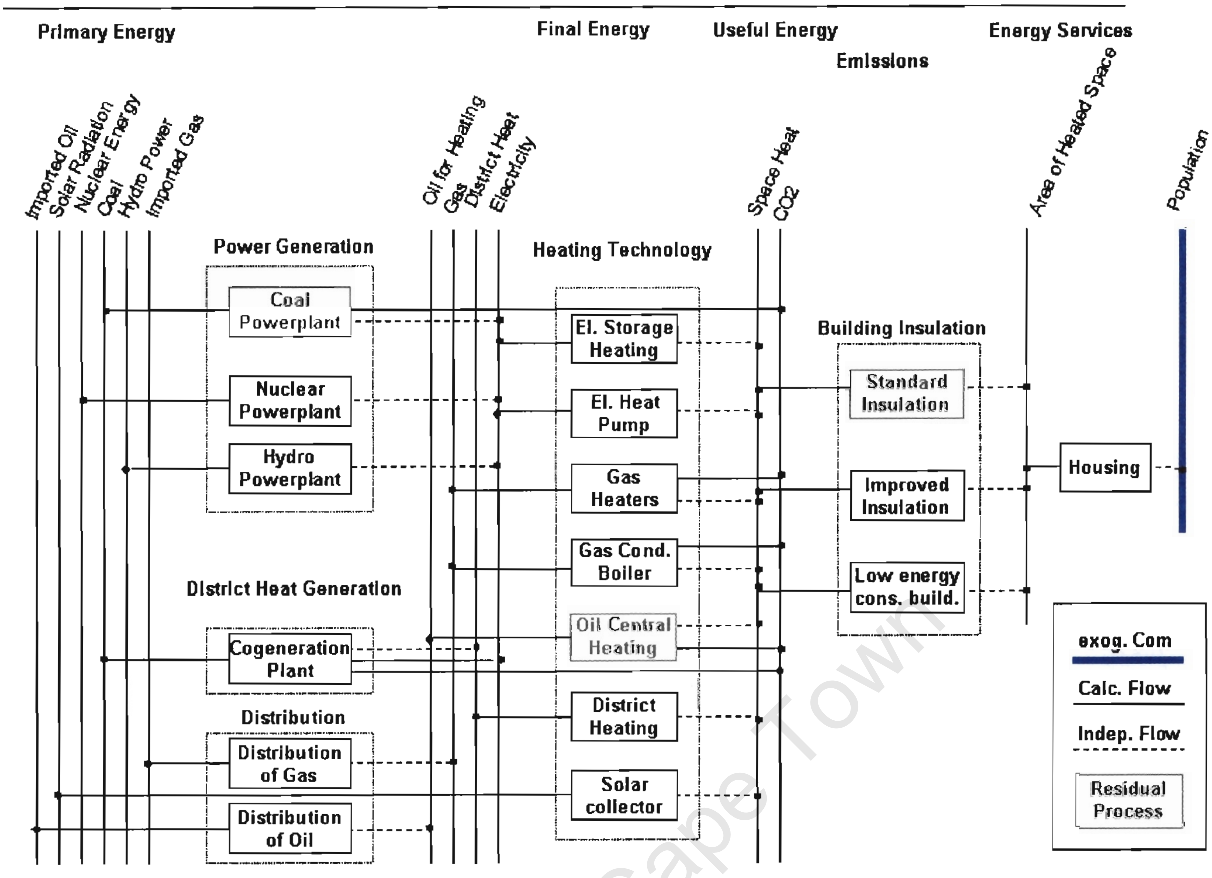

Figure 1.3. A technology mix for Residential space heating needs.

1.5. Global Energy Planning

Because of unpredictable energy crises, countries need to develop robust energy utilisation strategies. This takes away the dependence on one type of energy carrier, such as imported crude oil.

Currently, a global energy model is being developed in the model TIMES. [14] The plan is to have a 20-country version running to do global bottom-up modelling for the Assessment Report of the Intergovernmental Panel on Climate Change. (IPCC)

TIMES would not be the first energy model to be created with this multinational participation. MARKAL was originally developed by two teams with representatives from 16 countries, one working in the U.S. at Brookhaven National Laboratory and one in Germany at the Energy Research Center in Jülich. Designed 20 years ago to meet the differing requirements of 16 countries, MARKAL has the flexibility that has led to its being used in more than 40 countries. [14]

1.6. Integrated Energy Planning in South Africa

Integrated Energy Planning is in its infancy in South Africa. The energy sector is going through a restructuring process with many of the big energy parastatals being privatised. This IEP process is thus important to assess the economic and social benefits of this restructuring process for the country. This is especially so for the accounting of the energy resources available in the country. Any development South Africa makes as an emerging economy will have to be sustainable.

South Africa hosted the United Nations World Summit for Sustainable Development (WSSD) for 2002. Thus, initiatives like the IEP process were positive contributions to the Summit. Having started the process, South Africa can now learn what the critical issues are for sustainable development and incorporate these in the next round of analysis for their IEP process.

1.7. Objectives of Energy Modelling

In the context of this research, energy modelling forms part of a broader and more detailed analysis in the process of energy planning. It is always important to remember that the objectives of energy modelling are to provide a means to evaluate large-scale investments in a region, and provide insight to the commercial introduction of new energy technologies. The results of the model help provide insight into the impact of investments in the energy sector, and offer support for energy policy analysis.

1.8. Classification of Energy Modelling Tools

Energy models can be classified as:

- ***Bottom-Up*** type models, which provide a detailed engineering-based analysis.
- ***Top-Down***, which perform aggregate econometric analysis of energy systems. Top-Down models are useful for studying pricing and taxation, and less for studying detailed analysis.

These tools can further be broken into Simulation tools and Optimisation tools.

A simulation model is defined as a descriptive model based on a logical representation of a system. This model is aimed at reproducing, in a simplified manner, the operation of the system. [27]

An Optimisation Model is defined as a model describing a system or a problem in such a manner that the application of rigorous analytical procedures to the representation of the results is the best solution for a given variable(s) within the constraints of the relevant limitation. [27]

Both models utilised in the analysis are bottom-up analysis tools. LEAP (short for Long-range Energy Alternatives Planning) is a simulation tool, whereas, MARKAL (short for Market-Allocation) is an Optimisation tool.

1.9. Limitations of Energy Modelling Tools

Given the amount of data that needs to be input in the model, the models tend to have limited performance capabilities on desktop machines with RAM of less than 32 MB. The models, as detailed as they are, should not be used to perform specific fuel/energy carrier Integrated Resource Planning. A case in point is electricity. Unlike other energy carriers, electricity energy consumption is defined hourly using load duration data. The allowance for load description in both models is limited. (See Appendix E). There are various effort with new models to introduce short-term planning (hourly) energy models that can also retain the long-term (annual aggregate) planning functionality.

For long-term planning purposes, electricity models are able to perform modular production costing, generation expansion for use by utility planners to evaluate integrated resource plans, independent power producers, avoided costs and plant life management programs. Aggregate energy models are also capable to perform these functions.

However, IRP specific tools also have to specifically accommodate demand-side management options, to facilitate the development of environmental compliance plans, and to evaluate generating units in a competitive marketplace

Existing electricity integrated resource planning models are used to perform the following functions:

- Development of generation expansion plans
- Environmental dispatch and optimisation of alternatives to comply with the Clean Air Act
- Integrated resource planning studies
- Analysis of independent power producers (IPPs)
- Power pooling and economic dispatch studies
- Impacts of cogenerators and small power producers
- Marginal cost, contract, and other rate evaluations
- Plant life management and repowering evaluations
- Avoided energy and capacity costs
- Reserve and system reliability analyses
- Generating unit evaluation with bid-based pricing

The basic capabilty of both IEP and IRP models are such that they can develop optimum expansion plans in terms of two objective functions: present worth of revenue requirements and levelized average system rates ($/MWh). These objective functions can be used to simulate a life cycle Total Resource Cost (TRC), Rate Impact Measure (RIM), or the Most Value test similar to those usually computed in a DSM screening analysis. The output details the type, size, and installation date of each demand- and supply-side alternative. [15]

Typically, electricity-specific models can handle non-dispatchable technologies such as solar, wind, run-of-river hydro, co-generation, and demand-side management programs along with conventional alternatives such as fossil, combustion turbine, and nuclear. Storage, hydroelectric and other energy-limited generation can also be modelled. Environmental compliance plans can also be developed in the optimisation process.

Both MARKAL and LEAP have limited capabilities in handling these requirements. It is important to always compare IEP results with IRP specific planning tools, to avoid unrealistic results outputs.

CHAPTER 2: ENERGY ANALYSIS -LITERATURE REVIEW

This chapter serves to establish the background information needed for the energy models. With that in mind, the energy sector for South Africa is briefly discussed. Much of the information was obtained from The Background to Energy Outlook in South Africa: 2002. The chapter also briefly explains what energy modelling tools have to offer. [10]

2.1. Some Energy Definitions

Energy is classified into different categories for information purposes. There is primary energy, final energy and useful energy. These definitions are explained by way of example below

Primary energy is the amount of energy available in a resource before any processing is done on it. For example, it is the energy content of the coal in the ground before transformation into a secondary state, such as oil products (by Sasol) and electricity (by the Electricity Supply Industry).

Final energy is the amount of energy that is used by an energy-consuming device to meet certain energy needs, such as to boil a kettle of water.

Useful energy is also called an **energy service**. For instance, bringing a kettle of water to boil will require a fixed amount of (internal) energy at standard atmospheric pressure conditions. It should be noted that an insulated kettle will require less final energy to meet the useful energy demand. Thus, the difference in final energy and useful energy is determined by the efficiency of an energy-consuming device in converting final energy to useful energy.

2.2. Final Energy Demand (Energy Consumption)

The South African economy may conveniently be divided into six sectors: industry, agriculture, commerce, residential, transport and non-energy. Fig. 2.1 shows the final energy demand by sector for 2000 (Total: 2363 PJ excluding non-energy).

2.2.1. The Industrial Sector

The industrial sector (interchangeably called 'industry') consumes over 40% of the final energy demand in South Africa, as is shown in fig. 2.1.

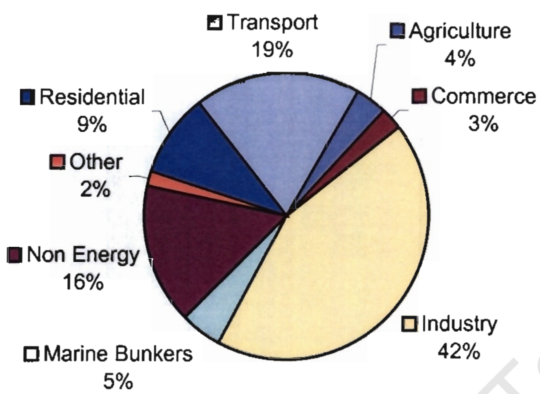

Figure 2.1. SA final energy demand by sector

The industrial sector, for the purposes of this modelling work, includes all mining except coal mining. Other sub-sectors under industry are the Chemicals, Iron & Steel, Non-ferrous, non-metallic, Food & Tobacco and Pulp & Paper production sectors. The rest of industry consists of a wide range of enterprises, including manufacturing and processing, which are usually on a much smaller scale. Because of the mining activities, the South African industrial sector is highly energy intensive. It uses large amounts of energy for every rand of added value, compared with industries in the developed world. [10]

Industry is also the largest user of electricity in South Africa. Figure 2.2 below shows the electricity used by each economic sector in 2000 (Total: 613 PJ).

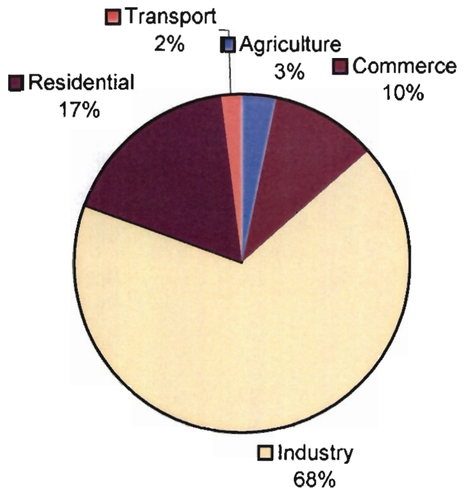

Figure 2.2. Electricity demand by South African sector

In fig.2.3 below are shown the fuels used by industry in 2000, dominated by coal, which is the cheapest source of energy in South Africa. (Total: 1325 PJ).

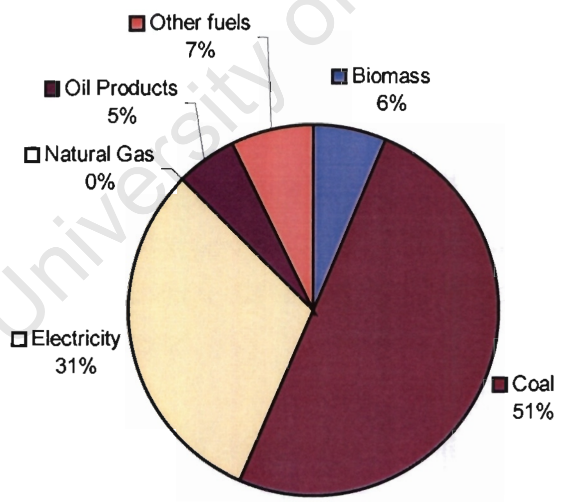

Figure 2.3. Industrial energy demand by fuel

Fig. 2.4 below shows the energy demand for each of these sub-sectors in 2000, with Iron & Steel consuming almost a third of industrial energy requirements. (Total: 1325 PJ.).

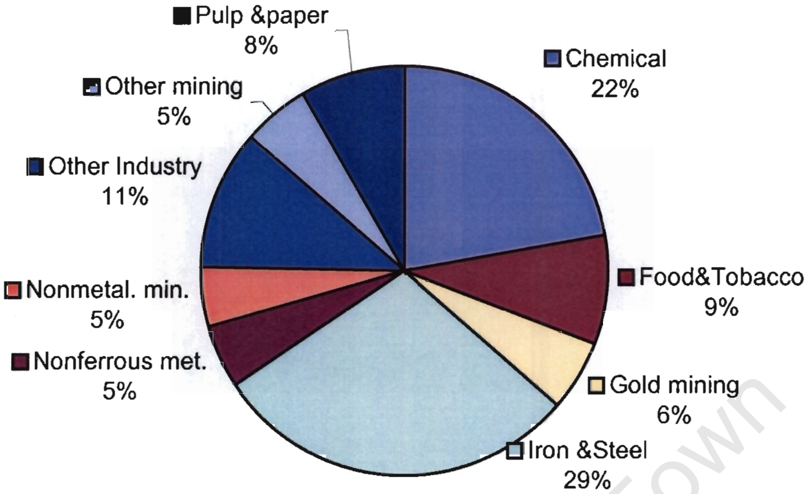

Figure 2.4. Industrial final energy demand by sub-sector

2.2.1.1. Mining

For the purposes of this study, South African mining has been divided into gold mining and other mining.

Gold production is in decline because the richest ores have been worked out. However, increasing depths and worsening ore grades mean that more energy is required to produce each additional ton of gold. Other mining has better prospects and is likely to grow with the economy. Table 1 below shows the energy demand by fuel for mining in 2000. [10]

Table 1. Final energy for mining in 2000 (PJ)

	Gold Mining	Other Mining	Total
Coal	2.0	16.0	17.9
Diesel	3.3	15.3	18.6
Electricity	67.3	47.0	114.3
Fuel Oil	0.1	0.6	0.7
Hydrogen Rich Gas	0.4	0.3	0.6
LPG		0.1	0.1
Paraffin		0.4	0.4
Total	73.1	79.6	152.7

Electricity, which already is the largest energy source for mining, is likely in future to increase its proportion of energy used, as the mining levels increase in depth, requiring more energy to mine.

2.2.1.2. Iron & Steel

South Africa has all the minerals necessary for steel production except for coking coal. Coking coal is imported. South Africa is increasing its production of stainless steel to meet world requirements.

Steel prices are low and, with over-supply around the world, there is little prospect of their improving in the future. It is expected that iron and steel production will grow more slowly than GDP. Table 2 shows the final energy demand by fuel used in iron & steel production in 2000. [10]

Table 2: Final energy for iron & steel energy in 2000 (PJ)

Coal	54.7
Coke oven coke	11.2
Diesel	16.1
Electricity	33.5
Fuel Oil	6.7
Hydrogen Rich Gas	4.9
LPG	6.1
Methane Rich Gas	4.9
Petrol	0.6
Paraffin	6.2
Total	**144.8**

It is likely in future that more steel will be produced in electric furnaces and that gas will be used instead of coal for making iron & steel.

2.2.1.3. Chemicals and Petro-Chemicals

This sub-sector produces chemical feedstocks, plastics, fertilizers, explosives, agro-chemicals and pharmaceuticals. These chemicals can be made from oil, gas or coal. South Africa's special expertise and experience in making liquid fuels and chemicals from coal gives it a unique advantage in this field. The prospects for chemicals are good and this sub-sector is likely to grow with GDP. Table 3 shows the final energy demand by fuel for this sub-sector in 2000. [10]

Table 3: Energy for chemicals 2000 (PJ)

Coal	237.3
Electricity	50.3
Fuel Oil	0.6
Hydrogen Rich Gas	1.3
Methane Rich Gas	1.3
Total	**290.8**

2.2.1.4. Non-Ferrous Metals

Aluminium and titanium are the two predominant metals in this sector and their production is very energy intensive. Also, South Africa has more than 80 per cent of the world's platinum reserves, and is the world's largest producer of platinum group metals (PGMs). These vast resources occur together with the world's largest reserves of chromium and vanadium ore in the unique Bushveld Complex geological formation. South Africa's PGM output is derived almost exclusively from the Bushveld Complex, with only about 0.1 per cent coming from the gold deposits of the Witwatersrand and Free State, and the Phalaborwa copper deposit. [10]

Apart from South Africa's platinum mines, only Stillwater Mine in Montana, USA, and Hartley Platinum in Zimbabwe are major primary producers of PGMs.

South Africa has the world's largest reserves of titanium but no commercial reserves of aluminium. With electricity being relatively cheap in South Africa, the aluminium smelters at Richards Bay have been economically successful, as electricity is the major component of the production cost. PGM smelting in South Africa takes place exclusively in electric furnaces at present. [16]

Various expansions of titanium and aluminium are being considered or are already in progress. The growth of this sub-sector, in the short term, is likely to grow more quickly than GDP. Table 4 shows the final energy by fuel in producing non-ferrous metals in 2000.

Table 4: Final energy for non-ferrous metals 2000 (PJ)

Coal	1.5
Electricity	61.5
Hydrogen Rich Gas	1.4
Total	**64.4**

2.2.1.5. Non-Metallic Minerals

The main activities in this sub-sector are the manufacture of cement and bricks, processes for both being energy intensive. Demand for cement and bricks follows GDP quite closely and growth in this sub-sector is likely to be the same as that of GDP. Table 5 shows the final energy demand by fuel in this sub-sector for 2000.

Table 5: Energy for non-metallic minerals 2000 (PJ)

Coal	32.7
Electricity	20.5
Fuel Oil	3.4
Hydrogen Rich Gas	6.5
Total	**63.0**

2.2.1.6. Pulp & Paper

South Africa has a substantial pulp & paper industry which exports around the world. Pulp is made from both softwood (pine) and hardwood (eucalyptus), both of which grow more quickly in South Africa than in Europe. The climate conditions here are particularly suited to hardwood, which is good for tissue paper.

The main energy sources for pulp & paper manufacture are coal, electricity and biomass. Coal is brought to the mills. The biomass comes from the timber, which is the feedstock for pulp production. Some electricity for pulp manufacture is brought in from Eskom and the rest of the electricity is generated by the mills from coal and bark. Modern pulp mills in Scandanavia are completely self-sufficient in energy. [1]

Unfortunately, in South Africa, the area suitable for forests is small and this puts a limit on the size of this industry. Table 6 shows energy consumption for pulp & paper in 2000.

Table 6: Final energy for pulp & paper 2000 (PJ)

Coal	51.4
Electricity	24.4
Methane Rich Gas	0.4
Wood	34.4
Total	**110.6**

South Africa's pulp & paper industry is likely to grow with GDP, all within the limits of the industry, and to become more energy efficient in future, following international trends.

2.2.1.7. Food and Tobacco

The food, beverages and tobacco division includes sugar mills, food processing, breweries and tobacco processing. The biggest single component is the sugar industry, which in the year 1997/8 reaped 22 million tons of sugar cane to produce 2.4 million tons of sugar. [1] Sugar cane consists of approximately 10% sugar (sucrose), 35% fibre and 55% water. The fibre is known as "bagasse" and most of it is fired in boilers to make steam for electricity generation or process heat. (Some of it is used as a feedstock for paper mills.) The calorific value (CV) of dry bagasse is approximately 14 MJ / kg, which is comparable to the CV of some of the coal used for electricity generation is South Africa. Table 7 gives the estimated annual final energy for this sector

Table 7 below shows the energy used by this sub-sector in 2000.

Table 7: Final energy for food & tobacco 2000 (PJ)

Bagasse	49.6
Coal	49.0
Electricity	12.7
Fuel Oil	1.3
Hydrogen Rich Gas	0.9
Total	**113.4**

2.2.1.8. Other

"Other" is a large and various sub-sector, which includes manufacturing of motor vehicles, clothing, electrical goods (etc.). Good growth has been experienced in areas such as motor vehicle exports and motor parts. The proposed Coega industrial zone offers a potential for these industries to expand. New textile clusters have been suggested in both Botswana and Lesotho. It is expected that energy demand in this sub-sector will grow more quickly than GDP. Table 8 below shows the final energy demand for this sub-sector in 2000. [1]

Table 8: Energy for other 2000 (PJ)

Coal	66.0
Electricity	33.5
Oil Products	35.6
Other fuels	9.7
Total	**144.8**

2.2.2. The Commercial Sector

This sector consists of government, office buildings, financial institutions, shops, recreation and education. This is the "service" sector of the economy. The energy is used mainly for lighting, heating and air-conditioning although office machines such as computers, fax machines and printers are becoming more important as energy users. Most of the energy used in this sector is electricity. There is large scope for improved energy efficiency including better design of buildings, more efficient lighting, more efficient air conditioning and heating, and better management of energy use. Electricity is likely to take an even bigger share of energy in future. [1]

As countries advance economically, this sector produces an increasing share of the GDP. In the future the South African energy demand for this sector is likely to grow more quickly than GDP. Table 9 shows the energy used in this sector in 2000. [10]

Table 9: Commercial final energy demand 2000 (PJ)

Coal	6.2
Electricity	62.0
Fuel Oil	3.0
Hydrogen Rich Gas	0.8
LPG	2.4
Paraffin	0.2
Town Gas	0.3
Total	**74.9**

2.2.3. The Agricultural Sector

As economies mature, agriculture uses a decreasingly smaller share of national employment. Small farms are replaced by large co-operatives and agriculture produces an ever-smaller fraction of GDP. Total agricultural energy demand is expected to grow less than GDP. Table 10 shows the final energy requirements in the agricultural sector in 2000, dominated by diesel. [10]

Table 10: Final energy for agriculture 2000 (PJ)

Coal	9.2
Diesel	58.9
Electricity	21.2
Fuel Oil	0.1
LPG	0.8
Petrol	3.6
Paraffin	3.0
Vegetable Wastes	10.8
Total	**107.6**

2.2.4. The Residential Sector

Residential energy falls into three categories: (i) traditional - consisting of wood, dung and bagasse, (ii) transitional - consisting of coal, paraffin and LPG, and (iii) modern - consisting of electricity. The universal trend around the world is from (i) through (ii) to (iii). Table 11 shows the fuels used in the South African residential sector in 2000. [1]

Table 11: Final energy for the residential sector 2000 (PJ)

Coal	58.0
Electricity	106.9
LPG	4.7
Natural Gas	0.0
Paraffin	25.3
Solar	0.2
Vegetable Wastes	4.3
Wood	84.7
Total	**284.2**

South Africa has recently been following a vigorous programme of electrification, spearheaded by Eskom. From 1994 to 2000, 3.1 million households a year were electrified. Currently, 70% of households have electricity (approximately 80% in urban areas and 50% in rural). [10]

The benefits in using electricity are many. There are huge benefits in terms of improved health, economics and opportunities to join the modern economy. There are also drawbacks, mainly because of affordability as many of the newly electrified households find it difficult to buy sufficient electricity to make it profitable for the utility. They also find it difficult to buy electrical appliances such as electric stoves and continue to use coal and paraffin even when they have electricity. [23]

Residential energy use can be classified into the following activities: space heating, water heating, cooking, lighting and other (such as refrigerators, radios and television sets). In future the trend from using traditional fuels through transitional to using electricity is likely to continue. Residential energy demand is expected to grow at the same rate as the population. Even with increased energy access residential demand will not grow faster than population as the majority of people gaining access to electricity still cannot afford the appliances to make use of it. Table 12 shows the final energy demand for the residential sector by activity in 2000.

Table 12: Residential energy use 2000 (PJ)

Cooking	113.4
Lighting	15.4
Other	35.1
Space heating	90.8
Water heating	29.5
Total	**284.2**

2.2.5. The Transport Sector

This sector deals with the transport of people and goods by land, sea and air. Energy for transport is completely dominated by liquid fuels, such as petrol, diesel and jet fuel.

The overall consumption of petrol in South Africa is currently significantly higher than that of diesel. The oil refineries struggle to produce even as much as 7% more petrol than diesel, whereas the synfuels production plants can produce as much as 15% more petrol than diesel from their respective processes. The role the transport sector has in helping to restore a balance in these liquid fuel products will be discussed later.

It is more difficult in this sector than any other to switch from fossil fuels to other sources of energy. Table 13 shows transport final energy demand by fuel for 2000. [10]

Table 13: Energy for transport 2000 (PJ)

Aviation Gas	1.1
Coal	0.6
Diesel	169.6
Electricity	12.4
Jet Fuel	61.0
Paraffin	0.4
Petrol	331.9
Total	**577.1**

Air transport uses jet fuel (very similar to paraffin) for gas turbine engines and aviation gas (petrol with a higher octane rating than that of road vehicles) for piston engines. Marine engines today are nearly entirely diesel, and these use mainly heavy fuel oil (bunker oil) rather than diesel, which is only used for very small boats. Land transport is dominated by petrol and diesel with some electricity used by trains.

Table 14 shows the final energy demand by mode, i.e. land, sea and air.

Table 14: **Transport energy by mode 2000 (PJ)**

Air transport	62.1
Land Passenger	385.6
Land freight	129.0
Other	0.4
Total	**577.1**

The largest share of transport energy is for land and within it passenger transport takes more energy than freight transport. Sea transport is included in "other", which is only 0.4 PJ. This is because marine bunkers for ships travelling between South African ports and foreign ports have been excluded. [10]

2.2.6. Energy Efficiency

For each technology that consumes fuel, there is an efficiency for converting final energy to useful energy. To meet the same useful energy demand, each energy-consuming technology uses a different quantity of fuel. The fuel, such as wood or electricity, consumed by the technology is referred to as the 'final energy'.

This is important in understanding how the optimisation model chooses one technology over another.

2.2.7. Environmental Mitigation Analysis

Several South African studies have been concluded in mitigating the environmental impact in the use of energy. Many serve the purpose of establishing baseline cases for Clean Development Mechanism projects. [28]

It is important to understand that energy use by its very nature will always have a negative impact on the environment. Global warming concern is mounting and most of the developed world has ratified the Kyoto protocol, to set targets for reducing carbon dioxide emissions.

Stringent measures have been put in place to reduce toxic emissions from energy consuming technologies, and to mitigate against greenhouse gas emissions.

2.3. Energy Supply And Energy Prospects

Energy supply in South Africa is currently dominated by coal, which is a relatively cheap source of energy in the country. The main suppliers of energy are electricity generation and oil production.

The Electricity Supply Industry (ESI) has been able to sustain low electricity prices, because of the cheap coal that is supplied to most of Eskom's power stations. The oil industry also has some of the lowest prices for liquid fuel products in the world (petrol costing less than R5/ litre). The main reason for this is Sasol, with the production from its coal to liquids process.

2.3.1. Electricity Generation in South Africa

South Africa has a sophisticated ESI and produces some of the cheapest electricity in the world and generates over half of all the electricity on the African continent. There is currently a surplus of generation capacity in South Africa and according to various predictions new peaking capacity may be required from 2007 and base-load capacity some years later. Eskom, the public utility, produces over 95% of South Africa's current requirements with the rest coming from municipal power stations and auto-generators (industries which generate electricity for their own use). [10]

Electricity generating capacity is currently split between Eskom and non-Eskom generation as follows:

- **Eskom**: The total existing (combined base and peak load), committed and imported net generation capacity on the Eskom system is 37 845 MWe to be in operation by 2004. (NER Annual Report 2001/2)
- **Non-Eskom**: existing capacity is 2 615 MWe, including base and peaking.
- **New Options**
  New electricity generation technologies under consideration for the future include the Pebble Bed Modular Reactor (PBMR) which is being developed by Eskom and Combined Cycle Gas Turbine (CCGT) units.

2.3.2. Oil Refining and Production

Most of South Africa's liquid fuel supply comes from imported crude oil. Over 88% of this crude is supplied from the Arab Gulf, dominated by supply from Saudi Arabia.

South Africa has a limited supply of its own crude reserves from the Oribi field in the Bredasdorp basin. Since the crude oil tankers dock at the coastal ports in Durban, Cape Town and Saldanha, there is a pipeline network to transport this crude oil to the refineries inland. Transnet's subsidiary, Petronet, is responsible for the management of this pipeline. The costs of the pipeline are taken into account in the cost of liquid fuel products from the Natref refinery. [10]

The liquid fuels production capacity in South Africa is split between conventional oil refineries, and the synthetic fuels production plants. South Africa has four primary refineries. They are:

- Sapref jointly owned by British Petroleum (BP) and Shell, with a crude input capacity of 8,2 million ton per annum.
- Enref, owned by Engen, with a capacity of 5,2 million ton per annum.
- Caltex, with a capacity of 4,5 million ton per annum.
- Natref owned by SASOL (63%) and Total (37%) also with a capacity 4,5 million tons per annum.

The synfuel plants are separated into those converting either coal or gas to liquid fuels. These are:

- SASOL Secunda's Coal to Liquids plant, with a crude oil equivalent capacity of 8,0 million tons per annum.
- Mossgas, in Mosselbay is a Gas to Liquids process. It has a capacity of 1,7 million tons per annum of crude equivalent.

2.3.3. Resources and Prospects

South Africa has very little resources other than coal. Neighbouring countries like Mozambique and Namibia hold some prospects for natural gas supply, which will serve as imports for South Africa.

A large potential for renewable energy in South Africa has been identified. However, currently, attention has been focused on its use for electricity generation. Capacity for renewable energy electricity generation is primarily from wind along with solar power and municipal waste. The Department of Minerals and Energy have set the renewable energy targets shown in Table 15. [10]

Table 15: Targets for renewable energy in South Africa

Resource	Theoretical Potential	2010 Target (MW)
Wind Energy	1960 MW	300
Solar Thermal	limited by storage	100
Photovoltaics	limited by storage	25
Small-scale Hydro	8360 MW	850
Bagasse	42PJ per annum	750
Wood Residue	22PJ per annum	560
Wave Power	56 800 MW	30
Landfill Gas	25PJ per annum	90
Total		**2705**

2.3.4. Environmental Impact of Energy Supply

As with energy consumption, energy production does make an impact on the environment.

Coal use in power generation presents the problem of ash storage and other gaseous emissions such as greenhouse gases.

With a Combine Cycle Gas Turbine plant, efficiencies of over 70% can be achieved. This means that less gaseous emissions go to the atmosphere and there is no ash from this plant. These considerations in terms of planning for the future are important if South Africa is to project itself as an environmentally friendly economy. Currently, the costs for a CCGT plant are higher than that of a coal plant of the same size.

Similarly, nuclear technology such the PBMR does not produce any greenhouse gases, and is ideal for mitigating against these emissions. However, there is concern about the nuclear waste that is produced. Nuclear technology costs are also higher than coal and gas technologies.

2.4. Valuation of Supply Side Options

The energy sector in South Africa is still government regulated. There are plans to privatise national utilities such as Eskom. Although companies like Sasol are privatised, they still enjoy the benefits of a local regulated energy market. In this regard, there are different methods used for the economic valuation of future investments in energy projects. For a regulated environment the concept of a Net (Real) Present Value of all future cash flows is normally used. [15]

This is the method used in this research. However, whenever there is competition the NPV approach is no longer applicable, as the markets for the sales of energy will become uncertain. Other financial/economic techniques become necessary and one of those is briefly discussed in section 2.4.2 below.

2.4.1. Net Present Value Method

One of the driving assumptions in the modelling was the value of the Net Discount Rate (NDR), or the real discount rate. All new projects, i.e. in the coal, oil, and electricity sectors, are assessed on this common basis of a real discount rate. This approach simplifies the calculation of net present value (NPV) of all future cash flows. Should the NPV be positive, the utilities or energy supplies make a decision to invest. If, however, the NPV is negative then a decision is made to retire plant.

The following is the mathematical formulation of the net discount rate. The discount rate is defined as: the rate of interest reflecting the time value of money that is used to convert benefits and costs occurring at different times to equivalent values at a common time. Developing countries often use rates that are substantially higher than those in developed countries, to reflect both the scarcity of capital and the much larger profitability of new investment projects that compete for limited resources. [15]

If a certain project costs C to be invested in year 0 (that is, current year or base year of analysis) in N years that amount will have been increased by the inflation rate, i. (See fig.2.5. below).

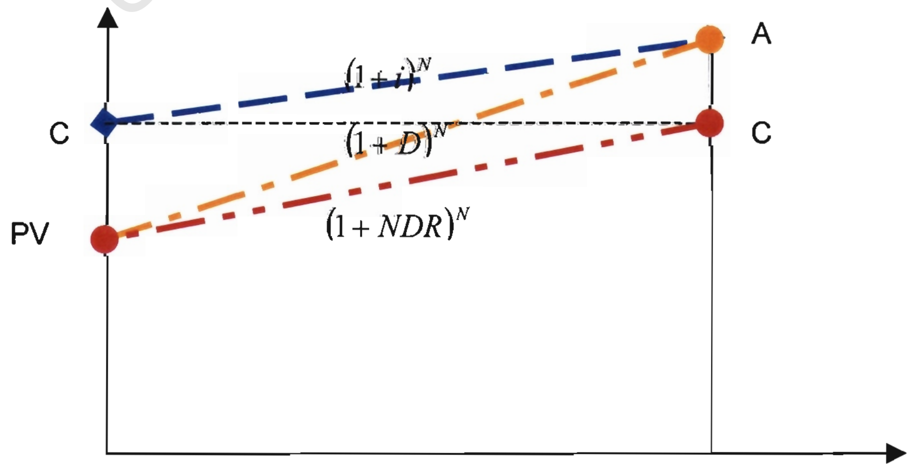

Figure 2.5. Graphical representation of the Net Discount Rate.

That is to say,

$$A = C \times (1+i)^N \qquad (1)$$

To invest in such a project, it is studious to curb inflation by investing some amount, PV, currently and getting returns on that investment at a nominal discount rate, D, to meet the inflated capital in N years. This nominal discount rate is a mix of debt and equity, and can reflect the risk profile of an investor.

Mathematically relationship is as follows,

$$A = PV \times (1+D)^N \qquad (2)$$

At point A, (1) and (2) are equal

$$PV \times (1+D)^N = C \times (1+i)^N \qquad (3)$$

Thus,

$$PV = C \times \frac{(1+i)^N}{(1+D)^N} \qquad (4)$$

In developing the Net (Real) Discount Rate, NDR, the concept of zero inflation (real or constant money) is applied. Thus, i = 0 and PV is discounted at the NDR, to maintain the same cost C in N years

That is,

$$PV \times (1+NDR)^N = C \qquad (5)$$

Or rather,

$$\frac{1}{(1+NDR)^N} = \frac{(1+i)^N}{(1+D)^N} \qquad (6)$$

The net (real) discount rate is then used for the implementation decision of all the projects. This is to say, to invest that same amount C in N years, the cost of capital, C, must be escalated by the inflation rate, i, to the new cost A, and discounted to the

Present Value by the discount rate, D. This is the same as discounting C in N years, by the Net Discount Rate to the Present Value, PV.

It is then possible to make economic comparisons between technologies, of different size/capacity using similar techniques as those described above for cash flows. An example would be when trying to decide between a 200 000 bbl/day output crude oil refinery and different size output Coal to Liquids process technology.

It is important to note that the comparison can only be made because these technologies meet the same demand. This is achieved with the calculation of an annual equivalent capacity for each technology. This is equivalent to the calculation of an annual levelized cost for uneven future cash flows for different projects.

2.4.2. Option Valuation Theory

For the competitive markets, where the price of electricity and other energy forms are unpredictable, utility investment and retirement decisions made using the NPV methodology are not appropriate. In competitive markets, most investments and retirements (or shut down) decisions are both deferrable and irreversible. This means the energy supplier can postpone such decisions, but once an investment/retirement is actually made, reversal of such a decision is cost significant. For this class of decisions, the NPV rule can yield dramatically incorrect results. New methods based on financial techniques for evaluating option contracts are ideally suited for such decisions. [12]

In a competitive environment, utilities have a right and NOT the obligation to invest/retire (or shut down) plant. The NPV approach does not take into account the fact that decisions are deferrable. As such, in future analysis of the South African energy market, the NPV approach alone will be insufficient.

Different valuation tools using the options concept are constantly being developed and revised.

2.5. Energy Modelling Tools

The analysis on which this report is based utilises a simulation tool and an optimisation tool.

2.5.1. Simulation models

There are a number of simulation models in the market, but very few that are user friendly and desktop oriented. Two of the more widely used models are MESAP and LEAP.

2.5.1.1. MESAP

The Modular Energy Systems Analysis and Planning (MESAP) tool was developed by the Institute for Economics and Rational Use of Energy (IER) at the University of Stuttgart, Germany.

MESAP has found a lot of application in Germany and has been used to study the phase out of nuclear power plants and electricity supply for the Southern African Development Community (SADC). MESAP is currently being improved for interfacing with The Integrated MARKAL-EFOM Systems (TIMES), which would combine the simulation capabilities of MESAP with the optimisation strengths of TIMES.

The MESAP database is connected to the planning models by a standardised open data interface. This allows data storage to be independent of individual models. New modules can be added easily to the system. The modules all use the same data source. Data exchange between modules can be done easily via the central database. MESAP consists of the following:

- The **ANALYST** is a standalone program for a quick and lucid visualisation of data stored in MESAP model databases and ENIS statistical databases. The ANALYST can present time-series data in the form of tables and graphs and supports the generation of standardised reports. The ANALYST can combine data and results from different databases. Through a permanent link between databases and ANALYST, the visualised data always represents the latest state of the information stored in a database.

- The **PlaNet** simulation model performs a process-engineering oriented analysis of energy and environmental systems. It is based on the reference energy system (RES) concept, which is used as a standardised scheme to represent the structure of the energy system. Again, in a simulation model, the user defines equations and data values for the energy planning analysis and solves the equation system for the unknown variables. As a result, the simulation gives the energy flows in the system, the consumption of resources, emissions, process capacities and required costs for the energy supply.

- **ENIS** (Energy Information System), which allows for the management and access of the MESAP database.

Because of this modularity, MESAP is not user friendly. MESAP is currently being developed with a better user Windows interface, and is not yet available for commercial use. Also, there is concurrent development by the IER group to interface it with the TIMES optimisation tool. An initial attempt was made to create a reference energy system with all the relevant South African data. This exercise proved successful and will be updated in the future when an upgraded MESAP system is available.

2.5.1.2. LEAP

The Long-range Energy Alternatives Planning system (LEAP) is also a simulation tool developed by the Stockholm Environmental Institute (SEI) in Boston. LEAP is useful in terms of accounting for energy consumption and supply, costs and the environmental impact.

LEAP is divided into 3 main modules to process data. The first is DEMAND, which accounts for all the energy consumption in the various sectors. Another is the TRANSFORMATION module that deals with the mining and conversion of primary energy to secondary forms of energy. Lastly, there is the RESOURCES module, which specifies the amount of energy reserves and resources available, and accounts for all the fuels (or energy carriers) that are used in the energy system model.

LEAP is completely integrated and has a special Technology Environmental Database (TED) module, which can be updated from various sources, such as the internet. The module contains information about technologies, such as consumption data, fuels used by the technologies, emission factors for the fuels, etc. It also allows the classification of each technology by country or region. This is useful for quick analyses of countries that use similar technologies, especially the developing countries, as these technology data can simply be retrieved from the TED database.

The LEAP interface is user friendly and makes it stand out from the other energy simulation tools in the market. Because of its integration, LEAP became the simulation tool of choice. It was also commercially available at the beginning of the project.

2.5.2. Optimisation Tools

There are a number of energy optimisation tools available. The first that the ERI was introduced to was TIMES, which is a development of two current existing optimisation tools, MARKAL and EFOM.

MARKAL is short for Market allocation and EFOM stands for Energy Flow Optimisation Model. TIMES is currently under development and is yet to be released for commercial use, whereas MARKAL has been used extensively. MARKAL is a linear optimisation tool, optimising on least cost to the system. This least cost target is often referred to as an objective function.

MARKAL is different in many ways, but similar to LEAP in its basic structure. The main components of MARKAL are Commodities, such as energy carriers, materials (e.g. water, waste, etc) and emissions, and Technologies. Technologies are further divided into sets (or type). For instance, a power station belongs to a special set called the conversion (CONV) set. Any other technologies belong to the processes (PRE) set. The PRE technologies are further divided into sub-sets, as follows

- DMD for energy consuming devices, such as cars, light bulbs, etc.
- MIN for resources extraction processes, e.g. coal mining
- EXP for exporting energy carriers
- IMP for imports

The solution to the linear program describes a set of energy technologies and energy flows that constitute an energy system that is feasible and optimal. Feasibility is an indication that all variables add up mathematically and that the limits are satisfied. Optimality implies that of the thousands of feasible solutions, the model has chosen the one with the least cost. MARKAL is designed to solve a set of linear constraints (or equations), with variables, coefficients and limits specified by the user as input data (boundary values). The model attempts to provide a solution for the energy balance of an energy system, which can be described mathematically as,

Production + Imports – Exports – Consumption $\geq$ 0

Capacity transfer constraints can also be described as,

Capacity in current period = Remaining residual capacity + New investments made in previous periods that are still available

Note that the term "variable" used above serves to indicate the unknowns in the linear equations. In energy modelling terminology, input data is called parameters. A typical variable is the amount of installed capacity of a power station (in MW), which would be determined by the model. A coefficient is the investment cost per unit of capacity (R/kW). And a typical limit would be the maximum growth of capacity to be expected in a projected period. In creating the linear equation, the user would specify that the amount of installed capacity of such a power plant must be less than or equal to the maximum projected capacity in a future year. [14]

An example, in the case of industrial thermal demand, is that there are different energy carriers (e.g. gas, diesel, coal) in addition to the different devices that constitute the final energy demand.

2.5.2.1. Marginal Costs

Each device has an efficiency value dependent on the energy carrier used (electricity, gas, coal etc.). The final energy demand is satisfied by minimising the cost based on the cost of energy supply coupled with the appliance efficiency. In this example, for simplicity, it is assumed that the marginal costs described in the paragraph below include all resource and investment costs incurred to deliver each of the final energy of the devices.

For example, consider the marginal cost of electricity supplied to an electric stove at 44R/GJ and gas supplied to a gas stove at 53R/GJ. If the electric stove has an efficiency conversion to useful heat energy of 60% whereas the gas stove has an efficiency of 75% then the final energy cost for heating by electricity is 73.3R/GJ and by gas is 70.6R/GJ. The optimal solution will choose heating by gas.

2.5.2.2. Shadow Pricing

However, it is possible in MARKAL to also compare the value to the energy system of technologies as different as an electricity generating technology on the one hand, or an end-use conservation technology, such as building insulation, on the other, on the same scale. The first method of comparison is called "shadow pricing". This allows for the substitution of different marginal technologies. In choosing a least expensive mix of technologies and energy services for the energy system being modelled (where the objective function is least system cost), MARKAL also calculates the value of an additional unit of capacity of different technologies. Important to note is that the value is not just the cost per additional capacity of the technology as usually measured but the difference between the technology with a cost A and that being substituted, with a cost B. The shadow price (A-B, where A< B) indicates the value of an additional unit of the technology by the difference it would make in the total system cost. Shadow prices are always negative in value, because it is comparison of costs of a additional unit of a least cost technology against a marginal technology that costs more (hence being substituted). [24]

2.5.2.3. Reduced Cost

The opposite of the above applies to, for example, two technologies that may differ slightly in cost. Because of the methodology employed by linear programming, the least cost technology mix might include all of one but not of the other (of course, depending on the maximum penetration levels), which might not be a practical solution. MARKAL allows the user to observe how much cost improvement of the one the technology can be implemented in order to introduce it in the solution. This value is indicated as the "reduced cost". This value is the difference between cost (C) of the additional capacity of the "costly" technology and the cost (D) of the next marginal technology (where D< C). Since the "costly" technology is more expensive the difference is positive (C-D >0), and this would be an increase in the total cost of the energy system.

Hence this reduced cost value (C-D) measures how much the cost of the "costly" technology would have to be further reduced to enter the solution.[24]

MARKAL, as a linear program, is able to provide what is called a dual solution, by making available additional information to what is shown in the primal solution. This is an important issue that separates optimisation from simulation. To emphasise the point, marginal costs can be explained as the change in the objective function of one more or less unit of said entity (e.g. energy, emissions, demand, new investment in or total installed capacity of technology).

The user is also given the option of having more than one objective function, e.g. where the optimisation would also include the maximum allowable emissions from the system, along with the least cost constraint.

CHAPTER 3: PRIMARY MODELLING ASSUMPTIONS

In developing the integrated energy strategy, some assumptions have been made. This chapter serves to highlight the overriding assumptions for the models and justifies why these were the chosen assumptions.

3.1. Terms of Reference

This chapter sets the stage for the analysis that was performed in this report. The terms of reference for the analysis are described below and were continually reviewed with the progress of the work.

3.1.1. Objectives of the research

This thesis was expected to have the following outputs associated with it. Firstly, the development of four future scenarios for the South African energy sector. Secondly, a simulation of two of the scenarios in LEAP and an optimization of both of these in MARKAL.

3.1.2. Scenario development

Focus in the project was placed on justifying the assumptions made in developing these four scenarios. The key issues were:

- economic (e.g. growth and sectoral mix of the economy),
- political (e.g. regional integration),
- environmental (e.g. emissions, climate change and the CDM),
- demographic (e.g. population growth and AIDS/communicable disease),
- technical (e.g. new technologies) and
- energy market transformation (e.g. privatisation GDP , black economic empowerment) considerations.

Particular attention was to be paid to national priorities such as increasing access to energy for a large part of the population, the taxi industry recapitalisation and the penetration of renewable energy resources.

3.1.3. Energy sector modelling

The energy model programs used are well tested, and include a linear, non-optimisation model, LEAP – an upgrade of LEAP95 - and an LP optimisation tool, namely MARKAL. Key steps in the construction of the national model include:

- The translation of the energy scenarios into modelling input data requirements. These can be divided into the demand sectors (industrial, mining, commerce, transport and residential) and energy supply sectors (coal mining, oil and gas extraction, electricity generation, oil refining, synthetic fuel production).
- Obtaining additional information required in populating the programs from various sources.
- Structuring LEAP and MARKAL for the selected energy scenarios.
- The compilation of modelling input data and modelling assumptions for workshop presentations.
- Run LEAP and MARKAL for the selected scenarios. Compare model results and refine models appropriately. Test sensitivities of various assumptions.
- Define future studies required for more accurate results.

3.1.4. Results

The results were presented at the two National Integrated Energy Planning Workshops, hosted by the Department of Minerals and Energy, in 2001 and 2002. Also, the details for the modelling were presented to the ESKOM steering committee for Integrated Strategic Electricity Planning.

In developing the models assumptions had to be made and were deliberated by a team consisting of staff from the ERI, ESKOM and the DME.

3.2. Physical Boundaries for the Integrated Energy Plan

The analysis was restricted to energy behaviour within the borders of South Africa. All energy projects considered had to be South African projects or joint ventures with South African partners. All energy projects had to be technologically feasible, economically viable and with adequate accuracy of costs.

3.3. Scenario Assumptions and Period

Many in business and politics have used the concept of scenario development. It is said that scenarios are *not* predictions, as it is not possible for humans to predict the future with certainty.

Scenarios serve to prepare planners for the future. They serve as a tool for helping to plan in a world full of great uncertainty. The fact that no one can be sure of the future should be motive for cautious planning. [24]

There are an infinite number of possibilities for the future. Political decisions, new discoveries in technology, economic trends, unforeseen world events, natural phenomena such as new diseases and changes in climate, social trends and fashions all affect the future. One may roughly divide the variables into independent and dependent variables, although the division is by no means always clear.

The independent variables are political decisions, choice of economic system, state control or free market, nationalism or internationalism, the level of co-operation with neighbouring countries, the competence and integrity of political leaders, reserves of natural resources, natural phenomena such as climate, and discovery of new technologies.

The dependent variables are economic growth, level of employment, demand for resources and economic goods, choice and use of technology, population growth (which is lower in rich countries), concern for the environment (which is higher in rich countries), imports and exports, and so on.

For the scope of work of this project, it was decided to keep the drivers constant and to have one scenario to test specific changes to some of the more pertinent planning assumptions relevant for the country. This scenario is referred to as the **Business-as-Usual** scenario. It is not a prediction of South Africa's future, but was simply developed to form a baseline case, or reference case from which other studies can be developed.

Four cases from this scenario were developed to test specific questions. The cases consist of two variations of "Baseline" (Business as usual / reference case) and two of "Siyaphambili" ("we are going forward": a scenario with deliberate policy interventions for diversifying energy away from coal and increasing clean energy access for the poor).

This approach allowed for benchmarking the computer optimisation model MARKAL with the computer simulation model LEAP thereby insuring the accuracy of the computer models used in the modelling process. Benchmarking was achieved through simulating specific plans of the major energy transformation processes (electricity generation, liquid fuel production etc) in each of these models and testing their accuracy. The cases considered consist of two that are simulated and two that are optimised. These are described as follows:

- **Simulated Baseline** (or reference case) – reflects a simulation of the current plans of the major energy transformers in the energy market. This plan takes into account the minimal environmental constraints as currently imposed and maintains these levels over the 20-year planning horizon.
- **Optimised Baseline** – attempts to optimise the simulated Baseline plan through better and more economic utilisation of energy and applying energy efficiency programmes and fuel switching applications. In this plan minimal environmental constraints, as currently imposed, are maintained over the 20-year planning horizon.
- **Simulated Siyaphambili** – reflects a simulation of the current plans of the major energy transformers in the energy market where these plans take into account increasing environmental constraints and diversification into technologies which are more environmentally friendly, albeit at higher cost.
- **Optimised Siyaphambili** – attempts to optimise the simulated Siyaphambili case through better and more economic utilisation of energy and applying energy efficiency programmes and fuel switching applications.

3.4. General Assumptions

The following are the general assumptions for the modelling:

- A twenty year planning period (2001 to 2020) was assumed

  This planning period is seen asa medium to long term period. It has been adopted from planning studies that are performed by stakeholders in the energy sector, government departments and other international sources, such as the International Energy Agency (IEA).

- Process performance data, costs and commodity prices were specified at 1 January 2001 values. This allows for the common basis of assessment in the Net Present Value analysis.

- The rate of exchange is $1 = R8 (1 January 2001)

  It is not easy to predict what the future exchange rate will be. Since all projects are analysed on a common basis, choosing a constant value for the rate of exchange simplifies the analysis. The cost structure of each technology should ideally be divided into local and foreign portions. To observe the effect of the exchange rate would then only require the escalation of the individual portion in the relevant currency PPI. This can only be done if the cost and price data is collected in the separate local and foreign portions in each modelling cost parameter.

- The Net discount Rate was put at 11%

  Long-range planning studies can be performed by either including or excluding inflationary effects. In both cases, however, it is essential that all costs and economic parameters used in a study (e.g. the discount rate and escalation rates) be treated consistently. A study that includes the effects of inflation, such that monetary values are expressed in terms of actual prices of each year, is defined as being in terms of current (or nominal) monetary amounts.

  In contrast, a study that excludes the effects of inflation such that monetary values are expressed in terms of general purchasing power in a base year is defined as being in terms of constant monetary amounts. While both methods are acceptable, it is recommended in most literature that expansion planning studies be performed in terms of constant monetary amounts. [15]

  The Net Discount Rate reflects the risk of investment profiles of the different energy projects. Usually, well-established companies require returns between 10-20%. Projects with a high up-front capital expenditure component (e.g. hydro schemes for electricity generation) and a low operation cost component are more attractive with low discount rates. The reverse is true for projects with low capital expenditure and high operational costs.

- The Population Growth: 2000 = 44 Million, 2010 = 50 Million (1.3% p.a.), 2025 = 57 Million (0.87% p.a.). These figures do not include the impact of Aids and other communicable disease.

- GDP Growth: 2.8% average annual growth over period

  This growth rate is reflective of current economic growth in South Africa. This is also in agreement with government projections for moderate economic growth in the country.
- Gas was assumed to be generally available from South Africa, Namibia and Mozambique at $2.5 / GJ and escalated at SA PPI. This means that should the gas options fail to be viable

at SA PPI, then at foreign PPI they are worse off, deeming any gas projects not viable for implementation in South Africa.

- There would be a 20% coal price increase for Sasol from 2008.
  This increase in the coal price is predicted by sources in the petroleum industry. Unless this is realised, it will make it difficult for the gas process to compete with the coal process at Sasol.

- At least 15% Sasol coal-to-liquid process would be replaced by gas/liquid process by 2015

- Coal supplied to industrial and other processes, except electricity generation, at R6/GJ.
  There is talk that this value will increase tremendously if black economic empowerment objectives are realised in the coal-mining sector.

The specific assumptions for each case are described in Table 16 below.

Table 16: Specific Assumption for Each Case

Basic Principles:	Projection of status quo	Lowest cost	Seeks to diversify energy and reduce dependency on coal. i.e. partly addresses environmental concerns by delaying coal. New energy processes, as alternatives to coal, are built to specified dates prior to coal processes being built.	Seeks to diversify energy and reduce dependency on coal. Addresses poverty and environmental concerns. New energy processes, as alternatives to coal, are built when economic prior to coal processes being built.
Energy Efficiency and DSM	❖ No energy efficiency programmes ❖ load management programmes to modify electricity demand only.	Includes Energy Efficiency programmes and a full range of electricity DSM options. Policy incentive(s) in place for implementing DSM and energy efficiency programmes.	❖ No energy efficiency programmes ❖ load management programmes to modify electricity demand only.	Includes Energy Efficiency programmes and a full range of electricity DSM options. Policy incentive(s) in place for implementing DSM and energy efficiency programmes.
Electricity Generation	Based on coal as primary fuel source: ❖ builds 3556MWe mothballed PF Stations from 2007 ❖ Four sites for new 6X640MWE dry-cooled coal-fired plants with FGD from 2013 ❖ 1x750MWEe CCGT plants in 2014 ❖ Four sites with each 3x333MWe pumped storage plants from 2011 ❖ 5x240MWe simple cycle gas turbines (jet fuel) for peaking built at max rate of one pa. from 2011 ❖ No new hydro imports, nuclear, renewable energy sources	Can choose new generation technology on lowest cost from the following options: ❖ 3556MWe mothballed PF Stations ❖ Four 6X640MWe dry-cooled coal-fired stations without FGD. ❖ 3x750MWe CCGT plants using Kudu gas ❖ 1X750MWe CCGT plant using Pande gas ❖ 2684MWe imported Hydro Electricity ❖ 11X125MWe PBMR units ❖ 2330MWe new FBC ❖ Up to 5% renewable energy sources by 2010 consisting: ❖ Solar ❖ Wind ❖ Municipal waste	New technologies built before new coal options as specified: ❖ 3556MWe mothballed PF Stations from 2007 at a max rate of 500MWe/a ❖ 3x750MWe CCGT plants in 2005, 2006, 2007 using Kudu gas ❖ 1X750MWe CCGT using Pande gas in 2014 ❖ 2684MWe imported Hydro Electricity from 2008 at max rate of 550MW/a ❖ 125MWe PBMR in 2005 followed by 250MWe/a from 2008 with a max of 1375MWe. ❖ 2333MWe new FBC built at max rate of 466MWe/a from 2015 ❖ 5x240MWe simple gas turbines (diesel) for peaking built at max	Can choose new generation technology on lowest cost before new coal options (except mothballed stations) from the following options: ❖ 3556MWe mothballed PF Stations at a max rate of 500MWe/a ❖ 3x750MWe CCGT plants Kudu gas ❖ 1X750MWe CCGT using Pande gas ❖ 2684MWe imported Hydro Electricity at max rate of 550MWE/a ❖ 1375MWe nuclear PBMR at a max rate of 250MWE/a ❖ 2333MWe new FBC built at max rate of 466MWe/a ❖ 5x240MWe simple gas turbines (diesel) for peaking built at max rate of one pa ❖ 5% of electricity generation supplied by

			rate of one pa from 2020 ❖ 5% of electricity generation supplied by Renewable options in time as specified by DME ❖ New 6X640MWE dry-cooled coal-fired plants with FGD are only considered once previous alternatives are built	Renewable options extent as specified by DME ❖ New 6X640MWE dry-cooled coal-fired plants with FGD are only considered once previous alternatives are built
Liquid Fuels	❖ Keeps existing Sulphur levels ❖ Does not build new refinery capacity ❖ Mossgas ends in 2008 ❖ Imports new finished products as required	❖ Can choose new refineries or imports based on cost ❖ Keeps existing Sulphur levels ❖ Can choose whether Sasol should use coal to oil or gas to oil	❖ Refinery processes upgraded to produce low sulphur fuels ❖ Builds new refinery capacity instead of importing. ❖ Mossgas is sustained	❖ Can choose new refineries or imports based on cost ❖ Refinery processes upgraded to produce low sulphur fuels ❖ Sasol can only expand using gas to oil
Gas	No new gas except for limited amount in electricity generation	If economic	5% of Total Primary Energy Supply	If economic
Fuel Switching	No	Can switch to coal or gas if economic.	No	Can switch to gas if economic.
Residential Sector	Status quo consumption trends	Optimises on energy efficiency in electricity usage	Status quo consumption trends	Optimises on energy efficiency in all energy usage
Commercial Sector	Status quo consumption trends	Optimises on energy efficiency and fuel switching options	Status quo consumption trends	Optimises on energy efficiency and fuel switching options
Transport	Status quo consumption trends	Optimises on energy efficiency ❖ Taxi recap. ❖ electric vehicles	Status quo consumption trends	Optimises on energy efficiency ❖ Taxi recap. ❖ electric vehicles
Industrial Sector	Status quo consumption trends	Optimises on energy efficiency and fuel switching options	Status quo consumption trends	Optimises on energy efficiency and fuel switching options

3.5. Reference Energy System, South Africa

A detailed Reference Energy System (RES) was developed for the purposes of accounting for the energy flows for the region of South Africa, thus creating a structure for the model database. The reader is referred to figure 3.1 below. Here different supplies, processes and devices compete for the end-use devices for the gold mining sector is illustrated.

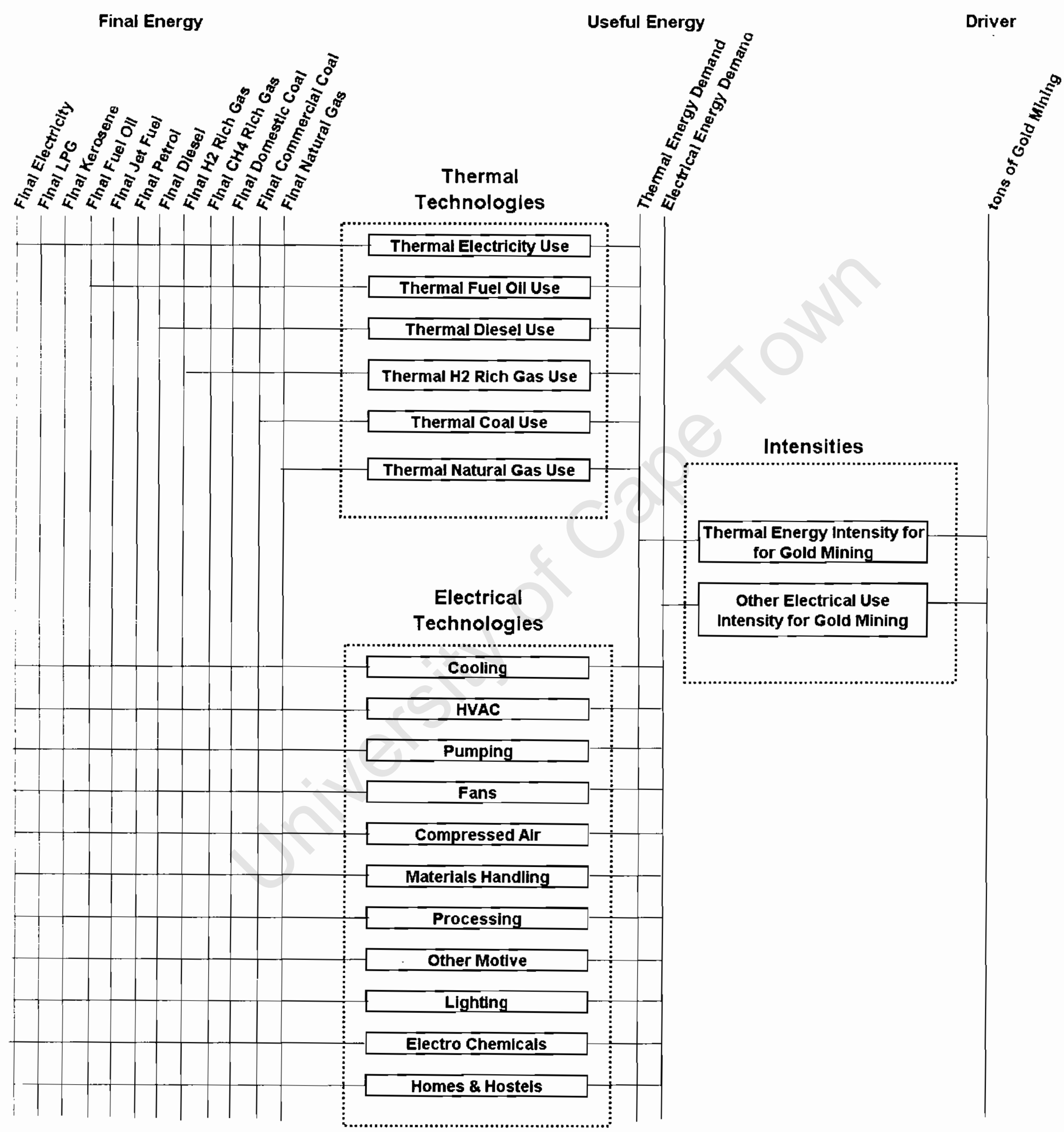

Figure 3.1. Depicts a flow of energy in typical reference energy system (RES).

In this RES, the Driver is a prediction of Tons of gold mined per annum relative to international market demand. The energy required to produce the tons of gold is influenced by two primary parameters; increasing depth for mining and decreasing concentrations of gold in the ore. This impacts on the energy requirement for gold mining into the future and is represented by different energy intensity factors changing over time. Applying these energy intensity factors coupled with the projected market demand will determine the useful energy requirement for gold mining into the future.

The projection of useful energy demand after adjusting for energy intensity can be split into two groups; thermal energy (all fuels) demand and electricity (non-thermal) demand. For each group there is a choice of different devices that can be used (e.g. Cooling devices, Heating, ventilation and air conditioning (HVAC)). Further in the case of the thermal demand, there are also different energy carriers (e.g. gas, diesel, coal) in addition to the different devices that constitute the final energy demand.

Each device has an efficiency value dependent on the energy carrier used (electricity, gas, coal etc.). The final energy demand is satisfied by minimising the cost based on the cost of energy supply coupled with the appliance efficiency.

The following is a discussion of the modelling aspects associated with future energy demand, transformation systems and end-use devices.

These sections cover three broad groups of energy conversion and utilisation equipment, differentiated according to the energy carriers upon which they depend:

- Conversion technologies: all kinds of load-dependent plant generating electricity;
- Process Technologies: all kinds of load-independent processes converting one energy carrier into another; and
- Demand technologies: all devices consuming energy carriers to meet energy demands.

The complete RES for South Africa is attached in Appendix D

CHAPTER 4: METHODOLOGY FOR MODELLING

4.1. Modelling Energy Demand

There are many ways to structure data in both of these models, and each method of structuring data is dependent on the type of question that needs to be answered. The structure for the current models is discussed and ways to improve the structure will be recommended.

In order to construct the demand sector for modelling, it is important to establish:

- The energy services required by the energy economy. (Useful Energy)
- The growth in energy service demand.
- The devices that could be used to meet this demand.

4.1.1. Assumptions and Drivers

The useful energy demand for the Agricultural, Industrial and Commercial sectors has been split into thermal requirements (such as furnaces and steam raising) and non-thermal electricity requirements. This is represented graphically in fig. 4.1 below.

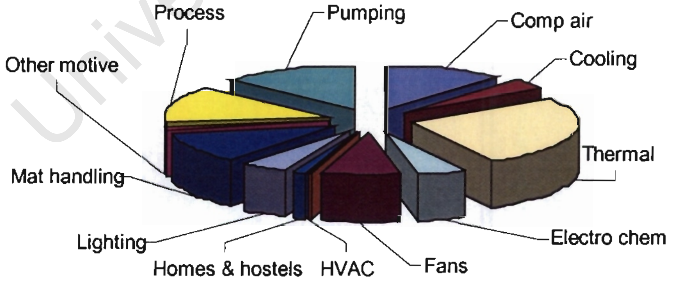

Figure 4.1. Services for electricity consumption.

The relative consumption of energy to meet selected energy service for more sectors is illustrated in the summary table (Appendix B)

4.1.2. Elasticities

In projecting energy demand into the future, several relationships between a driver and energy consumption can be derived. For a first approximation, the demand for energy E can be expressed as function of a driver Q raised to some elasticity, β, as seen in equation (1)

That is,

$$E = Q^{\beta} \quad (1)$$

The elasticity can, for instance, relate the rate of growth of GDP to the demand for energy growth of the sector. Even though the elasticity does not have to be constant over the planning period, it appears that when considering the relationship of the growth of the national income or GDP and the growth of the national energy demand, the changes in elasticity are small. Thus the LEAP model bases its forecast on this first approximation. Hence, for small changes in Q, representing GDP in this case, the elasticity can be expressed as,

$$\beta = \frac{\Delta E / E}{\Delta Q / Q} \quad (2)$$

Or in words,

$$\beta = \frac{percent\text{-}change\text{-}in\text{-}Energy}{percent\text{-}change\text{-}in\text{-}Driver} \quad (3)$$

Price elasticities are derived in the same way. [9]

In deriving the elasticities for this modelling work, growth estimates for various sectors had to be observed, in the context of an average moderate GDP growth of 2.8% over the period 2001 to 2020 . [10]

4.1.3. Useful Energy Intensity

Energy intensity refers to the amount of energy that is required in performing a given activity to satisfy the energy services requirements. For example, the intensity is the amount of energy required to produce a ton of product or to produce a unit of GDP, expressed as GJ/ton, or GJ/GDP index, respectively. Energy is often changed from a secondary fuel such as diesel to a more useful form such as compressed air. The useful energy (i.e. the compressed air's energy content) is estimated and the 'useful energy intensity' is derived from this.

'Useful energy intensity' is the amount of energy 'service' required per unit of activity. An example would be the amount of compressed air that is required to produce a ton of gold. The useful energy intensity, together with sector growth, is used to project useful energy demand into the future. [10]

As processes change and more efficient practice is adopted, useful energy intensities may drop. Estimates were developed with Eskom's Integrated Strategic Electricity Planning (ISEP) department. It was assumed that there would be a drop in useful energy intensity of close to 10% over the period for agriculture, commerce and most of industry, because of a gradual passive modernisation. The exceptions in industry were Gold Mining and Other Mining. Gold Mining intensities have been increasing and this trend is likely to continue because of the increase in mining depth and the decrease in ore quality. Other Mining energy intensity was kept constant as moves to more efficient equipment were thought to counter increased depths that would be required in the future. The residential sector and the transport sectors are modelled more explicitly and the efficiency improvements are not just symbolised by a change in technology efficiency, but rather actual technologies replace inefficient technologies.

The energy intensity for passenger transport for the following modes has been estimated as listed in Table 17

Table 17. Passenger transport intensities

Vehicle	Intensity (MJ/pass-km)
Petrol taxis	0.6
Diesel taxis	0.4
Passenger trains	0.2
Petrol cars	2.9
Diesel cars	2.6

The values in Table 17 taken together with the percentage of passenger kilometres by the modes above represent an estimate of current practice in South Africa. With the exception of passenger trains, a less energy intensive (more efficient) option has been established compared to the above. Change in the vehicle stock and practice is represented by allowing for different penetrations of efficient options. [10]

For the simplification of this analysis the energy intensities for the residential sector are considered constant over time, and different estimates are given for each service required, such as useful cooking energy required per household.

In the residential sector, 'other' demand refers to electrical requirements such as refrigeration, television etc. This service is not supplied to all of the households in South Africa, and is dependent on access to electricity and financing. It is assumed that in 2001 approximately 60% of households have access to and require 'other' services, and this figure increases to 80% at the end of the planning period.

The amount of energy required per household for the various functions is estimated and summarised in Table 18 below and is derived from population, fuel consumption and device efficiencies.[10]

Table 18: Energy intensity for various activities in the residential sector

Service	Intensity (GJ/household)
Cooking	12.3
Lighting	1.6
Water heating	3
Space Heating	9.5
Other	5.6

4.1.4. Energy Efficiency

In the case of the industrial, commercial, agricultural and transport sectors, energy efficiency measures are based on improvements relative to current practice. This improved practice is characterised by increased capital and operating costs required per unit of service delivered. For the residential sector, specific technologies, such as incandescent lighting and compact fluorescent (CFL) options are entered explicitly into the model, together with characteristic lifetimes and cost data. A life-cycle cost calculation is used by the MARKAL model to estimate system total and marginal costs.

The MARKAL model uses the efficiency data to establish the potential for increased energy efficiency practice, and to establish the potential for switching from one fuel to another. This is in conjunction with the shadow pricing abilities of MARKAL, as explained in chapter 2.

4.1.4.1. High-temperature thermal technology efficiencies

Thermal energy efficiencies are split into two components, one for the distribution of heat (such as for steam through piping in a factory) and one for the heating of the medium to be distributed (such as the generation of steam). The efficiencies of the heating devices are multiplied by the efficiency of the distribution system. The efficiency of the distribution system has been derived from the observed losses that can be reduced, to conserve energy, in a distribution system.

4.1.4.2. Thermal efficiency improvements summary

Table 19 below gives the efficiencies of standard and efficient devices. These figures show an improvement of about 15% of energy consumed for solid fuels and about 10% for electrical systems.

Table 19: Thermal energy efficiency improvement

Thermal Fuel	Existing efficiency (%)	New system efficiency (%)
Solid	56	66
Liquid	60	69
Gas	64	72
Electricity	76	84

4.1.4.3. Non-thermal electricity consuming technologies

An average value of 60% has been chosen for the conversion of final to useful energy for these electricity devices. [10] The only exception is lighting. This value is only used as a standard against which to measure the effect of more efficient technologies. Energy efficiency improvements are detailed below.

- **Compressed air systems**

Compressed air systems around the world have a great potential for reducing electricity demand by improved energy efficiency. This is often realised through well-managed compression, treatment, distribution and monitoring of the compressed air systems. It has been assumed that a 20% improvement was possible for compressed air systems. Estimates from several studies suggest that up to 40% of compressed air could be saved in South African industry by better management. [10] These savings were assumed to have a payback of one year, and it was further assumed that ten percent of the cost saving per year after the first year would be put into maintaining the improvements. The costs chosen here are high estimates.

- **Variable speed drives (VSD's)**

Variable speed drives in some applications can reduce electrical demand and the greenhouse gas emissions associated with electrical generation. This saving is achieved because motor output can closely match demand during times of low output and draw less electricity.

For fans it is reported that savings can amount to 30%. [10] This was felt to be optimistic, and reduced to 25%. The application of VSD's for pumping, HVAC and other applications such as mining was not considered because of the extra control requirements, which would need to be integrated into the system. There is potential in gold mining for complete automation and VSD control as part of an integrated approach but this has not yet found wide application.

- **Electrical motors**

Because of technology changes over time and the drive for increased profits and energy efficient practice, high efficiency motors have become available both internationally and locally. [10] Other potential savings options include motor downsizing, minimising load, cutting the power supply during no load times and the application (discussed earlier) of variable speed drives [10]

The following assumptions were made for the motor stock in South Africa:

- A 5% improvement could be realised per motor over the base case over 25 years [10]
- The average life of the motor was 10 years,
- The increased capital cost per motor was $7.3 per kW [10]
- The average load factor was assumed to be 70%,
- The systems that would be affected by introducing high efficiency motors include: 'pumping' and 'motive energy use'.

- **Lighting**

Using higher efficiency light bulbs, switching them off when the light is not needed and making use of skylights in sunny areas offers significant opportunities for saving electricity and reducing greenhouse gases. For industry much of the lighting energy is used on the factory floor. The assumptions are taken from a recently completed case [10], which looked at some depth into factory lighting options .

- **Efficient Heating Ventilation and Cooling (HVAC) equipment**

Various measures can be taken to help improve the efficient operation of heating ventilation and cooling systems. These include:

- Ensuring minimum hours of operation
- Proper maintenance of heat exchanger surfaces
- Waste heat utilisation
- High efficiency motors and VSD's

It is suggested that for South African HVAC, 25% of energy could be saved in new installations and 37% in old installations compared with the baseline case. [10]

- **Energy Star Equipment**

  Most computers and other office equipment are shipped to South Africa with the energy saving capability de-activated. Savings can amount to 40% of energy consumed per unit [10] For this work, it was assumed that up to 30% electricity saving was possible.

- **Heat Pumps**

Reports suggest that replacing electric resistance heaters with heat pumps could reduce energy consumption by 67%. For this study, so as not to overestimate the savings potential of this equipment, it was assumed that 50% savings might be realised. [10]

- **Solar Hot Water Heating**

The potential for solar hot water heating was considered. Costs per installed unit were taken as R462/GJ of useful energy produced and 3% maintenance costs. [10]

Table 20: Summary of non-thermal energy efficiency improvements

Measure	Existing Efficiency (%)	New Efficiency
VSD	60	86
Motors	60	63
Comp air	60	75
Lighting	50	77
HVAC	60	80
Heat Pumps	60	120
Energy Star Equipment	60	86
Solar Hot water Heaters	N/A	N/A

4.1.4.4. Residential energy efficiencies

The residential sector differs from the industrial, commercial and agricultural sectors. For example, the coal brazier is normally used for cooking and water heating in the summer season. In winter it is used for the aforementioned uses and also for space heating. The energy efficiency value for this device needs to account for all these uses.

4.1.4.5. Efficiencies of cooking devices

Table 21 illustrates different efficiencies for cooking devices.

Table 21: Efficiencies of cooking devices

Cooking		**Efficiency**
fuel	**appliance**	
electricity	hot plate	65%
	oven	65%
	micro-wave	60%
paraffin	wick	28%
	primus	43%
gas	ring	50%
	stove	65%
Wood	stove	25%
coal	stove	25%
	brazier	8%

4.1.4.6. Efficiencies of water heating devices

Table 22 illustrates the efficiencies of different water heating devices. It should be noted that solar hot water heaters could be fitted with other auxiliary heating equipment.

Table 22: Efficiencies of water heating devices

Water heating		**Efficiency**
fuel	appliance	
electricity	geyser	70%
paraffin	wick/kero/pot	35%
gas	geyser	84%
solar	SWH (integral)	100%
Coal/wood/wastes	stove(jacket/pot)	40%

4.1.4.7. Efficiencies of space heating devices

Table 23 illustrates efficiencies for heating efficiencies of various appliances. It should be noted that while all energy eventually degenerates into heat, significant losses due to smoke leaving households, and un-combusted ash reduce efficiencies of direct fuel burning.

Table 23: Efficiencies of space heating devices

Space Heating		**Efficiency**
fuel	appliance	
electricity	Radiant heater	100%
paraffin	heater	73%
Gas	heater	75%
wood	open fire/stove	40%
coal	stove	59%

4.1.4.8. Efficiencies of lighting devices

Table 24 indicates the relative efficiency of converting the fuel source into useful light.

Table 24: Efficiencies of lighting devices

Lighting		**Efficiency**
fuel	**appliance**	
electricity	incandescent	17.5%
	fluorescent	50.8%
	Compact Florescent	70.0%
paraffin	wick	00.3%
	pressure	01.3%
gas	pressure	01.0%

4.1.5. Transport Intensities

In the transport sector, various modes of transport such as petrol cars, diesel trucks or electric trains convert fuel into an energy service. It is more useful to consider this service rather than the useful energy. The conversion ratio between the fuel and the service delivered is therefore referred to as an intensity, rather than an efficiency. The services delivered in the transport sector are passenger kilometres and tonne kilometres for the passenger and freight sectors respectively. For each of these sectors, more efficient modal options have been estimated.

4.1.5.1. Passenger transport

Various methods can be used to increase the efficiency of vehicles in terms of energy consumed per passenger kilometre travelled. These include more efficient design of vehicles and increasing the number of passengers. Two efficiency levels have been calculated and the vehicle fleet over time is described as a percentage split between these two levels.

4.1.5.2. Freight transport

Fig. 4.2 below shows the energy intensities used for the freight transport sector. Only one energy efficient option is considered in this report, and that is for energy efficient diesel trucks.

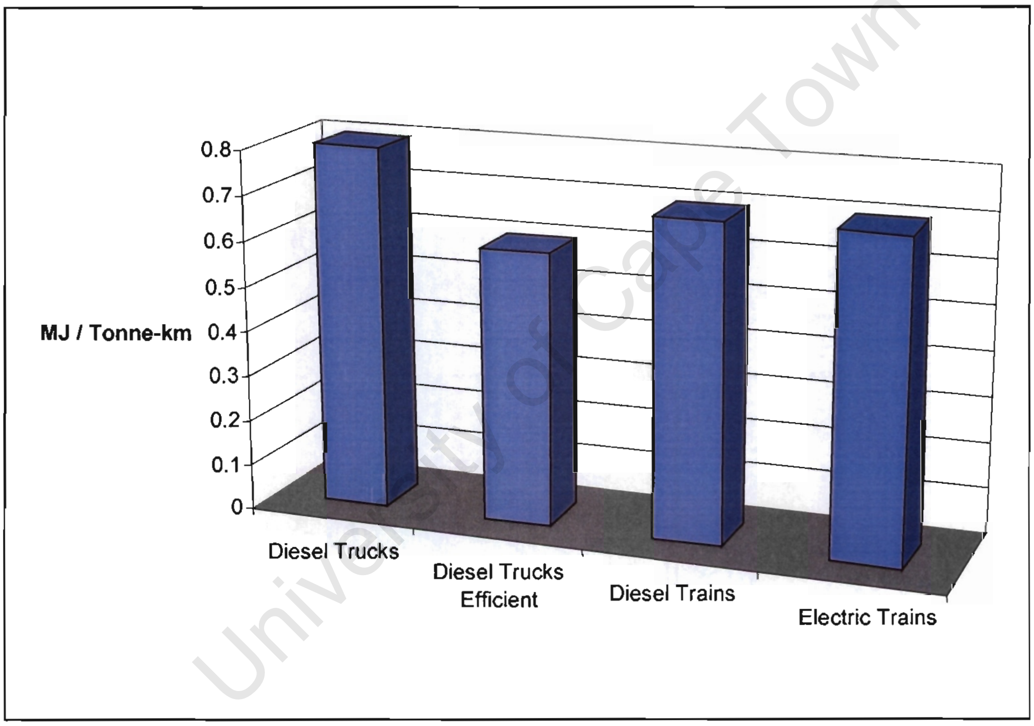

Figure 4.2. Freight energy intensities for transport sector

4.1.6. Energy Efficiency Penetrations

In the Siyaphambili Simulated case, a 5% penetration of natural gas is allowed at the expense of other fossil fuel carriers. In the MARKAL model, fuel switching is done to achieve the least cost supply of energy. The MARKAL fuel switching potential is calculated as a function of the new energy demand required by a sector, an estimated rate at which existing technologies are decommissioned due to age, and the relative proportions of fuel consumed in the simulated cases. The parameters are summarised below:

For the optimised cases, the potential for energy efficiency and fuel switching is assumed to be the same for both optimised cases. Each year thermal energy is needed as the sector grows. It was assumed that the optimised case would be allowed to switch up to 5% above or below projections used in the simulated case. The reason for this strict limitation is to ensure that, if recommendations come from the resulting model runs, they would be realisable.

Energy efficiency penetrations were allowed to be accelerated in the first five years due to policy promoting their uptake. In the first five years, a 5% penetration was allowed for, and by 2020 a 10% penetration.

4.2. Modelling Transformation

Transformation modelling is concerned with the modelling of the processes that convert energy from its primary form.

4.2.1. Liquid Fuel Supply

The modelling issues in this sector have to do with the complexities of the refinery processes. Isolating only the energy component of these processes for modelling purposes is complex. The use of bio-diesel production plants has been debated and estimates are that such plants could contribute to about 1% of the current diesel demand. However, because of a lack of conclusive data, it has not been modelled in this analysis. [10]

4.2.1.1. Existing Refining Capacity

The liquid fuels production capacity in South Africa is split between conventional oil refineries, and the synthetic fuels production plants. South Africa has four primary refineries. These have been modelled according to existing capacity. Allowance was made for creep expansion of all existing plants as was suggested by industry experts [10]

For this analysis it was assumed, based on information from industry experts, that in order to meet the increased oil demand, the oil production plants will expand their capacity during the period of this analysis. When these individual expansions have been completed new oil production capacity has been made available. [10]

4.2.1.2. Liquid Fuels Production

There are some important aspects which impact on the cost of producing liquid fuels in South Africa:

- The overall consumption of petrol in South Africa is currently significantly higher than that of diesel.
- South African refineries deliberately produce a larger fraction of lighter products than their counterparts in the rest of the world so as to reduce the fraction of heavy oils, which are used for heating and for which there is much less demand in South Africa. Running refineries in this way is expensive.

- The heavy oil that is produced by South Africa's coastal refineries is used for ship's bunkers. Inland the problem is worse because there is no demand for ship's bunkers. The Natref refinery produces a smaller fraction of heavier oils, and this further increases its refining costs.

4.2.1.3. Liquid Fuels Demand

The most important liquid fuels for this country are petrol and diesel. It is, however, important to note that oil production capacity in South Africa is built to produce a number of fuels and the mix of the local demand for oil products disadvantages the South African refineries.

- The growth in petrol consumption over the past 15 years has been significantly higher than the economic growth, averaging 4% per annum. However, there has been a significant drop in petrol consumption from 2000 to date caused by a significant increase in the crude oil price, and a simultaneous depreciation of the R/$ exchange rate.

- Some consultants and strategic planners from the oil industry consider that petrol growth may stagnate over the next 15 years, contrary to the conventional view in the sector. Currently petrol consumption is decreasing and the reasons vary from changing consumer spending patterns (e.g. cellphones and the lotto), to users converting to diesel engines. The consultants' view of the future growth in consumption of liquid fuels is illustrated in fig.4.3 below.

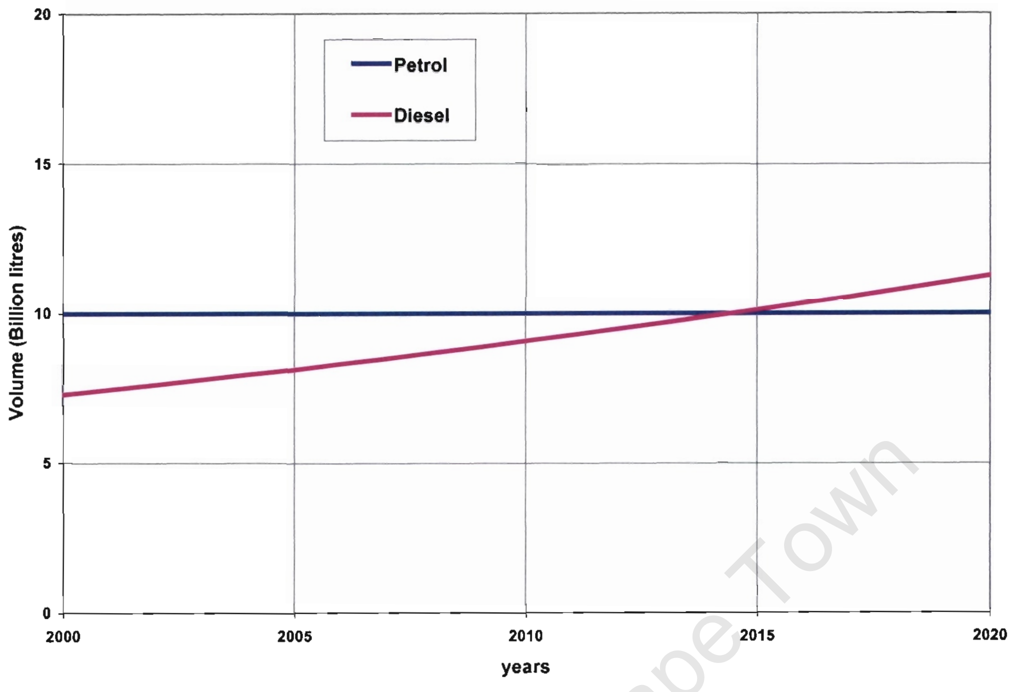

Figure 4.3. Liquid fuels projection

- Historically diesel demand has been growing at 1% per annum. This is attributed to the drop in diesel demand for public transport and a rise in petrol mini-bus taxis. Also, open cast mining and the military have had less demand for diesel.

- The growth in demand for fuel oil has been static since 2000. However, this component is a small fraction in terms of total energy consumption and has negligible impact on the analysis.

- There has been a 5% per annum growth in demand for LPG from 2000 for domestic use. [10]
- South Africa exports both to the Southern African Customs Union (SACU) countries, and beyond these borders. LPG is produced at almost twice the amount consumed locally and the balance is exported to the SACU and other Southern African countries.

- Diesel produced by the conventional oil refineries does not meet international standards due to high sulphur levels. Synfuels plants produce a sulphur free diesel and this is mixed with the conventional refineries' diesel to reduce the sulphur levels to international standards.

- The petrol/diesel imbalance has been long identified as a problem, and one of the measures that have been proposed to curb this imbalance is the taxi recapitalisation. This seeks to replace the old petrol mini-bus fleet with new bigger diesel mini buses.

4.2.1.4. New Refinery Capacity

A new refinery with 200 000 bbl-per-day crude oil input capacity situated at the coast with an existing port to take in a big crude carrier would cost approximately $2 billion to build (undiscounted or "overnight" costs). These are estimate costs based on consultation with some leading strategists in the refinery business. [10]

Fig. 4.4 shows the life-cycle costs of a new oil refinery compared to a new gas to liquids and a coal to liquids plant. With this approach it is possible to assess before modelling how new plant capacity competes economically.

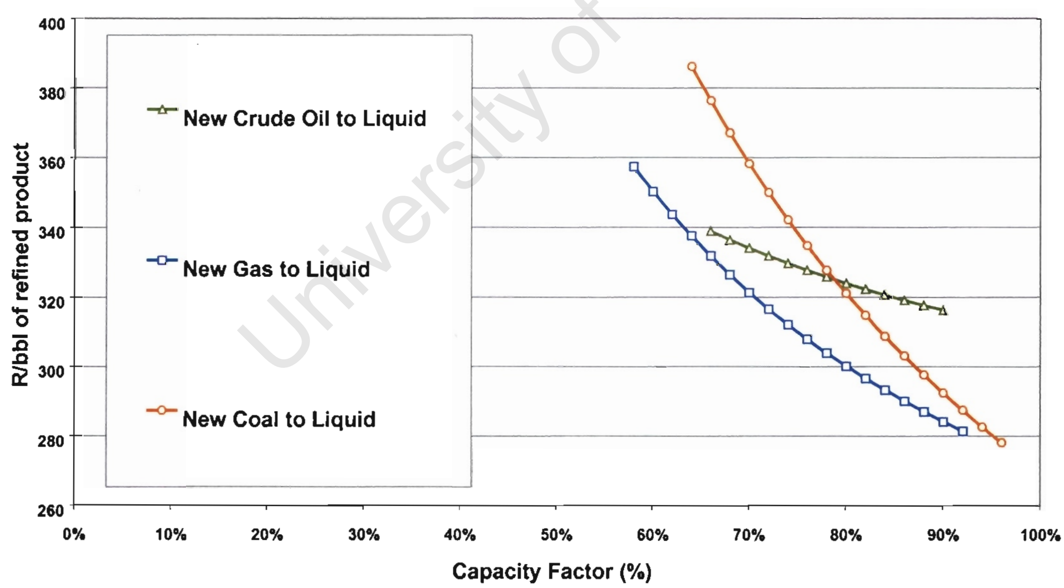

Figure 4.4. Life-cycle costs for new oil production capacity.

In MARKAL all three new plant options are available to meet increased new demand for liquid fuels. These options compete with the costs of importing finished fuel products.

4.2.2. Electricity Supply Industry

Modelling electricity is unlike the other energy carriers. The most important issues are:

- Modelling Base and Peak load plants. (Appendix E)
- Modelling storage plants (MARKAL is better than LEAP in that there is some capacity to model the feedback-loop involved in running a pumped storage plant).

The production of the National Integrated Resource Plan (IRP) for electricity as published by the National Electricity Regulator (NER) has been taken into account extensively in these studies. The NER document quantifies the prime motive for developing the IRP as being an "assessment of the risk to the country from committing (prematurely or too late) in new supply-side and demand-side options, which would result in either an under utilisation of assets or of not meeting the anticipated demand." (NER Website)

This problem being multi-variable with often contradictory attributes has no single solution. The aim is to determine strategies that are robust under a number of scenarios and will lead to minimum regret if another scenario materialises.

As MARKAL is a long-term planning tool, several key factors raised by the IRP were factored into the modelling. Some of these are listed below:

- Regulation of the Electricity Supply industry (ESI)
- The electricity market within, and external to, South African borders
- Impact of the R/$ exchange rate, which has deteriorated severely in the course of the study

It is also necessary to assess the risk and uncertainties involved in planning for the future of the ESI such as restructuring, environmental pressures, societal challenges (including the AIDS impact). However, these issues were not addressed specifically in these studies but some sensitivity analyses were carried out in terms of technological advancement in generation technology as detailed in the primary assumptions.

4.2.2.1. Electrical Energy Demand

The forecast includes all local sales in South Africa and foreign sales where contracts are in place or could possibly be placed between Eskom and specific customers in neighbouring states. Eskom have determined that the annual demand will increase with a corresponding reduction in the overall system load factor. This is due to the fact that the peak maximum demand growth is higher than the energy (base load) growth or the energy (GWh) growth will be less than Maximum demand (MW) growth. The system is getting more pronounced peaks in its daily demand. The implication is a need for more peaking plant options in the future. (NER Website)

4.2.2.2. Existing Generation Capacity

In the past Eskom has been planning for electricity generation in the country. With current plans to restructure the ESI, and the privatisation of Eskom, the technology mix for generation capacity should change. Currently, Eskom dominates supply mainly with coal-fired stations. Both Eskom and non Eskom capacity has been modelled.

4.2.2.3. New Electricity Supply Options

The new options are detailed in the primary assumptions contained in chapter 3 in table 16, with the focus on the newly proposed CCGT plants, the PMBR units, and renewable energy capacity. Fig. 4.5 illustrates the available capacity for electricity generation. Demand exceeds capacity in the period 2006-10. This projected demand is based on estimations from Eskom, and the diagram only serves to highlight the need for new plant capacity.

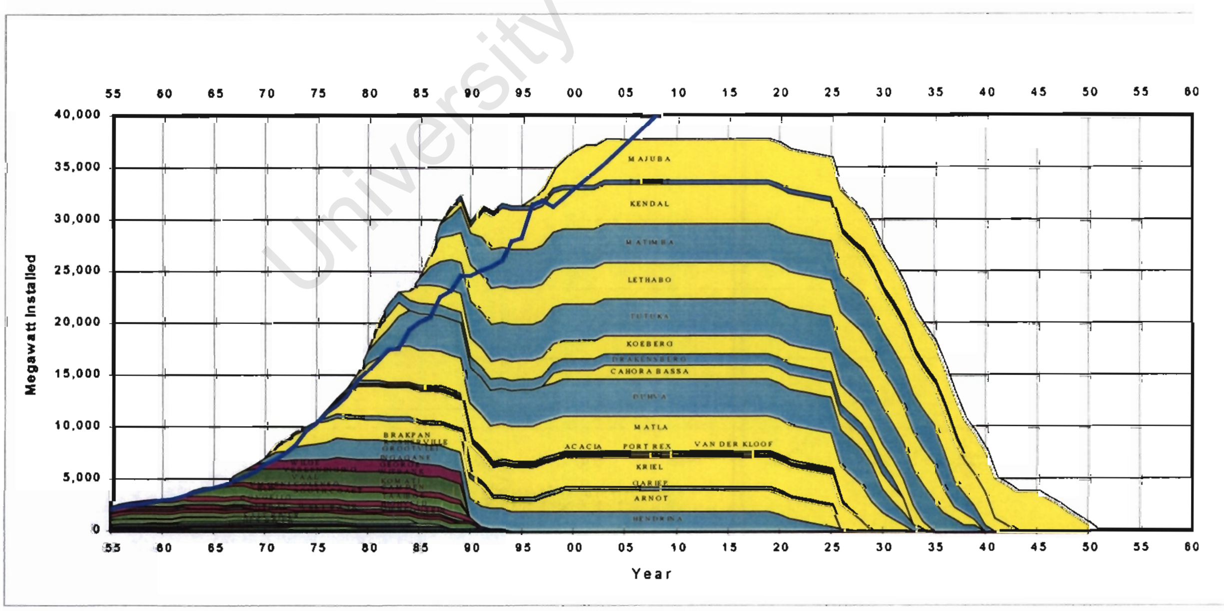

Figure 4.5. Increased demand over existing capacity.

As far as costs are concerned, for new electricity generation options, fig.4.6 below illustrates the levelised life-cycle costs for these new options. The most expensive option is the PBMR.

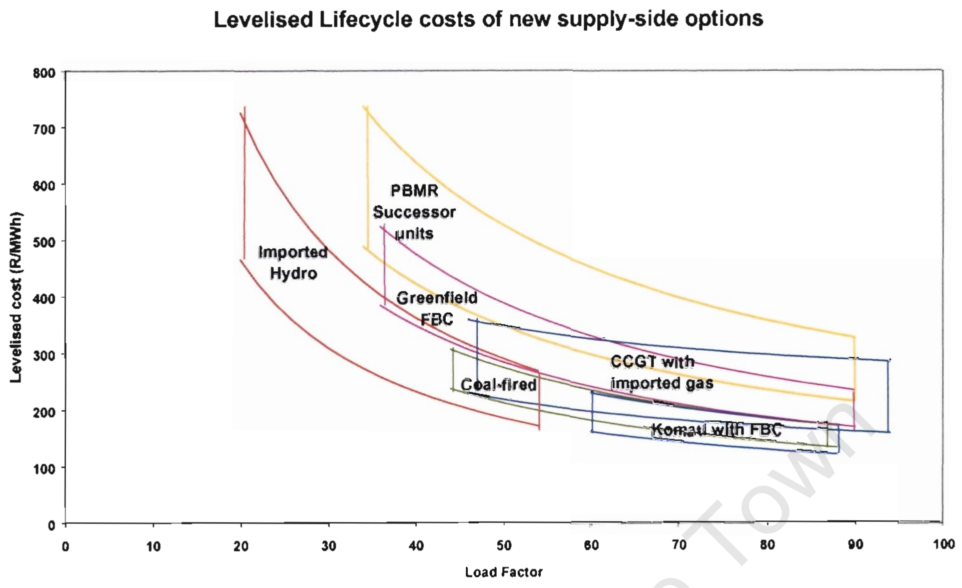

Figure 4.6. Life cycle costs of new electricity generation options. (NER Website)

4.2.3. Coal Mining

The South African energy sector is currently dominated by the use of coal. Most of the coal is used in the two important transformation sectors, electricity supply and liquid fuel production. The figure for South African coal reserves still stands at 55 billion tons. This also needs to be reviewed, as this number has been in use for the last 25 years.

4.2.4. Coke Ovens

Currently South Africa imports all of its coking coal. [10]. This analysis focused on phasing out the use of coking coal. Natural gas technology was seen as a probable replacement for coke ovens in the Iron & Steel industry.

4.2.5. Natural Gas Extraction

Natural gas reserves are currently only available at the Mossgas site in South Africa. New reserves have been identified outside South Africa's borders in the region, with Shell and Sasol leading the race in developing the infrastructure to extract this natural gas. The modelling work assumes enough natural gas for the planning period, as it is currently difficult to get final consensus of the proven reserves for the region. Also, specific focus is on the west coast gas, referred to as Kudu gas, which is costed at R20/GJ and the Mozambique/Sasol field, referred to as Pande gas, cost R11.73/GJ. Kudu gas is primarily used for the proposed Western Cape CCGT plant. This CCGT is seen as an anchor customer to facilitate the building of a gas infrastructure for the Western Cape. Pande gas is seen as replacing some of the gasified coal for the SASOL GTL plant at Secunda and also as chemical feedstock for Sasolburg. There is a potential for Sasol to also build a CCGT, and this has been considered in the modelling.

4.2.6. Biomass and Renewable Energy Resources

Renewable energy in South Africa has been identified to have a large potential for energy supply in general. However, attention is on electricity generation for this study. Electricity from wind generation has been factored into the analysis, along with solar power and municipal waste, according to the target set by government aspirations as detailed in Table 15 in chapter 2.

4.2.7. Environmental Impact of energy supply

Most of the transformation greenhouse gas emissions are from the burning of coal for electricity generation. Currently, some local experts have proposed the verification of the Intergovernmental Panel for Climate Change (IPCC) emission factors. This is important in lieu of the proposed Clean Development Mechanism for greenhouse gas mitigation. If these emissions are over or under stated, Southern Africa serves to lose out on the benefits for emissions trading.

4.2.8. Transformation Costs

Most of the costs for energy supply are highly confidential and difficult to verify. In some cases, the modelling had to assume estimates after consultation with sector experts. Real electricity supply costs were obtained from Eskom but have not been published in this report. This is obviously an area of great concern for planners. A model is only as good as its input data. With the restructuring of the energy sector, data will be even more difficult to obtain.

CHAPTER 5: MODEL RESULTS AND DISCUSSION

There are two stages of the analysis. The first is the simulation of the 'Simulated Cases' where the bounds are rigid and the dates for the implementation of projects are definite.

The second stage is the optimisation process that occurs with limited restrictions as the model is allowed to choose the most opportune time to implement projects, and is based on least energy system cost.

For the first stage of the analysis, LEAP was used to calculate the useful energy for all of the sectors. This useful energy serves as input to MARKAL. The import of the useful energy results allows for the benchmarking of the final energy results for LEAP against MARKAL. This is achieved by fixing (FX) all new technology capacity bounds for MARKAL and in this way turning this optimisation tool into simulation mode. After this benchmarking is done the MARKAL model is made less restrictive by introducing the upper (UP) and lower (LO) bounds for all technology capacity. The MARKAL model optimises between these technology penetration levels to come up with a lower cost for the entire system.

5.1. Useful Energy Requirements

This section is a description of the useful energy forecast for each of the sectors. Having described the relation of each sector activity with the drivers, elasticities and useful energy intensity changes, the useful energy demand projections can be calculated.

Fig. 5.1 below shows the useful energy demand by fuel for the Commercial sector. With electrical services increasing their share into the future. This is a result of the thermal requirements for this sector.

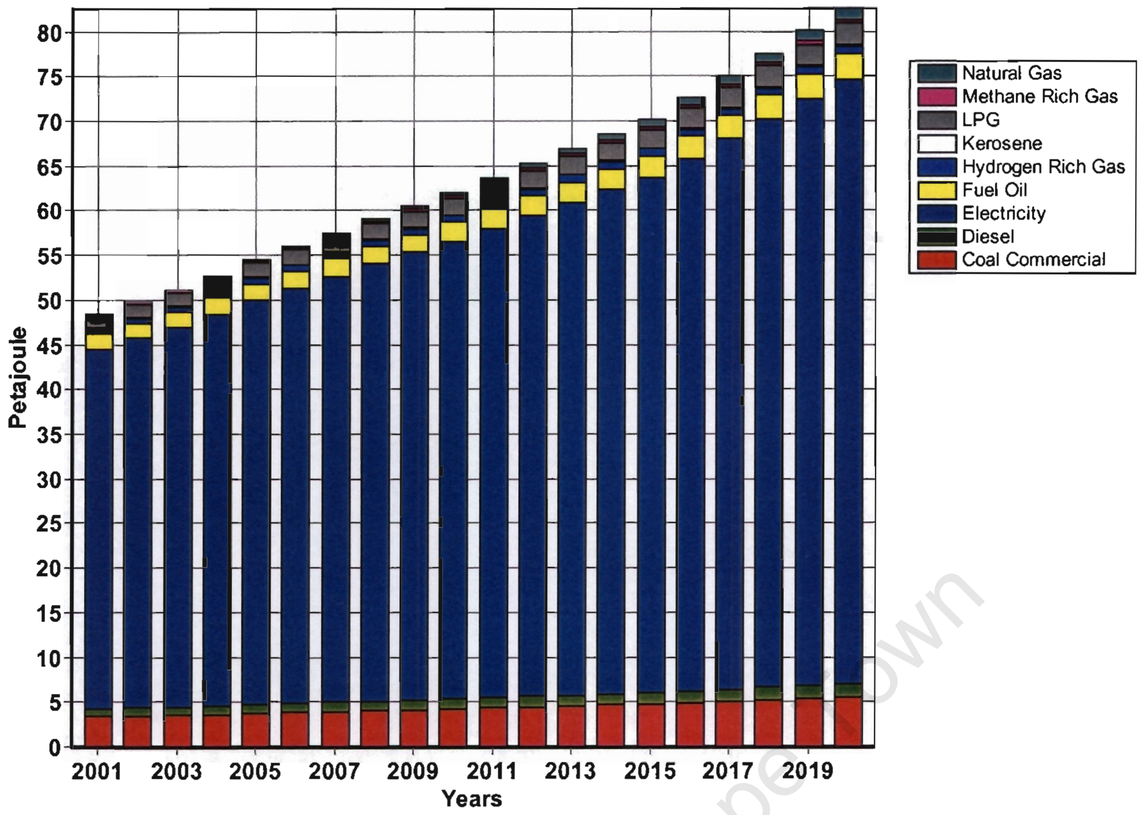

Figure 5.1. Useful energy requirements for the Commercial sector, by fuel.

Fig. 5.2 below illustrates the useful energy for the Agricultural sector. The Agricultural sector's useful energy demand is dominated by diesel early in the planning period. There is scope to switch some of the thermal requirements to electricity.

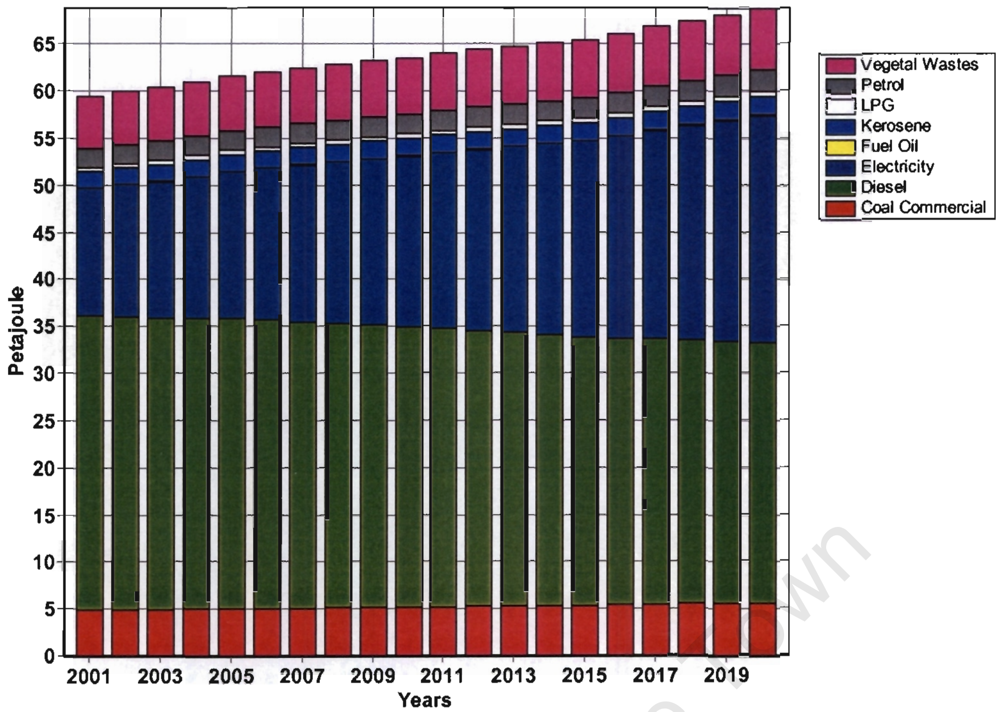

Figure 5.2. Agricultural useful energy service requirements, by fuel.

Transport energy is illustrated in fig. 5.3 below. It is dominated by land passenger energy requirements. This is mainly due to the petrol vehicles used for passenger travel.

Fig. 5.4 shows the energy requirements for the Transport sector by fuel. Remembering that these results are for the Baseline case, it is important to note that the diesel petrol balance can never be achieved if South Africa continues to passively replace petrol technology.

This imbalance will continue to impact negatively on the liquid fuels production sector for reasons laid out in chapter 5.

How best to overcome this petrol/diesel imbalance will be discussed later in this chapter.

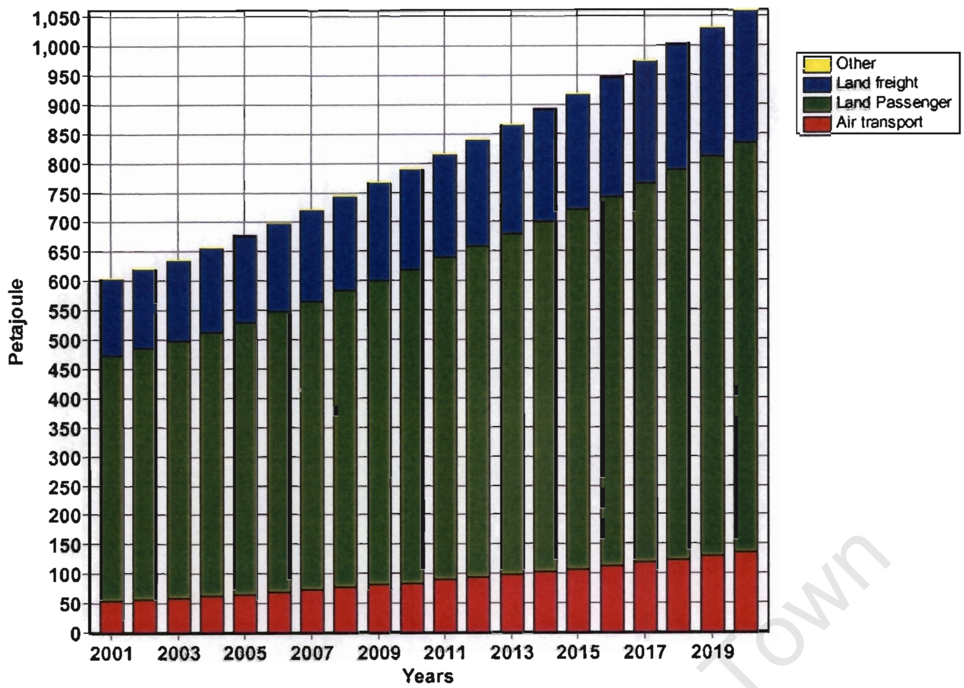

Figure 5.3. Transport sector energy requirements by mode.

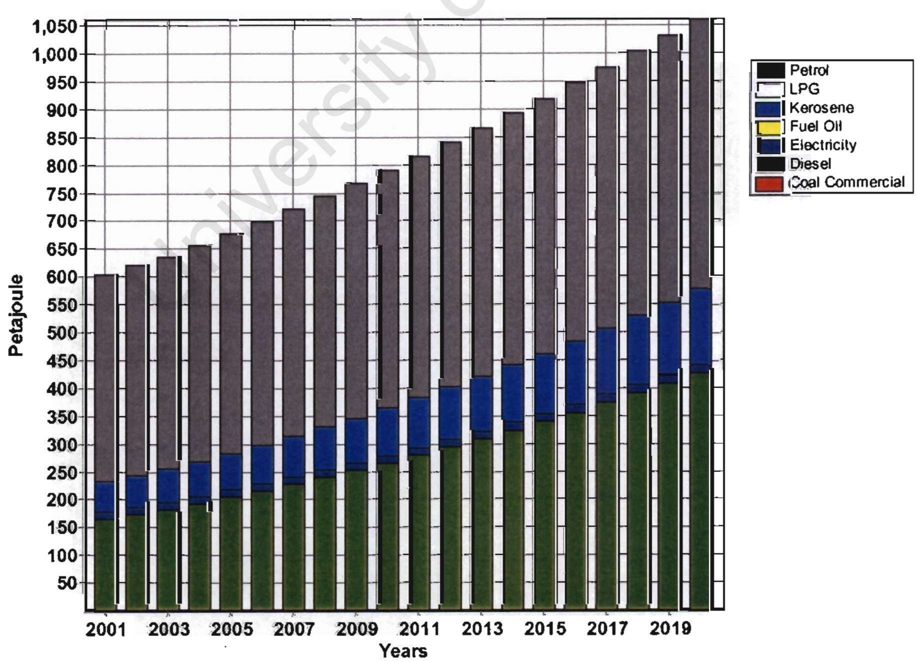

Figure 5.4. Transport sector energy requirements by fuel.

In fig. 5.5 below the useful energy requirements for the industrial sector is illustrated. Thermal energy requirements continue to rely heavily on coal. As Industry includes mining activities which require a higher than average energy service (mostly in the form of electricity generated mainly from coal) per tonne of mined product, this sector is seen to remain more energy intensive than others.

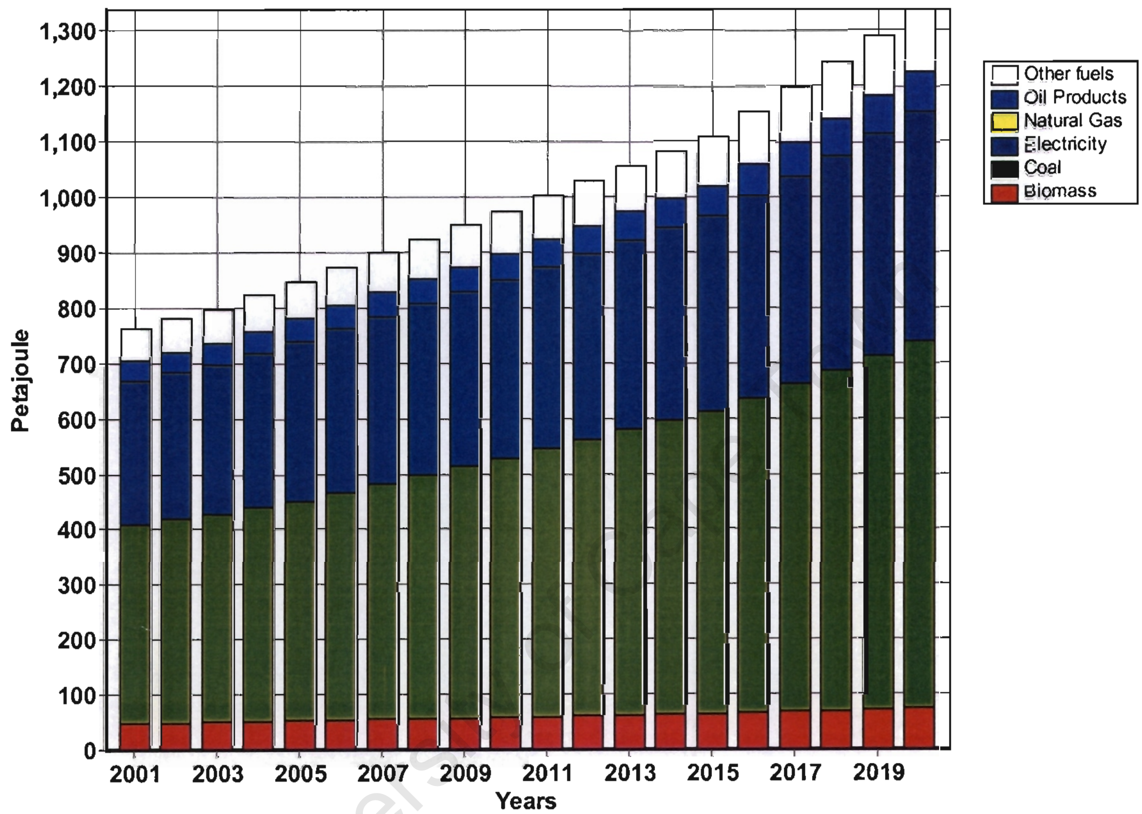

Figure 5.5. Industrial sector useful energy requirements by fuel.

Fig.5.6 below illustrates the useful energy requirements for the Residential sector. Most of the Residential sector energy goes into space heating and cooking. Other services such as TV's, refrigerators and other luxurious electrical appliances, are projected to gain popularity as the population grows and income levels become distributed. As such, the Other in fig.5.6 takes a larger share of the useful energy requirements, with electricity increasing its share as shown in fig.5.7.

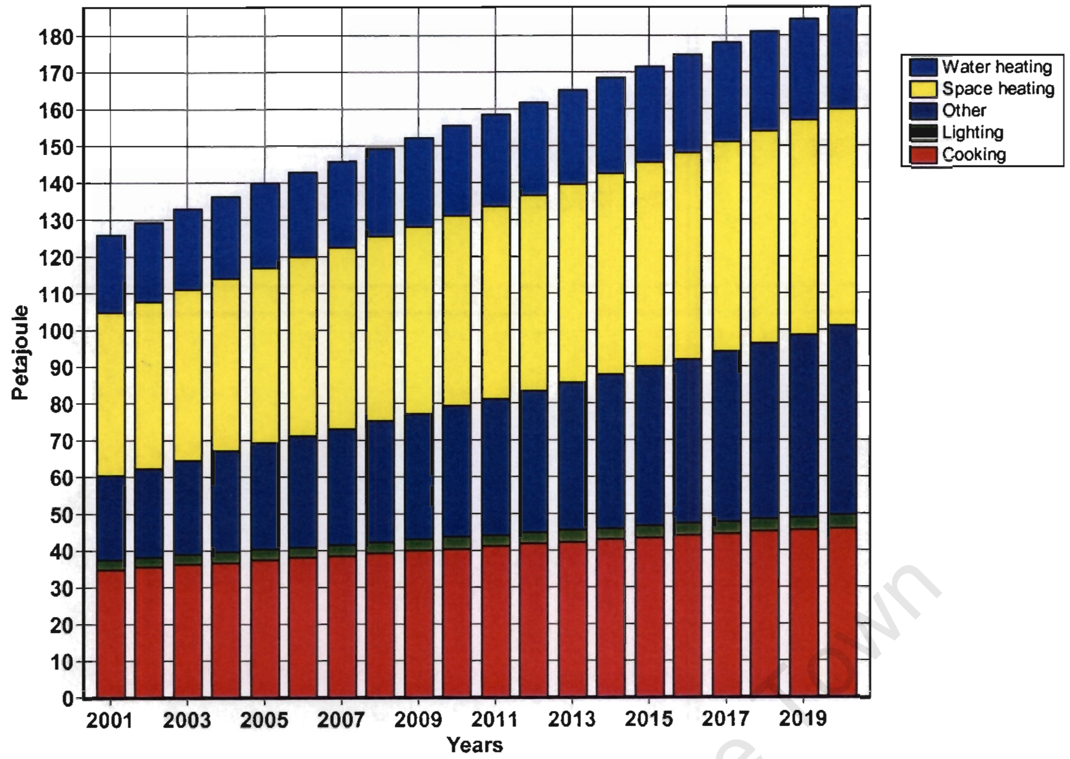

Figure 5.6. Useful energy requirements for the Residential sector.

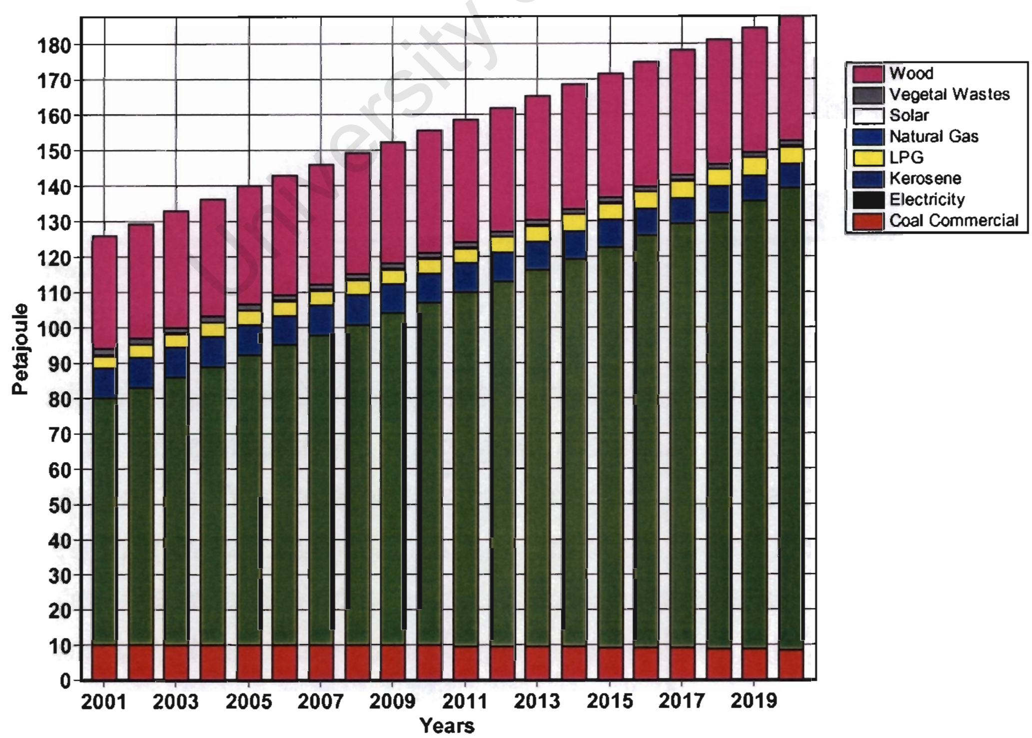

Figure 5.7. Residential useful energy demand by fuel.

5.2. System Energy Forecast

The useful energy described in section 5.1 is common to both the LEAP and MARKAL models. MARKAL optimises the mix of the final energy demand, based on least cost of supply. This section is devoted to explaining the differences between the model cases.

5.2.1. Important Scenario Results

These results shown graphically below illustrate the more important results. Detailed results from the modelling have been attached in Appendices B and C.

5.2.1.1. Primary energy

The total primary energy for each of the cases is illustrated graphically in fig.5.8. The zero values have been suppressed for better visibility.

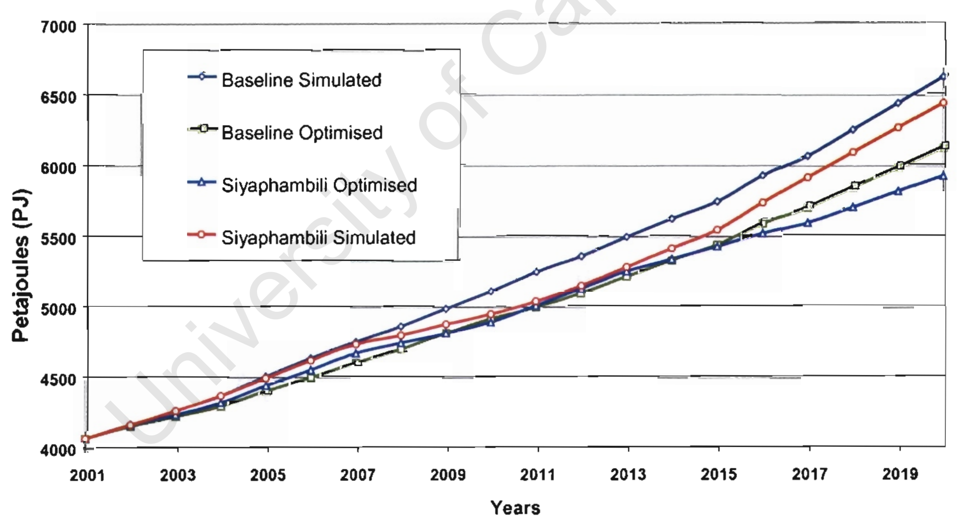

Figure 5.8. Total primary energy forecast for South Africa

These results show an overall cumulative saving in primary energy over the 20 year period of 4506PJ by optimising the simulated Baseline plan and of 2621 PJ by optimising the Siyaphambili simulated plan of the major energy transformers respectively.

5.2.1.2. Final Energy

The total final energy for each of the cases is illustrated graphically in fig.5.9.

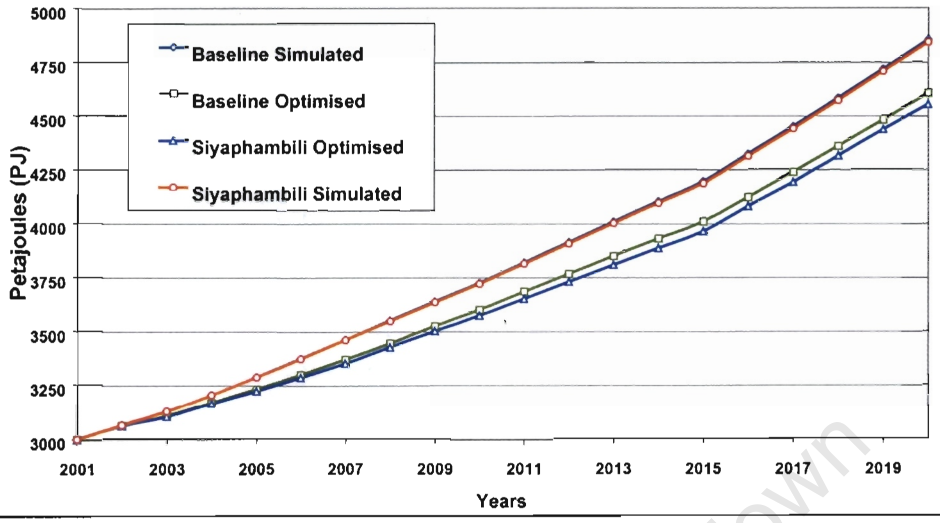

Figure 5.9. Final energy forecast for South Africa

These results show an overall cumulative saving in final energy over 20 years of 2533 PJ by optimising the simulated Baseline plan and of 2981 PJ by optimising the Siyaphambili simulated plan of the major energy suppliers (i.e. ESI and oil) through the more efficient use of the energy transformation processes and energy end-use appliances.

Optimising the Baseline and Siyaphambili simulated plans results in reductions to current electricity forecasts (projections) from Eskom (NER Website) and liquid and solid fuel projections [10]. The electricity demand as sent out by power stations is illustrated graphically in fig.5.10.

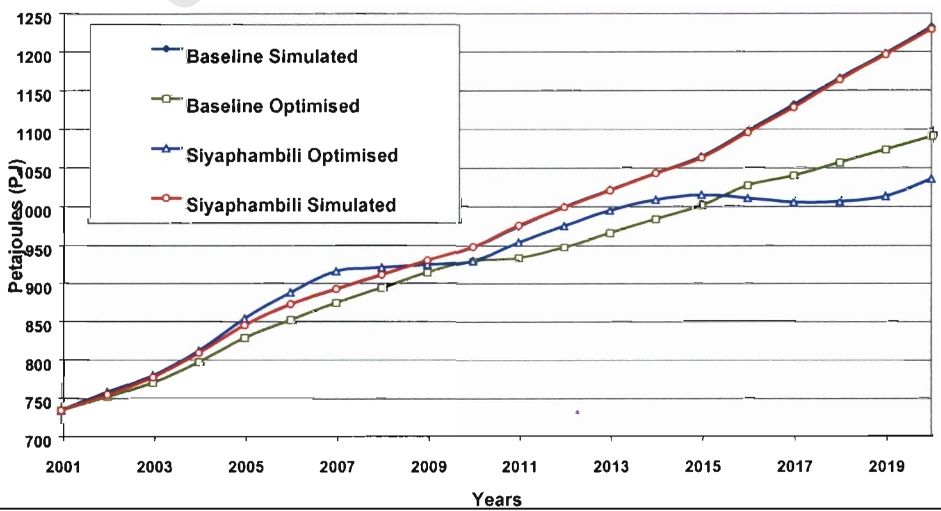

Figure 5.10. Forecast of electricity sent out by power stations in South Africa

The drop in electricity consumption for the optimised cases is more pronounced towards the end of the period and is the result of switching to gas. The reason for the delay in the reduction in electricity consumption early in the period is the lead-time required for implementing fuel switching and energy efficiency programmes.

Switching from electricity to gas is only achieved later in the period. This is not only due to the lead times for implementation but also due to the low marginal cost of electricity early in the period compared to the price of gas. Switching only becomes economic when the marginal cost for electricity coupled with the electrical appliance efficiency exceeds the cost of gas coupled with the gas appliance efficiency. The low marginal cost for electricity early in the period results from current excess generating capacity in the electricity market.

Liquid fuel consumption is severely impacted by implementing energy efficiency and fuel switching. This is illustrated graphically in fig.5.11 below.

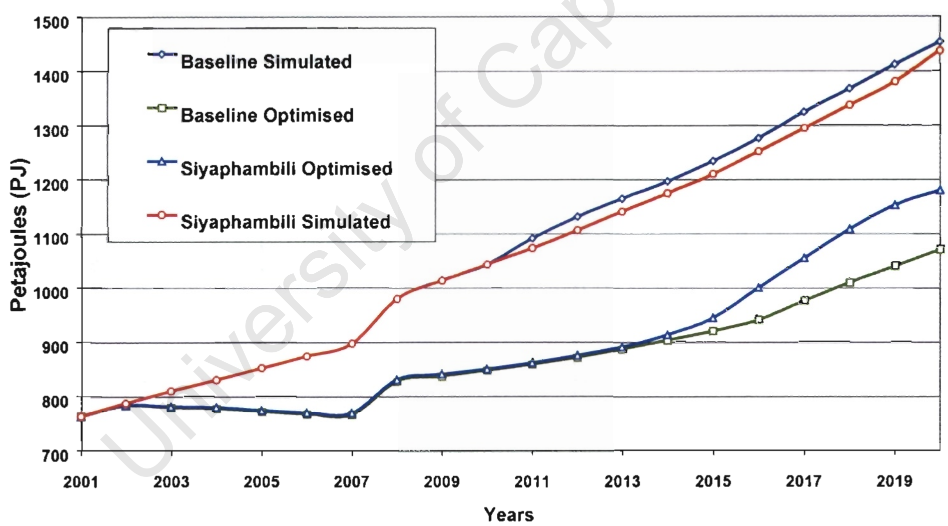

Figure 5.11. Forecast of liquid fuels demand for South Africa

Fuel switching is achieved through:

- switching from liquid fuels to electricity by implementation of electric train transport and electric mini-bus taxi transport, with re-chargeable batteries.
- switching from liquid fuels to solid fuels and gas in thermal processes.

Implementing energy efficiency programmes has marginal impact on the projected solid fuel (primarily coal) consumption of the Baseline case. This is shown graphically in fig. 5.12 below. In the case of the Siyaphambili case, implementing energy efficiency programmes reduces the forecast consumption in the long term. Forecast consumption of solid fuels is lower in the Siyaphambili case than in the Baseline case because less solid fuels are required for electricity generation.

The simulated Siyaphambili case is based on energy suppliers' aspirations for implementing projects diversifying away from coal, irrespective of economic considerations. In the optimised case these projects are implemented according to economic criteria and hence implemented later in the period. The solid fuel consumption (coal and biomass) is thus higher in the early period of the optimised Siyaphambili case than the simulated case.

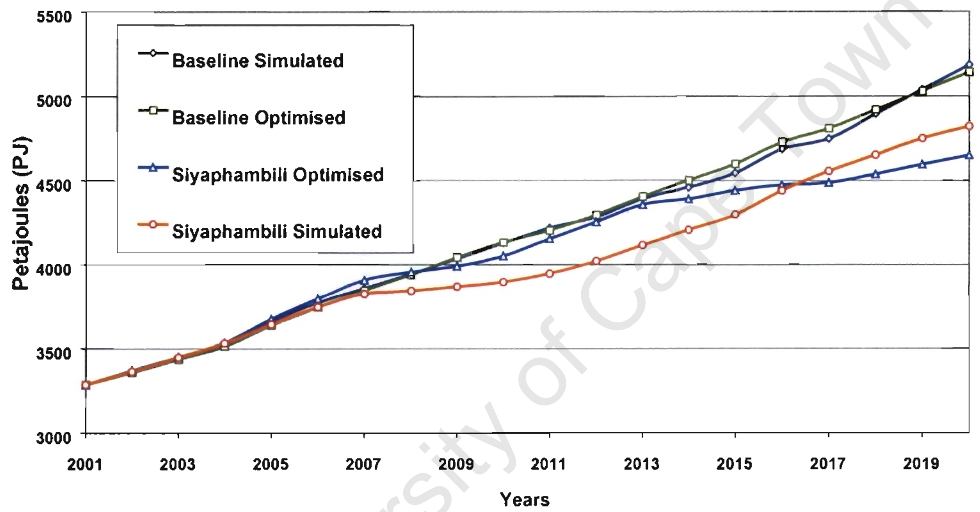

Figure 5.12. Forecast of solid fuels demand for South Africa

5.3. Mitigating CO_2 emissions relative to Baseline case

Fig.5.13 illustrates the reduction in carbon dioxide emissions for the cases compared with the simulated Baseline case, i.e. (Baseline simulated case emissions minus Other case emissions)

These results indicate a substantial reduction in CO_2 emissions by optimising the simulated cases over the 20-year period. As stated previously, the simulated Siyaphambili case is based on energy suppliers' aspirations for investing in projects diversifying away from coal irrespective of economic considerations.

Because of the least cost criteria, in the optimised Siyaphambili case these new projects are implemented according to economic criteria and are thus commissioned later in the planning period.

The reduction in CO_2 emissions is higher early in the planning period for the simulated Siyaphambili case since all environmentally friendly energy projects are implemented much early in the planning period. This trend is reversed later in the period when the diversified plants are built in the optimised case.

The optimised Siyaphambili case also has reduced CO_2 emissions because in this case only fuel switching to gas is allowed, whereas in the optimised Baseline case fuel switching to coal is more economic.

The reduction observed for the optimised Baseline case is due to the delay in choice, when optimising, of building new supply-side options and the implementation of energy efficiency and fuel switching.

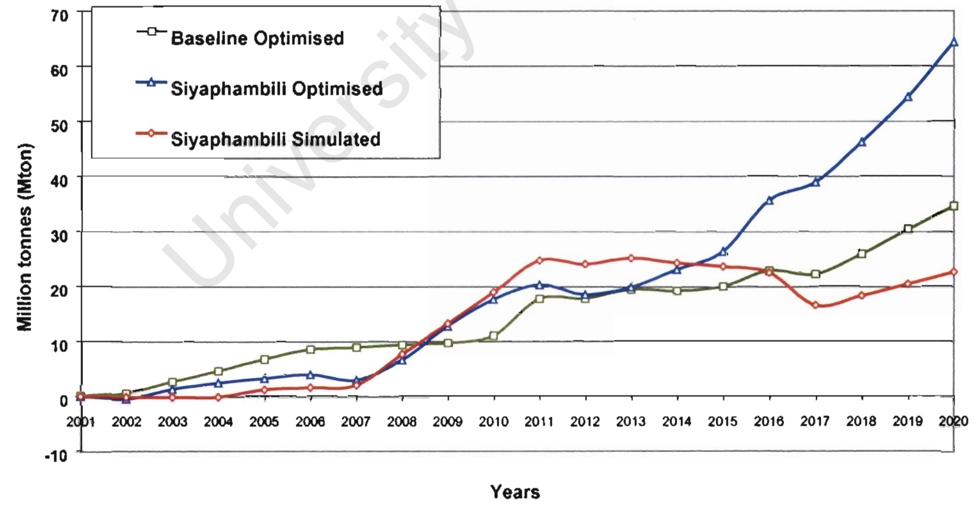

Figure 5.13. Reduction in CO2 emissions relative to Baseline case.

CO_2 emissions are not the only emissions that can be analysed in the models. Greenhouse gas (GHG) emissions (which include methane, nitrous oxides, etc.) in general are of importance. For GHG inventories all of these other GHG emissions can be expressed as CO_2 equivalents.

5.4. Energy System Costs

The costs, discounted at an 11% net rate (eqn. (6)), of the energy system for each of the four cases is illustrated graphically in fig.5.14 where the costs for each of the cases are compared with the simulated Baseline case. (i.e. Baseline costs minus Other case costs)

Investing in the options according to energy suppliers' aspirations and disregarding the economic timing of such investment will result in a very expensive plan for the country, as is so with the Siyaphambili simulated case.

If these aspirations are cushioned by a more economic investment strategy and by judicious implementation of energy efficiency and fuel switching programmes it will result in an optimised diversified plan comparable in cost to the optimised Baseline plan. This is so with the Siyaphambili optimised case.

It should be noted that switching to coal could be implemented sooner, resulting in a cheaper optimised Baseline plan. However, this is not the case for gas because there is currently limited gas infrastructure in South Africa and time is required to provide the resources to improve the gas distribution network to allow significant fuel switching to gas to take place.

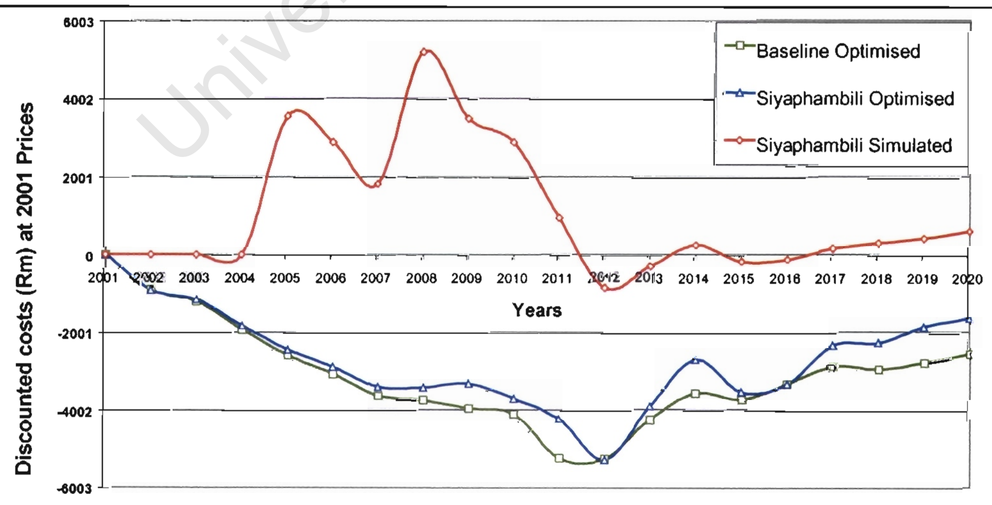

Figure 5.14. PV cost of scenarios relative to the baseline simulated

5.5. Specific Transformation Results

This section serves to highlight some specific results in the modelling. These are only for electricity supply from natural gas and from wind energy

5.5.1. New Energy Supply Options

There is a growing interest concerning investment in environmentally friendly technologies in the electricity supply industry. The Western Cape Province in particular has received attention with regards to its new 'green energy' policy interests.

5.5.1.1. Electricity from Natural Gas

The proposed CCGT plant from Cape Town takes many forms, and for the purposes of this modelling and on information received from electricity strategists, the plant capacity for this proposed gas power project was assumed to be a 750MWe unit. Three of these units have been proposed, each with a lead-time of one year.

The results of performing this study show that a Combined Cycle Gas Turbine (1X750MWe) using gas supplied from the Pande (Sasol/Mozambique gas pipeline) field is commissioned from 2014 in the optimised Siyaphambili case. However, commissioning (3x750MWe) CCGT's at yearly intervals from 2005 increases the total Present Value Cost (PVC) of the Siyaphambili Optimised case by R5 211 million. (See Appendix C)

5.5.1.2. Electricity from Renewable Energy

The Department of Minerals and Energy has expressed the wish to see a mix of primary energy sources for electricity generation, including some renewable energy capacity by 2010. The Siyaphambili simulated case caters for this and other energy supplier's aspirations, and the result is the most expensive case.

Implementing DME plans for renewable energy supply by installing 300 MWe of wind electricity generation by 2010 increases the total present cost of the optimised Siyaphambili plan by R1 038 million. However, there is a reduction of 7.86 million tons of carbon dioxide emissions over the 20-year period.

CHAPTER 6: CONCLUSIONS

The terms of reference for this study were ambitious. Energy modelling of the scale that was done for the South African National Integrated Energy Planning process is new in the country. It is important to distinguish between the tools and the process, and as such highlight the usefulness of the tools and how to further develop the planning process.

6.1. The Planning Process

In undertaking this study it was assumed that data would be readily available and there would be welcomed corporation from the stakeholders in the energy sector. Several issues have come to light:

- Presenting the results at the national workshops served as a backbone for the current process. Consensus on most of the assumptions could be reached.

- Data is available in many different forms and a process to quantify data in a form useful to the models needs to be developed. Even with the existing model, it will not be an effortless exercise to generate and collect the required data.

- Given the amount of time and pressure to perform the analysis, most energy sector stakeholders could not be thoroughly involved in this National Planning exercise.

- The Government carries the responsibility of sustaining this work into the future. The modelling work was received by the DME in form of Energy Outlook 2002 report [10], and the DME have subsequently developed a Plan based on this work. In discussions with the modelling teams, the acting chief of planning in the DME has identified the need to sustain the work .

6.2. The Modelling tools and their results

The tools have been very useful in quantifying much that has been debated in the energy sector. The tools themselves have their own limitations, but do provide a powerful means to assess energy investment interests for the region.

6.2.1. Overall Results

From the results of the modelling a few things can be drawn out:

- Fuelswitching and energy efficiency hold a lot of potential in the country.

- From the cost results, the most economic energy strategy for the next twenty years is to use coal as the primary fuel source (Baseline optimised). This does not take into account the costs of the environmental effects of burning coal, such as health and global warming concerns – external costs.

- Diversifying transformation processes away from coal as the primary fuel source will result in a more expensive option for the economy, as can be observed from the Siyaphambili cases. However, if the economic implementation of projects and more efficient use of energy guide this strategy, it will to some extent offset the additional cost of diversification.

- As can be observed from the Siyaphambili optimised case, increased energy efficiency will reduce primary and final energy demand significantly with a substantial decrease in cost to the energy system. Strategies aimed at switching new devices from current electricity usage patterns to coal or gas will also result in significant savings to the economy. This switching is currently impractical as energy users would be very reluctant to switch processes.

- It is more economic to switch from electricity to coal rather than gas, if environmental externalities are not considered. Implementing energy efficiency programmes and switching new devices from electricity to coal or gas will result in reduced demand for electricity. Given the uncertainty about current gas resources, the switch is likely to take time to be achieved.

However, switching to coal does not seem to be practical. In the unlikely event it does take place, this could result in stranded electricity generation assets if not taken into account by electricity planners.

- Electricity generation technologies based on coal remain the most economic available to South Africa under current national and international environmental legislation. Alternative electricity generation technologies identified to meet international pressure for increased environmental adherence are ranked in increasing economic cost to the economy over coal-fired electricity generation plant (fitted with flue gas desulphurisation) as follows:

  - Importing Hydro electricity from plants located in neighbouring States such as Mozambique (inclusive of Transmission costs and taking account of losses).
  - Coal with Fluidised Bed Boiler Technologies.
  - Gas combined cycle technologies using gas imported from neighbouring states.
  - New nuclear technologies such as the Pebble Bed Modular Reactor.
  - Renewable technologies using wind and solar.

- From fig.4.4, it can be observed that it is more economic to build new coal to liquid plants or gas to liquid plants to meet increased demand for liquid products than to build new oil refineries. However, it will be more economic to import finished liquid products than to build any new production capacity (oil to liquid, coal to liquid or gas to liquid) within the 20-year planning period.

6.2.2. Available Resources

The four cases addressed in this study require sufficient energy resources to enable them being implemented. The availability of energy resources for the four cases should not be automatically assumed, and the viability of the model results can only be justified based on the accuracy of the available information. Currently, information put out on each of the major energy carriers allows for the follows conclusions:

- There are sufficient coal reserves/resources to supply all case for the planning horizon.

- There are insufficient certified natural gas reserves in South Africa for the planning horizon for a major switch to gas. These gas reserves can be supplemented by natural gas reserves in neighbouring countries. Further exploration is necessary in the region to firm-up resource estimates.

- Currently, only approximately 5% of crude is supplied from indigenous reserves, the remainder being imported. Although there are some prospects of deep-water oil deposits off the west coast, these are yet to be confirmed. Hence, South Africa remains reliant on imported oil for the foreseeable future.

- There are limited unused hydro reserves in South Africa (approximately 600 MW) with other opportunities for pumped storage. Imported hydro electricity still requires development.

- With respect to renewable energy, South Africa has large areas of untapped reserves of solar (especially in the central regions) and wind (mainly on the coast) energy.

- There are sufficient nuclear reserves in South Africa, but currently the material must be exported to be processed into usable fuel.

6.2.3. Modelling Tools

Both modelling tools have been useful for processing the vast amounts of data for the planning.

- LEAP has been useful in calculating the required useful energy requirements that also served as input for MARKAL

- With the simplified electricity load duration curve (see Appendix E) that these models use to present electricity consumption, they lack the sufficient ability to model electricity supply accurately, for the purposes of simulating actual output from the power stations.

- The databases that both models have accrued are extensive. Over 20 000 data entries are accounted for in MARKAL alone.

CHAPTER 7: RECOMMENDATIONS

These recommendations are based on the aforementioned conclusions. There should be a continued effort to work with these modelling tools. As the modelling software tools keep being updated, it is important to maintain the links with the developers of the tools, and to improve on the data collection.

7.1. The Planning Processes

To help sustain the modelling and planning work already put in place, the following should be considered:

- More public participation in terms of collecting data and agreeing on some of the important planning issues, e.g. access to energy for the poor.

- Effort should be made to increase the gathering of provincial and national energy utilisation and energy cost statistics.

- Government must create a process to get energy sector stakeholders to participate in the decision making for this planning process.

- The Government should facilitate this process through funding mechanisms and sharing of data.

7.2. The Use of the Modelling Tools

The tools have proved themselves useful in quantifying some energy policy issues, as there is a lot to learn from the results that they produce.

7.2.1. Interpretation of the results

From the results of the modelling a few points should be mentioned:

- Fuelswitching and energy efficiency should be investigated further.
- It important to spell out clearly the stand which South Africa wants to take concerning the use of coal, as this is a cheap source of energy for South

Africa. This is particularly important for the economy of the country as oil and gas prices keep fluctuating. Any switching from coal comes at a premium to the South African coal workforce and the consumers.

- If diversification is going to be the norm, then national strategies to diversify the country's energy away from coal as a primary fuel source should consider the geographical distribution of the country's energy supply. This would offer a wider range of investment opportunities in the energy market. However, careful consideration must be given to reducing the costs of these options, as currently the diversified options are more expensive than the coal options.

- Provide national policy and strategy for new energy technologies and improvements in existing ones to make sure they are beneficial to the country.

- Import liquid fuels rather than build a new refinery to meet increased demand. This is more economic to the country and will reduce the risk of stranded assets in the event of a drop in forecast demand for liquid fuel products. It will also provide scope to make use of opportunities for low cost import options from neighbouring states. However, this makes the country vulnerable to imports and poses a risk to energy security. Imports would more likely serve for short to medium term purposes. Thereafter, a refinery would have to be built. A detailed study of this phenomenon would have to be conducted.

7.2.2. Available Resources

For sustainable development it is important to make sure that the country's energy consumption is not detrimental to its economic future. Increasing the planning horizon would serve well to highlight the 'danger' period where the country does run out of indigenous energy resources.

7.2.3. Modelling Tools

There should be continued use of the modelling tools.

- LEAP is currently in the process of being upgraded into an optimisation tool. Continued communication with the developer should be maintained. As an optimised model already exists in MARKAL, the new LEAP could be properly benchmarked against MARKAL.

- The ETSAP group have approved of the South African modelling efforts in MARKAL and this has ensured ERI with access to their new optimisation tool, TIMES. A TIMES model of the South African IEP should be developed speedily as soon as TIMES is commercially available

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APPENDIX A: Input Data

Table A-1 Summary table of selected elasticity's and growth estimates for the South African industry

Sector	Elasticity or growth	2001 Percentage energy requirements per activity							Comment
	Unless otherwise stated, elasticities refer to ***GDP*** growth.	**High Temperature thermal**	**Compressed air**	**Lighting**	**Cooling**	**HVAC**	**Pumping**	**Fans**	
INDUSTRY									
Gold Mining	Negative growth of 1.7% pa	9%	9%	19%	4%	6%	0%	16%	This may change depending on efficiency improvements in the sector.
Iron & Steel	Elasticity of 1.6	76%	76%	1%	1%	0%	0%	1%	Growth in this sector is expected to come from the Ferro-Chrome industry.
Chemical	Elasticity of 1.2	84%	84%	3%	1%	0%	0%	6%	Continued growth.
Other Mining	Elasticity of 0.53	21%	21%	12%	2%	4%	0%	10%	Should be further disaggregated into more sectors in the future.
Non-Ferrous Metals	Elasticity of 1.87	61%	61%	4%	3%	0%	1%	3%	Aluminium growth is expected during the period.
Non-Metallic Minerals	Elasticity of 1.37	75%	75%	6%	2%	0%	0%	1%	Increased local building and joint ventures with neighbouring countries with GDP growth is likely.
Pulp & Paper	Elasticity of 0.25	82%	82%	1%	2%	1%	0%	5%	Growth due to forest limits and water restrictions was thought to be limiting here. This assumption may need revisiting.
Other Industry	Elasticity of 2.0	78%	78%	4%	2%	1%	0%	4%	Small processing industries are likely to increase over the period.
Food & Tobacco	Elasticity of 1.5	91%	91%	1%	1%	2%	0%	1%	Increased processing is likely within this sector as wealth increases.
Commerce	Elasticity of 1.08	47%		15%	3%	25%			The measure of commercial growth is m^2 of floor space.
Agriculture	Elasticity of 0.45	82%	82%	0%	1%	2%	1%	5%	This sectors growth is limited by arable land constraints.
Other	Elasticity of 1	100%							Essentially this sector exists to balance the statistics. Therefore it is assumed to grow with GDP.
TRANSPORT									Sub-sectors not included in the table are 'air passenger' and 'international marine'.
Passenger		Petrol cars	Petrol taxi's	Diesel cars	Diesel Buses	Electric trains			Recently trends relating to expendable income and fuel price have become evident. It will be necessary to remodel this sector as the trends become better defined.
	Elasticity of 1	65%	24%	6%	4%	1%			
Freight		Diesel trucks	Diesel trains	Electric trains					Freight transport is linked to production. Two competing trends have maintained an elasticity of 1 with GDP. The trends are lower tonnages being transported more due to increased processing.
	Elasticity of 1	86%	7%	7%					
Air passenger		Jet aircraft	Gasoline turbo prop						

		2%	98%						
Residential	Elasticity of 1 to **Population** growth								Other sub-sectors, considered in the model, but not included in this table, are 'other', 'water heating' and 'space heating'. Cooking and lighting are used for illustrative purposes.
Cooking		Elec Hot plate	Elec stove	Kerosene Primus	Kerosene Wick	Coal Brazier	Coal Stove	Wood Stove	Other devices modelled but not included in the table are LPG ring stoves and electric microwaves. Provision is made for natural gas ring stoves in the future. In this round of the model devices were modelled to only supply one energy service. This is an artificial simplification, as stoves often supply the service of cooking, space heating and water heating.
		3%	16%	8%	10%	26%	23%	12%	
Lighting		Elec CFL	Elec Fluorescent	Elec Incandescent	Kerosene Pressure	Kerosene Wick	LPG Pres		
		<1%	6%	75%	9%	9%	<1%		
Space Heating		Anthr Heater	Dung Open Fire	Elec Heater	Kero Heater	LPG Heater	Wood		Refer to the note under 'Cooking'.
		2%	5%	12%	2%	1%	78%		
Water heating		Elec geyser	LPG geyser	Solar	Agri. waste	Coal	Wood		Refer to the note under 'Cooking'.
		98%	1%	1%	<1%	<1%	<1%		
Other		LPG	Elec						This energy service refers to items such as refrigerators, televisions, Hi-fi's etc. It is assumed to grow with electrification over the period. It should be noted, however, that demand levels are likely to related not only to access but also expendable income.
		4%	96%						

APPENDIX B: Energy Forecasts

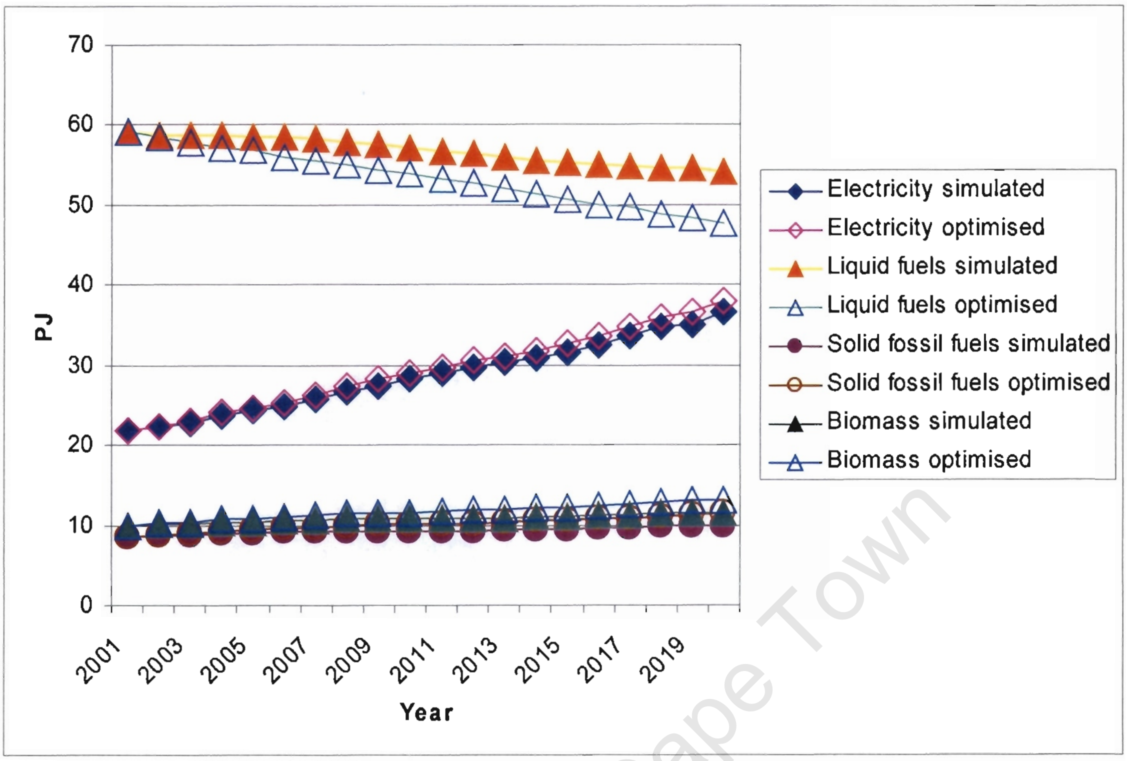


Figure B.1. Fuels used in agriculture: For the Siyaphambili Cases

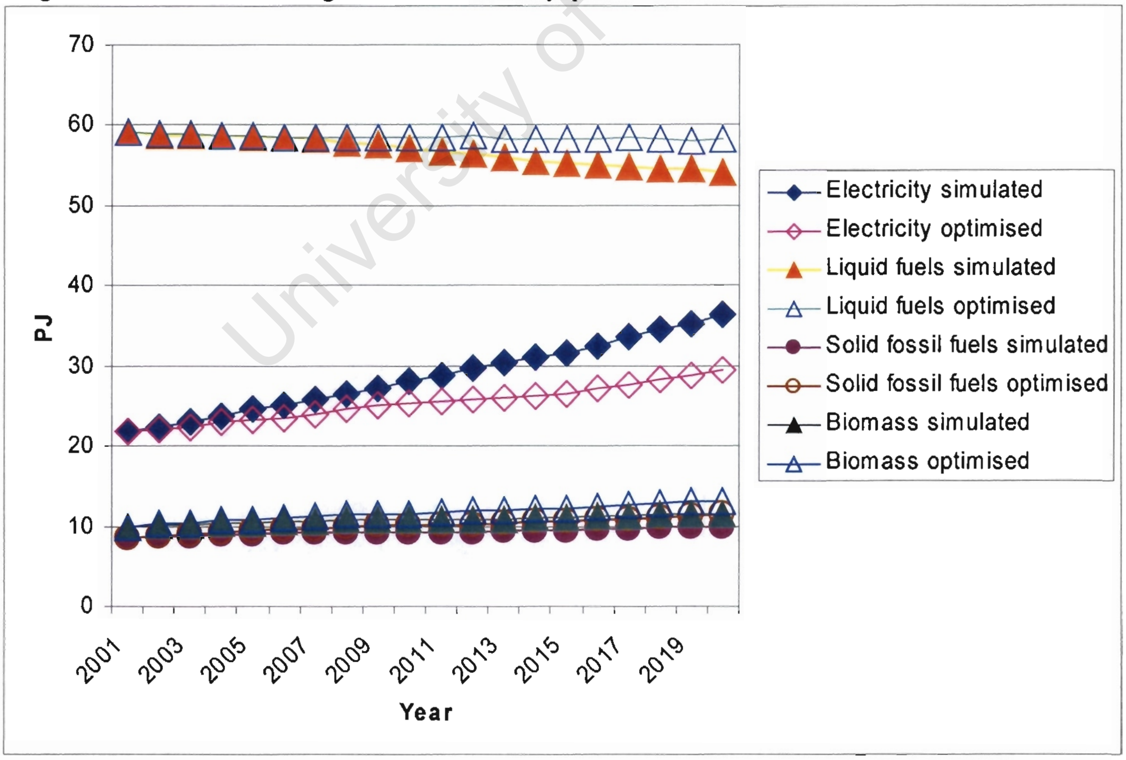


Figure B.2. Energy demand for agriculture: Baseline cases

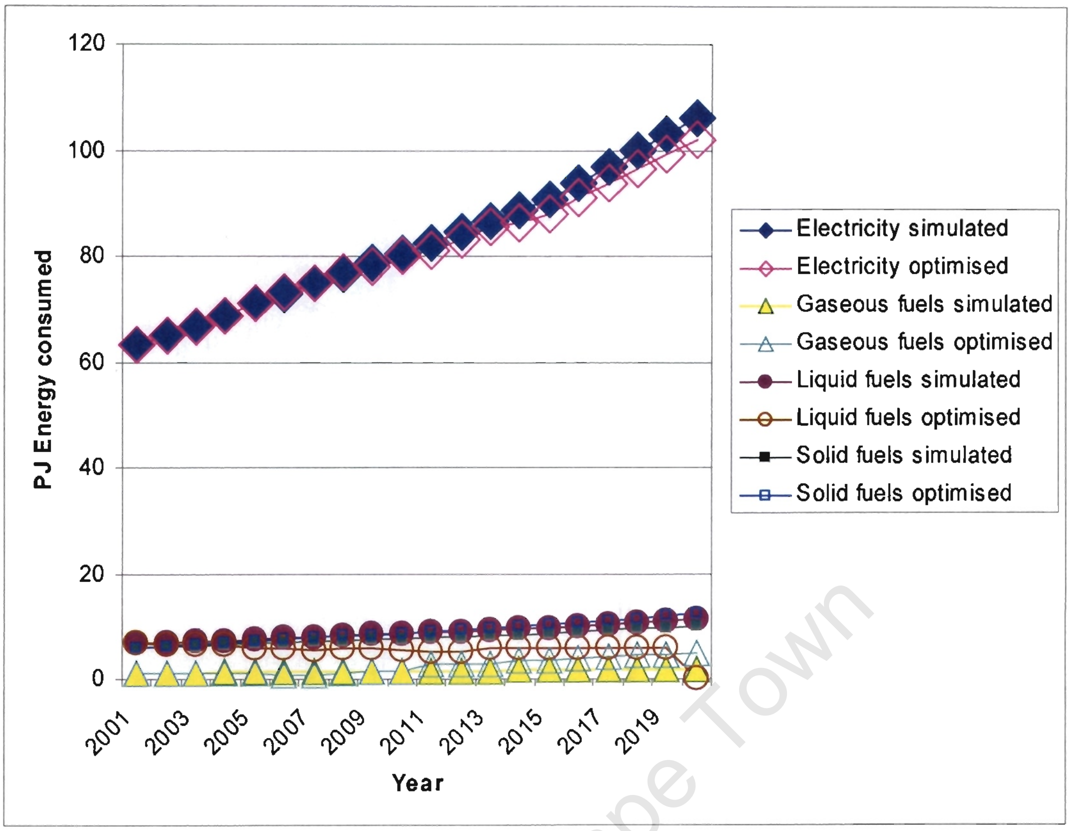


Figure B.3. Energy demand in the commercial sector for the Baseline cases.

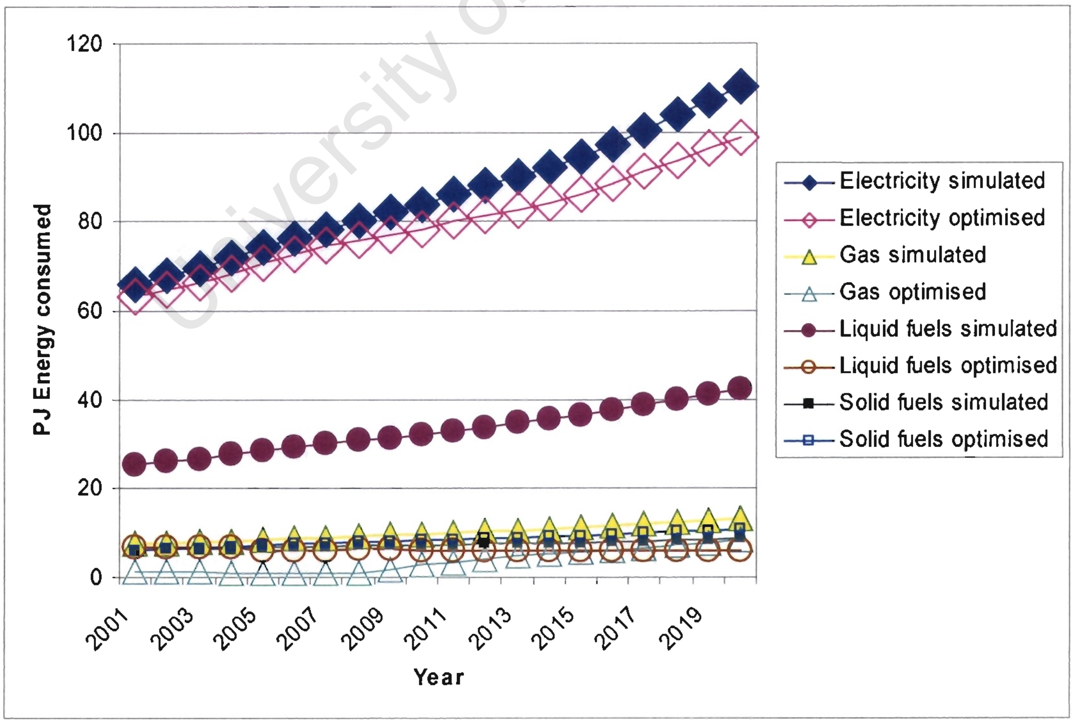


Figure B.4. Energy demand for the Siyaphambili cases.

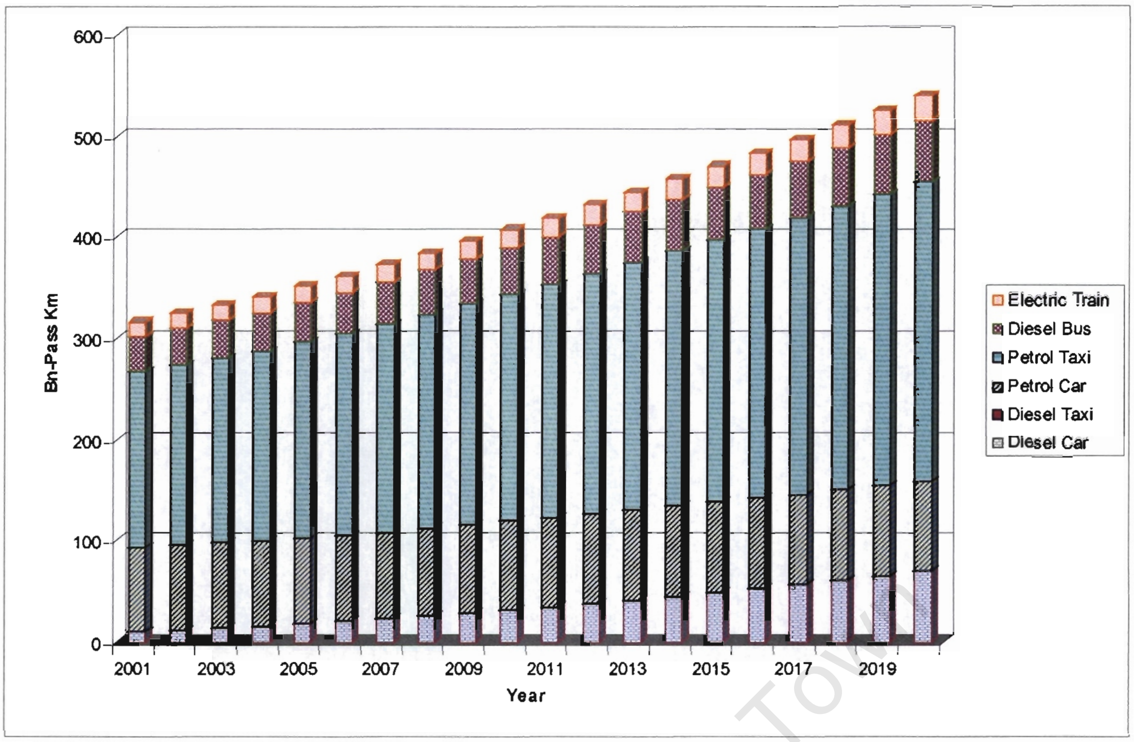


Figure B.5. Transport trends: Baseline simulated

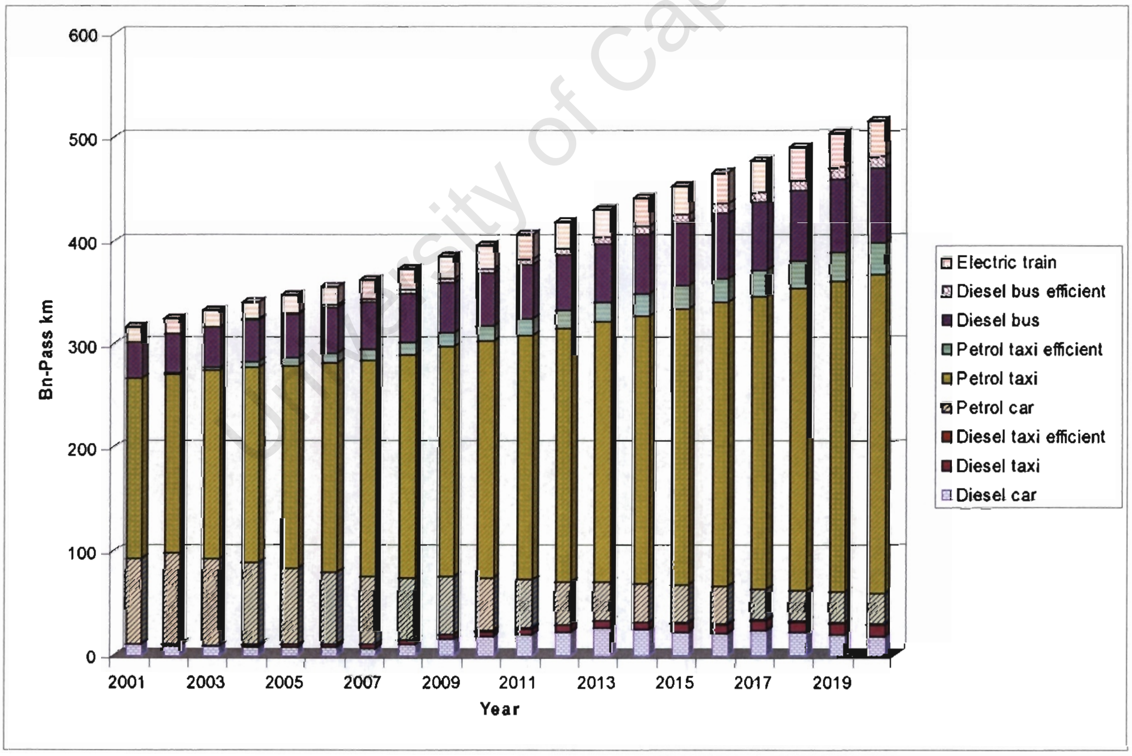


Figure B.6. Transport trends: Baseline optimised

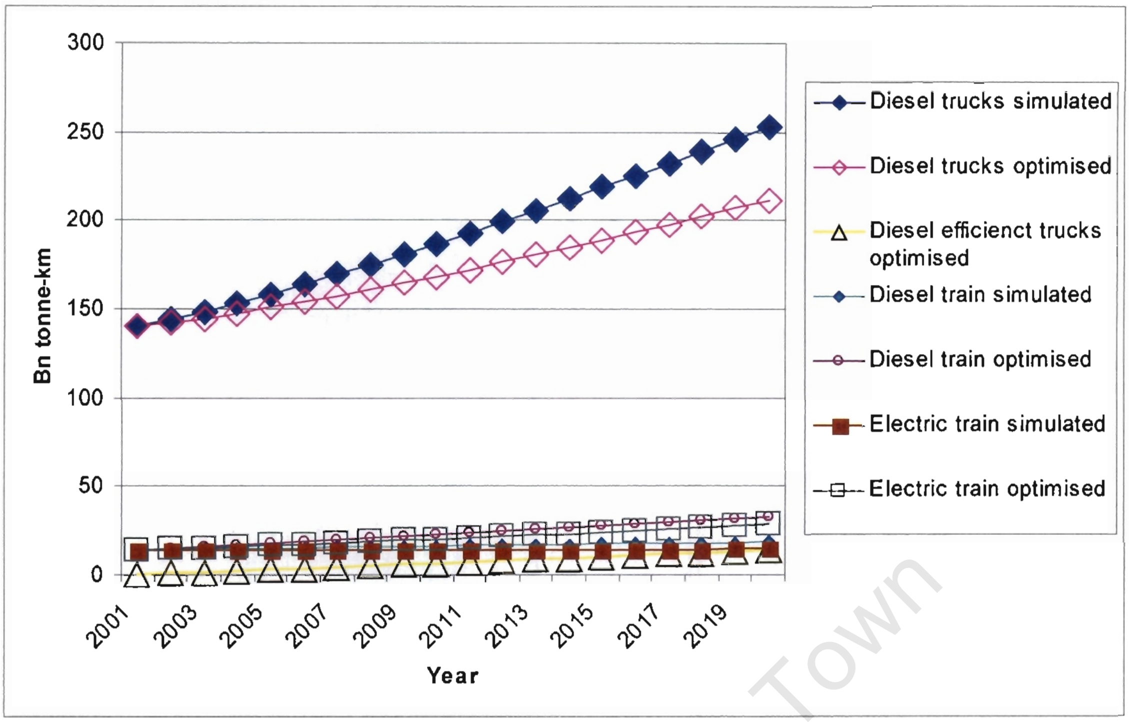


Figure B.7. Freight transport in the Baseline scenarios

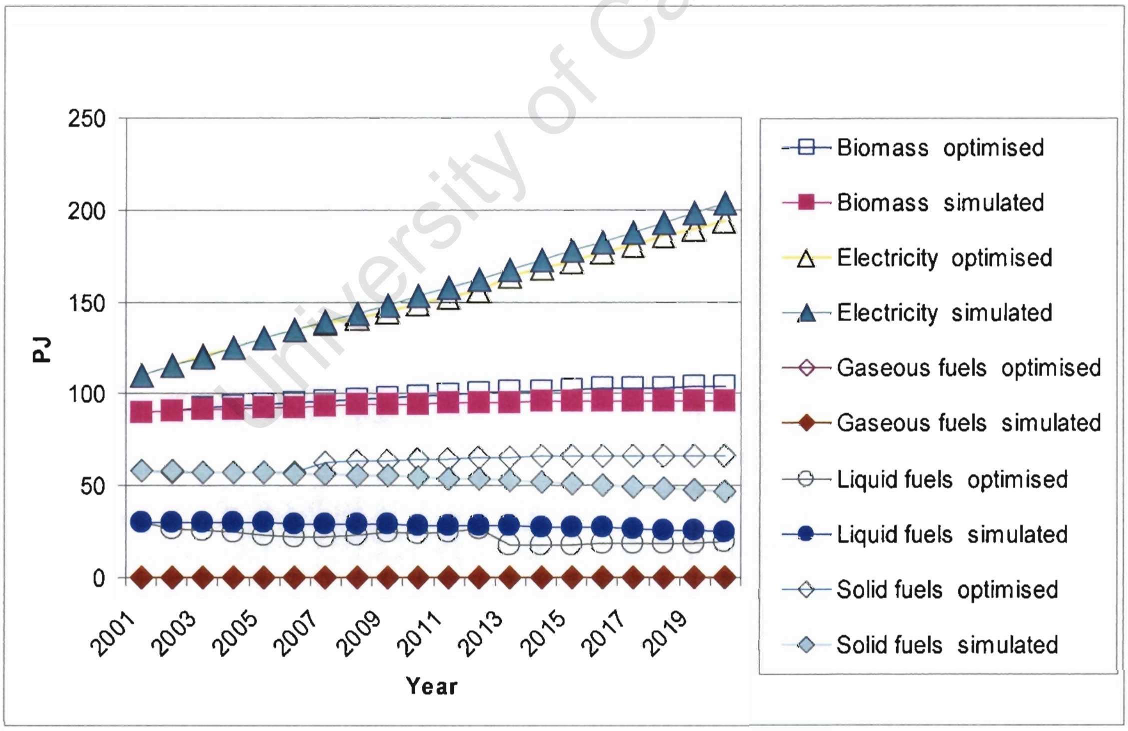


Figure B.8. Residential fuel demand: Baseline cases

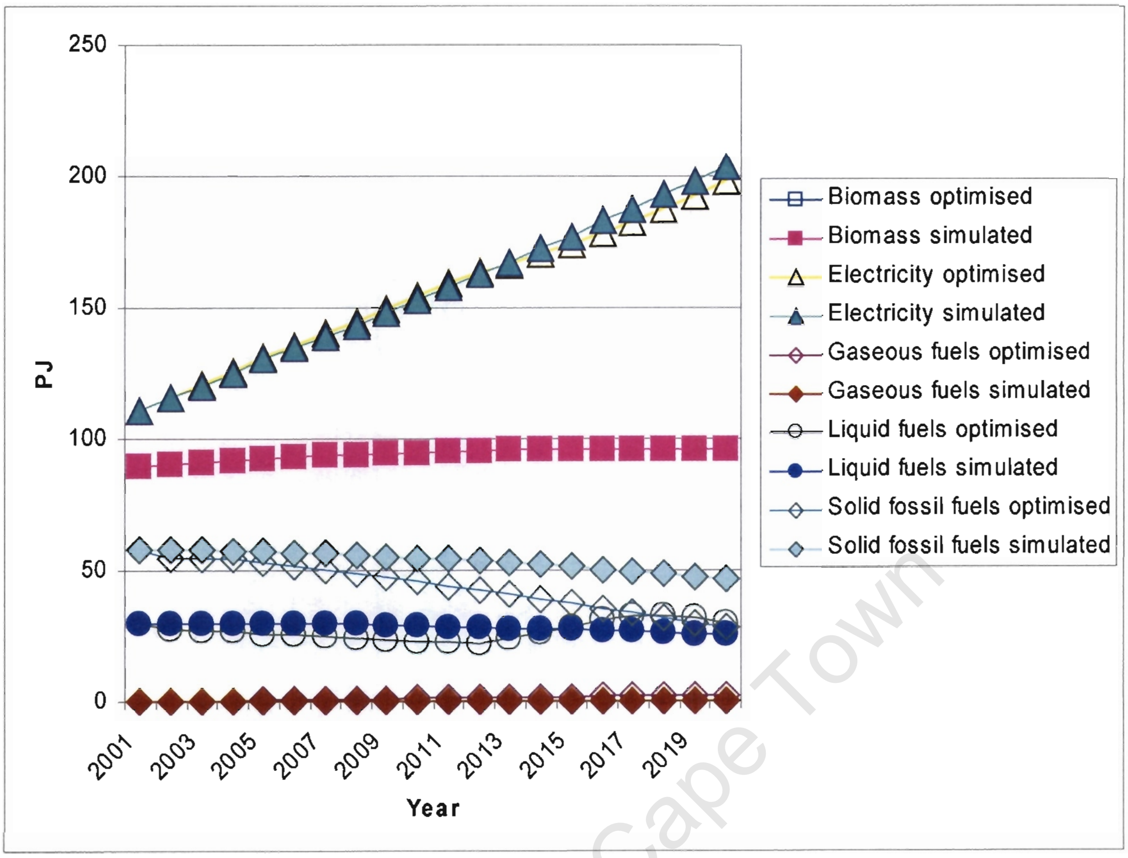


Figure B.9. Residential fuel demand: Siyaphambili cases

APPENDIX C: Electricity Capacity Expansion

In Table 25, the Baseline simulated scenario is dominated by coal as the primary fuel source, with the mothballed plants coming online first. In this expansion plan, the new coal-fired power stations are commissioned before non-coal options. The demand-side options are set as maximum MWe target savings that can be achieved in a year, and more studies would have to be done to establish whether or not these MWe target savings can be increased.

Table 25: Baseline simulated: electricity expansion

Baseline Simulated: 1/1/2001 Prices

	Mothballed				Coal-Fired				Gas		Pumped Storage				Demand-side Options			Capacity Changes			
YR	Cam (PF)	Gr'vlei (PF)	Kom (FBC)	Kom (PF)	PF (1)	PF (2)	PF (3)	PF (4)	CCGT (1)	GT	PS (A)	PS (B)	PS (C)	PS (D)	Int Load	ICLM	RLM	De-rate Garlep & VDK	Cahora Bassa	De-com	Syst Res
											EIA				Decide	Decide	Decide				
2001																		-16			29.6%
2002											Decide				562		49	-4			28.6%
2003	Decide											Decide				53	49	-4			24.7%
2004																53	49	-4	367		22.2%
2005		Decide														53	49	-4			19.2%
2006				Decide	EIA								EIA			53	49	-4			16.5%
2007	380		EIA													53	49	-4			15.3%
2008	380				Decide				EIA				Decide			53	49	-4			14.0%
2009	380	188	Decide			EIA										53	49	-4			13.3%
2010	380	376		270					Decide							53	49	-4			13.7%
2011		188		90		Decide	EIA			240	668					53	49			-630	12.9%
2012											334	668				53	49	-34			12.9%
2013		188	228	90	640		Decide							EIA			49				13.3%
2014		188	228						750								49				13.6%
2015					640			EIA		240		334		Decide			49				14.0%
2016					640	640											49				14.6%
2017								Decide					334				49				12.8%
2018					640		640										49				13.1%
2019						640	640			240							49				13.9%
2020						640	640										49				14.1%
2021					640	640				240							49			-900	12.7%
2022					640	640	640	640		240			668				49			-2260	12.6%
2023						640	640	640									49			-688	12.6%
2024								640						668			49			-380	11.9%
2025							640	640									49			-650	10.7%
TOTAL	1520	1128	456	450	3840	3840	3840	2560	750	1200	1002	1002	1002	668	552	535	1182	-86	367	-5528	

In Table 26 optimising the Baseline scenario with energy efficiency and fuelswitching, base-load plant capacity is deferred to the year 2011. This Baseline optimised plan is based on coal as a primary fuel source. Because of fuelswitching away from electricity, new coal-fired options are only needed from 2015.

Table 26: Baseline optimised electricity expansion

	Mothballed				Coal - Fired				Pumped Storage				DSM Options	
YR	Cam (PF)	Gr'tvlei (PF)	Kom (FBC)	Kom (PF)	PF (1)	PF (2)	PF (3)	PF (4)	PS (A)	PS (B)	PS (C)	PS (D)	ICLM	RLM
									EIA					Decide
2001														
2002									Decide					49
2003										Decide			Decide	49
2004														49
2005														49
2006													53	49
2007	Decide												53	49
2008		Decide	EIA		EIA								53	49
2009						EIA							53	49
2010			Decide		Decide								53	49
2011	380					Decide			668				53	49
2012	380	188							334	668			53	49
2013	380	376											53	49
2014	380	564	228										53	49
2015			228		640					334			53	49
2016					640	640								49
2017					640									49
2018					640									49
2019					640	640								49
2020					640	640								49
TOTAL	1520	1128	456		3840	1920			1002	1002			535	936

In Table 27, the simulated Siyaphambili plan, the decision to return Camden to service has to be made by 2003. In order to make a decision on new plant options an Environmental Impact Assessment (EIA) has to be conducted and approved. The lead times for commissioning the pumped storage plants (PS) can be 10 years.

Table 27: Siyaphambili simulated: electricity expansion

Simulated Siyaphambili Plan 1/1/2001 Prices

	Mothballed				Coal-Fired				Gas			Pumped Storage				Hydro Imports		FBC	Nuclear	Demand-side Options			Capacity Changes			
YR	Cam (PF)	Gr'tvlei (PF)	Kom (FBC)	Kom (PF)	PF (1)	PF (2)	PF (3)	PF (4)	CCGT (1)	CCGT (2)	GT	PS (A)	PS (B)	PS (C)	PS (D)	Cah Bass North Bank	Mep Unc	Green field FBC	Pbmr	Int Load	ICLM	RLM	De-rate Garlep & VDK	Cahora Bassa	De-com	Syst Res
										EIA										Decide	Decide	Decide				
2001										Decide						Decide	Decide						-16			29.6%
2002																				552		49	-4			28.6%
2003	Decide																				53	49	-4			24.7%
2004																					53	49	-4	367		22.2%
2005		Decide								750									125		53	49	-4			21.8%
2006			EIA	Decide						750											53	49	-4			21.2%
2007	380									750											53	49	-4			22.0%
2008	380		Decide						EIA							492	548		250		53	49	-4			24.2%
2009	380	188										EIA					548		250		53	49	-4			25.5%
2010	380	376		270					Decide								548		250		53	49	-4			27.8%
2011												Decide					548		250		53	49			-630	25.7%
2012		188	228	90										EIA					250		53	49	-34			24.7%
2013		188	228	90									Decide									49				23.3%
2014		188			EIA	EIA			750					Decide								49				22.8%
2015							EIA											233				49				20.6%
2016					Decide	Decide												466				49				19.2%
2017							Decide											466				49				17.6%
2018								EIA										466				49				16.0%
2019																		466				49				14.4%
2020								Decide			240	668						233				49				14.2%
2021					640	640					240											49			-900	12.9%
2022					640	640	640					334	1002									49			-2280	12.4%
2023					640		640				240			334								49			-688	12.2%
2024					640						240			668								49			-380	12.0%
2025					640			640			240											49			-650	11.2%
TOTAL	1520	1128	456	450	3200	1280	1280	640	750	2250	1200	1002	1002	1002	0	492	2192	2330	1375	552	535	1182	-86	367	-5528	

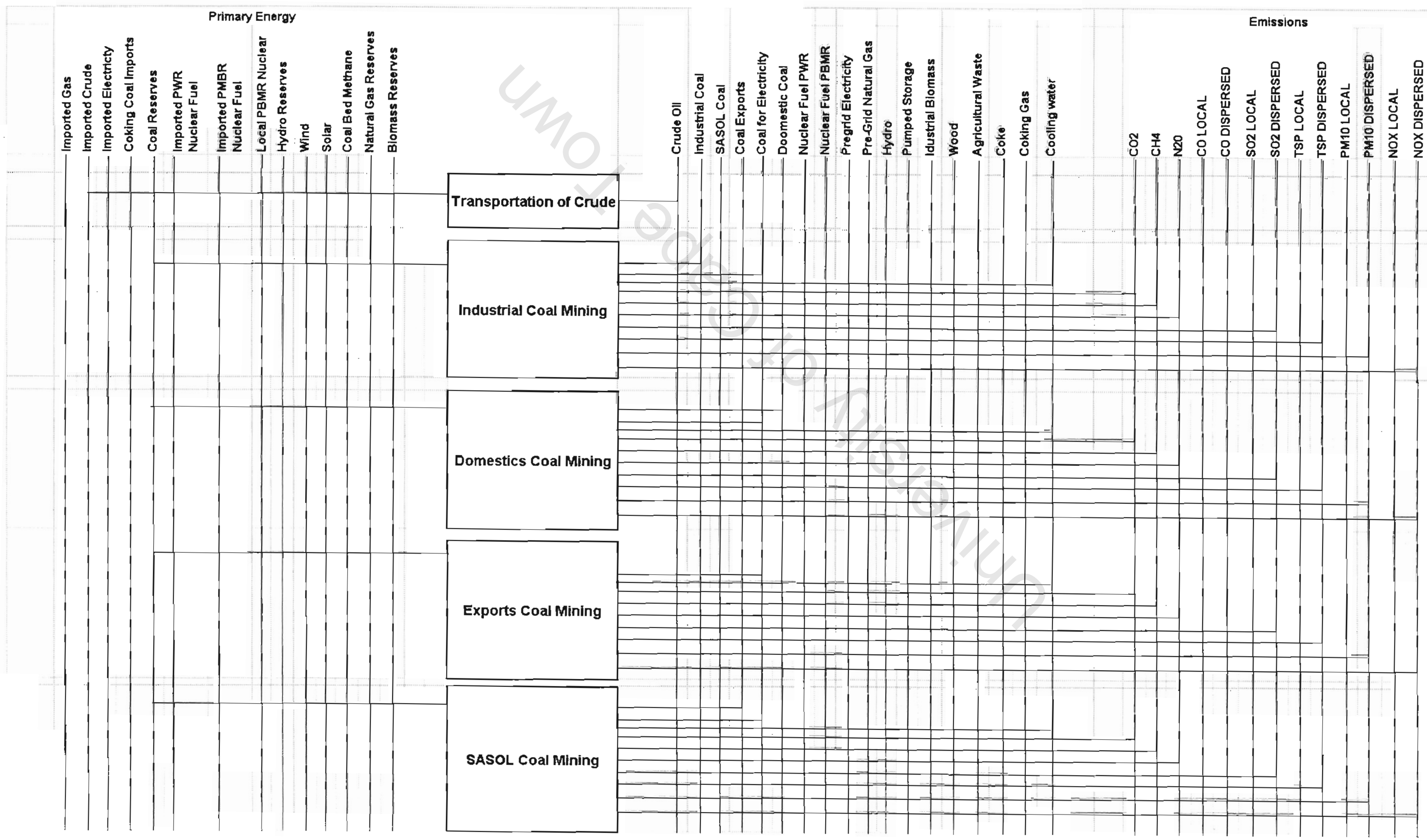
In Table 28 the Siyaphambili optimised scenario also optimises on energy efficiency and fuelswitching. The fuel switching is only to gas as switching to coal is not allowed. In this plan, new plant is also deferred to later in the planning period.

Table 28: Siyaphambili optimised: electricity expansion

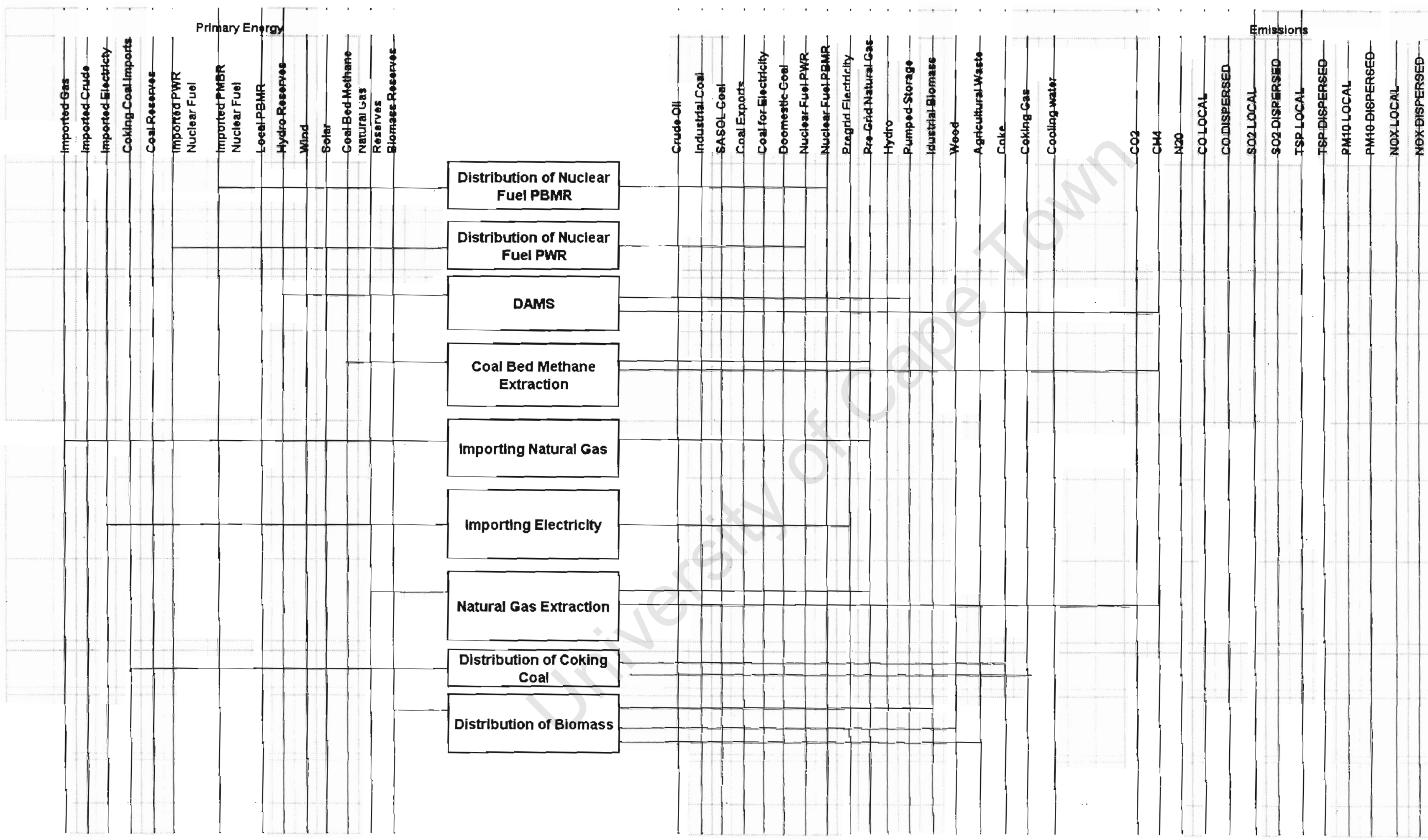
	Mothballed				Coal-Fired				Gas			Pumped Storage				Hydro Imports		FBC	Nuclear	Demand-side Options			
YR	Cam (PF)	Gr'tvlei (PF)	Kom (FBC)	Kom (PF)	PF (1)	PF (2)	PF (3)	PF (4)	CCGT (1)	CCGT (2)	GT	PS (A)	PS (B)	PS (C)	PS (D)	Cah Bass North Bank	Mep Unc	Green field FBC	Pbmr	Int Load	ICLM	RLM	De-com
												EIA										Decide	
2001																							
2002												Decide										49	
2003													Decide									49	
2004																						49	
2005																						49	
2006																					Decide	49	
2007																						49	
2008									EIA													49	
2009																					53	49	
2010									Decide												53	49	
2011												668									53	49	-630
2012												334	668								53	49	
2013	Decide		EIA																		53	49	
2014									750												53	49	
2015			Decide																		53	49	
2016																					53	49	
2017	380																				53	49	
2018	380																				53	49	
2019	380		228																			49	
2020	380		228								240							466				49	
TOTAL	1520		456						750		240	1002	668					466			535	936	-630

APPENDIX D: The Reference Energy System

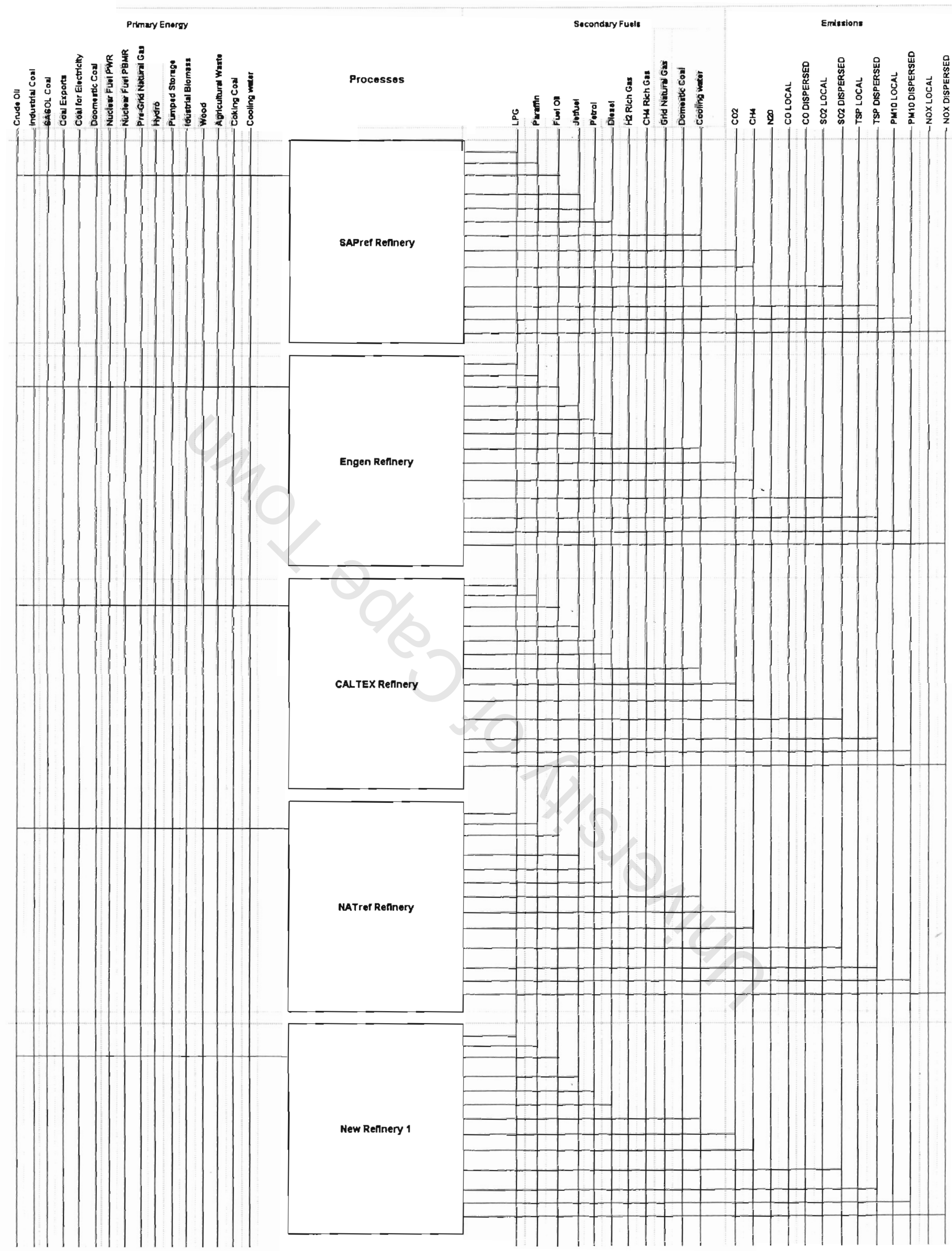
Primary Energy Imports, Extraction and Conversion



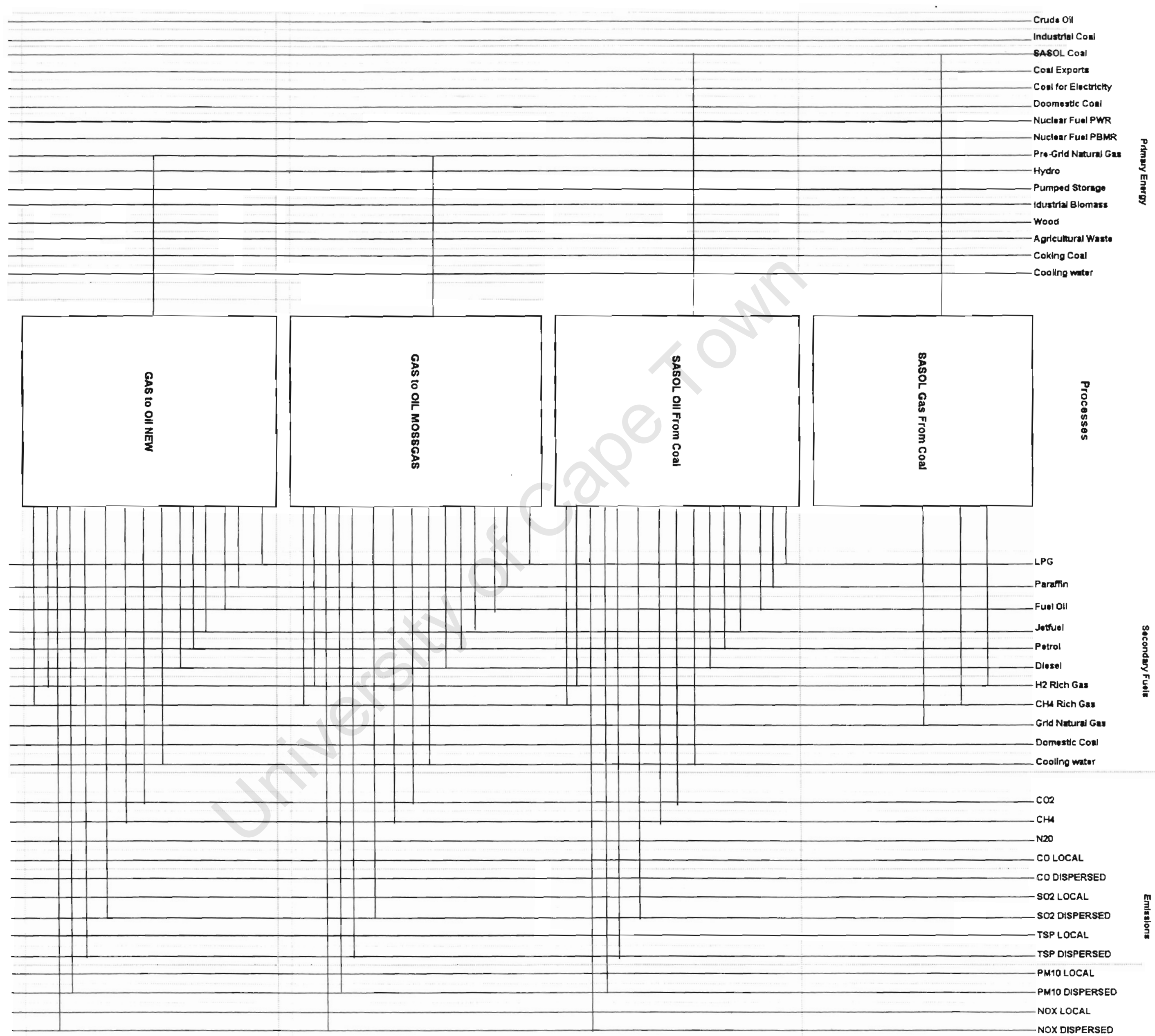
Distribution of Primary Energy



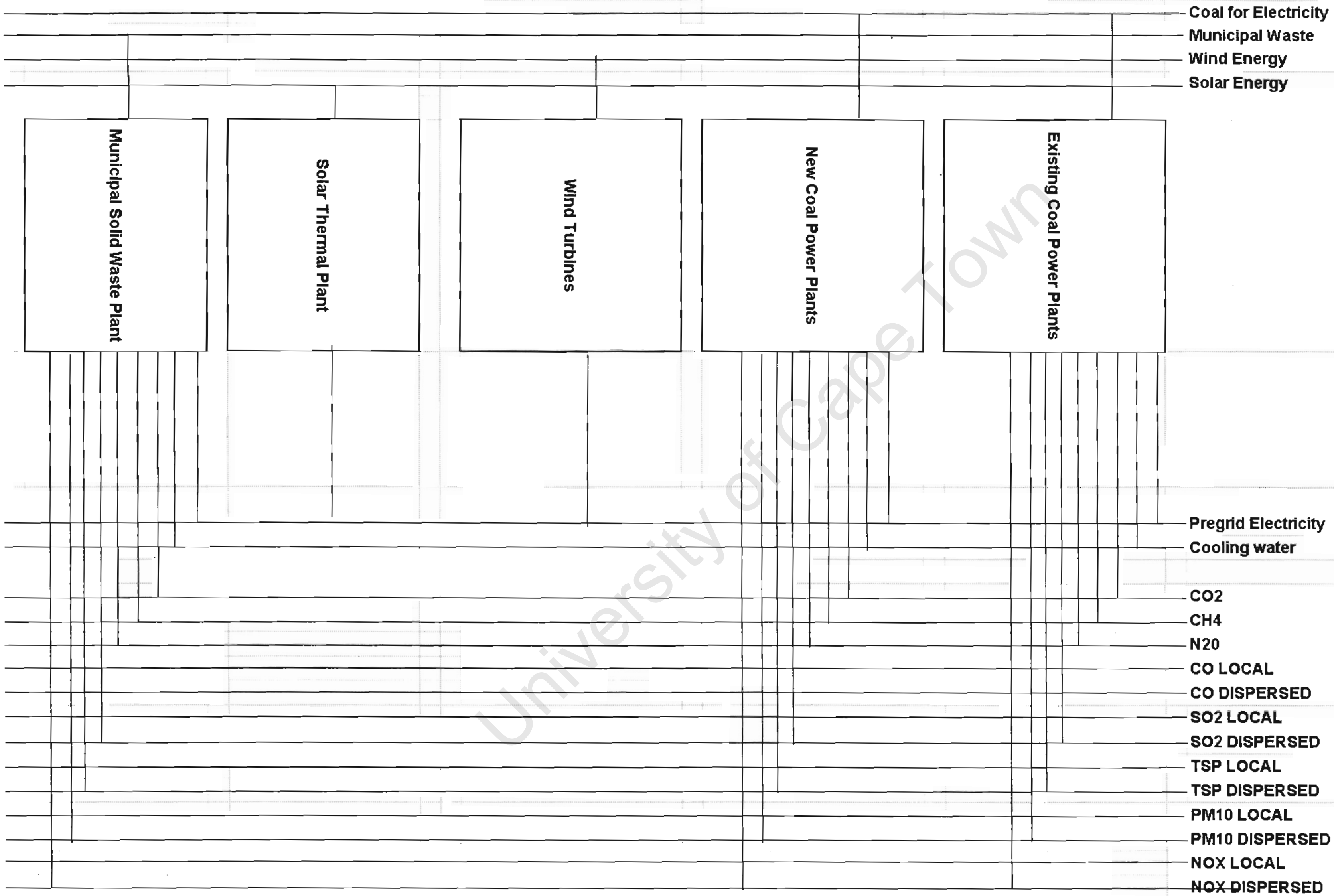
Oil Refining



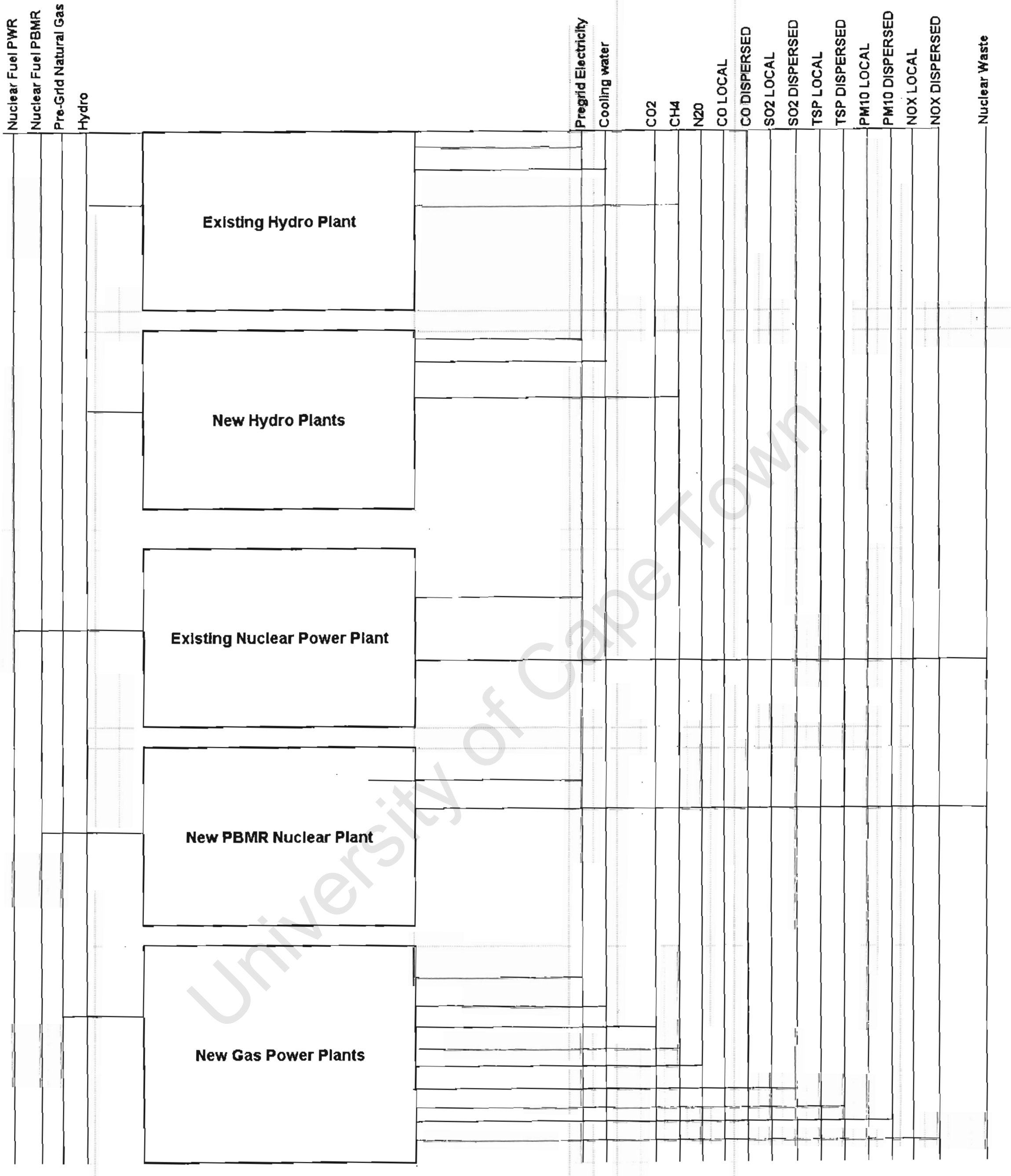
Liquefaction of Coal and Gas



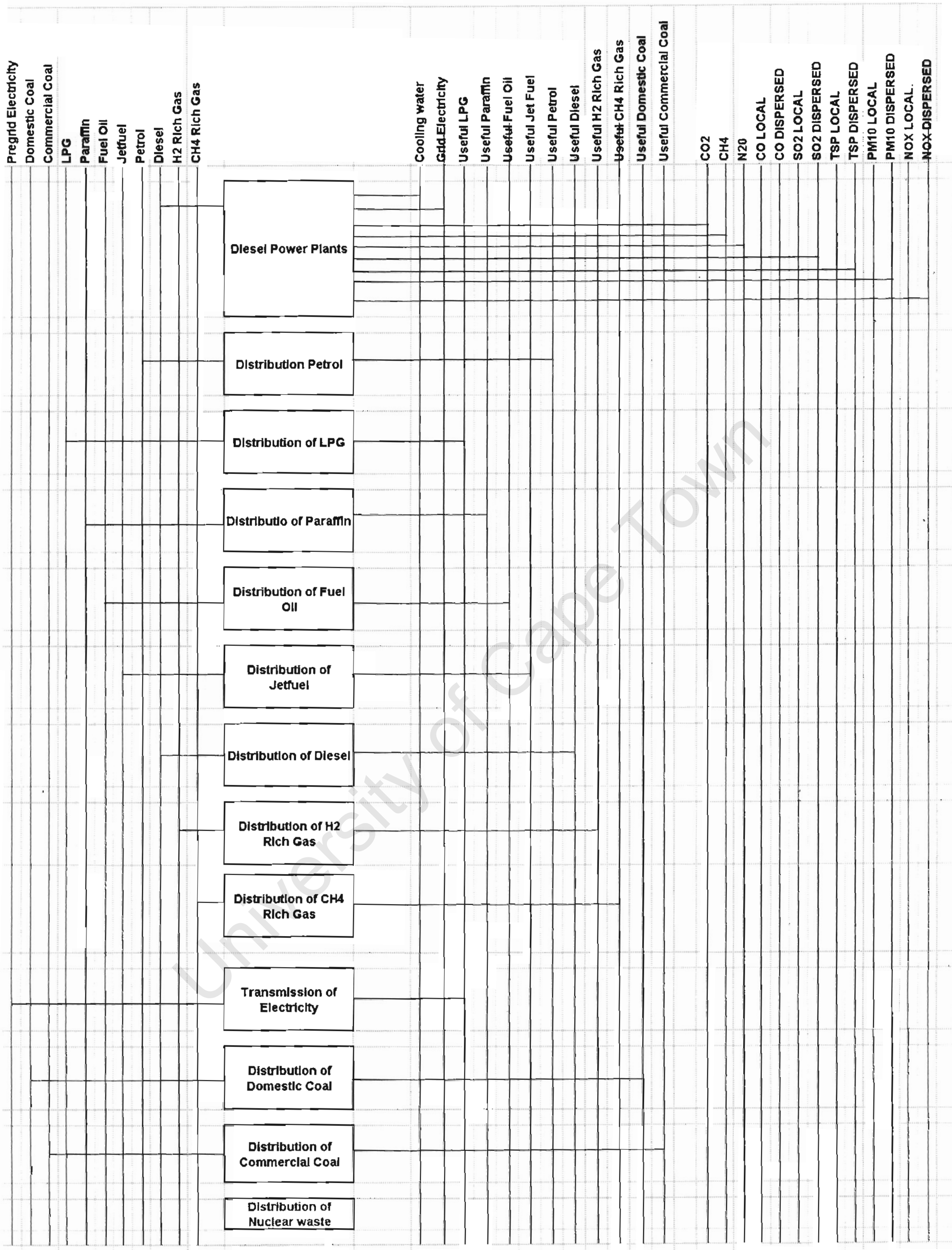
Electricity generation



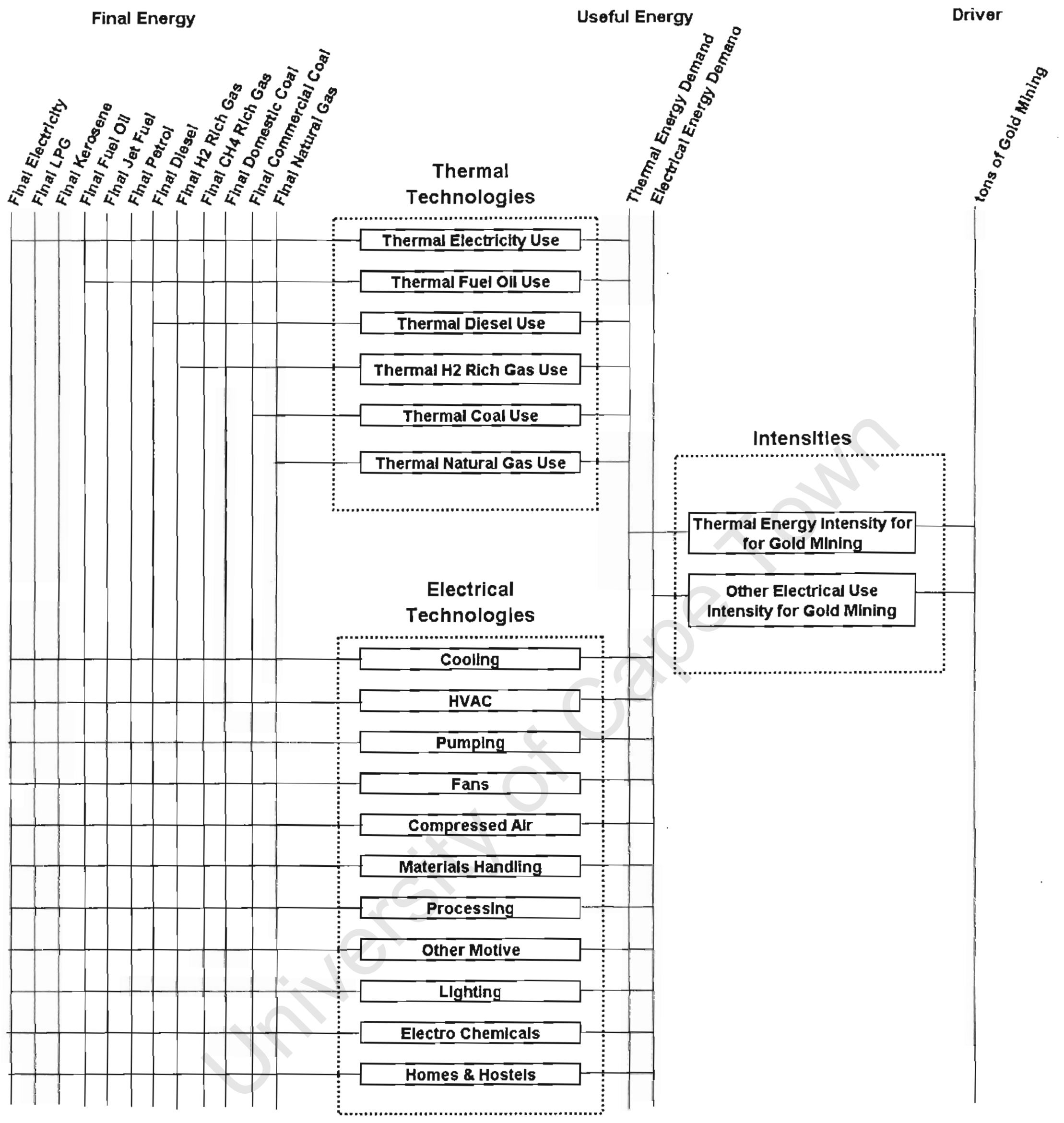
Electricity Generation



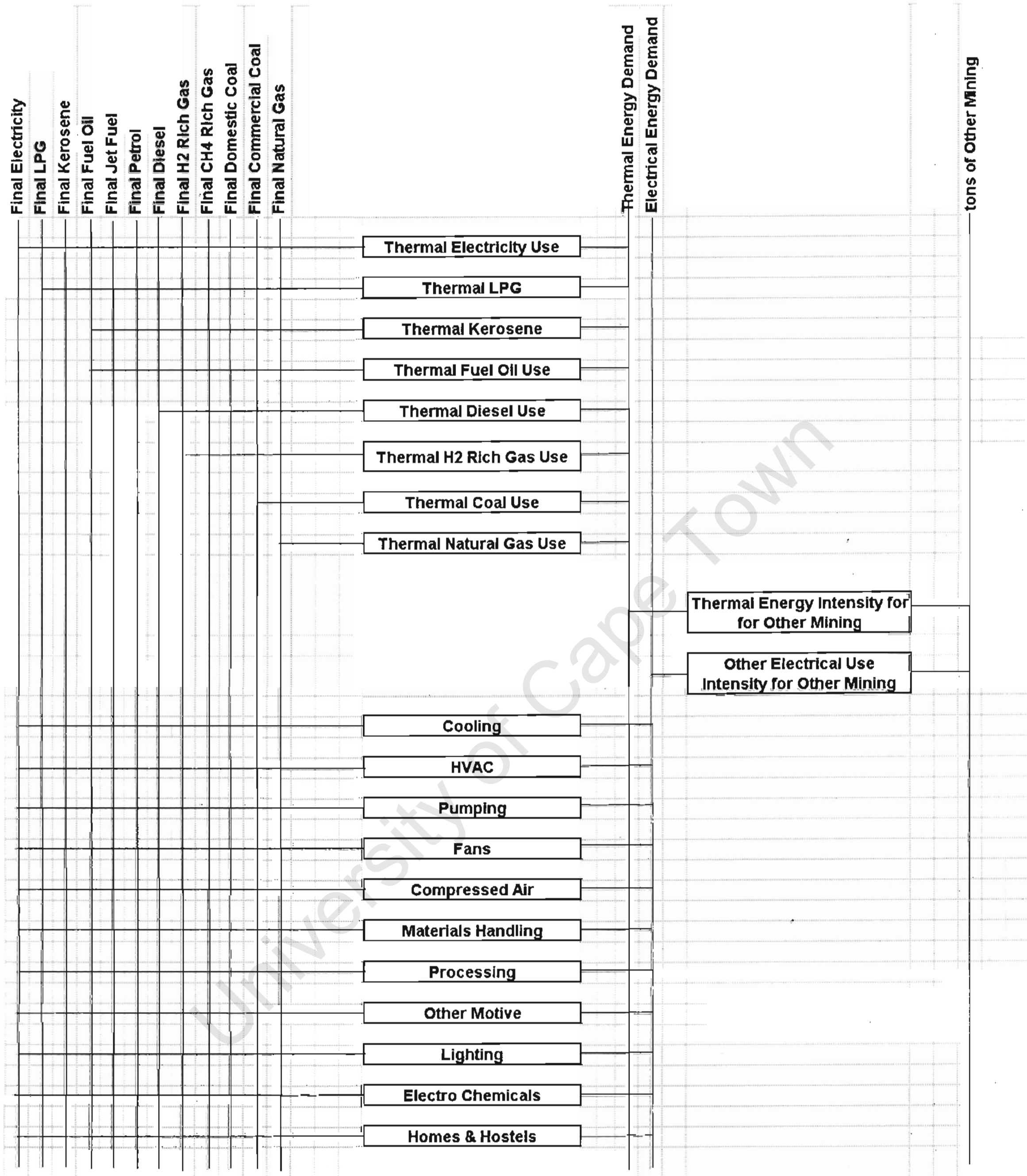
Distribution of secondary energy



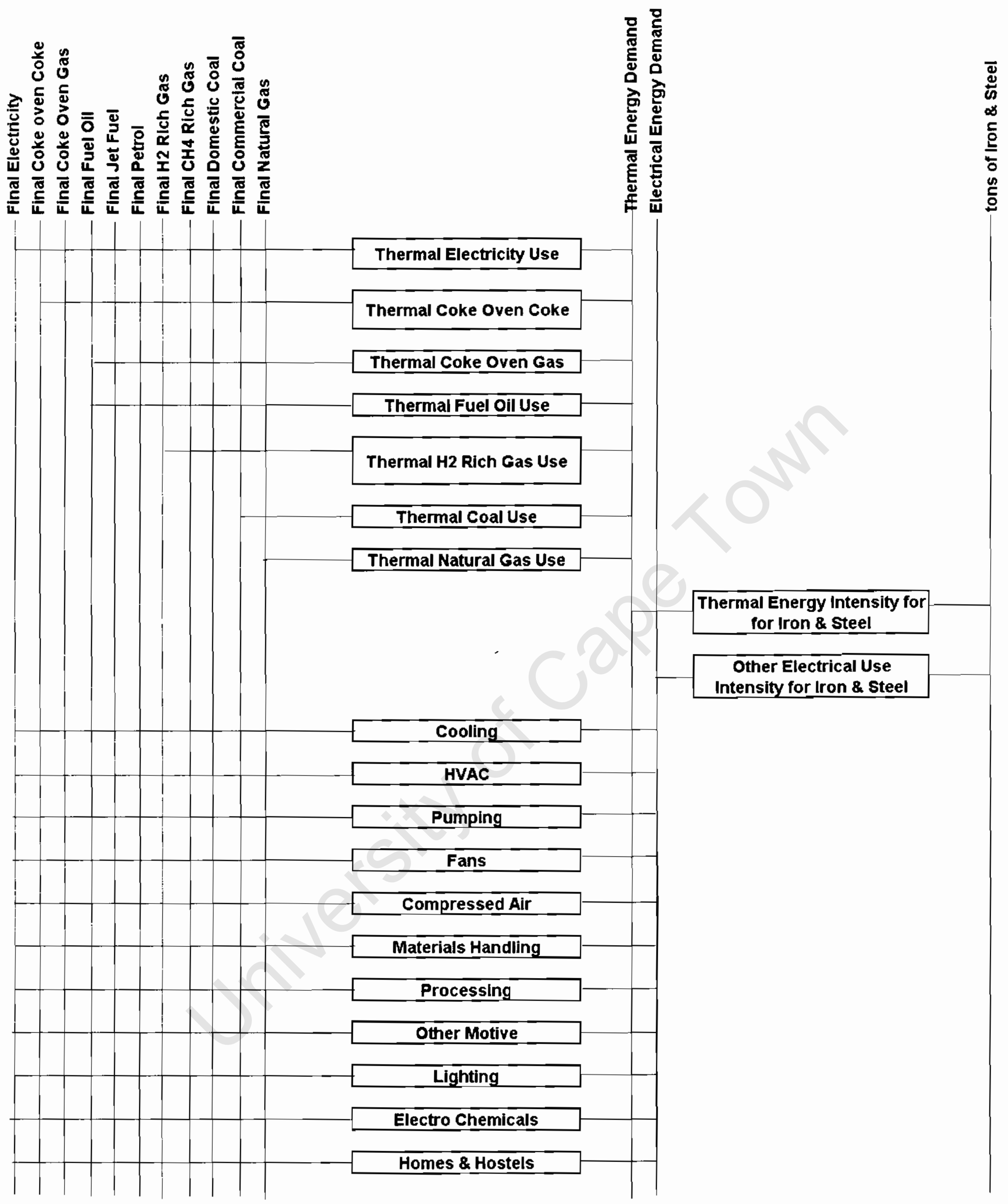
Final and useful energy demand for Gold Mining (Excluding emissions from Energy use)



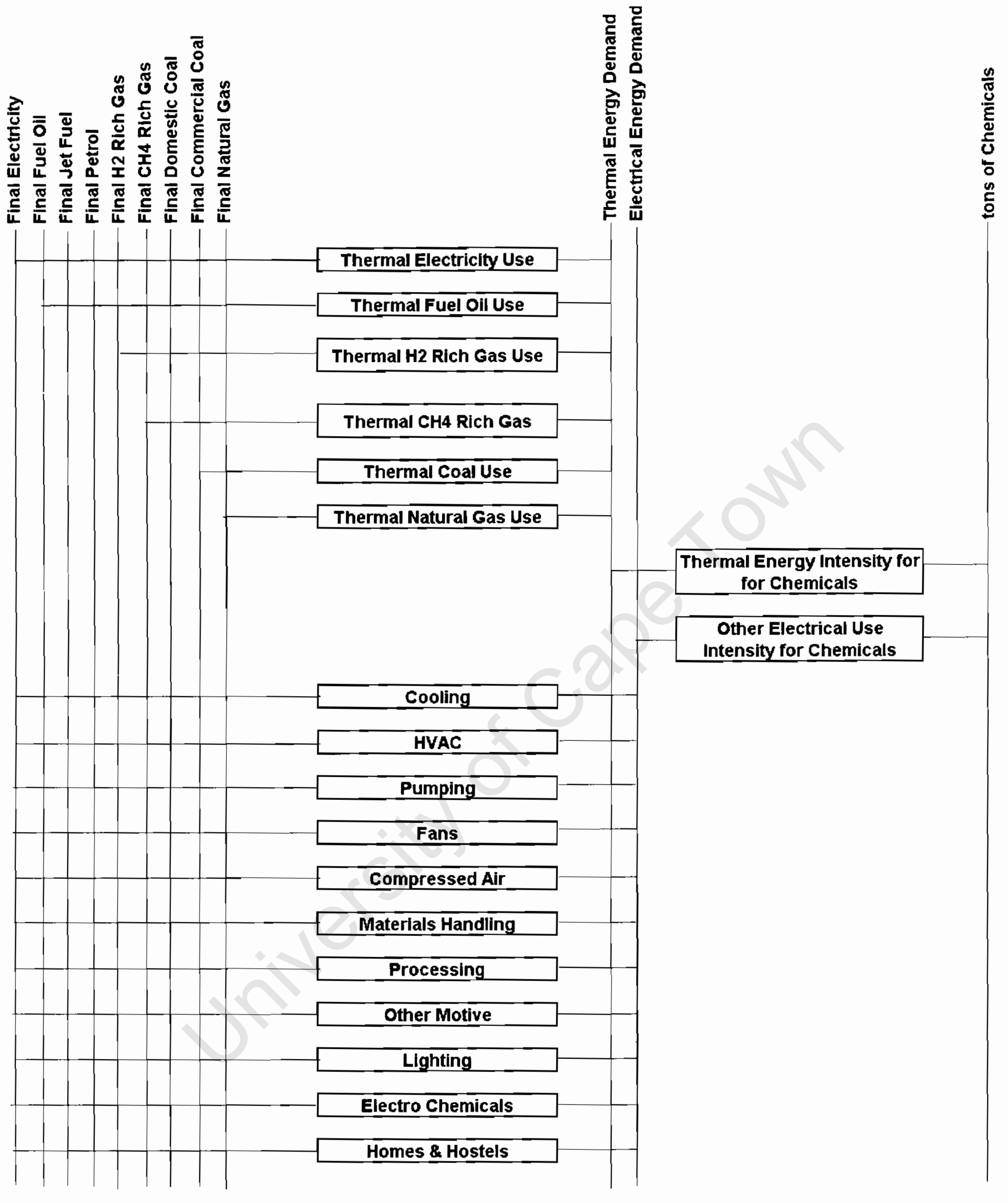
Final and useful energy demand for Other Mining (Excluding emissions from Energy use)



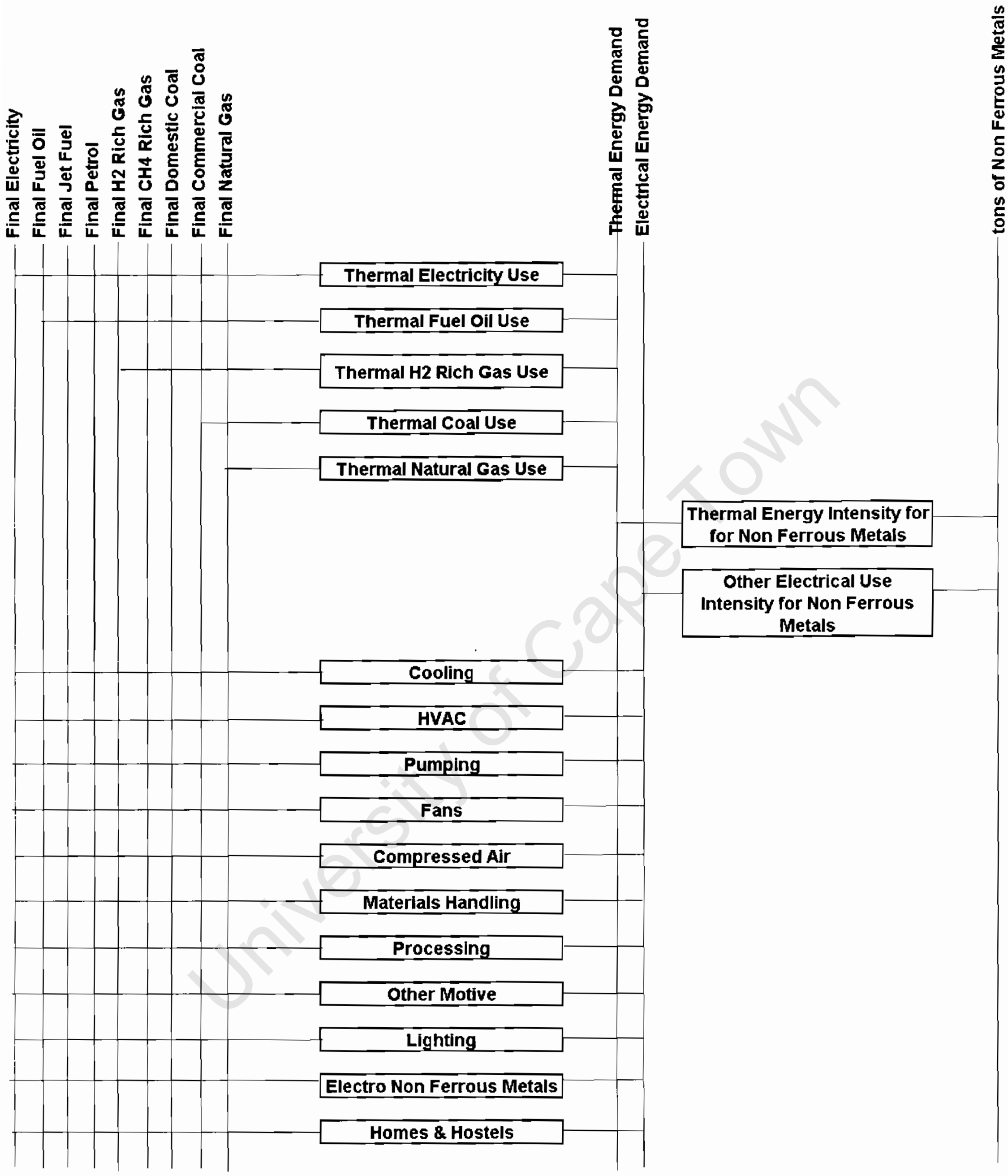
Final and useful energy demand for Iron & Steel (Excluding emissions from Energy use)



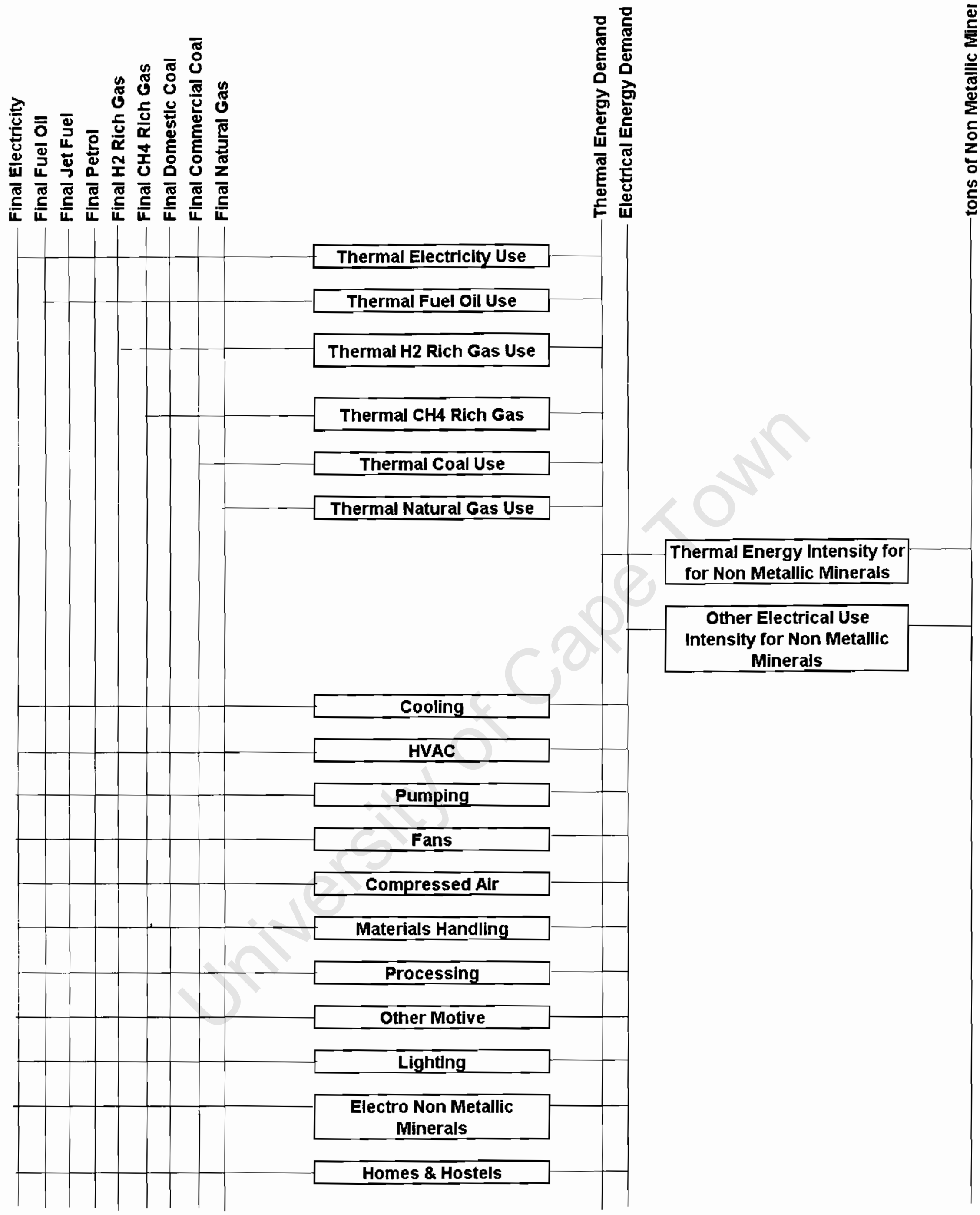
Final and useful energy demand for Chemicals (Excluding emissions from Energy use)



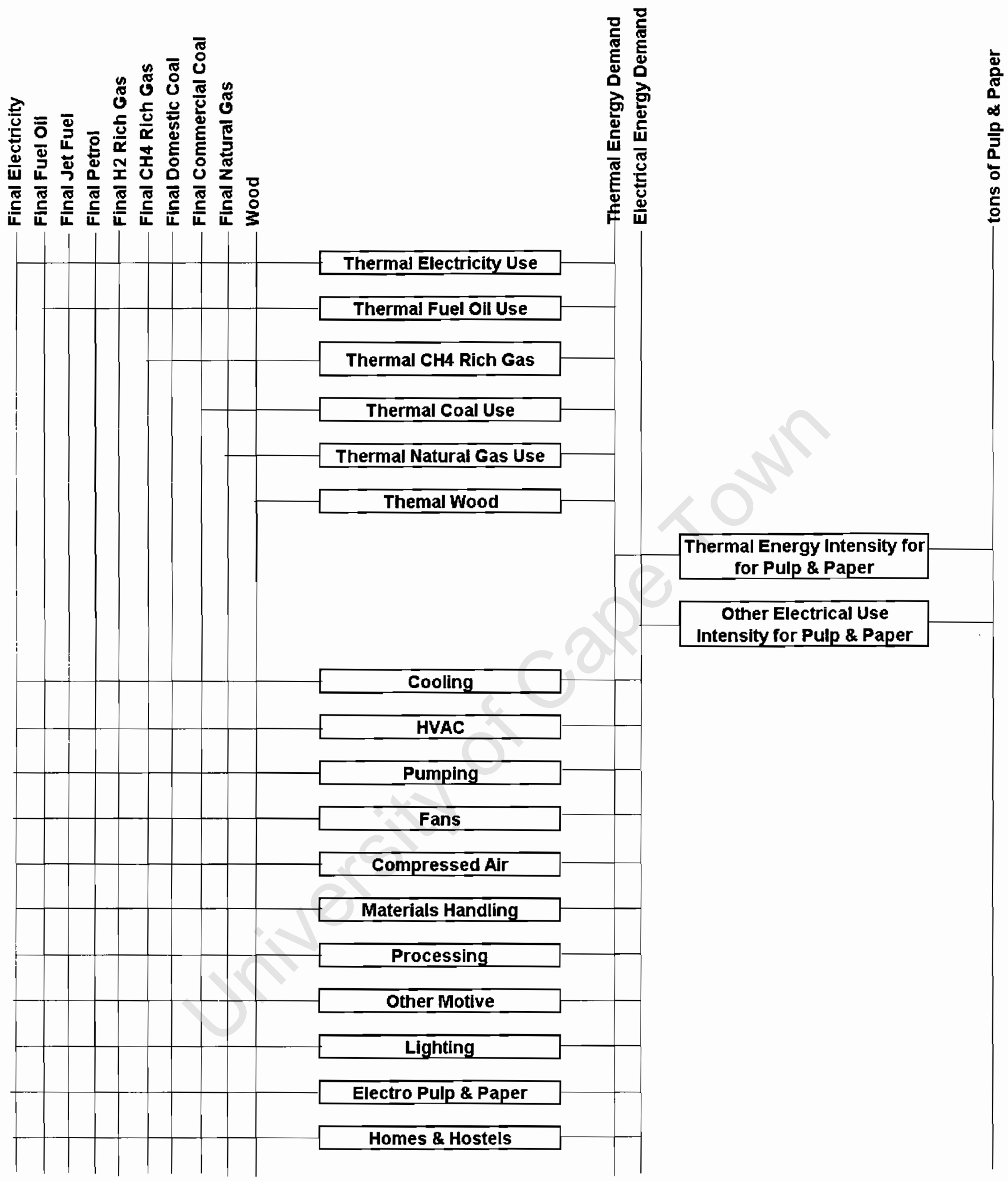
Final and useful energy demand for Non-ferrous metals (Excluding emissions from Energy use)



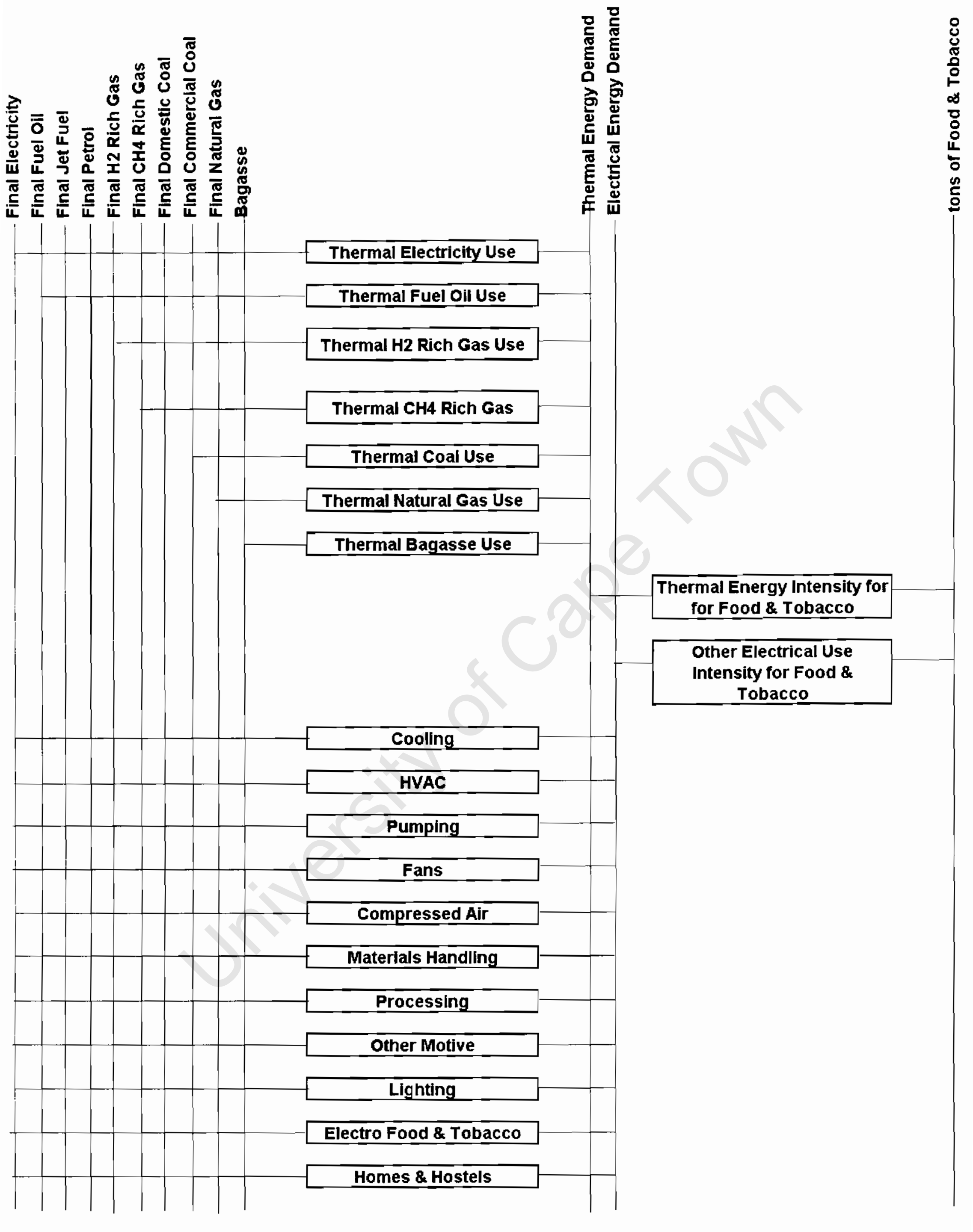
Final and useful energy demand for Non-metallic Industries (Excluding emissions from Energy use)



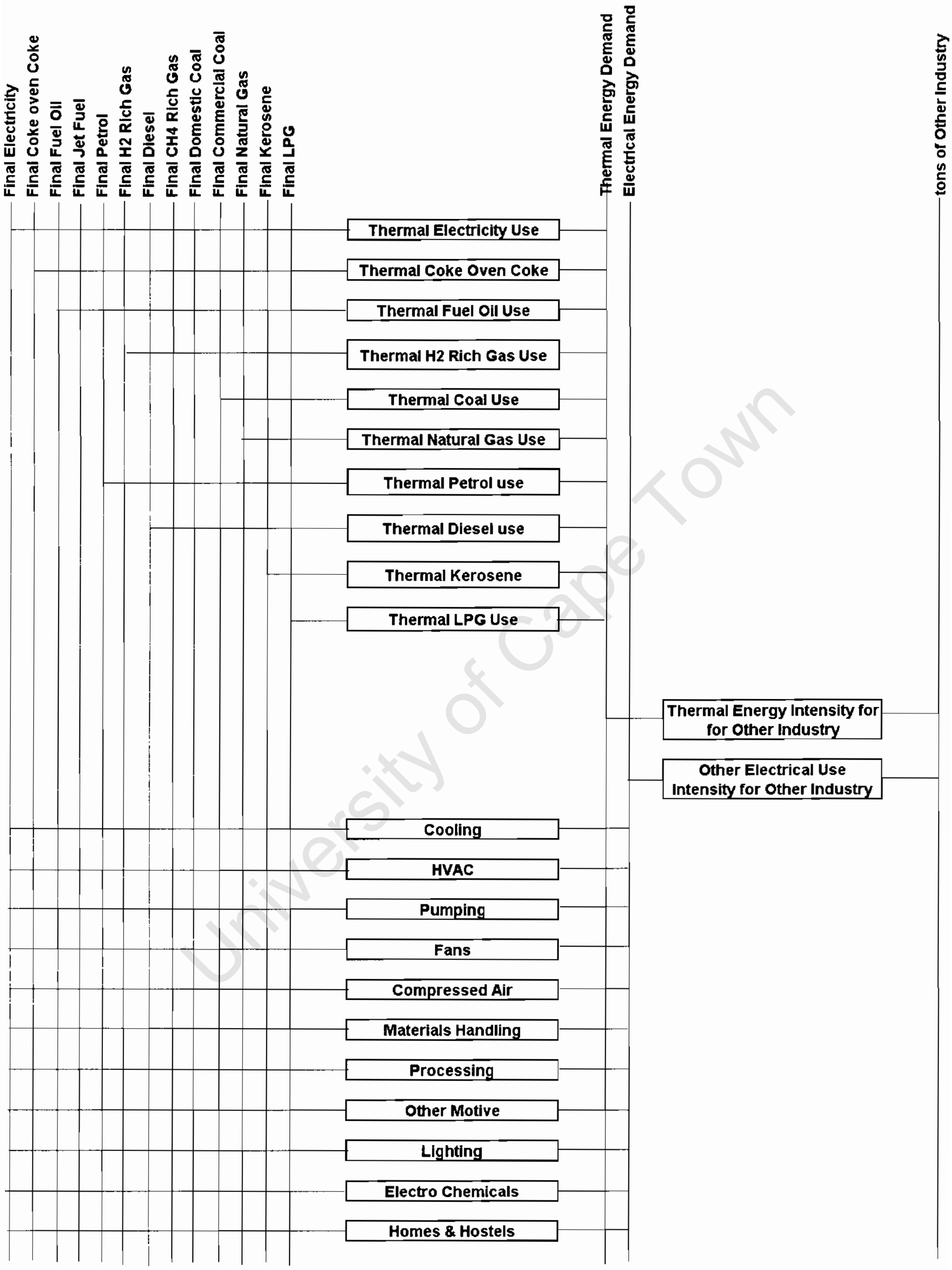
Final and useful energy demand for the Pulp and paper industries (Excluding emissions from Energy use)



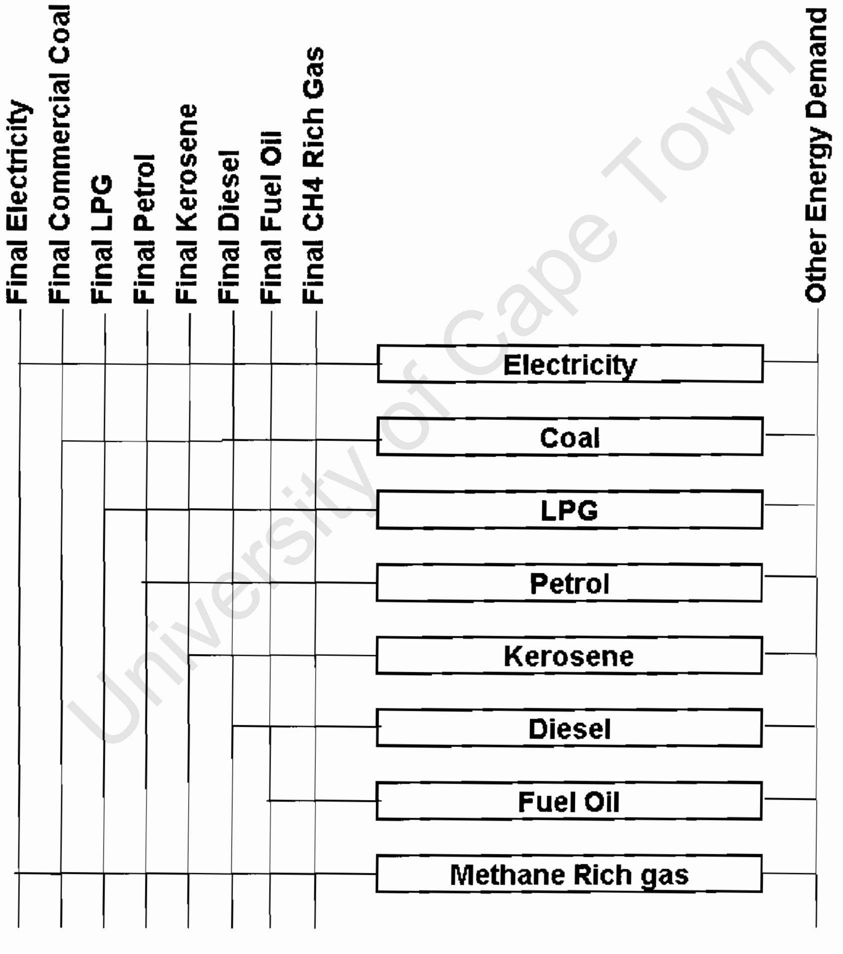
Final and useful energy demand for the food and tobacco industries (Excluding emissions from Energy use)



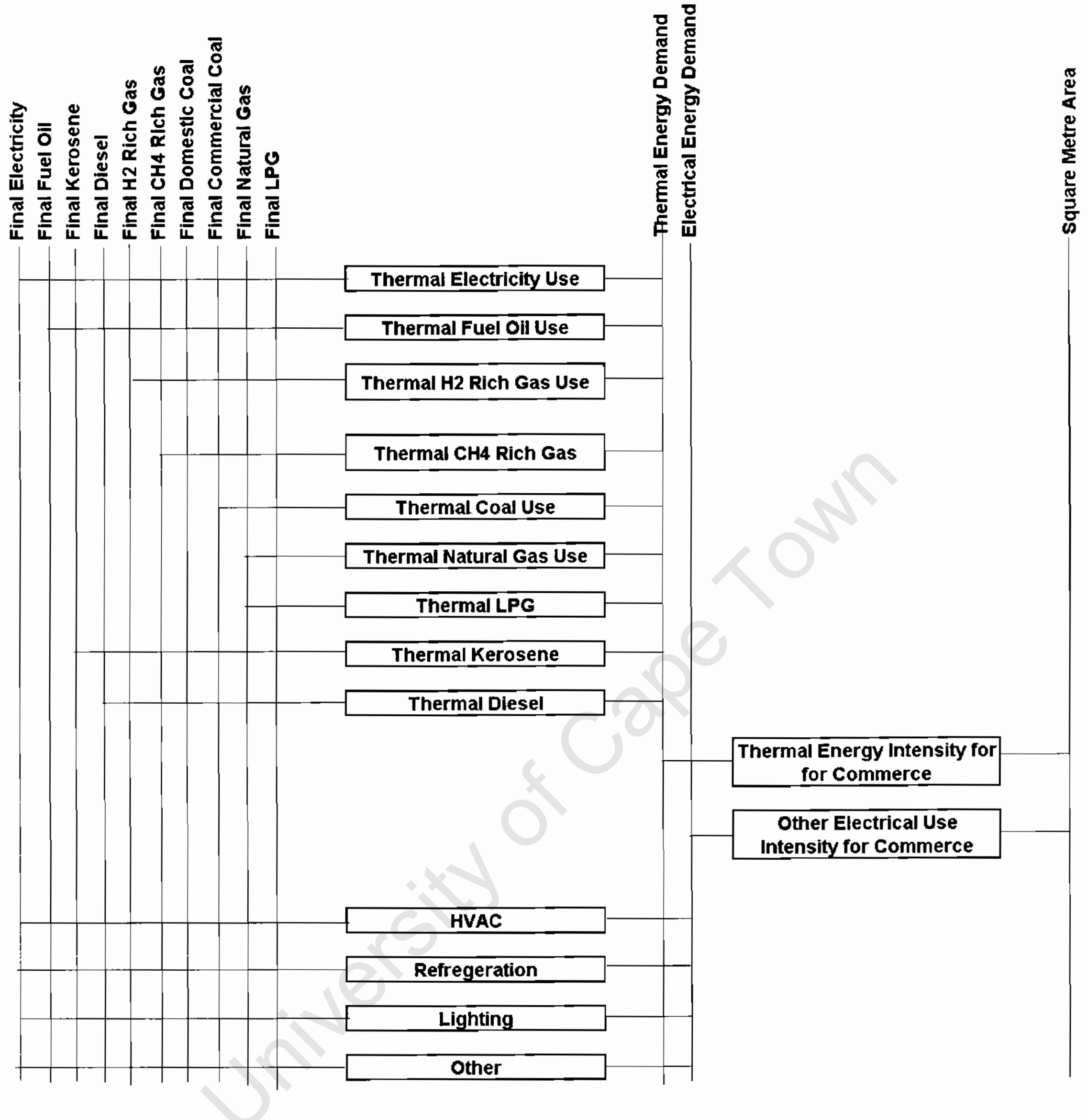
Final and useful energy demand for Other industry (Excluding emissions from Energy use)



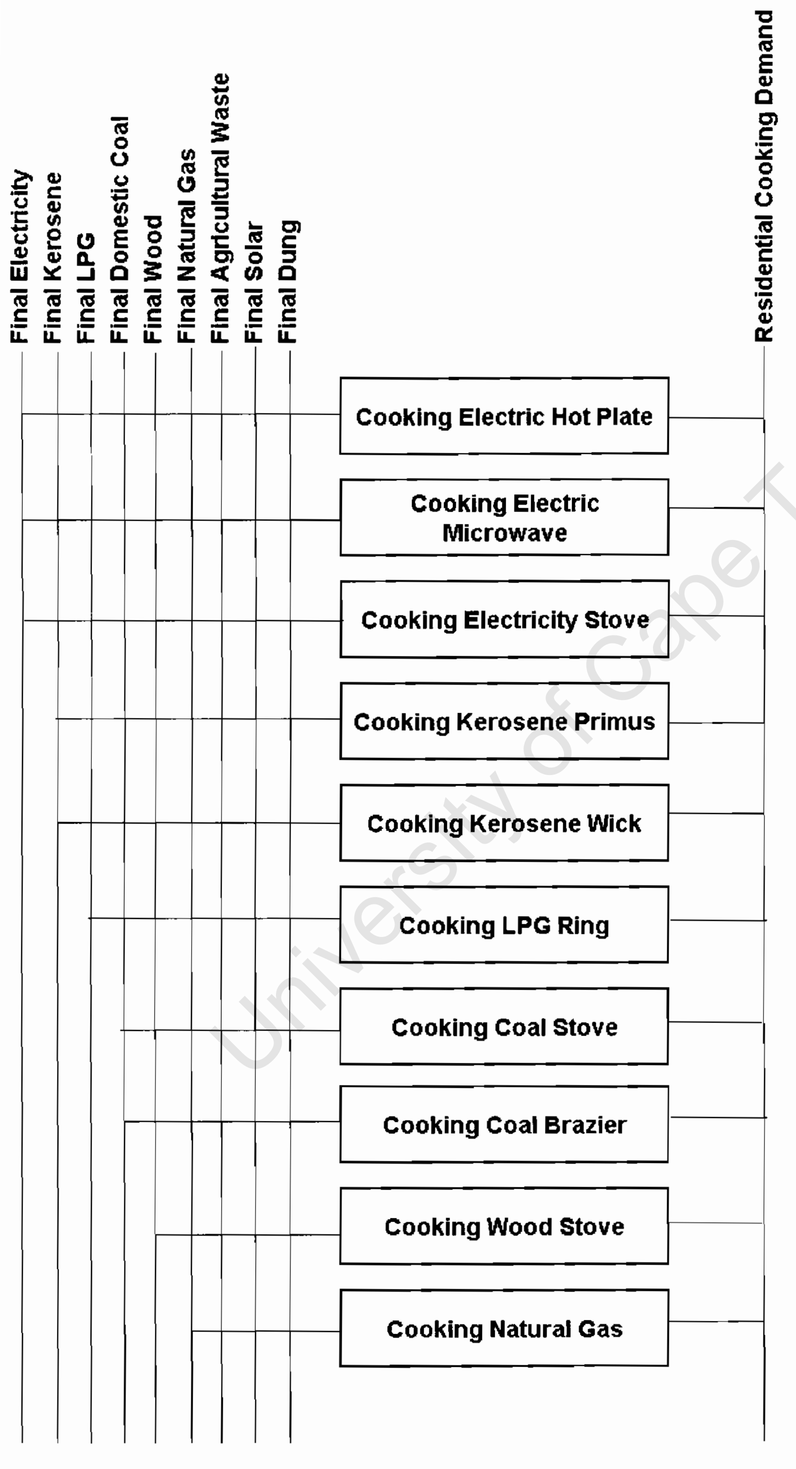
Final and useful energy demand for other non-specified industry (Excluding emissions from Energy use)



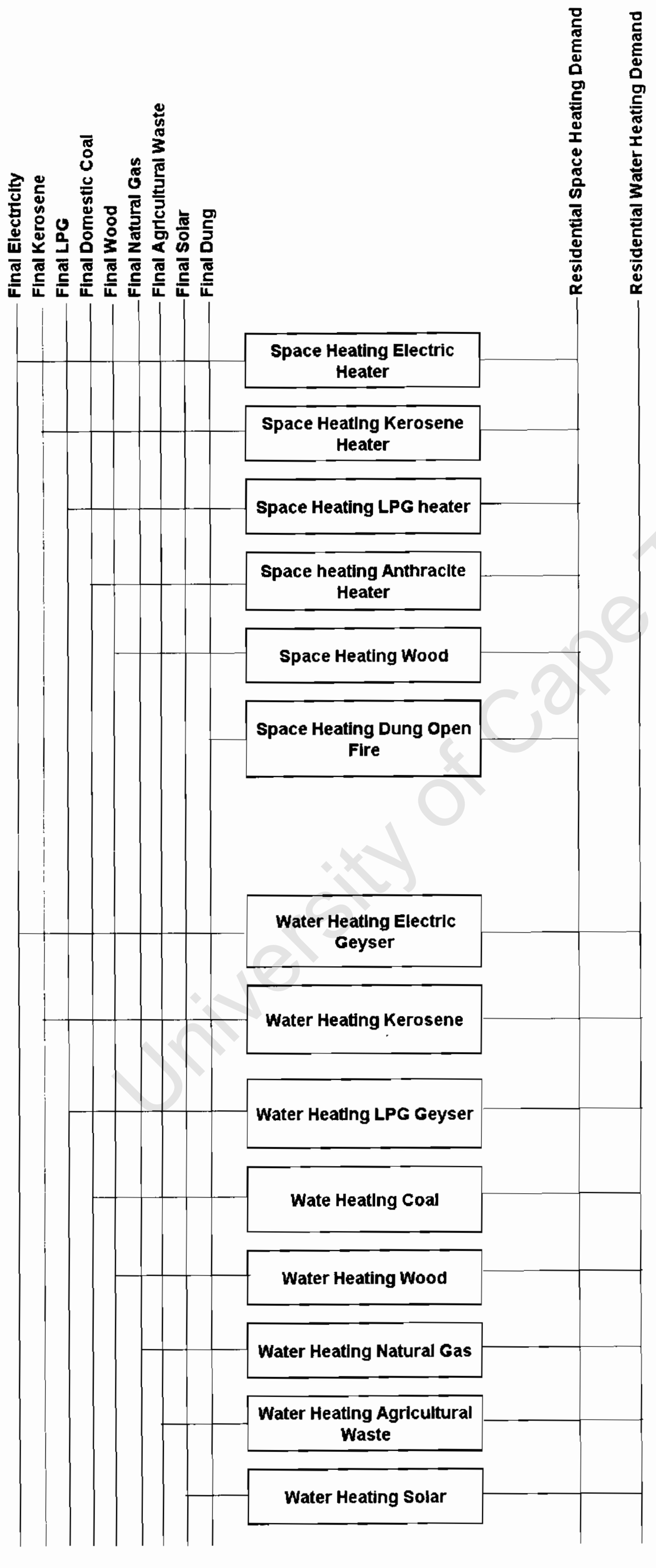
Final and useful energy demand for the Commercial Sector (Excluding emissions from Energy use)



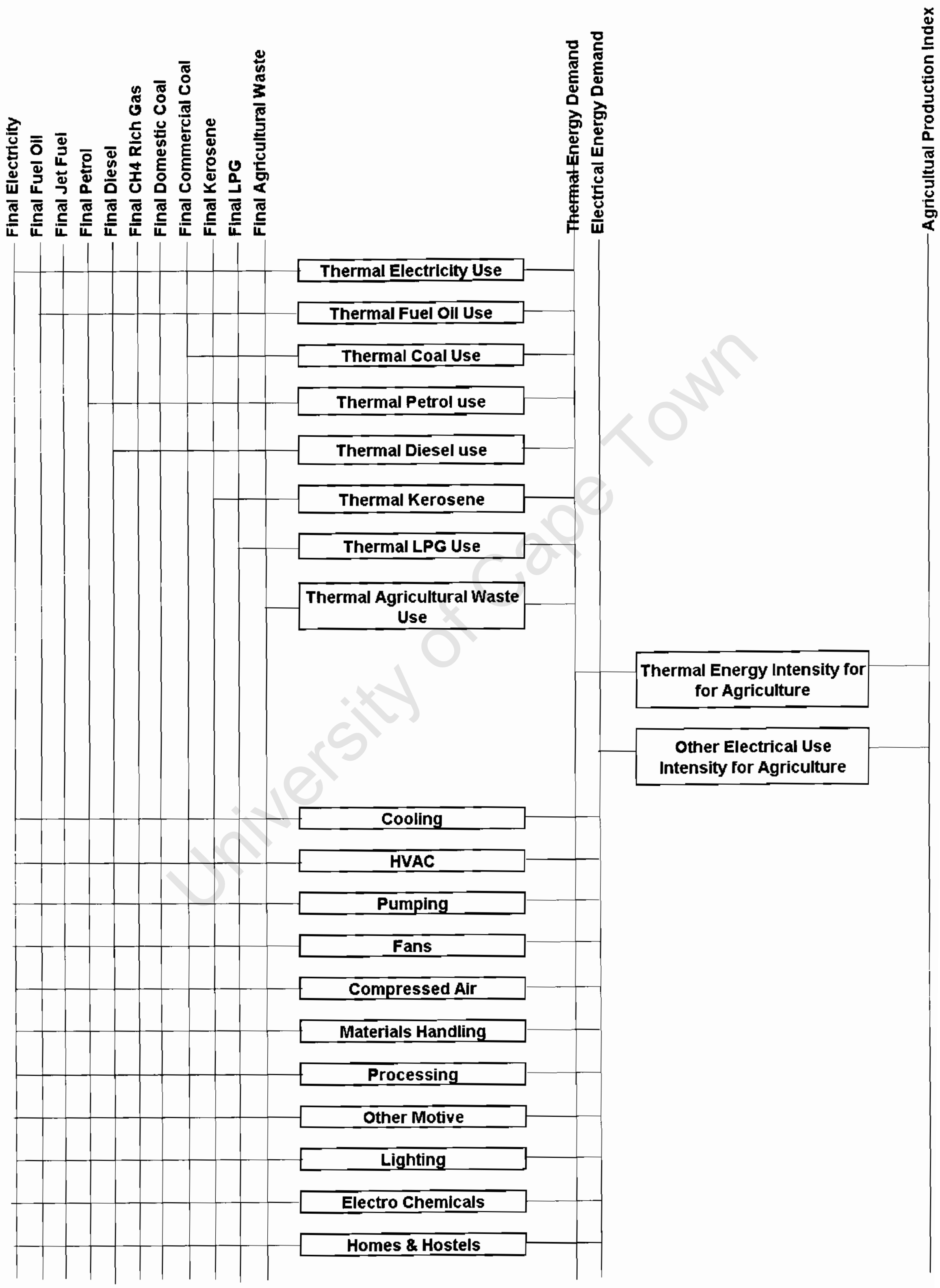
Final and useful energy demand for Residential cooking (Excluding emissions from Energy use)



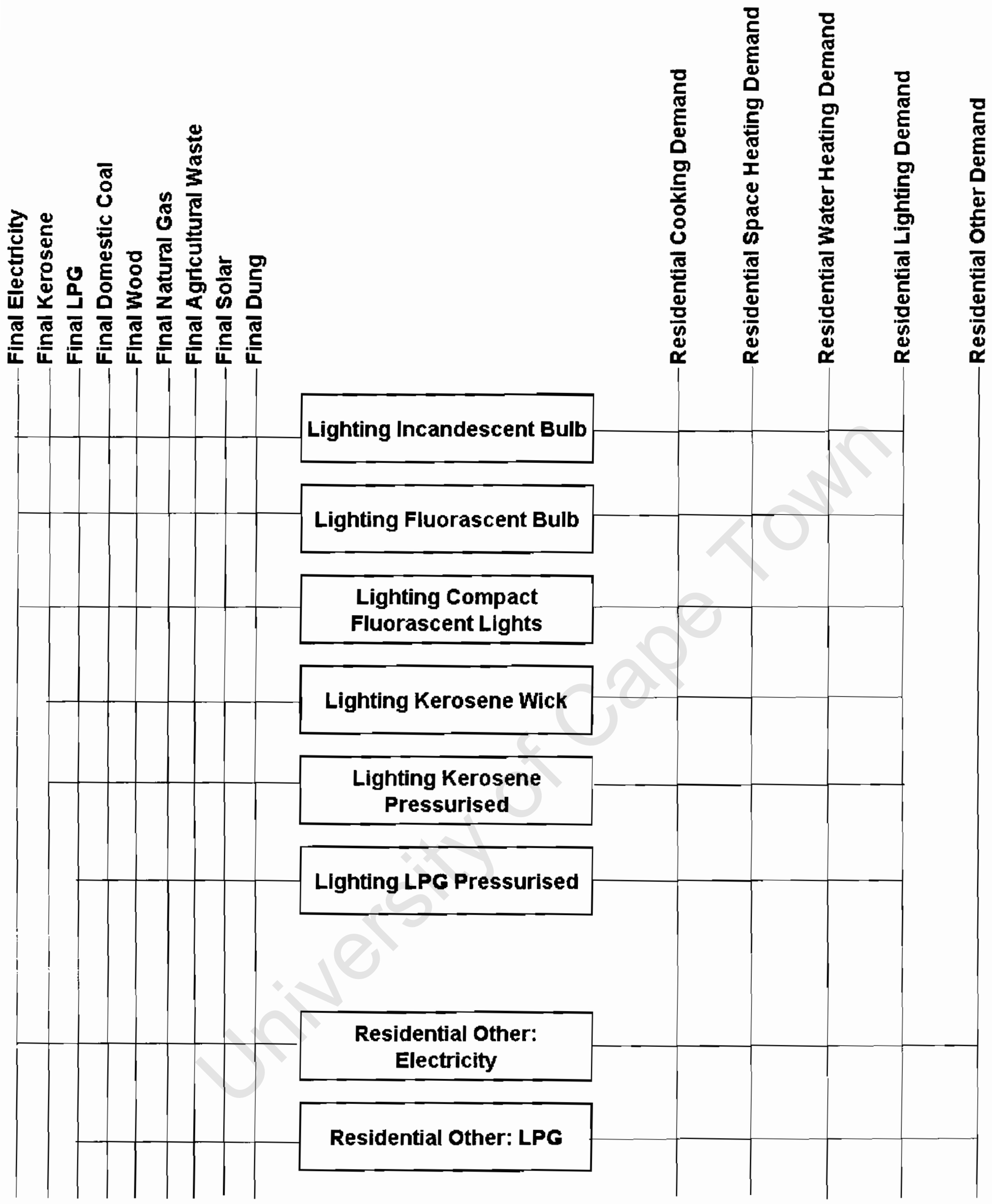
Final and useful energy demand for Residential Space and water heating (Excluding emissions from Energy use)



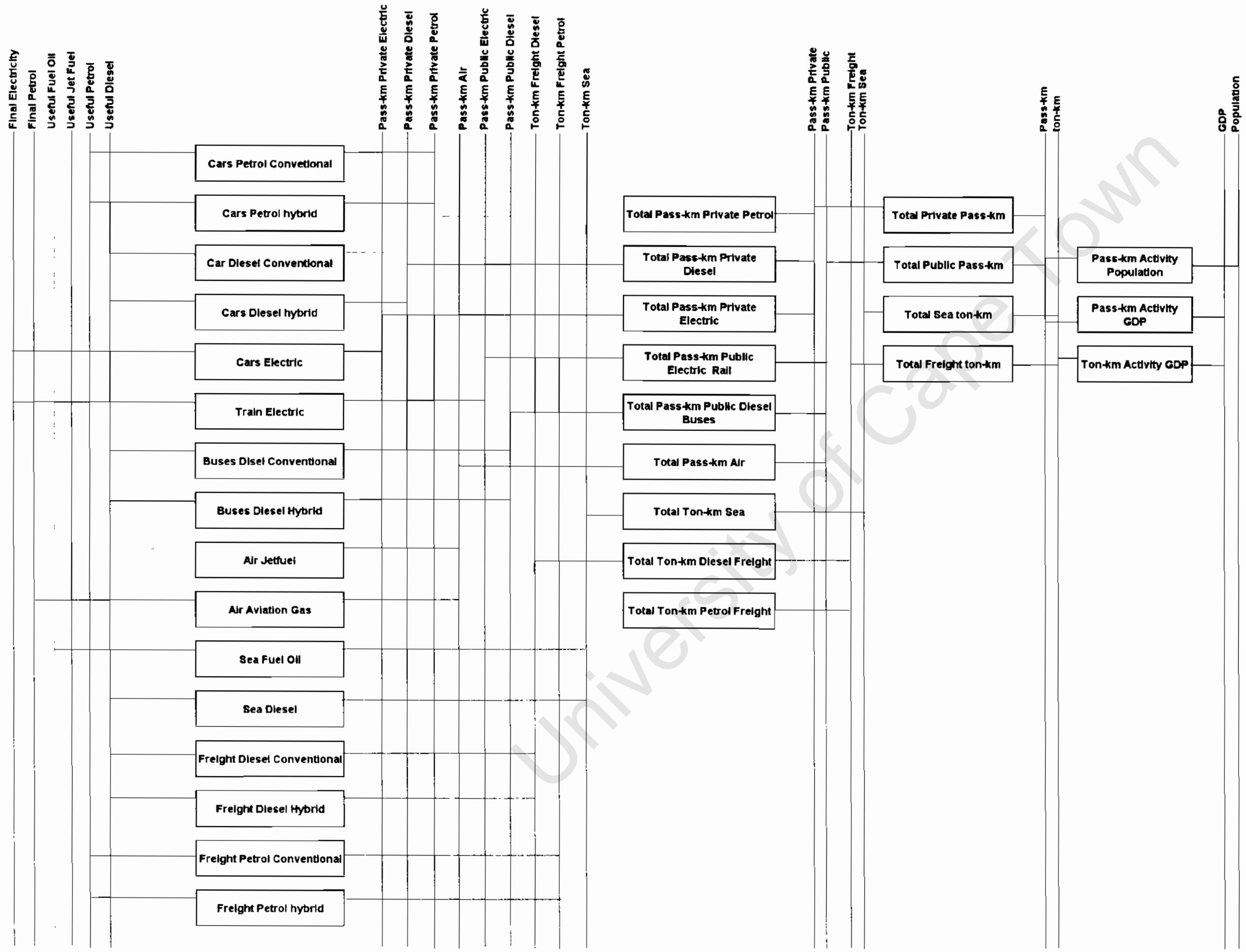
Final and useful energy demand for Agriculture (Excluding emissions from Energy use)



Final and useful energy demand for Residential lighting and Other demand (Excluding emissions from Energy use)



The Transport Sector



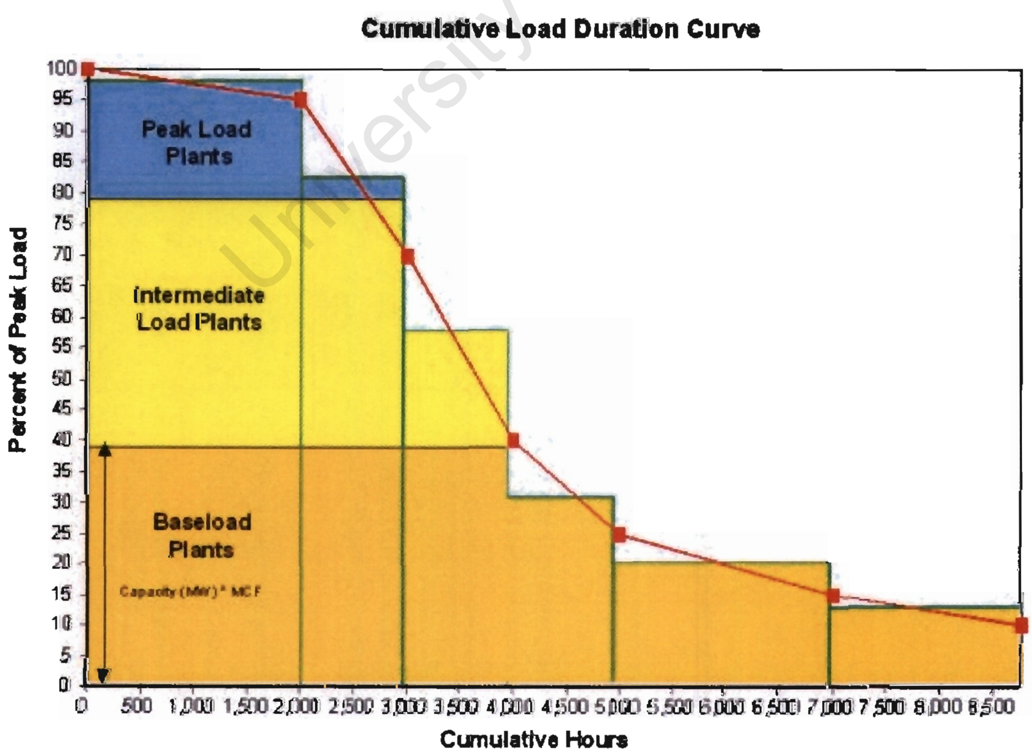
APPENDIX E: Electricity Dispatching

The following information is extracted from the LEAP and MARKAL help files.

E.1. Dispatching Processes on a Load Curve in LEAP

To simulate the dispatch of processes, LEAP first makes a list of processes, sorted by their merit order. This information is used to calculate the available capacity of each group of processes with the same merit order, (i.e. those that are dispatched together).

Next, LEAP makes a discrete approximation of the load curve and divides it up into 6 vertical "strips" (see below), as defined by the 7 data points specified in the Load Curve screen. The height of each strip is equal to the overall system peak load requirement multiplied by the average percentage of peak load of two adjacent points on the specified load curve. The width of the strip is the difference in hours of those same two adjacent data points. Overall peak system load requirement is calculated from the energy requirements on the module, and the module's load factor (the mean height of the load curve) as follows:



Tip: For greater accuracy, more points are specified where the load curve is steepest. Next, each group of processes is dispatched in vertical "strips" in order to try and fill the area under the load curve. Base load plants are dispatched first at the bottom, followed by intermediate and peak load plants. To properly represent the average technical availability of each plant (i.e., allowing for periods when plants are unavailable because of planned or unplanned outages), the maximum height of each strip is the available capacity for each group (i.e. the sum of Capacity x Maximum Capacity Factor) for all processes in the group. Each group is dispatched in turn until the load curve strip is filled. In cases where the available capacity of the group exceeds the amount required, the actual amount of each process dispatched is reduced, so that each process is dispatched in proportion to its available capacity.

Limitations: simulating dispatching in this way does not allow for the tendency of some plants to be more available at times of higher (or lower) average loads. For example, hydro plants tend to be more available in wetter seasons, and hence planned maintenance tends to be scheduled for dryer seasons. This seasonal variation is not reflected in the maximum capacity factors used to dispatch processes on the system load curve. Also, the simulation does not attempt to simulate load-levelling plants (such as pump-storage hydro plants) which have a positive instantaneous capacity, but a negative overall annual electricity output. This type of situation can be simulated by amending (flattening) the shape of the load curve.

E.2. Modelling Electricity Demand and Supply in MARKAL

LOAD PATTERN -- DEMAND

The demand for electricity in each season (Z = Winter/Summer/Intermediate) and time-of-day (Z=Day/Night) is calculated at the level of the demand categories (DM). If the demand is flat, or uniformly distributed over the year, the demand in each time division (Z)(Y) is governed by the general breakdown of time divisions in MARKAL as given by the entries QHR(Z)(Y) in TABLE CONSTANT:

$$ELC_{DM}(Z)(Y) = DEMAND_{DM} \text{ x } QHR(Z)(Y)\ ;\ \text{if } DM_{DM} = UNIFDIST \qquad \text{E-1}$$

Alternatively, a breakdown of the seasonal/diurnal demand can be specified by the user by specifying entries FR(Z)(Y) in TABLE DM(DM):

$$ELC_{DM}(Z)(Y) = DEMAND_{DM} \text{x} FR_{DM}(Z)(Y);\ \text{if } DM_{DM} \neq UNIFDIST \qquad \text{E - 2}$$

The relative load in each time division for such non-uniform demands equals:

$$LOAD_{DM}(Z)(Y) = DEMAND_{DM} \text{ x } \frac{FR_{DM}(Z)(Y)}{QHR(Z)(Y)} \qquad \text{E-3}$$

All sectoral demands are aggregated into an overall demand per season and time-of-day:

$$ELC(Z)(Y) = \sum_{DM} ELC_{DM}(Z)(Y) \quad \text{E-4}$$

LOAD MANAGEMENT -- SUPPLY

If a conversion plant (denoted by the internal MARKAL SET CON) is not constrained by specific technical or operational conditions, it can produce electricity in each time division up to a level governed by the generic availability factor (TABLE CON(CON) - AF). The CAPUNIT factor allows for capacity units to be converted into electricity production units. The most commonly used CAPUNIT is the one linking GW capacity and PJ production: 31.536 (unit less).

$$ELC_{CON}(Z)(Y) \leq CAP_{CON} \text{ x } CAPUNIT \text{ x } AF \text{ x } QHR(Z)(Y) \quad \text{E-5}$$

Instead of a fixed and constant availability throughout the year, seasonal and time-of-day dependent values can be assumed. E.g. reflecting resource constraints for renewable power plants (hydro, solar, wind):

$$ELC_{CON}(Z)(Y) \leq CAP_{CON} \text{ x } CAPUNIT \text{ x } AF(Z)(Y) \text{ x } QHR(Z)(Y) \quad \text{E-6}$$

If AF values are used, the production in each time division cannot exceed the level given in the two formulas above. The actual level of production for certain plants is then established during solution of the MARKAL model, subject to these constraints and the demand load pattern. For a variety of reasons the user may wish to limit the load following characterists of specific power plants. E.g. to avoid unrealistic operation schemes, such so-called eXternally Load Managed (SET XLM) plants can be introduced. Their production in each time division is fixed by the user through the CF or CF(Z)(Y) parameters:

$$ELC_{XLM}(Z)(Y) = CAP_{XLM} \text{ X } CAPUNIT \text{ X } CF \text{ X } QHR(Z)(Y) \quad \text{E-7}$$

or:

$ELC_{XLM}(Z)(Y) = CAP_{XLM} \text{ x } CAPUNIT \text{ x } CF(Z)(Y) \text{ x } QHR(Z)(Y)$ E-As a side benefit, XLM plants do not infer generation of six production variables for the six time divisions in each period, as is the case for other plants, and are thus less demanding in terms of the model dimensions. Each plant in a nine-period MARKAL model that is moved to the SET XLM saves 54 variables. Of course, care must be taken to leave sufficient freedom for operation of power plants to respond to fluctuating demand levels.

BASELOAD CONSTRAINTS

Baseloaded power plants (members of SET BAS) are assumed to produce at the same rate during day and night of each season (Z). In addition, their aggregate production during the night cannot exceed a user-specified share (TABLE CONSTANT - BASELOAD) of the total electricity production during the night in each season (Z).

PEAK REQUIREMENTS, RESERVE MARGIN

A user specified share (TABLE PEAK - CON) of the installed capacity of each plant is assumed to contribute to meet the peaking requirements. The peak is assumed to occur in either the winter day (WD) or the summer day(SD), both being evaluated by MARKAL. The minimum installed capacity is calculated by a mark-up factor to the (levelized) total electricity demands in WD and SD. The mark-up factor is called the electricity reserve margin and is entered in TABLE CONSTANT - ERESERV. Note that ERESERV is typically much bigger than prevailing rule-of-thumb values in the electric utilities. The reason for this is that the reserve margin in MARKAL also encompasses the difference between the levelized WD (or SD) demand and the actual peak occuring on one day in that same period, . The contribution of demands to the electricity peak can be adjusted downward by specifying which share of the total demand (TABLE DM(DM) - ELF) coincides with the peak. Individual demand devices can be operated as night storage devices (members of SET NST), implying that all demand per season is shifted to the night hours. These NST plants do thus not contribute to the peak.

TRANSMISSION & DISTRIBUTION - LOSSES & COSTS

MARKAL distinguishes two kinds of power plants: centralized (SET CEN) and decentralized (SET DCN). Costs and losses of electricity transport and distribution up to a certain level can be accounted through entries in TABLE CONSTANT:

ETRANINV, ETRANOM, EDISTINV, EDISTOM and TE; see the enclosed diagram. Costs introduced at this general level apply to all electricity produced. Sector and/or application specific distribution costs are to be handled by assigning delivery costs to individual end-use devices accordingly (TABLE TCH(DMD) - DELIVELC).

Centralised plants are charged with both transport and distribution costs, while decentralised ones only face distribution costs. Moreover, losses in the electricity grid occur at the transport level only, so DCN plants are not associated with any grid losses. These properties should be kept in mind when assigning power production plants to either of the two sets. As to the use of the investment cost parameters, it must be noted that these are to be treated with great care. They are added to the investment costs of the power plants themselves. As a consequence, their impact on total costs depend upon the lifetime and utilization rate of the plants concerned. E.g. a EDISTINV of $250 will add 0.23 cts/kWh to the production cost of a baseloaded (AF=0.8) coal power plant with a long life (30 yrs), but 0.92 cts/kWh to a wind turbine (AF=0.25) with a shorter life (20 yrs).