Analyzing sustainable energy in developing countries:
Selected South African case studies

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Submitted towards the degree of Doctor of Philosophy at the University of Cape Town

Declaration

I confirm that this is my own work and has not been submitted for degree purposes at this or any other university.

Signed by candidate

14th May 2008

Abstract

This thesis demonstrates the use of selected Energy-Environment-Economic (E3) modelling techniques to provide insight to developing country issues. The work focuses on analyzing combinations of technologies and energy use to satisfy potential requirements of consumers at the lowest cost to society. (Tools such as MARKAL- of the Energy International Energy Agency's (IEA) Technology Systems Analysis Program (ETSAP) - are used often). The thesis shows how these models may be adapted in novel ways to tackle different challenges in different contexts. The applications covered range from macro-economic problems to the micro-economic village level analysis of fuel and appliance use.

The thesis demonstrates through a national (South African) analysis selected greenhouse gas (GHG) mitigation potentials. By examining markets in low-income areas dependent on biomass it shows relationships between institutional- and information-failure and traditional fuel use. Using the increased functionality available in the TIMES model (the successor to the afore-mentioned MARKAL), detailed dynamics of low income fuel use are simulated. By adopting simplifications, a robust, simple and critical analysis of an energy subsidy is made. Using a Multi-Criteria Decision Analysis (MCDA) approach a range of GHG mitigation options are compared in a developing country context. The thesis reports on environmentally friendly development paths derived from the application of the Goal Programming extension of MARKAL. Finally it questions the appropriateness of the Clean Development Mechanism's policy of supporting only "additional" GHG mitigation in certain circumstances. In an appendix it develops an efficient industrial data collection process using an MCDA analysis.

The main theme of this thesis is to show how suitable modelling can not only warn of inefficiency in development policies, but also indicate technical scenarios of how such inefficiencies are best remedied.

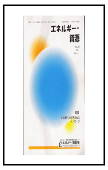
***Key words**: South Africa, Energy-Environment-Economic Modelling, MARKAL, TIMES, Efficiency, MCDA, Greenhouse gas, Goal Programming, Clean Development Mechanism*

Preface

This thesis is based on a series of academic papers produced over the past few years by the author. All addressed, or provided support to show, how suitable modelling can not only warn of inefficiency in development policies, but also indicate technical scenarios of how such inefficiencies are best remedied. Some papers had co-authors, who have contributed to the work in terms of editing, rewording and mechanical detail, for which the author is most grateful. Where their input has also included intellectual additions, these have been duly and clearly noted. In particular the author would like to thank[1] (in alphabetical order): David Victor, Denis Van Es, Kevin Bennett, Lindsey Jeftha, Mavo Solomon, Philip Lloyd, Skip Laitner, Tom Alfstad and Tony Leiman.

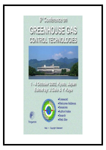
The original papers are summarized in the table below:

Thesis section 1



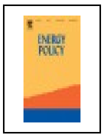
Howells M., 2001, Sustainable Energy Development in South Africa: Optimizing the energy, societal and environmental relationships in the medium and long term, *Journal of the Japan Society of Energy* Resources Vol. 22 No 1 pp 46-50 (and early version in Howells M. 1998, Sustainable Energy Development in South Africa, *Journal of Energy in Southern Africa* Vol. 9, No. 4, November, pp 125-128)

Thesis section 2

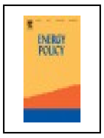


Howells, M. & Solomon, M. 2003. An Optimal GHG Mitigation Pathway for South Africa. In Proceedings: *GHG Control Technologies* 6, Kyoto. Pergamon and *Journal of Energy in Southern Africa*, Vol. 13, No. 4, November, pp 123-129

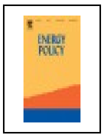
Thesis section 3



Howells M., Jonsson S., Käck, E., Lloyd, P., Conradie B. & Bennett K. Calabashes for Kilowatt-hours – Energy Transitions and Market Failures in Low Income Rural Areas, *Energy Policy*, Submitted.



Howells. M., Victor, D. G., Gaunt T., Elias, R. & Alfstad T. 2006. Beyond free electricity: The costs of electric cooking in poor households and a market-friendly alternative, *Energy Policy* 34 (2006) 3351-3358.



Howells, M., Alfstad, T., Victor, D., Goldstein, G. & Remme U. 2005,A model of household energy services in a low-income rural African village, *Energy Policy*, Volume 33, Issue 14, September 2005, Pages 1833-1851 and presented at the International Energy Workshop Vienna, July 2003

Thesis section 4

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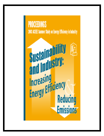
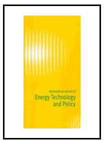
[1] Tony Leiman and Philip Lloyd are thanked in particular for their efforts reviewing this work. I would also like to thank my wife Wilma for her incredible patience and care when I was a little more than distracted by this effort.



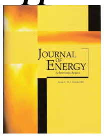
Howells, M. & Laitner, J. 2003. A Technical Framework for Industrial GHG Mitigation in Developing Countries. In *Proceedings: Summer Study: Industrial Energy Efficiency*. New York, July



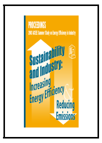
Howells, M., In Press a., Mapping out development pathways for climate friendly economic growth in a developing country, *International Journal of Energy Technology and Policy*., Special Issue: Modelling Technology Characterization.

Howells, M., House J., & Laitner, J. 2005, Beyond the Baseline – Large Scale Climate Friendly Development, *International Energy Workshop*, Tokyo, July and as well as modelling components Winkler, H., Howells, M., and Baumert K., (2007). Sustainable development policies and measures: institutional issues and electrical efficiency in South Africa, *Climate Policy*, Volume 7, Number 3, 2007, 212–229

Appendix



Howells, M. 2006, Industrial Energy Efficiency Data: Targeting DSM in South Africa. *Journal of Energy in Southern Africa*, Vol 17 No 1 , February



Howells, M. & Laitner, J. 2005, Industrial efficiency as an economic development strategy for South Africa. In *Proceedings: Summer Study: Industrial Energy Efficiency*. Proceedings and presented at the *International Energy Workshop*, Paris, July 2004

All papers have either been published or accepted by peer reviewed Journals or conferences or have (in one case) been submitted with review pending. The peer reviewed journals and peer reviewed conferences are:

1. *The Journal of Energy in Southern Africa,*
2. *Energy Policy,*
3. *Climate Policy*
4. *International Journal of Energy Technology and Policy,*
5. *Journal of the Japan Society of Energy Resources*
6. *the American Council for an Energy Efficient Economy Summer Study*

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Introduction

Policy makers in developing countries face an array of development policy challenges. Included in those are attempting to meet the urgent needs of fueling economic growth and meeting social needs. Yet it is also necessary to include and account for the environment. The *energy* policy maker is faced with an array of related priorities. These may be conflicting or complementary. They may relate to wider development goals, in which case, their policies may need to be evaluated in the light of those goals. They may have a limited and incomplete set of tools with which to carry out these evaluations. Decisions made to alleviate the lot of the poor households can be less than optimal and stress the provision of energy to economic activity. Fueling economic activity is needed to sustain and increase employment. At the same time, hopes that the policy maker may be able to take advantage of international protocols such as the Clean Development Mechanism (CDM) may be misplaced – or difficult to evaluate. Some of these and other development policy challenges are presented in specific case studies in this thesis. Attempts to address them – using transparent methods - are also made. It is shown how suitable modelling can not only warn of inefficiency in development policies, but also indicate technical scenarios of how such inefficiencies are best remedied.

Thesis hypotheses

This thesis is based on a series of updated and amended papers[2] on a central theme: to show how suitable modelling can not only warn of inefficiency in development policies, but also indicate technical scenarios of how such inefficiencies are best remedied.

The thesis is organized into four sections. The first provides a brief introduction to South African energy issues and common Energy-Environment-Economic (E3) modelling approaches. The second focuses on national energy modelling, section three addresses energy supply to the rural poor, while the final section focuses on greenhouse gas (GHG) mitigation. The hypotheses by chapter and section are given in Table 0.1.

0-1 Table 0.1 Hypotheses addressed in this thesis.

(Section one is used to provide selected background information).

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[2] As such there is often some overlap and repetition. The guiding principal adopted was to allow the repetition to remain if its omission were to affect the readability of the chapter as a quasi-stand alone piece.

Section 2

Hypothesis 1:

Under South African conditions, power sector environmental goals can be realized at lower economic costs.

Section 3

Hypothesis 2:

Institutional and information failures in low income rural areas tend to encourage the use of traditional biomass.

Hypothesis 3:

The South African government's provision of free basic electricity (FBE) is an inefficient energy subsidy.

Hypothesis 4:

Modelling of low income rural settlements is improved by considering the dynamics of concurrent space heating and cooling in more detail.

Section 4

Hypothesis 5

The multi-attribute costs and benefits of GHG mitigation options, under different scenarios of criteria preference, can be included in a Multi-Criteria Decision Analysis (MCDA) approach.

Hypothesis 6

Aspects of an energy systems and Input Output model can be integrated and used to indicate optimal (but limited) multi-goal development paths.

Hypothesis 7

Conforming to strict Clean Development Mechanism (CDM) additionality criteria, may mean that certain large scale greenhouse gas mitigation options will be missed.

Thesis outline and analytical challenges

The economic provision of energy, without unduly harming the environment or society, is an important topic. There is evidence that poor modelling and a lack of awareness of the opportunity costs involved in certain policy interventions have imposed (or could impose) unintended costs on the South African economy. This thesis, with its hypotheses, and its core theme of improved market efficiency and model development, is a synopsis of specific work undertaken which attempts to address these deficiencies.

A brief description follows for each chapter in this thesis. The first two chapters are introductory, superficially setting the scene for specific analysis which follows. Chapter 3 gives an analysis of the entire energy system, Chapters 4, 5 and 6 discuss aspects of household energy provision. Finally Chapters 7, 8 and 9 focus on large scale greenhouse gas mitigation in a developing country context.

Section 1: Setting the scene

The first two chapters of this thesis help to set the scene and discuss aspects of the South African energy system as well as common quantitative modelling tools available for analyzing the energy system.

Chapter 1: Energy in South Africa and options for sustainable development

The chapter discusses system sustainability. It then describes some benefits that may be derived by analyzing technical scenarios of development and internalizing externalities. Finally it describes South African energy supply and demand and the options for future energy provision.

The South African energy sector faces challenges and opportunities. On the one hand it has inherited aspects of a well planned system of supply. On the other it suffers from inefficient – and sometimes harmful - energy use. This chapter sketches some aspects of the energy system and postulates potential qualitative options for its development.

The chapter does not translate any of the suggestions into quantitative values for policy development. It provides a qualitative background to the issues; quantitative analyses follow in subsequent chapters.

Chapter 2: A short introduction to common E3 modelling techniques

This chapter outlines some of the more common approaches, setting the context for analyses that follow. Approaches described are: general equilibrium, input-output, optimization and simulation models, all in the context of energy policy analysis.

Many ‘standard’ approaches can be used for the quantitative analysis of an energy system’s interaction with the environment and the economy. Each has its own strengths and weaknesses.

Section 2: National energy modelling

This section uses quantitative modelling to analyze the mitigation of greenhouse gas (GHG) emissions of the South African energy system.

Chapter 3 A least cost GHG mitigation pathway

This chapter estimates the levels of Green House Gas emissions from the South African energy system and the costs of reducing them over a period of time. These reductions are evaluated against a business-as-usual ‘baseline’ scenario. Estimates of the most suitable configuration of the energy system are also to be established. The costs and emissions savings of a number of technical measures are computed in order to estimate 'macro' mitigation potential.

The chapter demonstrates that under certain (common) circumstances, environmental goals can be realized while simultaneously lowering economic costs.

The analysis models scenarios of the supply and consumption of energy in the South African system. It includes technologies and associated costs required to supply and to save energy as well the emissions that result from their use. One scenario represents the evolution of energy supply and consumption with business as usual (baseline) practice. Another estimates a more cost effective (optimized) scenario. This optimized scenario is then subjected to a series of constraints – forcing it to meet increasing limitations on the emissions of Carbon Dioxide. The scenarios are compared in terms of their costs and emissions.

An important simplification is that the energy system is approximated by a number of linear equations. This approach is common for such an analysis (see Chapter 2). It provides mathematical approximations of different configurations of the technologies that comprise the energy system. The E3 model used in this analysis is called an optimization model (and a description of this and other approaches is provided in the next section.) While useful, the approach is also limited as it assumes that the demand for services which require energy is unchanged for each scenario. Although the demand for services derived *from* energy may change as the economic ripple effects of energy investments are felt, this feedback is not included. The model simply arranges technologies in the most cost effective manner (under different constraints) to meet an exogenous demand for services.[3]

The resulting work was the first attempt to develop such an integrated cost benefit analysis for South Africa. It helps quantify the concept of a range of economically profitable and environmentally benign interventions. It also clearly identifies supportive technology investments.

Section 3: Energy Supply to the poor: consideration and models

In the next section, the focus is on low income consumers. It begins with a non-modelling piece which describes some aspects relating to market inefficiency in low

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[3] Note that the effect of reduced consumption of fuel with higher energy prices is estimated as more costly, but efficient, appliances are allowed to enter the model solution. However, consumer decisions to sacrifice the consumption of certain energy services due to higher prices, is not estimated. This simplification is made as the cost fluctuations between scenarios is small and supporting data not available.

income rural areas. Following this, a simple model is developed to consider the efficacy of a subsidy which supplies a quantum of free electricity to poor households. The final chapter in this section shows the benefit of improved modelling of households in a typical optimization model

Chapter 4 Calabashes for kilowatt hours - rural energy and market failure

The chapter begins by broadening the definition of fuel transition to include changes in patterns of use as well as fuel type. It then discusses factors that can drive energy consumption (both by consumers and producers). Assuming that these drivers hold, the effect of common market related failure - on these and therefore - on fuel consumption is suggested. Finally the chapter describes a case study, where over-harvesting of woodland was resulting in the loss of a valuable carbon sink. A subsidy was provided at levels comparable to the international price of CO_2 mitigation (at that time) to attempt to correct for the environmental damage. The changes in energy use patterns were noted as well as possible market related failure which could have influenced these.

Markets rarely work perfectly. And this is perhaps particularly so in low income, remote rural areas in developing countries. The models used and developed in this thesis point toward the shape of a perfect market (assuming perfect completion, (full and non-asymmetric) knowledge and no abusive monopoly power). However, due to information, governance and other failures, energy use patterns may be distorted. In low income settings, energy use can have severe effects on health. In particular the traditional use of biomass, associated with poor ventilation and emissions controls[4], is associated with the death of over one million people annually (WEC/FAO 1999).

This analysis involves no modelling. Rather it discusses and identifies possible market related failures in rural low income areas. Anecdotal arguments and information from the literature are collected, as well as some quantitative data from a case study. (This same case study is then analyzed in more detail in the next chapter in a modelling effort.) Taking this information, it argues that there is a causal link between these failures and energy use in low income rural areas in some developing country settings.

The objective of this chapter is to show that with certain market related failure, traditional patterns of biomass use (together with their associated health effects) can be entrenched.

Unfortunately the analysis is limited as there is no formal regression or attempt to formally link and measure changes in 'market related failures' with measured changes in

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[4] This is in contrast with, for example, wood burned in a well ventilated home with a chimney.

energy use patterns. It does however serve to introduce some of these notions in a single discussion.

The work assumes that low income users in remote settings would tend toward the energy-use patterns of the rich. As incomes increase and with that often the affordability of "fuels of choice", there is a move toward more convenient and healthy[5] energy-use patterns. (There is often a reverting back to the use of biomass in developed countries, however this is often with different patterns of use: the fuel is often fully commercialized, ventilation is much improved, and it is rarely the main source of fuel[6].) Further, it may be that the transition away from traditional patterns of biomass use is related to increases in the price of biomass, making alternatives relatively cheaper. This chapter argues that if that is the case (increasing biomass prices) then land and other factors comprising the cost of biomass are probably being allocated more efficiently – reducing market failure. Or in some cases, the opposite: the commons may be tragically eroded and unable to meet the demands for fuel.

Chapter 5 Beyond BEST – the efficient provision of pro-poor energy subsidies

The chapter begins by introducing the South Africa's recent history of pro-poor energy provision, including tests carried out for the provision of free basic electricity. It then goes on to describe the model and analysis methodology. Finally, it discusses the results and concludes with policy recommendations.

In many countries governments introduce subsidies to encourage social, economic and environmental goals. (In the case of South Africa, the provision of a Free Basic Electricity (FBE) policy is being implemented.) However, these subsidies may not be executed in the most market friendly manner. It may be that better subsidy design (should the path of subsidy be committed to) could yield far greater results. Further, modelling the dynamics and costs of the energy system, and therefore the implications of interventions such as subsidies, can be complex. The policy maker may not be equipped to decipher the results of an essentially "black box" energy model. The results of such modelling may be brought into question as the methodology is not easily tested or well communicated.

The aim of this chapter is the development of a simplified but robust model to compare the cost of two energy subsidy "interventions": the provision of a quantum of electricity

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[5] However, while local environmental and health conditions have improved in developed countries at the point of fuel use, damage has often merely been displaced.

[6] In no developed OECD country, for example, does biomass constitute the major household fuel, while it does in many developing countries.(See IEA (2007d))

and an alternative. As electricity system dynamics are complex, simplifying its representation, may affect the accuracy of cost estimates. However, if an analysis could be done such that, at each simplifying turn, the cost-estimate of electricity production is clearly underestimated, the result can be useful. As, if for the same price calculated for electricity provision (which is now underestimated) more utility can still be gained from the alternative, it is clear that electricity subsidy may not be optimal.

The objective of this piece is to show that by developing a simplified electricity model, the South African government's provision of free basic electricity is a potentially inefficient subsidy.

Additions to knowledge include a simple and novel method for estimating the "floor cost" of electricity provision. This is a cost of provision that is lower than the actual cost. Using this estimate, inferences are drawn about the efficacy of alternative fuel subsidies. Further, it shows that in the case of South Africa, alternatives to electricity should perhaps also qualify for subsidies as the user has much to gain – should alternative be acceptable to them.

The work is limited in several respects. It considers the South African case only, though the methodology is "abstracted" and could be applied elsewhere. It also focuses on cooking activities. This is a single use of fuel and one in which electricity and alternatives compete. Although, this is an important use of energy, there are other uses for which electricity holds distinct advantages. It is not argued however that the consumers use, or the government subsidize, a single energy carrier, but rather that alternatives be included as potential targets for the subsidy. (If the costs of a "multi-fuel" strategy are not prohibitive, the consumer is free to choose his or her preferred combination.) While the alternative compared in this case is Liquid Petroleum Gas (LPG), there are several others that could have been chosen. As with all fuels, LPG is also subject to its limitations; if not treated with care it carries significant health and environmental risks.

The analysis relies on several assumptions. In particular the cost of fuel used in calculations and other attibutes are subject to a sensitivity analysis. Further the cost of LPG provision and administration is based on the results of a pilot study whose longer term effects and costing are not available.

Chapter 6 Appropriate analysis of low income energy use

The energy use patterns in remote rural low income households have not been described well in a quantitative manner. Models have often oversimplified aspects of energy use and therefore produced incorrect results. In particular in South Africa, home to one of the most successful recent electrification programs, model estimates of electricity consumption have been greatly exaggerated. For example, a dynamic not included in previous modelling, though common amongst low income users, are the use of appliances for multiple purposes (such as concurrent space heating and cooking). Further household surveys, as typically carried out in these areas, do not include information required to model a move to electricity use. For example, “time of activity data” is rarely included, but needed to construct load curve information.

The aim of this chapter is to better describe the use of energy by low income consumers in a quantitative optimization energy model, from survey design through to analysis. This should result in model results and representations which are closer to reality than previous attempts.

The objective is therefore is to show that appropriate modelling of low income rural settlements can be improved by considering dynamics such as concurrent space heating and cooking.

The work contributes to knowledge by showing that previous efforts to model the dynamics of low income rural energy users can be significantly improved. Both the application of standard modelling technique is novel as well as adjustments to those techniques.

Aspects of the modelling are limited. Some of these limitations are standard to the techniques employed. These include reducing user preferences to costs as well as problems associated with cost-based choices. Optimization models will tend to the cheapest solution whether cost differentials are high or not[7] – while in reality choices may not be as discreet. There are also limitations associated with using questionnaires rather than measured data to calibrate a model.

The layout of this chapter is as follows: it begins with a brief introduction to energy use in rural Africa, the modelling framework employed including its special aspects, notes on the survey used and the village case study. Finally scenarios are developed, results analyzed and conclusions and recommendations drawn.

Section 4: Development and GHG mitigation in industry

In the final section, the focus shifts from low income households to large scale greenhouse gas (GHG) mitigation from industry. The focus is on energy efficiency mitigation options which can at the same time help promote other national development goals. The first chapter demonstrates a method for comparing different mitigation options

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[7] Often metaphorically compared to “modelling on a knife edge”, even the smallest difference in cost causes one option to be completely chosen over another.

with different attributes. The method employed is a simple multi-criteria decision analysis (MCDA). Building on this work, the next chapter describes an optimization model which is programmed to solve for multiple goals. Rather than comparing mitigation options in isolation in a static manner, it derives scenarios of development and includes some economy-wide interactions. Finally, the model of the previous chapter is used to demonstrate the benefits of a national energy efficiency policy, which may not benefit under mitigation policies such as the Clean Development Mechanism (CDM).

Chapter 7 A framework for analyzing greenhouse gas (GHG) mitigation options

The chapter begins with a brief introduction to the problem statement. It then describes the simple Multi Criteria Decision Analysis (MCDA) method employed, including the mitigation measures and criteria for their assessment. The attribute data of the measures is gathered and estimates of data uncertainty and the artificial scenarios of development are made. Finally results and implications for policy are drawn.

In order to reduce global greenhouse gas emissions, developing country governments need to be engaged. It is estimated that the developing world will pollute more than the developed (on an annual basis) by 2020. However for developing countries, there may be far more urgent goals. In the case of South Africa, whose unemployment level is over 30%, efforts are directed at job creation. Further studies which indicate the effects or attributes of measures to reduce greenhouse gas emissions are often disparate. They vary in accuracy and scope. Finally there may be varying or changing opinions of what constitutes the most important development goals.

The aim of this chapter is to use a simple multi-criteria decision analysis to provide a first-order ranking of greenhouse gas (GHG) mitigation options in terms of selected development goals. These ‘goals’ are simply attributes of the wider economic, social and environmental setting that mitigation options may affect. For example (as they are mitigation measures) they will reduce emissions; by changing activity in the economy more efficient, they may affect jobs; and as some reduce costs, they improve industry profitability. (All of these are important development goals). The analysis uses deliberately extreme scenarios of which goals or attributes are most important and, in these contexts, mitigation measures are compared. It is shown that certain mitigation measures may rank highly in different extreme scenarios of development. If they rank highly under those scenarios, they are likely to rank highly under less extreme, more realistic and likely scenarios.

The objective is to show that a Multi Criteria Decision Analysis (MCDA) approach can be used to indicate the multi-attribute costs and benefits of greenhouse gas (GHG) mitigation measures under different scenarios.

The work is important as it provides, in a simple application, a method for exposing greenhouse gas (GHG) mitigation options which are in the interest of the developing country.

Analysis is limited in at least three important aspects. Firstly, I consider only attributes which are affected by these greenhouse (GHG) mitigation options (and am limited to considering mitigation options only). Therefore goals which may be very important but are not affected by or are not GHG mitigation measures will not be considered. Sanitation and primary health care may be a more important focus area competing for a government's scarce resource, for example, but is not considered here. Secondly, there are limitations associated with the approach. As an integrated system is not considered (data is collected from disparate sources) the effects of combining mitigation measures may not be well estimated. Finally, a more rigorous analysis of the results could by made such as considering varying confidence intervals or deducing statistical differences when error intervals overlap. This may however this may detract a little from the central message aimed at policy makers. The analysis limits itself by not commenting on the nature of the robustness of the mitigation measures. It is the case that the outcome, from an analytical point of view, is simple. There is little complexity, and deliberately so. From a policy maker perspective, this simplicity can serve to improve buy-in and guide future detailed analysis.

It may be assumed when developing artificial and extreme development scenarios that a solution which is common to all of them will also feature when development goals are given more moderate and realistic weightings. However, this approach has specific limitations. In this case the "solution plane" is continuous (as everything is weighted in some linear manner), in other cases it may not be. Thus, in this case it can be claimed that extreme and artificial scenarios can bound the likely solution. If the same solution appears in all of the extreme scenarios, it is likely to be robust. The approach can show how it may be important to determine aspects such as the accuracy or weighting of development goals more carefully[8].

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[8] This is particularly the case when, given a certain confidence interval, competing options can have overlapping range of results. Overlapping result ranges can occur as ranges of uncertainty is attached to attribute data of options as well as the weighing of different goals. A scattered set of results for each option considered is generated by simple Monte Carlo runs. Inference is made about the range of the results subject to a given confidence interval common to the score of each option. While overlapping results do not make them devoid of statistical inferences, for simplicity we consider only a single

The contribution to knowledge of this piece, in the South African context, is simply that greenhouse gas (GHG) mitigation options can be compared more broadly than simply using a cost benefit analysis. It also shows in a simple transparent manner that certain measures encourage development.

Chapter 8 Mapping out climate friendly development

The chapter begins with an introduction and background. Next the methodology is described followed by a note on the integration of the MARKAL model with an Input Output model. It describes the scenarios used and draws conclusions and recommendations.

While it is useful to collect reports and analysis to compare in the MCDA methodology described in the previous chapter, this holds several undesirable restrictions. As the relationships in the MCDA analysis (described above) are static, there is no way that combinations of related mitigation measures can be analyzed. Because dynamic assessments of different combinations are not possible, it is also not possible to derive the optimal combination of measures to meet the goals mentioned above. Furthermore, a standard optimization approach, as described in chapter 3, has other problems. Firstly, it is normally set up to optimize for a single goal – cost minimization. Secondly, the demand for energy may be a function of new investments in the energy system. Some argue that new investments which reduce emissions, but are also cost effective, will ultimately lead to more emissions. The argument is that they will lead to increased economic activity – causing emissions to "rebound". In chapter 3 the modelling effort sought only to find the least cost configuration of energy technologies to meet an exogenous demand.

The aim of the analysis in this chapter is to apply a model which will optimize an energy system for several goals, rather than just minimizing cost. This model should also include an estimate of changes in energy demand as a function of energy investments. From this, optimal combinations of mitigation measures that meet other development goals and take into account emission "rebound".

The objective is to show that by combining aspects of an input-output model, included in an energy systems model, optimal (but limited) multi-goal development paths can be indicated.

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confidence level of 95%. Should the result ranges of two options overlap we will not be able to say with a 95% certainty that one is better or worse than the other.

This analysis is important as it begins to lay a relatively transparent framework for analyzing and developing quantitative scenarios for mitigation strategies.

The approach is however limited in several respects. Firstly, the focus is on the electricity sector, both in terms of new power station investments and electrical energy efficiency measures. (This sector is the biggest single emitter in the African context.) Secondly, the input output approach is not dynamic. A static table is used, which means that the possible substitution of production is not considered. The multipliers (relating investment to changes in demand for electricity), are also based on a single snapshot of the economy - these may change in the long term. However, energy investments (or rather changes in energy investments) are specific – and unlikely to change significantly. Thus, they are assumed not transform in nature and in this analysis the cost changes are marginal.

The work represents an addition to knowledge as it combines aspects of an input output model with a multi-goal optimization model.

Chapter 9 Beyond the baseline: Kyoto, mitigation and development

The chapter begins with an introduction and then a description of the opportunity that industrial energy efficiency offers the economy. It then contrasts a reference scenario with an alternative "energy efficiency" scenario using the model developed in the previous chapter. Results in terms of greenhouse (GHG) emissions saved and jobs created are reported. Finally it discusses policy and potential international incentives which would help encourage these efforts.

The mechanism developed to effect greenhouse (GHG) mitigation in developing countries under the United Nation's Kyoto agreement is the "Clean Development Mechanism" (CDM). The CDM allows developing countries to receive funding to mitigate GHG emissions. These emissions savings must be "additional". That is, they should not happen without receiving the said funding. What then is the plight of emissions which may be mitigated under different "business as usual" development scenarios? What of emissions which may be mitigated, but would have been mitigated simply as a co-benefit of addressing other national development goals? With effective policy they may be mitigated, with ineffective policy they may not. Whatever the case, it is difficult to argue that the savings are "additional".

The aim of this short chapter is simply to illustrate that were the South Africa government to meet its energy efficiency policy it would reduce significant quantities of greenhouse (GHG) emission. However, if this policy target is not met, it would be difficult to motivate that CDM funds should be used as the policy is not additional.

The objective of this note is to show that, by having to conform to strict Clean Development Mechanism (CDM) additionality criteria, large scale greenhouse gas mitigation options may be missed with the current CDM structure

The work is important as it adds impetus to the urgency to expand the framework which has been developed to reduce global greenhouse gas emissions.

The work is limited in that it is indicative. It shows the benefits for meeting the national energy efficiency target of South Africa by using the model developed in the previous chapter. There is no way of knowing whether the scenario will or will not be met. It is however clear that the CDM will play a little role in encouraging this future unless it is amended or re-interpreted.

The work contributes to knowledge simply by illustrating that large-scale emissions mitigation may not be occurring as quickly as it could.

Conclusion

The introduction outlined the various chapters of this thesis, along with their objectives, analytical challenges and additions. The thesis is compiled from a series of peer reviewed papers which cover a range of topics: from the analysis of discreet rural village of Africa, to the electricity supply system of South Africa to global international environmental agreements. The thesis shows that improved modeling can warn of inefficiency in development policies and provide quantitative scenarios of how these may be remedied. In each case there are two common and broad notions. One is the analytical approach: macro aspects of the energy system are indicated by considering its components on a relatively micro level. The other is the sense of relation. The entire system is connected. Sustainable energy development is a function of household choices and of international policy.

Section 1: Setting the scene

This section of the thesis sketches the scene for the detailed analysis in the chapters that follow. This helps identify selected existing and future policy-challenges, for which modeling will be developed and employed to illustrate potential inefficiencies and suggest solutions. Both chapters 1 and 2 are superficial and provide only brief introductions. I begin with a summary of the South African energy sector. It has abundant cheap coal, inefficient industrial energy use, insufficient generation capacity, inequitable access to energy, misguided subsidy policy and, in rural areas, high dependence on traditional biomass and kerosene fuel. As a member of the global community it also needs to consider how best to engage in greenhouse gas (GHG) mitigation actions while not compromising its development. There are various technical options available for its expansion with different economic and environmental costs. The challenge is to arrange the system in a manner that is sustainable.

In order to address that question, various modeling approaches are available. Chapter 2 outlines some of these. They vary in terms of their attributes, such as data requirements, scope of analysis, time frame considered as well as others. Four model types are introduced. They include: General Equilibrium, Input-Output, Optimisation and Simulation models. Where the tools are used later in the thesis they are described in more detail in that chapter. In this chapter the reader is provided with a sense of their application and scope.

Chapter 1: Energy in South Africa and options for sustainable development [9]

This chapter outlines challenges and opportunities faced by the South African energy sector. It also outlines selected technical and policy options which it may adopt in the future. Finally it sketches the scene for the more detailed analytical chapters that follow.

Introduction

This part of the thesis superficially sets out certain notions related to sustainable energy development in South Africa. In particular it highlights key policy challenges, some of which will be the focus of modeling efforts later in the thesis. It encompasses governmental obligations, an outline of the South African energy sector and a qualitative description of various technical scenarios for its development. The chapter sets the scene for detailed modelling and for the quantification of technical scenarios. As the focus is the medium term, it is assumed that technological change and the impact of energy technologies (as well as their change) on the environment may be estimated. Or, that consistent pictures can be built of increasing energy services with a set of available technologies. Different arrangements of these technologies, bound by resource, thermodynamic and other limits, will result in different impacts on the environment and costs which can be calculated. This provides the focus of the chapters which follow. It is argued that moving the system to one that is present value (PV) cost optimal – including environmental externalities – will tend to move it to being more sustainable. That is not to say that it will necessarily be sustainable as more constraints may be required.) In later chapters it is shown empirically that simply moving the system to one that is PV optimal, even without the inclusion of environmental externalities, will reduce its environmental burden as well.

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[9] This chapter draws heavily from two earlier papers: Howells M. 2001, ‘Sustainable Energy Development in South Africa: Optimizing the energy, societal and environmental relationships in the medium and long term’, *Journal of the Japan Society of Energy Resources*, Vol. 22 No 1 pp 46-50 and Howells M. 2000, ‘Sustainable Energy Development in South Africa’, *Journal of Energy in Southern Africa*, Vol. 9, No. 4, November, pp 125-128)

Sustainable energy

South Africa is made up of diversity and contrast. Economically and culturally there is a mix of the developed and developing world. Among the challenges to sustainable growth is the necessity to provide affordable, acceptable, cleaner energy. On the one hand the system must sustain a growing economy. On the other it must provide essential services.

One can rephrase the well-known Brundtland definition of sustainable development and apply it to the national energy system: 'A sustainable energy system would be one that provides for present national energy needs without compromising the ability of future generations to satisfy their energy, or other – economic, environmental and social – requirements'.

Different views of sustainable development abound. Certain "economics" literature suggests that sustainable development requires an efficient economy. One in which the natural environment is taken into account as a valuable input, along with capital, labour and other resources. It is suggested that an extra role for the government as a custodian of the environment is needed to prevent the erosion of this common resource. Marglin (1963) argues that the economic man (individuals and firms) and the citizen (government with a longer-term interest in sustainability) are distinct. Government therefore needs to set the bounds in which individuals operate. Those bounds are based on a longer-term (intergenerational) commitment to preserving the environment. Note that not all commentators are in agreement with this view. Koopmans (1960), for example, argues that simply maximising the present value (PV) of the economic system is sufficient – no extra effort is required to include special environmental preservation. But it is clear that movement towards an economy and energy system which accounts for environmental effects - at the very least at a level which reflects their present worth - would be more sustainable than an inefficient non-optimal system which does not. Environmental effects may have costs which are external to normal transactions. These costs can be real and result in increased burden on economic actors. Including the external environmental costs would help explicitly to reduce the system's environmental and health impacts, while minimising the present value (PV) of such a system would help incresase the affordability of the energy used. It would be more affordable for social needs or as an economic input[10].

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[10] In order to derive the PV optimal system, all future costs are discounted. Some argue that "discounting" the "value" of the finite and limited environment, thereby reducing its importance to future generations, is flawed. Later in this thesis it is shown that even simply moving to a PV optimal system for our case studies improves the environmental performance of the system.

Certain "development" literature suggests that sustainable development is supported by three pillars: economic, environmental and social (see Winkler (2006) for a summary of that literature and an application). This literature also argues that economic, social and environmental development are essential and interrelated. "Development" should ensure that the environment is not unduly harmed, that the economy can grow, and that the social situation of individuals is improved. In the context of poverty, social development targets – the Millennium Development Goals (United Nations (2005)) – have been adopted by many as reasonable targets for sustainable development. And while energy provision is not explicitly mentioned in any, it is required for all. Further, given that reducing class divides is important for society's inter-equity sustainability, the provision of basic needs becomes imperative in the context of countries such as South Africa.

Another view of sustainability is labelled the "strong view" by Pezzy (1992), also called "ecological" or "environmental" sustainability. It argues that the environment cannot be substituted, as it is a resource which has been irreparably damaged. (Consider the loss of species, coral reefs, arable land to deforestation etc.) This resource can be further damaged, degraded and lost. Working backwards using the precautionary principle this view argues that certain levels of environmental stocks are always to be maintained (Daly (1990)).

This chapter suggests that technical scenarios are important. Knowing how a power station, for example, operates in terms of fuel used, costs incurred and pollutants emitted, can be extended to include other elements within an energy system. Physical and cost effects for consistent future pictures (technical scenarios) can be developed. Plausible effects of different configurations of the energy system can be thus be estimated.[11] Clearly, cognisance needs to be taken of the limits of the approach of the limits of growth. That work did not account for large scale changes in technology performance and deployment. Nor did it forecast that price changes may influence switches from one input of production to another. These are both limits of the famous work by Meddows et al (1972). Secondly, it is suggested, for Marglin's "economic citizen" or the government, appropriate information gathering and dissemination are needed for effective policy implementation. This helps sets the rules under which profit-maximising firms and individuals can act and be protected. An important set of policies would thus appropriately include aspects of environmental accounting (Repetto et al. (1989)), as well as environmental rebates, costs and penalties. Finally, assuming that investments will be

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[11] A quantified scenario of technologies and energy flows can be associated with system costs. Such an approach can provide insights into the affordability of the energy system.

made in a cost-optimal and profit-maximising manner, PV-optimal technical scenarios can be developed further to simulate possible 'perfect market'[12] behaviour.

Technical scenarios

Employing quantified technical energy scenarios, consistent future pictures of the energy system can be developed. These are useful for estimating the energy system impact on the economy, resources, society and the environment for the medium to longer term. Though this has limits[13], it can be a useful approach to analysing sustainability. This is a method for which there are precedents.[14] From such scenarios information for certain types of policy development and investment needs (in the context of our current state of knowledge) may be established. As scenarios can be used to explore the limits of the system (see IPCC (2000), for example, on global greenhouse gas (GHG emissions)), they can be useful for identifying important aspects and effects of the system. Robust interventions which are common to all scenarios could be used to identify specific strategies for development or hedging against identified risks. Some areas of specific interest and strategic research direction are needed – and being undertaken – to improve some scenarios in the South African context. These include:

- the possibility that current energy sector development will lead to future over-dependence on finite resources or on imports and other security risks;[15]

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[12] Note that (and considering also monopoly-related contortions in California in the last decade) energy markets are often less than perfect.

[13] Like Meadows et al., we may also underestimate the potential role of possible technology changes. However, as the time period is relatively short some changes may be envisioned. This is particularly the case where technology development takes time itself. The inertia in its development allows the analyst to attempt to include envisioned changes based on current technology development.

[14] For example, (IAEA (2005)) uses a methodology developed by a number of UN and related bodies to assess the energy sector's sustainability in terms of the environmental, social and economic aspects using a number of indicators. By this method, technical scenarios of energy sector development have been evaluated in several studies. This was applied to technological scenarios of energy development in South Africa to analyse both the status quo and policy or technology interventions (Winkler et al. (2005)). Similar approaches have been undertaken for Brazil, Ghana, Korea, Cuba and other countries (IAEA (2006)). For the European Union, techno-economic modelling has been carried out by Criqui (1996), in the OECD by IEA (2002) and Gielen (2003), for the United States (EIA (1997)), as well as for major developing countries such as Brazil (IAEA (2006)) and China (Kypreos et al. (2005) and DeLaquil et al. (2003)). These efforts focus on developing technical scenarios in order to understand the potential physical (and other) effects of the energy system on the environment, resources and so forth. The modelling approach used – and described later – is an optimization energy-economic-environment (E3) model.

[15] For a more detailed analysis of the quantification of the costs and benefits of energy security see Rogner et al. (2007) which includes an analysis on countries of the same type as South Africa. In this case, the risks established included environmental unsustainability and high petroleum prices, as well as the role

- the potential for economic cost savings – where the energy system is not PV optimal. Especially where these could have the concurrent effects of reducing the cost of supply, extending local, national, and regional resources while also reducing emissions.[16] (This is a focus of subsequent chapters);
- the technical potential for power pooling in the region and the implications of energy demand growth rate predictions for South Africa and neighbouring countries;[17]
- the potential for distributed power generation where energy is generated close to the consumer. Examples include instances when power sources may be cheaper at the location required than the combined costs of electricity generation, transmission and distribution[18] (Chapter 6 considers this for remote villages);
- the impact of novel or alternative[19] technologies or fuel chains;
- scenarios establishing the applicability of technology transfer. For example, the US initiated climate action USAID (2007) is based primarily on technology-transfer activities which transfer lower carbon technologies to developing countries. Though not focused primarily on transfer, the Kyoto mechanisms the Clean Development Mechanism (CDM) and Joint Implementation (JI) could have the same effect. Modelling these is of importance. Nevertheless, technology-transfer solutions need not be limited to "north-south" examples;[20]
- scenarios examining the effect of improved (thermal) energy efficiency[21] and other technological options which affect energy use as a function of cost. These must be established (this, for industry, is a specific focus of chapters 7, 8 and 9);

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that technical options such as renewable resources may play in mitigating these energy security risks.

[16] See: DME (2004a)

[17] An example of such an analysis is one undertaken by Alfstad (2005), which considered the savings that would accrue by accelerating interconnections in the Southern African region. Earlier studies were carried out by the Southern African Power Pool Sparrow et al. (1999).

[18] Studies which focus on the analysis of the distributed generation in the African region included in this thesis are Howells et al. (2005) (chapter 6). In South Africa, off-grid generation is of particular importance for supplying millions of people with electricity where distance from the national grid increases the costs of conventional connections, although the economic rational for this argument has recently been questioned Gaunt (2002).

[19] In the aforementioned (Rogner et al. (2007)) work, the role that large-scale alternative Renewable Energy Generation could play was analyzed in comparison to conventional sources. This was done under different conditions and in the context of different countries.

[20] The national electricity supply body Eskom, for example, is completing the construction of a Fluidised bed plant together with an Indian consortium (van der Riet (2003)). Both countries have similar coal types.

[21] The appendix of this thesis presents an analysis on a national level and is drawn from Howells (2006); other related studies include Hughes et al (2003) and Trikam et al. (2003)

- PV, PV + environmental cost optimal,[22] and emissions mitigation scenarios (see Chapter 3) in the context of national development goals (see Chapter 8).

Externality costs

In order to develop PV optimal scenarios which include environmental effects, it is important to assign a cost to these effects. We do so by adding an approximate "external cost" to the cost already included in the energy system analysis. Typical (non-external) costs included in a partial energy-systems optimization analysis include resource, capital, operation and trade costs. An environmental externality is "a change in utility or welfare of an agent, brought about by another, where this change in welfare is not compensated for, or appropriated, by the latter" (van Horen (1996b)). This externality[23] may be either positive or negative and the focus in this work is on damage to the environment or to the health of individuals which is not compensated. Including externality costs derives a basis for estimating the impact of the energy system on the environment or society which tends to be more completely[24] PV optimal. This in turn can help the policy maker to set minimum targets for reducing the environmental impact of the system. (The difference in effect on the environment between a cost optimal scenario with and without external costs could be translated in to policy in a number of ways. One way may be to impose limits on the environmental effects of the energy system to mimic the impact of accounting for external costs.) As discussed in section 1.2, this level of environmental protection may not be sufficient, but it is nevertheless a rational starting point. As evaluating external costs is often a subjective process,[25] the methodologies used must be transparent and include stakeholder acceptance.

Information and policy

Information dissemination is a prerequisite for a national system which tends to sustainability. Given that knowledge is missing or asymmetric, an effective role for government will be both to disseminate knowledge and to develop appropriate market rules which tend to protect individuals (and the environment) from the investment distortions that result. As South Africa requires significant social investments, setting

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[22] For a limited estimation of externality costs in the South African context see: Chapter Six of this thesis, Howells et al. (2005), and de Villiers (1999). The question is also discussed in detail by van Horen (1996a) and van Horen (1996b).

[23] This externality is distinct from occurrences that shift production along the efficient production frontier.

[24] By definition these external costs are already born by the system, by keeping them external from the culprits their decisions are not PV optimal.

[25] See de van Horen (1996a), and ExternE (EC1999) for a detailed treatment of the subject of energy and the external costs and benefits – the former deals with South Africa and the latter the EU.

appropriate rules and subsidies for the market to drive down the costs of these investments is an important step towards improved market efficiency.[26] Several examples of this exist in the current energy system.[27] Unfortunately, particularly in the area of energy efficiency potentials[28] and recently illustrated by power supply shortages,[29] clear information availability or dissemination – and rule setting – has not been effective. For this reason,[30] amongst others, it is estimated that energy savings are possible for industry and commerce with significant medium-term financial gains.[31] A useful start would be the development of comprehensive databases of current fuel cycles from energy resources, its use, its impacts on the economy (and vice versa), social development and specific strategic issues – such as improved security, electrification options , sufficient energy supply options, potential fuel export roles, etc. Such information, in coherent accessible databases, can help further form the basis for sensible policy.[32]

In the short term, governmental 'encouragement' of sustainable energy development is essential. This should be underpinned where appropriate by the analysis of economically, environmentally and socially optimal development paths. The tools used for the

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[26] Social investment in the energy sector is argued by Munasinghe (1992) and others to be essential for development.

[27] An example is off-grid electrification in the South African context. It is too costly to be borne by the consumer directly Gaunt (2002), so remote areas are divided up into "concession" areas. Private companies bid to provide these areas with off-grid electricity – including maintenance – and the lowest technically competent bidder is awarded the contract.

[28] See for example information pertaining to industrial energy efficiency (http://www.dme.gov.za/energy/efficiency.stm). Various links on this site provide much of the limited official data available to South African industry. In South Africa, the only other publicly available repository of information is www.3e.uct.ac.zahttp://www.3e.uct.ac.za/. Only recently was some information released relating to potential power station costing for South Africa (NER2004). Even this did not include information on detailed load profiles for electricity production – necessary for comprehensive power station costing. In households there is no database which reports detailed fuel use by activity by household type. National statistics do report questionnaire data, but this is limited, with no absolute quantities reported (see for example: http://www.statssa.gov.za/census2001/digiAtlas/metadata.html#28). A detailed review of available data is given in Hughes et al. (2002), and new – but unverified – estimates are compiled therein.

[29] Though warned in several highly visible reports (see, for example, NER (2004) and DME (2003)), government failed to encourage new power station investments urgently in the early 2000s.

[30] Some examples of the potentials for electricity savings in industry are given in Appendix A and Howells (2006).

[31] This inference is based on detailed energy audits undertaken by the author and others of high profile industrial plants based in South Africa: the world's second largest brewer SAB-Miller (Kenny et al. (2000a)), AngloGold (the world's largest gold mining company (Kenny et al. (2000b)), VW South Africa (van Es et al. (2002)) and SAPPI (Kenny et al. (2000c))).

[32] Currently data exists in separate studies (see, for example: Louw et al. (2006), Gaunt (2002), Gaunt (2003), Haw & Hughes (2007), Howells (2006), Winkler et al. (2005), Afrane-Okese, Y. (1999) as well as others mentioned in previous footnotes).

implementation of such integrated energy planning into policy vary and could include (according to Munasinghe (1990)):

- physical controls, such as short-term supply rationing;
- investment policies;
- education policies;
- taxes or subsidies;
- market controls, such as regulating residential coal prices or the marginal pricing of electricity;
- establishing energy efficiency agencies.

With the necessary information, appropriate regulation and appropriate use of the marked, the basis for a more sustainable energy system could evolve. A short description of major national energy carriers, reserves, fuel supply and demand sectors in South Africa follows. Mention is also made of shortcomings of the energy sector. Of special interest are the energy options for the residential sector, which is characterised by the imperative of meeting basic needs of the poor. In the industrial sector energy efficiency holds special cost, fuel and emissions mitigation potential. Another important aspect is the electricity supply shortage. These and other needs are discussed and possible technical solutions suggested.

An introduction to the national energy system

South Africa presents a good example of the challenge posed by the need simultaneously to reduce pollution (such as greenhouse gases (GHGs)) and promote economic growth. The South African economy is emissions-intensive; seven hundred and seventy tons of CO_2 are emitted for every million international[33] dollars of economic output (WRI (2005)). This is 27% more than in the United States. The energy system is next summarized in terms of energy carriers (supply) and consuming sectors (demand).

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[33] Purchasing power parity exchange rates and emissions levels for the year 2001 are quoted.

Energy supply[34]

Coal

The national energy supply system has in the past been relatively secure[35] and relatively well-structured, with recent and significant shortages in the electricity sector. South African energy is dominated by coal, which contributes 72% of primary energy (DME (2005b) and IAEA (2007a)) and fuels 94% of electricity production (DME (2005b) and IAEA (2007a)). Currently, 35 % of the coal mined is exported. Of the total South African supply, 59 % is transformed into electricity, 19 % into petroleum products, 5 % into gas and the remaining 16 % is used directly (Howells et al. (2002) and IAEA (2007a)). Energy supply is therefore also carbon dioxide intensive. Much of the coal mined is of low quality; it is often, therefore, mechanically beneficiated (DME (2004e)). Solid waste is discarded annually and about 6.3 million tons were produced in 2003 (DME (2004e)). The industrial, commercial, transport and residential sectors all directly consume coal. Using a Gaussian analysis and extrapolating from historical rates of consumption and depletion, Dutkiewicz (1994) estimated that pressure on coal supplies would only be felt from 2012, with peak production occurring in 2070.

Petroleum

Petroleum products account for 32 % of total final (energy) consumption (TFC). Liquid fuels are derived from refined crude oil, liquefied natural gas and coal. The last-mentioned is carried out by the Sasol coal-to-oil process. Most of the refined crude oil in the country is imported and a small amount of natural gas is liquefied in the Mossgas liquefaction plant. Of the TFC of liquid fuels, 75 % is derived from crude, 33 % from coal and 1 % from natural gas. In 2005, 151 million barrels of crude oil were imported (IEA (2007a)). Currently there is an imbalance in the diesel to petrol demand from the transport sector. As this situation persists and is exacerbated, pressure is be placed on refineries and refined petroleum products (petrol) have to be imported. Although small oil reserves are located offshore, petroleum supply is associated with a high import dependency. Gas field reserves are also limited, and the Mossgas installation is unlikely to continue much beyond the decade (Howells et al. (2002)).

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[34] Definitions of energy supply and demand are based on International Energy Agency Standards (IEA IEA (2004))

[35] The system has been secure in the sense of sufficient investment in supply technologies. Many of these investments were however driven by possible (insecure) supply risks associated with politically motivated embargoes.

Gas

Gas consumption plays a small part in the South African energy mix, accounting for only 3 % of primary energy supply and 3 % of final consumption (DME (2005b) and IEA (2007b)). Natural gas supply has in the past almost exclusively been used by the Mossgas gas-to-oil plant and most of the gas consumed directly is produced by coal gasification. By international standards gas consumption is low, due to small reserves, and little has been done to establish industrial gas networks. Although total domestic reserves are not significant, the opportunity for using this potentially low CO_2 emission fuel is not being taken advantage of. Recently, gas imports from Mozambique have entered South Africa, providing 77 400 Tera Joules (TJ) of gas to industry and for the expansion of the SASOL plant to include some Gas to Liquids processing.[36]

Electricity

Electricity supplies 28 % of national demand (DME (2005b)). The national supply body, Eskom, supplies 95 % of demand, with the remainder supplied by small inputs from independent power producers. Due to an inexpensive coal supply, Eskom boasts the lowest electricity cost in the world.[37] Ninety-one percent of electricity is generated from coal, with small amounts coming from hydro and pumped storage (4 %) and nuclear (5 %). Sulphur- related emissions from power stations, though significant at about 1.5 million tons per year (NER (2004) & Eskom (2004)) are tapered as the sulfur content of local coal is low.[38] Particulate (smoke) emissions control equipment are in place on much existing stock of electricity generating plant.[39] Recently the electricity system has been strained with low reserve capacity. This was predicted by previous studies principally (Howells et al. (2002), NER (2004), DME (3002). In order to fund urgent new

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[36] Indeed, SASOL is currently moving towards becoming a leading international provider of synthetic fuels production, based on natural gas feedstock, with pilot plants being build in Qatar and Nigeria. (IEA (2005)).

[37] For a detailed breakdown of ESKOM's current and South Africa's future electricity production costs, see NER (2004). Of particular interest is the exceptionally low cost of coal at just over $10 per ton. This is in part because the coal is of low quality and in many cases cannot be used for any other industrial process. Some coals have a Calorific Value of 13GJ/ton. This is so low that it cannot be lit with a blow torch (van Horen (1996b)). It can however be sintered and burned in the exceptionally large boilers of 6000 MW units (NER (2004)), typical of South African power stations.

[38] Average values for South Africa are about 1% sulfur, while international averages vary from about 0.5% to 3% (IPCC (1996)).

[39] This is divided between "bag filters" and electrostatic filters. These have a typical efficiency of over 80%.

expansion, provision has been made for the electricity price to be increased by 19%.[40] In 2006, the price of South African electricity to industry was 2¢US, less than 20% of the average tariff in the UK (IEA (2007c)). Much of rural South Africa is without access to grid electricity and the cost associated with grid extension has resulted in an increased use of small-scale renewable generation sources such as photovoltaics and micro-hydro. South Africa has a large off-grid electrification program. Although small in respect to total generation, such units are of special significance in terms of meeting 'basic needs' and providing access to affordable, appropriate and acceptable energy.

Biomass

Biomass, mostly fuelwood, is an important fuel in the South African context, supplying just over 15% (IEA (2007b)) of the national final energy consumption. The biomass fuel cycle is unregulated and, as a result, shortages exist in various areas. In particular, with reference to the loss of biomass as a carbon sink, Scholes & van der Merwe (2000) estimate that 10-30% percent was harvested unsustainably. That is, the rate of regrowth was slower than the rate of harvesting. This causes the loss of a carbon sink as well as – depending on the circumstances – land damage and vegetation change. Most biomass is consumed directly by the domestic sector, with small amounts used for charcoal production and industrial consumption in the form of bagasse and waste in the pulp and paper industry. Most of the household fuelwood used is collected from the areas in and around the consuming settlements. This has resulted in land degradation (Scholes & van der Merwe (2000)); however, many different formal and semi-formal arrangements for fuel harvesting exist and are reported in detail in the Biomass Initiative (Williams et al. (1996)) carried out in the mid nineties.

Energy conversion and demand

Whereas national energy supply is, in general, well-structured and secure – with the notable exceptions of some biomass harvesting and short term electricity supply constraints – consumption is often characterised by cheap costs, inefficient, acutely environmentally damaging use and often uninformed decision-making. Energy misuse and therefore "overconsumption"[41] have important environmental and efficiency implications. More final energy is supplied to energy users. The use of final energy has

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[40] See NERSA (2008) for a detailed breakdown of the tariff increase application. Also included are aspects of the cost components of ESKOM's costs.

[41] By "overconsumption" I do not make a judgment on the morality of materialism, but rather that the services consumed are provided at a higher monetary, energy, and environmental cost than they need be.

environmental and cost effects. These effects are amplified by the upstream transformation and extraction needed to supply that final energy. The major consuming sectors discussed next are: industry, commerce, transport and residential. Of special interest is the residential sector, where access to affordable, appropriate energy supply (and appliances) is both a need and a precursor for socioeconomic development. Also of interest is the industrial sector in which there is potential for improved (thermodynamic and economic) efficiency.

The cost of commercial energy is kept low as a result of an abundant, inexpensive coal supply and relatively efficient (though CO_2 intensive) power generation. It is argued by analysts that this offers South Africa an important economic edge, reducing import requirements and freeing up the use of energy intensive technology which may otherwise be uncompetitive (Dutkiewicz (1994)). However, due to a lack of specific knowledge, poor market structures and data availability,[42] it has often been incorrectly assumed that medium- to long-term profits are being maximised. This is discussed in more detail in Chapter 3. The result is inefficient energy use. This in turn leads to accelerated national reserve depletion, increased costs, and increased environmental emissions. Current low energy costs – as argued by Eberhard & van Horen (1995) – are also retarding the potential development of new energy sources. Thus increased fuel mix and diversity is limited, which can (though it does not necessarily) carry associated supply security risks.[43]

Large quantities of coal are used for power generation, liquid fuels production, and direct consumption. Linked with its extraction are noticeable environmental impacts. Thus increased electricity and petroleum demands result in important 'upstream' emissions and environmental impacts. For example, most of the methane released from the South African energy sector is a result of coal mining (Lloyd et al. (2002b)). Land scarring occurs with pit digging and discard dumping. Discard dumps are prone to spontaneous combustion, water pollution from run-off and increased surrounding particulate concentrations (Howells & de Villiers (1999)). The conversion of coal to petroleum products is about 40 % efficient,[44] with significant emissions resulting. National power generation is relatively efficient, operating at about 35 % (NER 2004). Coal-burning power stations produce large amounts of CO_2, SO_2, NO_x and ash. However, current stacks

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[42] See DME (2004a) for a detailed critique of industrial energy use patterns.

[43] An example of a security supply risk owing to South Africa's dependence on coal is discussed in Rogner et al (2007); a continued expansion in coal usage may incur penalties were new GHG emissions trading regimes, such as a carbon tax, implemented.

[44] That is, measured as energy content, for every 100 units of fuel consumed, only 40 units of fuel are produced. (DME 2002).

that penetrate the inversion layers[45] and effective electrostatic (ESP) particulate controls minimise impacts by reducing or further dispersing all but the carbon dioxide emissions. This does not mean to say that the pollution is abated; rather it reduces the average load per unit of area of the local environment. A detailed treatise of the environmental effect of coal-fired electricity generation in South Africa can be found in van Horen (1996b). Also, the coal used by Eskom is of such low calorific value that it has no other commercial use. Thus its use has limited impact on potential foreign exchange earnings. From an economic point of view (barring environmental effects) the optimal use for this resource is currently electricity generation.[46] From a sustainability point of view a further question arises: should the coal be used now or preserved to be used later with more efficient technologies? With the current set of technologies and assuming little change, a PV-optimal response is to use it now. This is especially the case as there is little information which, with any confidence, can point to specific technology breakthroughs. Perhaps the most convincing motivator to delaying the use of coal would be its environmental effects – in particular GHG mitigation. However, until a clear and agreed greenhouse gas mitigation regime, which is likely to facilitate this change, is in place it is difficult to argue against the fuels continued use.

Industry

The industrial sector consumes just over 35 % of final energy, of which 39 % is from coal (including gas derived from coal), 41 % from electricity, 4 % from petroleum products and 8 % from gas (IEA (2007b)). Energy intensities (the energy used per unit of output from that industry) are high relative to OECD countries (Hughes et al (2002)). In some instances, specific industries consume up to twice as much energy per ton output (WRI 2005). The low cost of energy has encouraged the growth of energy-intensive industries such as aluminum smelting and mining. The use of this low-cost energy is (thermodynamically) inefficient, although there are significant opportunities to save energy and related environmental impacts cost-effectively by means of energy efficiency measures (Trikam (2001); ERI (2000)). Further, these measures will not necessarily change the economy's energy-intensive structure (Trikam (2001)), but rather move it towards better practice and increased profitability (Laitner (2004)). The South African

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[45] Note that this does not imply that the emissions are mitigated, rather that they are transported and dispersed. The damage per area of land is reduced as emissions concentrations are reduced. Future electricity expansion in coal-fired plants are expected to desulphurise their emissions to within World Bank Guidelines (NER 2004).

[46] Though with higher oil prices, this coal becomes more competitive for use in synthetic fuel production.

Department of Minerals and Energy recently (DME (2004a)) developed an energy efficiency strategy in order to help realize policy goals. It estimates that energy consumption in 2013 can be reduced by 12% over what is otherwise expected at that time. A renewable energy strategy has also been adopted which will have the net effect of displacing fossil fuel and reducing emissions, in many cases at a premium. The target for the strategy is to replace the equivalent of 800 tons of oil by 2013 (DME (2004a)).

Commerce

At present, the commercial sector consumes only 7 % of the national TFC. The fuels consumed are: electricity 53 %, coal 36 %, petroleum 11% and gas less than 1 %. Currently there are no thermal efficiency standards for South African buildings, thus increasing temperature control costs. Also, as developers are not involved in the utilities costs, these are typically borne by tenants. Tenants may be more interested in features such as location than utility bills. Thus little focus is placed on energy efficiencies. Studies estimate that 20 %-40 % energy savings are attainable in this sector, decreasing emissions and involving a 2-3-year payback period (IEA (1996)). Again, these increases in efficiencies offer proportional decreases in the pollution of the fuel carriers concerned.

Transport

The transport sector currently consumes 24 % of final energy consumption, of which 3 % is electricity, 0.2 % coal and 97 % petroleum products (DME (2005b) and IEA (2007b)). Energy intensities in this sector are high due to various inherited problems and poor enforcement of regulation. The national transport fleet is old and characterised by poor maintenance[47] and low occupancy.[48] The vehicle fleet has an average age of just under ten years and the heavy motor vehicle fleet about fourteen years (Bramert & Runeborg (2006)). Commuting patterns, shaped by apartheid settlement structures,[49] increase fuel consumption and thus emissions. Loading and maintenance regulations are not enforced (IEA (1996)) and potentially more efficient public transport systems are poorly planned. The result has been substantial smog increases and increased road damage.

Residential

The residential sector is characterised by extremes in living conditions and multiple fuel use (Williams (1994)). Fuels used range from electricity to, in more rural areas, complete

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[47] In South Africa there are no regular MOTs required, other than when a vehicle is sold to a new user.

[48] The average occupancy in South Africa is approximately 1.2 persons per vehicle (Howells et al. 2002).

[49] Under apartheid, the country's large (mostly black) workforce was forced to locate themselves at a distance from commercial centers. This results in larger commuting requirements.

dependence on biomass. In this sector little attention has been paid to energy efficiency until recently (DME (2004a)). Reasons include the relatively low cost of energy for the rich,[50] poor information relating to potential savings or the irrelevance of accounting for energy costs during dwelling construction in poor socioeconomic conditions. Three of the major challenges faced by this sector include (Williams (1994), Williams et al. (1996) & Eberhard (1992)): firstly, the provision of energy needs and environment reclamation, where overgathering has depleted traditional biomass supplies and damaged large areas of land:[51] secondly, the provision of services such as effective lighting facilities as a precursor for the economic empowerment and education of rural populations;[52] and, thirdly, the accelerated adoption of 'cleaner energy', reducing the current concentrations of indoor pollutants.[53] Also, in terms of consumption, commercial energy costs for the poor are high (Loyd & Rukato (2001)), thus improved efficiencies are of special importance. Under the current low-cost housing development programme, 50 %-90 % efficiency savings are attainable with only a 1 %-5 % increase in costs (IEA (1996)). There exists a significant window of opportunity to improve the energy efficiencies and emissions associated with residential dwellings. In terms of integrating the energy system with other development goals, the potential exists to promote energy-efficient practices via the education systems and community building forums. Initially, South Africa's Reconstruction and Development Programme (RDP) – now replaced by the Accelerated and Shared Growth Initiative for South Africa (AsgiSA) – instituted after the abandonment of apartheid, is driving the construction of over a million low-cost dwellings. By 2015, an estimated seven million new houses will be constructed in the country (Hughes et al. (2002)).

The sector is also associated with drastic health impacts that result from poor coal and biomass combustion conditions. High particulate emissions result and are exacerbated by poor ventilation in an attempt to increase thermal insulation (Eberhard & van Horen (1995)). The result of poor ventilation is incomplete combustion and emissions of

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[50] The cost of electricity to the residential consumer connected to the grid in 2006 was approximately 6¢US compared to 19¢US in the UK (IEA (2007c)).

[51] While this is common around usrban, peri-urban (Eberhardt & van Horen (1996)) and some growing rural settlements (Scholes and van der Merwe 2000), there are areas where overharvesting does not occur and woodfuel is the predominant thermal fuel (Williams et al (1996)).

[52] See Kanagawa and Nakata (2005a) and Kanagawa and Nakata (2005b) for detailed analysis of the improvement in literacy levels as a function of the provision of electricity and improved lighting.

[53] Traditional fuel use in huts, shacks (Eberhard & van Horen (1995)) and low-income homes without chimneys (DME (2005b)) has been identified as particularly harmful. Further these homes are often poorly insulated. During winter months, even more ventilation is sacrificed to contain the warmth.

poisonous carbon monoxide. These conditions have led to respiratory disease being the second highest national cause of infant mortality (Eberhard & van Horen (1995)). As fuelwood around settlements (Williams et al. (1996)) is being depleted (often as a result of lifestyle transition and the erosion of traditional structures and culture), the ecosystem is damaged and increased time is spent in the collection process; this is associated with losses in other opportunities. The adoption of cleaner energy in this context may help reduce particulate and noxious gaseous emissions as well as time spent collecting wood.

The short-to-medium-term potential options for the residential sector include further increased grid electrification, non-grid electrification, transition to low-smoke fuels, clean-burn stoves and general housing efficiency improvements – including chimneys (DME (2005b)) in new low-income housing. Some of the main hurdles for implementation are the establishment of fuel distribution networks (Gaunt (2002) and Afrane-Okese (1998)) and appropriate information dissemination. Potential new technologies, such as clean-burn stoves, photovoltaics, new fuel management systems and the utilisation of new commercial fuels may take time to be assimilated. Community woodlots[54] and controlled harvesting provide a method of reducing ecosystem damage. Current trends show a general movement from traditional fuels, such as biomass and dung, to the commercial fuels – coal, paraffin and gas – and finally to electricity, though not necessarily in a linear fashion (Eberhard & van Horen (1996)). This is consistent with global trends (Nakicenovic et al (1998), Victor & Victor (2002)) However, rates of penetration of commercial fuels are limited because of cultural norms, the level of expendable income, supply reliability and availability. Electrification is currently taking place rapidly, with recent estimates suggesting that by 2025 (Kenny (2002)), 92 % of households could be electrified, with 87 % using electricity only and 5 % using electricity together with other fuels. The remaining households, mainly in remote rural areas, are predicted to remain dependant on biomass. Current electrification is both via grid and off-grid supply. Off-grid supply is currently delivered to community centres such as schools and clinics and to households. The most common technologies presently employed include photovoltaics, diesel generators and micro-hydro schemes.

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[54] Williams et al. (1996) gives several examples of the mixed experience achieved by communal woodlots. In many instances, it seems that there were mismatches between the types of wood preferred and those grown. Often more than one wood type is used, varying from slow burning for cooking stews and starches, to faster burning species for boiling water.

Energy sector challenges and options

There are at least two important challenges faced by the South African energy sector. The first is to address the unacceptable lot of the poor and, secondly, to employ energy technologies and energy practices that provide inexpensive energy for a competitive economy. This should be done without excessively straining resources or the local, regional, and national as well as global environment. Clearly there are many possible future energy scenarios. The following section indicatively describes possible technical options for the future South African energy system. Although many of the technologies described are not new, they are presented in a time-frame that is probably realizable. Perhaps, within the context of responsible research, information dissemination, market rules and appropriate pro-poor policy, there lies the evolutionary development of an energy system that is optimised economically, socially and environmentally. In subsequent chapters this indicative scenario is replaced by detailed, consistent, and quantified scenarios, underpinned by E3 modelling.

Short-term options

In the short term, changes in electricity supply will be seen following the creation of the Southern Africa Power Pool (SAPP) and new domestic investment in coal, pumped storage and oil-based peaking power plants (NER (2004)). The power supplied to this pool from beyond the boarders of South Africa will presumably be generated by hydro, coal[55] and some gas.[56] The largest hydro reserves in this area are in the Democratic Republic of Congo, where a technical potential 100 000 MW exists, of which 40 000 MW of run-of-river may be harnessed (Alfstad (2005)). Currently, South Africa has a generation capacity of 48 000 MW (and more is being constructed), while the rest of the region has a maximum capacity of 6 000 MW (NER (2004)). Hydropower could significantly reduce the CO_2 emissions that would characterise extra coal power station investment, especially where run-of-river rather than damming[57] is used. Significant energy imports will follow which, however, will be limited by political and supply security considerations. Dutckiewicz (1994) suggests a limit in the short term of about 9 %, which would allow an internal reserve margin to cover supply if there are

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[55] Construction work is currently underway in Botswana of a 2400-3600MW coal power plant (Reuters (2006)).

[56] Several pockets of gas reserves – large enough for supplying power plant – exist in Mozambique, Angola and Namibia.

[57] Emissions of methane from flora and fauna covered by dams have been a recent concern of the mitigation lobby (see: Cullenward & Victor (2006)).

disruptions. This is a significant consideration considering the political instability over recent years in countries such as the DRC. Due to constraints on emissions there may be pressure to halt the building of coal-fired power stations within the next couple of decades, or at least to consider SO_2 reduction (NER (2004)) and perhaps, in the longer term, CO_2 cleanup (Schultz (2003)). In terms of non-grid electrification there will probably be site-specific renewable implementation as well as an extension of the national grid (Gaunt (2002)). Here the mix of supply will be determined by collected data from field and pilot plant projects (Dekenah (2002)) to suit both physical and social conditions. Demand will most likely be based on an analysis of 'useful' energy consumption per dwelling (see for example chapter 6). Demand-side efficiencies are likely to increase slowly, mainly as a result of fiscal and other policy involvement.[58]

The international community has ratified the Kyoto Protocol to help reduce global greenhouse gas emissions and revisions to this are likely with the end of the current commitment period (Aldy et al. (2003)). The Clean Development Mechanism (CDM) allows developed countries to invest in greenhouse gas mitigating projects that would not have otherwise gone ahead. The projects should therefore be 'additional'. The emissions that are saved are credited to the investors and the project should further the host country's sustainable development goals. Approximately twenty-one million tons of Carbon Dioxide equivalent[59] are currently expected to be saved over a seven-year period in South Africa from the CDM (DME (2005b)). Other opportunities which have a positive environmental effect exist, and are being pursued. The national electricity regulator assumes that coal-fired plant will comply with World Bank emissions standards (NER (2004)). New coal-fired (Fluidized Bed) plant is being considered which can burn otherwise discarded coal waste, reducing dumping burdens. While increasing emissions from power stations, subsidized electricity will reduce far more severe indoor air pollution (DME (2003a)). Other initiatives include the promotion of Basa Njengo Magogo, a scheme to reduce the emissions from coal and wood burning in residential areas using common informal stoves (DME (2005)) and the deployment of 'Energy Centers' dispensing clean fuels in low-income areas (DME (2003b) and Subramoney (2004)). Finally, the selected emissions standards for vehicles and liquid fuels standards have been strengthened to converge to European standards (Davidson & Winkler 2003).

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[58] See DME (2005b) for a list of measures considered.

[59] Gases other than carbon dioxide contribute to global warming. For simplicity's sake they are reported in terms of the greenhouse effect of tons of carbon dioxide. The combined total (including carbon dioxide) is reported as a carbon dioxide 'equivalent'.

Medium-term options

In the medium term, initial fossil fuel demand is likely to be supplied by the increased use of coal as the primary source, with some gas. International pressures placed on fossil fuels may result in increased imports from the SAPP (NER (2004)), depending on energy supply constraints, political and security considerations. It is possible that increased gas supply could be had from methane piped from the Waterburg coal-fields and also from pre-mining extraction (IEA (1996)). Other sources may include coal gasification and GHG friendly biogas from landfills,[60] sewerage works, and increased gas imports from Mozambique.[61] Demand that cannot be met from renewable energy, imports or coal may be met from increased domestic nuclear capacity (Howells & Kenny (2001)), probably characterised by high-safety 'passive' design.[62] Of particular interest in the South African context is the possibility of the development of the pebble-bed nuclear reactor, though some recent strategies include the construction of conventional reactors.[63] The pebble-bed reactor is designed to be (1) small, (2) have a low energy density, (3) inexpensive, (4) intrinsically safe, (5) of modular design and (6) gas-cooled (PBMR (2007) and Howells & Kenny (2001)). The modular aspect is particularly important as it helps get around the "lumpiness" of coal, hydro and conventional nuclear options which are being considered in South Africa at present (NER (2004)). It must be stated that as a complete unit, this technology and therefore its performance and cost parameters are untested. At present, plans are underway for pilot plant feasibility studies, as the system has potential for generation[64] where electricity demands are low. In terms of expanding the role of other new technologies, more efficient storage will allow for energy supply integration. Intermittent renewable generation will have increased scope for commercial generation. In the medium term, new energy carriers and mixes are likely to become important. It is envisaged that in this period energy efficiencies and emissions will have improved dramatically due to market forces and appropriate policy.

Long term options

The shape of the longer-term energy scene is difficult to conceive meaningfully, owing in part to potential changes in technologies. But the impact of low-temperature

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[60] See UNFCCC (2007)

[61] Currently gas is imported from the Temane field with other gas available from Pande (IEA (1996)).

[62] Note that while Renewable Energies will play an important role in terms of electricity generation, their potential is currently thought of as limited (DME 2003c).

[63] Announcement in Engineering News (2008).

[64] Note that until the pilot study is complete, there will be no authorative estimate of the Pebble Bed Modular Reactor (PBMR)'s costs and performance.

superconductors is likely to be revolutionary in terms of energy storage and generation. Fast-breeder nuclear reactors are likely to be in use, extending nuclear fuel reserves significantly. It has been suggested that nuclear fusion will be viable in this period and supply limitless quantities of hydrogen fuel. This hydrogen would most likely be stored in the form of methanol for easy handling. Other technologies that may characterise this period include advanced solar technologies, including molten salt 'power towers', and the artificial photosynthesis of sunlight into energy carriers (see Vessier (2005) for a more detailed economic analysis). Hopefully at this time all costs will include externalities, including appropriate environmental protection, and be optimised by market forces.

Conclusion

From a cursory view it appears that there are enough technical options to sustain and develop the national energy system. Considering technical scenarios further, it is clear that options should be considered in a consistent "modelling" framework, and this is done in future chapters of this thesis. This approach will help identify how the costs of the system to the economy can be reduced (chapter 3), how the cost of providing access to clean energy to the poor can be improved (chapters 5 and 6) and will include impacts on the environment (chapters 7 and 8 in particular).

Appendix: A summary of selected available indicators

Table 1.1: South African energy economy indicators

Priority issues	*Lead indicators*	*Type (SPIR)*	*Parameters*	*Units*	*Data source*	*Comments*
Topic: Nature of energy in SA						
Energy intensity	Energy used per million dollars of GDP using purchasing power parity	P	240	toe / million Intl $ GDP	WRI 2005	(yr 2001)
	Energy use (in tons of oil equivalent) per capita per annum	P	2.4	toe per capita	WRI 2005	By comparison the USA uses 8 toe per person (yr 2000)
Proportion of energy from fossil fuels	% electricity generation from coal	P	93%	Percentage	DME 2005	Bulk of non-coal generation is nuclear (yr 2001)
Level of renewable energy use	% renewable energy use	P	5%	Percentage	DME 2005	This is the fraction of *primary* energy required by the country (yr 2001)
Carbon intensity	Carbon emitted per million dollars of GDP at purchasing power parity	P	209	tons C / million intl $ GDP	WRI 2005	By comparison the USA uses 164 toe per dollar of GDP (yr 2000)
	International rank	P	34		WRI 2005	
Topic: Resource depletion						
Coal mining	Millions of tons mined per year	S	303	Million tons	DME 2004e	Of this only 239 Mtons of this was saleable (yr 2003)
	Percentage of saleable coal for local use	S	70%	Percentage	DME 2004e	(yr 2003)
	Solid wastes	S	6.3	Million tons	DME 2004e	(yr 2003)
	Reserves	S	33814	Million tons	DME 2004e	(yr 2003)
Oil imports	Bbls /year	S	139	Million bbls	DME 2005b	(yr 2001)
Topic: Emissions						
GHG emissions from energy	% of total South African GHG emissions attributed to energy use	S	75%	Percentage	WRI 2005	(yr 2000)
Carbon intensity of energy use	Carbon burned per unit of energy consumed	S	0.87	tons C / toe	WRI 2005	This makes the carbon intensity of South African fuels the 6th highest in the world (yr 2000)
Acidic deposition	SO2 from power stations	S	1469	Thousand tons	NER 2004/Eskom 2004	kg/kWhr*GWhr
Topic: Opportunities						
All emissions	Potential energy savings	O/R	12%	Percentage	DME 2004a	by 2013
Emissions and resource depletion	Renewable energy target	O/R	800	Thousand tons of oil equivalent	DME 2003c	by 2013
GHG emissions	Tons of $CO_{2\text{ equivalent}}$ saved between 2005 and 2012	O/R	23	Million tons	DME 2005c	Savings due to proposed CDM projects.

Toe – is short for 'tons of oil equivalent' and is a measure of energy.

Purchasing power parities (PPP) is an alternative exchange rate between the currencies of two countries. It takes into account that some goods, like real estate, services (e.g. medical services) and heavy items are non-traded and thus not reflected in the exchange rate.

The dollar value used is the 'international dollar' which is a hypothetical currency unit that has the same purchasing power as the US dollar has in the United States at a given point in time. It shows how much a local currency unit is worth within the country's borders. Conversions to international dollars are calculated using purchasing power parities (PPP). It is used for – in terms of gross domestic product (GDP) – comparisons both between countries and over time.

Chapter 2 A short introduction to common E3 modelling techniques

Having superficially described some aspects, development policy challenges facing and inefficiencies in the South African energy sector in Chapter 1, this chapter very briefly describes some of the common modelling techniques that are used for quantitative energy-environmental-economic-analysis. These are introduced to provide the reader with a brief context. In subsequent chapters they are applied and further developed to warn of inefficiencies in development policies as well as provide insights and scenarios to aid the policy making process. The techniques described are far from exhaustive, but have been applied to tackle related economic, energy and environmental (E3) issues.

Introduction

Energy-Environment-Economics (E3) models are generally computer based tools that are used to quantify relationships between energy use, the environment and the economy (Harnisch et al (2002)). Such models can emphasize different aspects of the E3 system, and are, like other models, simplified representations of real systems (Alfstad (2004b)). They are convenient tools for situations where performing tests or experiments in the real world are impractical, impossible or too expensive. This thesis uses such models to address a variety of topics: the costs and benefits of supplying poor households with appropriate energy, assessing the role of technology options, emissions levels associated with energy use It attempts to relate specific energy investments to economic impacts such as job creation.

General E3 modelling techniques

The purpose of much integrated energy modelling is to inform debate in a coherent manner and to develop insights into energy systems for reasons such as marketing services or meeting development objectives[65]. It is important to set a broad scene since the applications in this thesis are intended to provide policy support in the medium to long term. Widely employed techniques often fall into four broad categories – ranging from

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[65] A typical question would concern the energy requirements to sustain a given economic and population growth (assuming that a certain amount of service is to be provided) in the most cost effective and environmentally benign manner. This would involve the identities of technologies and the magnitudes and timings of investments in them.

economy-wide top-down models to disaggregated detailed 'bottom-up models' and these are listed below (Harnisch et al (2002)).

(a) The Computable General Equilibrium model (CGE)

This model has a strong theoretical basis and adopts a micro-economic view of consumer and producer behavior. It extrapolates the micro approach to derive macro insights. The production functions used and the supporting elasticities play a well-defined role in determining the results obtained. The empirical foundations, however, are often weak, data for model calibration are limited and it is often questionable whether the scenarios captured are realistically represented. This type of model has been used to address macro-economic research questions of national, multi-national and global significance (Harnisch et al (2002)).

In South Africa, CGE models have been used to determine the effect of tax as an instrument to reduce greenhouse gas emissions (van Heerden et al (2004)). Elsewhere CGEs have been developed to better represent energy using and production technologies for GHG mitigation studies. These notably include the Battelle and Argonne National Laboratory, second generation and AMIGA (Shelby et al. (2006)) models.

(b) The Input-Output (I/O) Model

This model is based on macro-economic interaction matrices, energy balances and labour market statistics. In relation to E3 analysis, activities are explained against the backdrop of sectoral development, energy carrier consumption and emissions development. It is difficult to incorporate changing conditions into models of this type, especially if the simulation period is over a long period. However, Jeftha (2003) did attempt to introduce dynamic change into I/O models of the South African energy sector. The I/O model type is typically applied to macro-economic and sectoral research questions. Since I/O models are based on *average* relationships they do not easily capture economic transactions that happen at the margin. As such, they are limited. Internationally I/O models for energy analysis have been used by Hawdon and Pearson (1995) and Muller (1979) amongst others. In South Africa, I/O models have been used to determine employment potentials for the introduction of renewable energy (DME (2004c)) and energy efficiency (Spalding-Fecher et al. (2004)) options. They have also been integrated with optimization models (Howells in Press, and chapter 8 of this thesis) to include explicit quantification of energy flows and emissions.

(c) The Optimization Model

This model uses technology databases containing detailed information on the intended area of application and the relevant cost aspects involved. Although these models are flexible, a high level of detail often needs to be incorporated into them for the simulation to be realistic. This requires information such as electricity load curves and technological requirement profiles, which are not always easy to acquire. Models of this nature usually implement a form of linear programming and try to find an optimal ('least cost' variant based on multi attribute criteria) solution subject to a collection of constraints. These models are usually applied when considering technology-related economic research questions. These models consider the cost of meeting demand and supply simultaneously, calculating the equilibrium point between the two. They are thus sometimes referred to as *technology rich partial equilibrium* models (Loulou at al. (2004)). (They are "*partial"* as they consider the "energy" component of the economy. They are "technology rich" as the demand and supply curves can often be related to specific technology choices. This notion is discussed in more detail in the next chapter and its appendix.)

An interesting aspect of these models is that they are based on observed physical relationships and therefore their components are "testable", hence their wide acceptance of technology related analysis (see below). This does not however mean that the systems (the sum of the components) and scenarios are necessarily "realistic". For one, in a cost optimizing tool, a perfect market is assumed. These often do not exist[66]. Optimizing tools, like the simulation tools described later, are useful for developing consistent scenarios, which are in turn useful for developing policies or possible roles for new technologies.

Optimization models have been used widely for global analysis. Examples include studies carried out by the EU (Criqui (1996), Criqui et al (1999) and EC(2005)), by the US Department of Energy (DOE) (EIA (1997) and EIA (2003)), by the International Energy Agency (IEA) (Gelien (2003)) and others (Labriet et al (2005)) for regional analysis in the EU (Seebregts et al. (2000)), Southern Africa (Sparrow et al. (1999)) and Alfstad (2005)), South East Asia (ACE (2006)) as well as numerous national economic analyses, (see for example Gielen and Chen (1991), Strachan et al. (2006), Loulou et al. (1997)) for examples in China, UK and India). This type of model has been applied in South African for both the Integrated Energy Planning (IEP) of the Department of Minerals and Energy (DME (2003a)) and the Integrated Resource Planning (IRP) of the National Electricity Regulator (NER (2004)). Eskom, as part of the IRP team, uses the EAGES expansion

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[66] The user may however, and often does, try to simulate some imperfection in the market being modeled.

planning model of Electric Power Research Institute (EPRI) (NER (2003)). It also uses this model to calculate the least-cost set of power stations when planning its investments in the national utility.

'All energy' modelling has been undertaken for the Department of Minerals and Energy using the Market Allocation (MARKAL) model of the International Energy Agency's Energy Technology Systems Analysis Program (ETSAP (2005)). Optimization models have also been used for the analysis of regional trade for the Southern African Power Pool (SAPP) (Alfstad (2005), Greber (2001) and SAPP (1999).)

(d) The Simulation Model

Like optimization models, simulation models use detailed information pertaining to the area of application and costs. Such a model, however, allows the user to explore different hypotheses via scenarios and typically capture the area of interest at a macro-economic level. These models are used to investigate technologically-oriented and policy measures where macro-economic interactions and price effects are less important.

The Long Range Energy Alternatives Planning model, sometimes referred to as an 'accounting framework' depending on the degree of complexity required, is a simulation model which has been used extensively in South Africa. In particular, the ERC has undertaken national modelling to determine the potential of national energy efficiency policies (Trikam at. al. (2003)), the cost and benefits of meeting national renewable energy targets (Alfstad (2004a)) and city wide analyses for Cape Town (Winkler 2005) and others. Other examples of simulation models widely used include Balance (Argonne (2008)) and MAED (IAEA 2007).

Some factors to consider

The question that needs to be answered and the detail required are pre-eminent in the choice of a model. Other aspects have to be considered when building a model. These include:

- level of complexity involved and data available;
- adaptability to specific task;
- ability to analyze different types of cost (investor, social, consumer);
- ability to model non-economic instruments;
- and level of technological detail.

Table 2.1 summarizes selected characteristics of the modelling tools described.

Table 2.1: Energy Model Characteristics

	General equilibrium models	***Input-output models***	***Optimisation models***	***Simulation models***
Timeframe	Medium to Long Term	Short to Medium Term	Short to Long Term	Short to Long Term
Focus	Macroeconomic (with micro-substructures)	Macroeconomic	Technological energy systems with cost structures	Technological systems with specific general conditions and barriers
Calibration	Usually one reference year	Usually many years	One reference year	One reference year
Critical Factors	Nesting structure, elasticities	Quality of the historical time series, dynamics	Additional conditions (Bounds)	Quality of technical and economic analyses
Level of Detail of the Energy Systems	Low	Low	High	Partially high
System Boundaries	Entire economy	Entire economy	Energy system	Energy system
Flexibility in terms of a sectoral question formulation	High	High	Limited	Low
Interaction and Feedback with the entire economy	Considered	Considered	Not implicit, only with coupling	Not considered
Classical Question Formulation	Macroeconomic effects of environmentally economic instruments	Sectoral effects on environmentally economic instruments	Cost-effectiveness analyses	Identification of priorities for a mix of technological measures
Price-Quantity-Relations	Implicit	Implicit	Considered	Only in part, not implicitly considered
Rationality and Market Balances	In principle assumed	Not relevant	Implicit for future decision-making	Independent
Development of Reference Scenarios	Endogenous	Dependent on level of endogenisation, usually considered endogenous	Plausible expert assumptions	With considerable exogenous guidelines
Technology and Technological Development	For the most part, combined together to single or few technologies	Aggregated at the level of interacting structures	As separate technologies and explicit estimations of each future development	As separate technologies and explicit estimations of each future development
Model Generator			Mostly yes	Mostly no
Strengths	Closed theoretical structure	Broad empirical foundation, sectoral disaggregation of industrial sectors	Applicable to technical total systems technological detailed questions, flexible application possibilities	Also usable without targeted entities for optimisation, applicable to technical total systems technological detailed questions
Weaknesses	Small empirical basis, often low level of sectoral differentiation	Statistical theoretical background, founded solely upon historical analyses, extensive model preparation and maintenance	Implicitly rational optimisation decisions, strongly influenced by bounds	Economic influences underrepresented, based considerably on the quality of expert knowledge
Theoretical Foundation	Neo-classical	Historical analyses of the macroeconomic interaction matrix	Optimisation with regard to technological-economic criteria	Primarily technological determinism of energy systems
Implementation of the Modelling	Decisions corresponding to nesting and elasticities	Econometric estimation of the interconnections of the interlacing matrix	Technological database with optimisation algorithms	Technological database, expert knowledge
Flexibility in	Low	Low	High, dependent	High for limited

terms of Technically Detailed Questions			upon the level of detail of the technological database	complexity
Flexibility in terms of the Scope of Reference	Medium	Fundamentally possible, low for existing models	High	Possible
Dynamics	Model inherent	Implemented in different degrees	Explicit via specific technologies	Explicit via specific technologies
Modelling Supply and Production	Function of production with nesting and elasticities	Interlacing structure via modelling	Endogenous	Scenarios
Modelling Demand and Consumption	Demand elasticities	Endogenous, in part also exogenous	In part, exogenous via scenarios, in part connected to economic development	On the basis of scenarios, coming out of economic growth

Source: Howells et al (2003) and Harnisch et al (2002)

Conclusion

This thesis used three of the four modelling approaches discussed: simulation, input-output and optimization models. Simulation modelling was particularly useful when constructing detailed future scenarios based on expert judgment and expectations of the development or operation of energy markets. It was used to analyze the national energy system and the provision of electricity at peak times to households for cooking (in chapters 3 and 5). Optimization tools have been used to consider how the system could be better and more economically configured (in chapters 3, 6, 8 and 9.) As there are economy wide effects not captured by the partial – energy focused - nature of the optimization tools, an input output model has been used to estimate these aspects (in chapters 7, 8 and 9).

Section 2: National energy modelling

Introduced here is the first model application of the thesis. It shows how suitable modeling (an optimization model) illustrates the inefficiency (of the energy system in terms of poor economics and GHG emissions) due to (electricity supply and demand) development policies. It also indicates technical scenarios, and certain cost implications, of how these may be remedied. This section consists of a chapter in which an energy optimization model is run for the South African energy system as a whole. There are a number of applications to which such a model can be put. The work is based on an earlier paper (Howells & Solomon (2003)) which provided the first such application for South Africa. Since much of the data used in that research was confidential, the case study used here has had to be redrafted using public domain data. It focuses on the electricity sector and improvements in the thermal and economic efficiency of industrial energy use. The chapter addresses the reduction of greenhouse gas emissions and the cost of that mitigation. A key question to be considered is whether the country's environmental performance can be improved using available technologies without incurring further costs for the economy.

In order to examine this question a business as usual or baseline scenario, is used to estimate a future balance of energy supply and demand. Contrasted to this are alternative futures based on – amongst other things – increased penetration of energy efficient practice and technologies.

Care was taken to adopt assumptions with broad stakeholder and official endorsement. Though these represent an official view of future developments in the energy system, many of them are not robust (the appendix of Chapter 3 cites some of these). It is clear that prices, market structures, and technology changes can affect future energy use patterns, and assumptions concerning them are therefore significant. A scenario that is reflective of current practice and thought provides a point of reference against which different future scenarios[67] can be compared to demonstrate what might be achieved by better management of existing or likely options. As the distant future is not considered, such an analysis can by useful for drawing or assessing short to medium term policy options.

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[67] As we are contrasting a scenario of the future with others that hold much in common, e.g. useful energy requirements by sector are all held constant, these 'other scenarios' might also be referred to as 'cases'.

Chapter 3: A least-cost GHG mitigation pathway for South Africa

Introduction

Following a description of the South African energy system in chapter 1 and selected modelling approaches in Chapter 2, this chapter[68] uses results of, and data from, the National Integrated Energy Planning (IEP) (DME (2004)[69]) optimization models. It discusses how better management of existing energy resources and improved energy efficiency provide an economic option for the country. Not only does this result in a more economic system and reduced final[70] energy demand, but also has the effect of reducing carbon dioxide emissions. While these results are briefly described, they are, unfortunately, based on data which is partially confidential. In this chapter, however, a specific application is reworked. This focuses on improving electrical energy efficiency and electricity supply. (All data on which this is based is included in the chapter appendix. Also added in the appendix is a mathematical description of the MARKAL model used) The chapter goes on to reference local case studies carried out by the Energy Research Center (formally the Energy Research Institute), with local industry. These, albeit anecdotally, clearly illustrate the potential (and site specific) benefits of energy management on a micro level.

It is commonly considered that forcing an economy to reduce emissions levels below current 'baseline' levels will increase system costs (see Di Cannio (2003) for examples and critiques of analyses which simply assume this). Such views implicitly assume that economies are operating at their efficiency frontiers, hence reducing emissions from one part of a system implies costs somewhere else, perhaps in terms of jobs or GDP. It has, however, been argued by some that economies can still be improved (using existing technologies). That is, they are not operating at their 'production possibilities frontiers'[71], but can be moved closer to them with little risk. This is illustrated graphically by Laitner (2002) in Figure 3.1.

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[68] Substantially based on Howells & Solomon (2003), with additions including a more focused application and public domain datasets.

[69] That report is summarized from Howells et al. (2002)

[70] It is assumed that the same level of service – or useful energy - is provided. However, as this is done more efficiently, less fuel is used.

[71] For an extensive array of energy (and if the fuel used is fossil based also emissions) savings measures see the database of the US Energy assessment program. (IAC (2008)) These measure both the reduced costs of production and reduced energy requirements. They are based on hundreds of energy audits of industrial facilities in the US. Other databases exist. However, this is the most extensive.

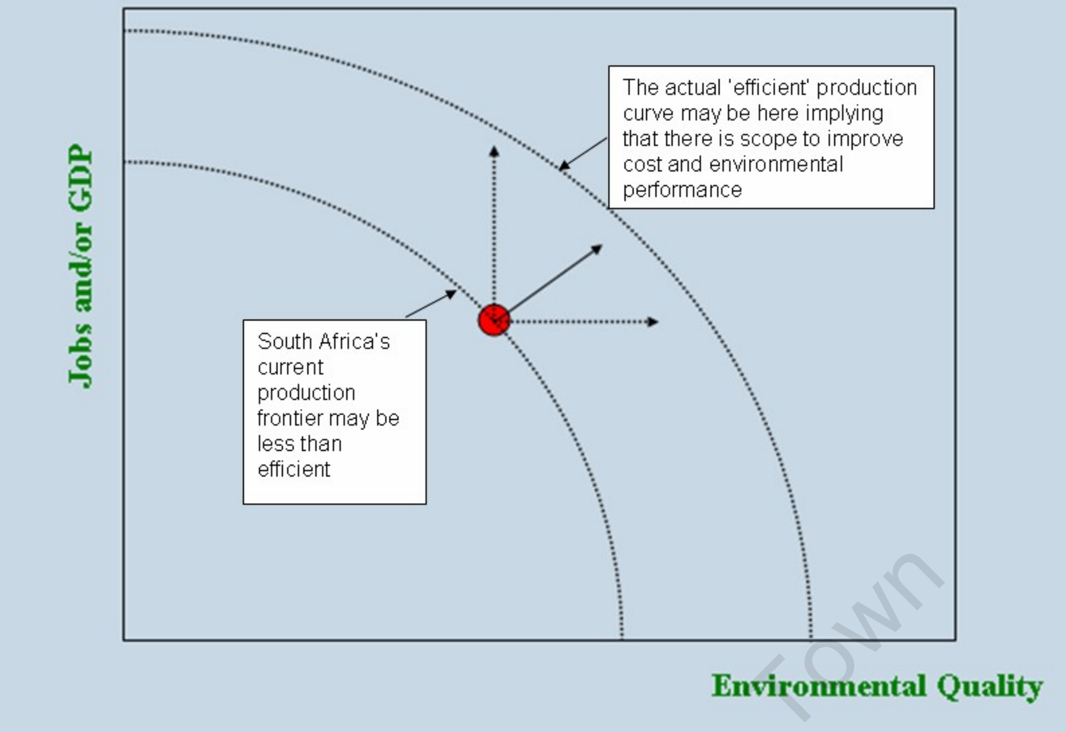

Figure 3.1: Production frontiers (Laitner (2002))

This chapter argues that greenhouse gas emissions from the energy sector can be reduced while simultaneously reducing the cost to the South African economy (compared to baseline[72] levels). Further, it is argued that this can be done while still maintaining its heavy reliance on coal.

The reporting and analysis begin by describing the energy sector and how it was modeled in an official exercise known as the Integrated Energy Plan (IEP), described in DME (2003a) and undertaken by Howells et al. (2002). Drawing from this official work this chapter shows that, relative to a baseline, both the GHG emissions and the costs of the energy system can be reduced. The objective of the optimization model is to meet a demand for services, subject to various constraints, at the lowest present value cost over a given time horizon. In this baseline scenario the technologies from which the model can choose are constraints. In contrasting scenarios, this limitation is removed. As much of the data in the official IEP is subject to confidentiality agreements and cannot be reprinted here, a detailed example is undertaken using a public domain dataset based on many of the same (IEP) assumptions, the data being reproduced in the appendix to this chapter.

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[72] Note that this hypothesis is in part a function of how the "baseline" scenario is constituted. This is described later. Essentially, however, it is assumed that existing market inefficiencies are perpetuated in the absence of effective policy.

Modelling the South African energy sector

The South African economy is energy intensive, using a large amount of energy for every Rand of value added. South African energy is dominated by coal; the economy is therefore also carbon dioxide intensive. It is also cheap, resulting in low energy costs, particularly for electricity (see NER (2004)), which is the cheapest in the world[73], though prices are increasing due to a "new build" program. South Africa has little oil, most of her crude is imported. She obtains useful amounts of energy from biomass and nuclear power, with smaller amounts from hydropower, natural gas, solar and wind. Much of the primary energy is transformed into final (sometimes called 'end-use') energy, such as electricity and liquid fuels, and is converted into a service, such as lighting or heating. These services are often termed 'useful energy' or 'useful energy services'. Final energy (that purchased by the end-user) is converted into 'useful energy'. For the South African economy, approximately proportional flows of energy (from primary supply to the end user) are represented below for illustration.

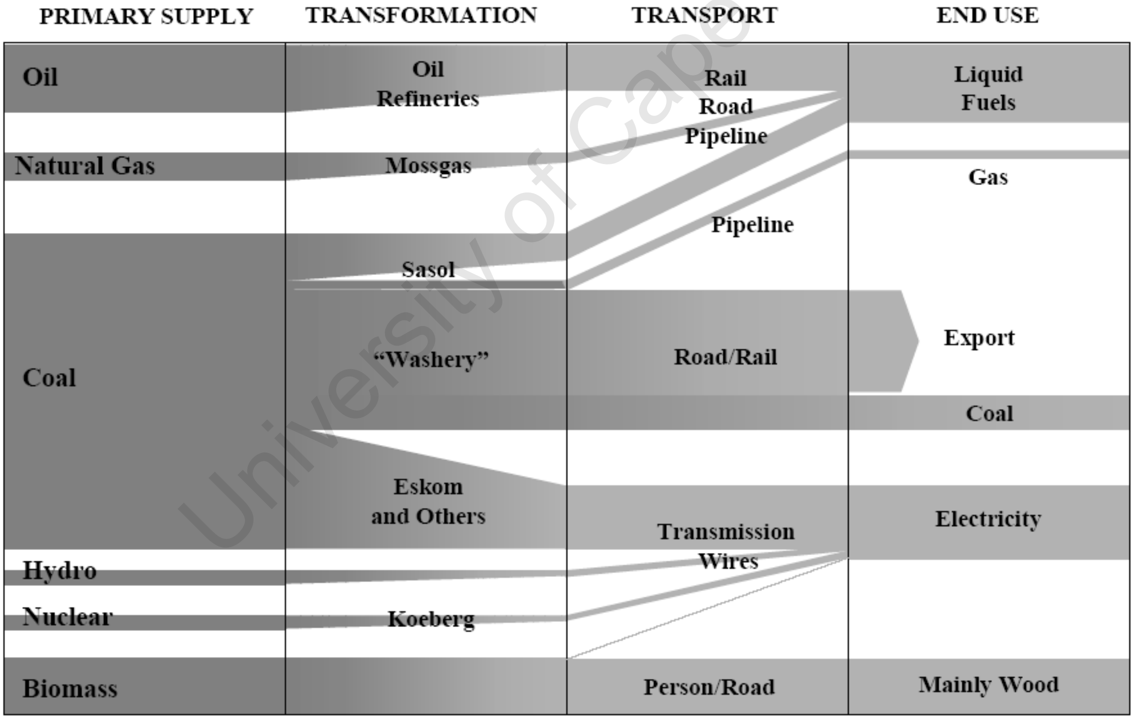

Figure 3.2: The South African energy system, (DME 2003a)

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[73] For a detailed estimate of current and future electricity generation costs, see NER (2004). For a comparison of South African compared to other international electricity prices see IEA (2007b). In part, the low costs are due to the low cost of coal, less than ten dollars per ton, as well as economies of scale that result from using some of the largest thermal generating units (several of these power stations are over three thousand five hundred megawatts each). The low cost of coal is the result of learning to burn very low grade (often up to 45% ash) coal.

Converting energy from one type to another requires 'technologies' (though terms such as "processes" or "appliances" may sometimes better apply). These include mining processes, import terminals and exports (for primary energy), various transformation processes, changing energy into more useful forms (e.g. from coal to electricity), those transporting energy in its various forms as well as appliances which convert final (end-use) to useful energy.

The MARKAL model

In order to consistently account for the attributes of the energy system (in this case, costs, quantities, capacities and emissions) and the role that changes may play in that system, the optimization model MARKAL[74] is used. MARKAL is a mathematical model used to represent an energy system. It does this by representing technologies or groups of technologies in terms of their thermodynamic efficiency, costs and other attributes, such as what fuels they consume and produce, their vintage, life time etc. The technologies are "linked" by the fuels that they produce and consume. This representation of fuels from resources, to primary, to secondary, to final and to useful energy – or a subset of these - is termed an "energy chain". Energy chains which are examined by an energy model are often represented graphically as a reference energy system or "RES". In the model, each step of this system is constrained so that the technologies produce enough energy to meet the consumer demand (which is entered – and estimated - exogenously) as well as other consumption from technologies that use the fuel. In engineering terms this called an energy balance. This constraint is met over the time horizon of the study period. The objective function of MARKAL is to minimize the cost of the system while meeting the system energy balance, as well as other constraints such as limits on resources or others defined by the user. A summary of the formulation can be found in the Appendix to this chapter.

To do this, the model configures the energy system at the minimum overall cost by simultaneously making technology investment decisions, operating decisions and energy supply decisions. For example, if there is an increase in (exogenously entered) demand for residential lighting energy service, the model will consider what technology/appliance is the most cost effective to meet that demand. It does this by taking into account the capital, operating and maintenance and fuel costs of the appliance. The fuel costs however are a function of the technologies or processes used to supply that fuel. If electricity is the fuel of choice this should be supplied either from existing generation

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[74] See Loulou et al (2004) and ETSAP (2005) for detailed documentation.

technologies (used more intensively) or new equipment must be installed. The choice of generation equipment (type and fuel used etc) is in turn a function of the cost of the fuel they will use, their capital, operating and maintenance costs. If the fuel used by the power station was extracted, transported or processed, those costs are also included in the analysis. Other aspects of technologies, such as lead time requirements for construction, may limit investment in them[75]. The level of detail and boundary of the analysis is determined by the user The model can thus be "vertically integrated", taking into account all levels of the energy system (from primary supply to useful energy) while at the same time being "dynamic" in the sense that it considers multiple time periods.

In economic terms the model computes an "inter-temporal partial equilibrium" of the energy markets, which means that the quantities and prices of the various fuels and other commodities are in "equilibrium", i.e. their prices in each time period will clear the energy markets (see figures 3.9 and 3.10 for a graphical illustration of that equilibrium). Economic efficiency requires marginal cost pricing; for example the prices determined are also the marginal costs of production. This is in part fallout of the linear programming solution method that is used. When the energy balance is satisfied, the Dual solution of the matrix yields the marginal cost of producing an extra unit of fuel. This equilibrium has the property that the sum of the consumer and producer surplus is maximized over the whole horizon hence its economic efficiency. Investments made at any given period are optimal over the horizon as a whole. (Loulou et al (2004)).

In the Appendix of this chapter more information is provided under "Specific MARKAL detail". Apart from having to meet the energy balance and other performance constraints of the system, the user can add constraints. One which will be used later is constraining the carbon dioxide emissions of the entire energy system. The user enters emission factor data (how much GHG is emitted per unit of fuel burned). As the model calculates the quantity of fuel burned the, the total emissions of the energy system are calculated over the study period. The user can then further limit the total quantity of emissions and the energy system can be reconfigured to use different technologies to meet this constraint. These may, for example, include renewable energy sources or more efficient appliances.

Model calibration

Important data (amongst others) entered into this modelling framework includes baseline energy consumption projections[76] (sector by sector), the attributes of current and future demand and supply side technologies, emission factors and constraints on available

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[75] For example, a coal fired power station with a lead time of five years would not be available to produce electricity until it was constructed.

resources. All assumptions used to ‘calibrate’ the model as well as those used to develop a future ‘baseline’ or business as usual scenario were reviewed at national workshops involving industry, government, NGOs as well as other experts during the government’s Integrated Energy Planning (IEP) process (DME (2003a) and Howells et al. (2002)).

The baseline scenario

The national IEP was produced by the Energy Research Institute (now Energy Research Centre) of the University of Cape Town together with Eskom (the national utility) and the National Department of Minerals and Energy (DME). It was sponsored by both Eskom and the DME (DME (2003a)). The work was developed using variants of two scenarios for the energy sector in South Africa. One scenario was based on ‘business as usual’ practice, which drew from studies of energy supply and use by sector. Those studies were neither explicitly integrated nor coordinated. An example of such a study would be Integrated Resource Planning (IRP) for electricity supply (NER (2004)[77]) which was based on a standard, but limited, unintegrated approach[78], though it is part of an integrated system. (Such limited approaches are common and accepted practice, see for example: UNEP (1997))

Another scenario was developed which was biased against coal. The business as usual scenario was called the “baseline simulated” scenario – hereafter referred to simply as the “baseline” scenario. Each fuel (or resource) and sector was individually considered. These

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[76] The energy demands were projected into the future based on estimates of economic growth, demographics, changes in energy intensities, sector specific forecasts and other factors. These projections are documented in Howells et al. (2002), Hughes et al. (2002) and EDRC (2003).

[77] Preceded by NER (2003b)

[78] Used here, the IRP approach is an approach which optimizes the supply of one fuel in isolation. For example the National Electricity Regulator (of South Africa) recently produced the National Integrated Resource Plan (IRP) (NER (2004)). This IRP considered most economic supply and demand side options for the provision of electricity. It did not consider in an integrated way any synergies that could be gained by including other fuels. Combined heat and power generation for example were omitted. Similarly, the South African Department of Environment Affairs and Tourism (DEAT), when considering GHG mitigation options for the country, considered each sector of the economy in isolation. Therefore mitigation options that affect energy supply by reducing its carbon intensity of fuels to be used would not be included in calculations where GHG mitigation on energy use was considered. Therefore, were electricity generation to move from carbon intensive coal based to carbon free renewable, calculations would reflect no mitigation benefit were consumers to switch to the carbon free renewable-electricity at the expense of burning a fossil fuel! It was assumed that the carbon intensities of electricity generation were not dynamic. The MARKAL model specifically includes changing supply side and demand site technologies and their emissions and cost effects in an integrated manner. (See for example Howells (2000b) for DEAT’s assessment of electricity supply, de Villiers (2000) for the commercial sector and de Villiers and Mathibe (2000) for DEATs assessment of the residential sector.)

'sector futures' (which involved stakeholder review and represented an official outlook for the energy sector) were then reconciled into a single scenario.

This baseline scenario had within it certain inefficiencies. Importantly these included a continuation of current (poor) energy management practice by industry. Local (but limited in number) energy auditing studies showed that for short paybacks, the efficiency of use of compressed air, motor systems, lighting and heating could be improved (Kenny et al (2000a, b, & c) and van Es et al (2002)). This should be seen against a background of countries such where more detailed and extensive energy audit data exists, such as the USA. This data shows that trends of potential energy savings are similar: the same service can be supplied using less energy at negative lifecycle costs (see IAC (2008) for a comprehensive database of industrial plant level energy assessments, including the costs and extent of various energy savings opportunities).

The modelling process

For the IEP, two models were used, though we focus here on the MARKAL model. Initially, a LEAP simulation[79] model was set up to project and then meet a range of useful energy or energy service demands, according to the 'baseline', future described above.

The MARKAL optimization model was then structured to meet the same useful energy demand. The model was run in both a highly constrained 'simulated' (reproducing the LEAP and 'Baseline Simulated' results) and an 'optimized' mode. It optimized on the basis of 'least cost', subject to a range of constraints. These constraints were developed such that the solution was both realizable and of use for policy formulation[80].

Least cost optimization

Unlike the baseline scenario, when run in optimized mode, the MARKAL model is free to choose the configuration of the energy system to meet the same useful energy demand or energy service required by the growing economy and population. This scenario is called the "optimized" scenario in this chapter[81]. It is similar to the "baseline scenario" as the same quantity of useful energy is demanded.

In the optimized scenario, the MARKAL model chose from a range of supply and demand options that were limited to projects and technology penetration rates, which again represent conventional and potential practice (Howells et al. (2002)). However,

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[79] See chapter two for a short description of the LEAP model.

[80] For example, if a large quantity of energy efficient industrial technologies or practices were economic; their full and immediate introduction would not be allowed. Rather, their penetration would be retarded to reflect real constraints on technology switching and taking up new practice.

[81] In the national IEP (DME 2003a) this scenario was referred to as the "baseline optimized scenario".

rather than official assumptions guiding the energy system, the scenario used those which it calculated would minimize system cost. Importantly, these technologies included options based on coal; a necessary proviso since currently over 90% of South African electricity is produced by coal, over 35% over petrol demand is produced by the liquefaction of coal and much final energy demand is also met by coal. Coal is the cheapest option for the economy. It is, however, carbon dioxide intensive

Results: Emissions, energy management and a least-cost pathway

Greenhouse gas emissions inventories for the South African energy sector have been carried out for the Department of Environment Affairs and Tourism (DEAT) by Howells & Solomon (2000). The same (emission factor) data sets were used to develop the inventory in the IEP model. Figure 3.3 below shows the progression of emissions that would be anticipated were the "baseline" scenario to be realized over the next twenty years.

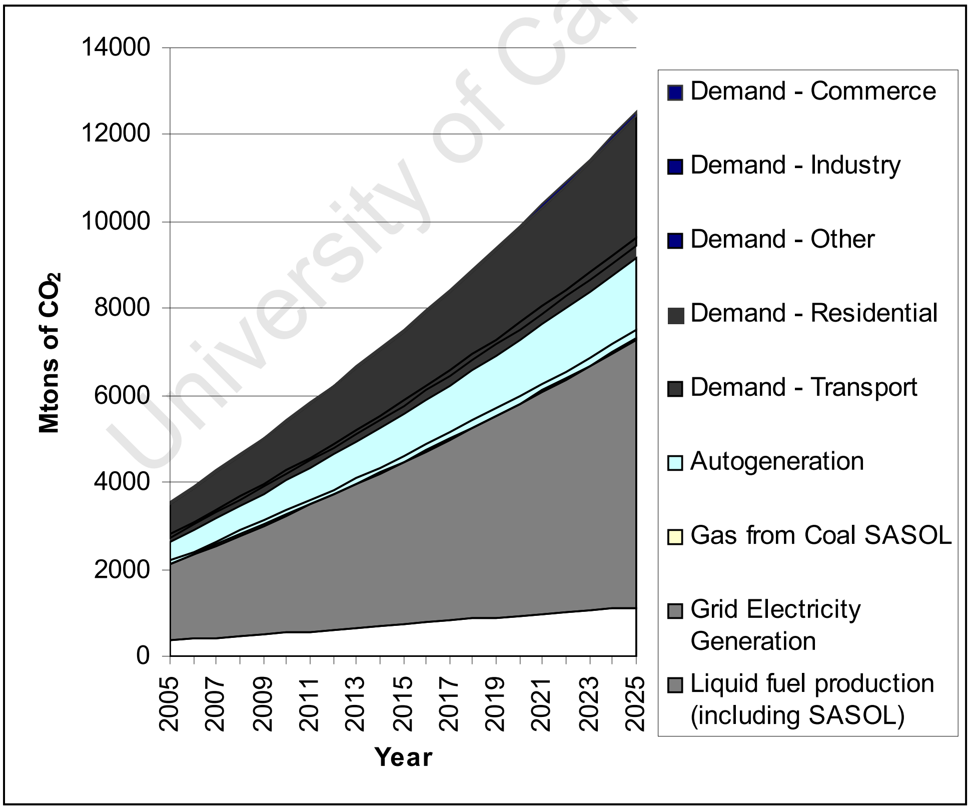

Figure 3.3: Emissions from the energy sector in the "baseline" scenario

With the MARKAL energy model being integrated, demand-supply effects can be captured simultaneously. For example, if power production were to shift from coal to nuclear, electricity would have lower carbon dioxide intensity than projected. This may make an electrical energy efficiency option, for CO_2 mitigation, less attractive than originally thought[82]. This work[83] reports the first significant attempt to show these dynamics for a South African case study.

In the "optimized" scenario, energy use patterns change in order to reduce costs (this is reported in detail in Howells et. al. (2002)[84]). This is particularly the case and well illustrated by the fuel use patterns in the industrial sector. In this sector there is a general shift to coal which is burned directly to produce process heat (such as steam), replacing electrical boilers. As coal displaces electricity, coal burning that would have been required to generate electricity is reduced[85]. Other important trends include the decreasing use of liquid fuels (and electricity) for thermal purposes and an increased uptake of energy efficient practice and technologies. The uptake of energy efficient technologies is again well illustrated in the industrial sector. As the marginal cost of electricity increases, due to power station capacity shortages, several energy efficient options become viable and are taken up, further reducing the demand for electricity – even in the context of low electricity prices.

The decreasing electricity consumption, thereby delaying the building of new power stations and using fuel more efficiently, has the twofold result of decreasing system costs and lowering emissions.

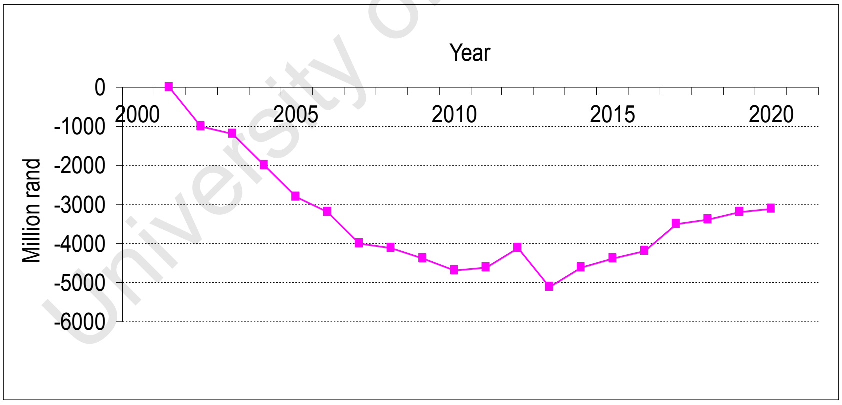

Figure 3.4: Cost of the Baseline versus the Optimized case (Howells et al (2002)[86])

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[82] Initially more efficient use of electricity would directly reduce coal-generated electricity.

[83] Initially published in Howells & Solomon (2003).

[84] And reported in less detail in DME (2003a)

[85] This represents a more efficient way to generate steam needed for industrial heating. Coal burned to produce electricity is done so at an efficiency of about 35% and an electrode boiler operates at about 90% efficiency. The combined efficiency therefore is close to 32%. When coal is used directly in a boiler it can produce steam at an efficiency of around 75% or more. Though the efficiency saving is significant, it is not always economic to use coal directly. Where the need is far from coal fields it is often much cheaper to transmit electricity than to transport coal. This effect, however, should be balanced by the realization that local pollution, without proper controls, will be increased. An implication is that 'clean coal' technologies may play an important role for South Africa in the future.

[86] And DME (2003a)

Note that the figure represents the discounted (PV) cost of the Optimized scenario minus the Baseline scenario. (When the costs are negative, which they are, the Optimized scenario is lower in cost than the Baseline. Further note that the reduction in savings towards the end of the period is not in real terms, but is discounted. This accounts for the apparent "narrowing" of the savings in the second half of the scenario period.) The discontinuity in Figure 3.4 is partly due to the postponement of large investment in base load power plant in the middle of the baseline period. This has a direct effect on the CO_2 emissions during the same period, as can be seen on Figure 3.5.

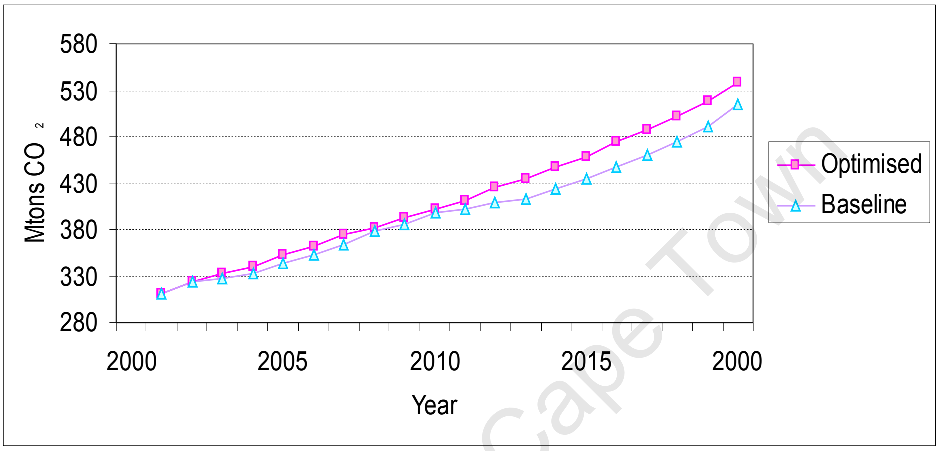

Figure 3.5: Emissions from the Baseline and Optimized scenarios (Howells et al (2002)[87])

Emissions levels are lower in the optimized scenario than in the baseline as energy efficiency measures are taken up and fuel switching occurs. Interestingly, the conclusion from this cursory analysis is that emissions from the energy system can be reduced while at the same time the system cost is lowered. Coal is still, proportionally, the dominant energy carrier to fuel South Africa (though the absolute consumption of coal is reduced due to the increased efficiency of the optimized scenario.) The industrial sector is important as it is a large user of coal and electricity and gains from increased energy efficiency and increased fuel switching to coal.

A special case: Industrial energy efficiency

The preceding discussion relates to an analysis based in part on data which is not in the public domain and therefore is difficult to transparently reproduce and interrogate. Thus here and in the appendix an example, based on public domain data is reported. Focusing on industrial energy efficiency (indirectly[88] and directly responsible for the greatest reductions in cost and emissions) the effect of increased efficiency (both economic and

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[87] And DME (2003a)

thermodynamic) is considered. This example departs slightly from that described above due to small differences in the data sets. It differs significantly from the above analysis however as an extra constraint is considered in the optimized scenario. Over the study period carbon dioxide emissions are limited to varying levels. A similar analysis was undertaken in Howells & Solomon (2003)), which was based on confidential IEP data, and the results are similar. The full data set of industrial energy efficiency and supply side technologies used for the example is based on NER (2004), Howells (2006) and Winkler et al. (2005) and is included in the appendix to this chapter.

Figure 3.6 shows the difference in Carbon Dioxide emissions and energy system costs between the "baseline" scenario and several cases of the "optimized" scenario (now based on public domain data). The optimized scenario cases are derived simply by stepping though different and more stringent limits on total carbon emissions from the energy sector over the study period. At each limit the costs of the energy system are calculated and the difference between the optimized case and baseline scenario emissions and costs are reported. This representation is an emissions mitigation cost curve i.e. it shows the marginal costs incurred as emissions are reduced progressively over a baseline future. The key finding is that it is possible to reduce both emissions and costs, up to a point, with underlying assumptions based on broad stakeholder input. Beyond that point, however, there is switching from coal fired generation to different power generation sources and costs are incurred.

The initial points of Figure 3.6 are the result of several effects; particularly the uptake of industrial efficiency (EE) measures. The origin represents the baseline scenario only. Recall that the baseline includes the restricted uptake of new options. It is relatively thermodynamically inefficient and characterizes current practice).

The first optimized scenario case is unconstrained by carbon dioxide emissions limits and is shown as the trough in the figure. In this case energy efficiency and other measures are taken up to a level that is economically efficient. After the energy efficiency measures are taken up to a level that is economically efficient any extra effort to reduce emissions will subsequently increase system costs. This inflection point (the bottom of the trough in Figure 3.6) indicates the production frontier (see figure 3.1). In reaching this frontier, both emissions and cost have been reduced.

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[88] It is indirect because a reduction in the quantity of electricity supplied (and power station emissions) reduces the need to build costly power stations.

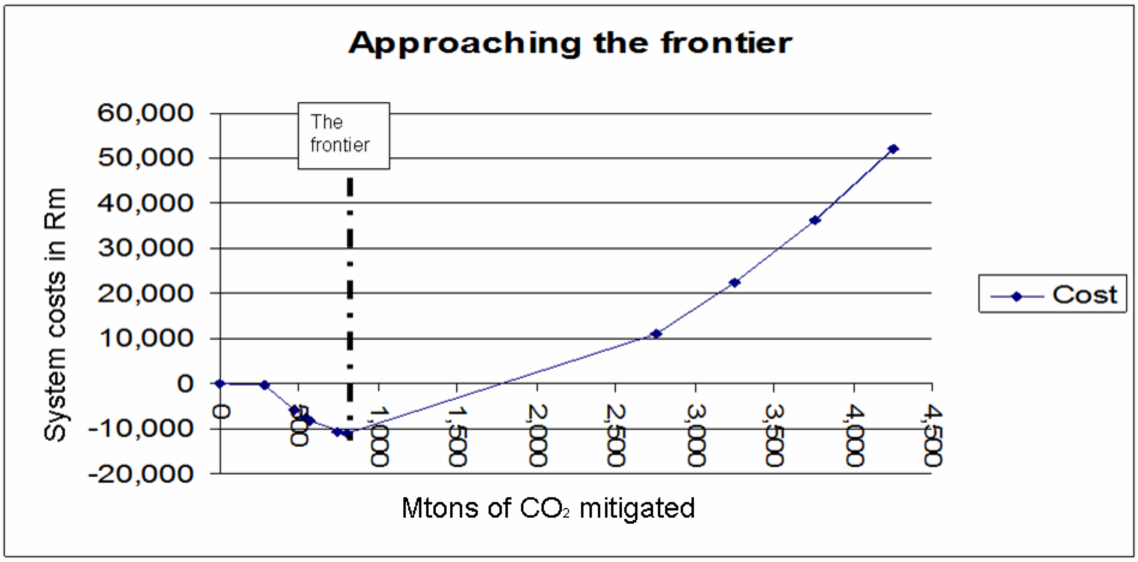

Figure 3.6: Cost of CO_2 mitigation for the energy system relative to the baseline

Discussion of results

The analysis suggests that the energy sector could both be run at a lower cost and with reduced CO_2 emissions, (compared to an artificial but plausible and "official" baseline scenario) – while still based on coal. There are implications that will be briefly discussed in terms of application to South Africa; these relate to bulk renewable energy, development needs and liberalized markets.

It is interesting that bulk[89] renewable energy generation options such as wind were not initially needed in order to reduce significant quantities of CO_2. These options are included in the model, however they are relatively expensive. When the system is constrained to meet emissions limits, large new power station investment is required only at the end of the period[90]. The fact that new generation capacity can be postponed may negate the benefits of developing renewable energy sources initially. There may, however, be a case for such renewables if CO_2 prices rise or if the costs of other environmental damages increase. In such cases, electricity with low CO_2 intensity could become a feasible 'mitigation fuel'. Other studies clearly show that solar hot water

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[89] Exceptions to this include smaller scale industrial biomass co-generation, solar hot water heaters and landfill gas installations. However as alluded to above, these are relatively small scale (see Alfstad (2004a) which reports the total potential for RE in South Africa).

[90] The most cost effective bulk electricity supply option, based on the costing estimates given in NER 2004, is in fact the Pebble Bed Modular Nuclear Reactor (PBMR) – for which there are no verifiable costs - followed by conventional nuclear. It is ironic that both economically efficient industrial energy efficiency (see chapter 10) and nuclear based greenhouse gas mitigation are not eligible projects under CDM.

heating at the point of demand may be an important and economically efficient renewable energy technology in the residential (de Villiers & Matimbe (2000)) and commercial (de Villiers (2000)) sectors. (Those sectors are not specifically examined in this analysis.)

In terms of national and local considerations greenhouse gas mitigation needs to be seen in the context of development. As is the case of South Africa, developing country governments and organizations are faced with an array of other pressing objectives and, as a result, greenhouse gas mitigation is rarely a goal in itself. Therefore, where other goals are coincident with greenhouse gas mitigation, the potential for intervention is greater. This should be considered from a national as well as a local perspective. Another issue to be dealt with is the local environment. If fuel switching to coal in industry represents an economic and mitigation opportunity, it is important that the local environment (in the vicinity of the industry) be protected. 'Low smoke' or 'clean coal' technologies could be encouraged to limit local environmental effects. If not carefully managed, local environmental damage may be unacceptably increased. This and some other considerations which could be born in mind are shown in Figure 3.7. (Note that this is simply an indicative, qualitative diagram only.)

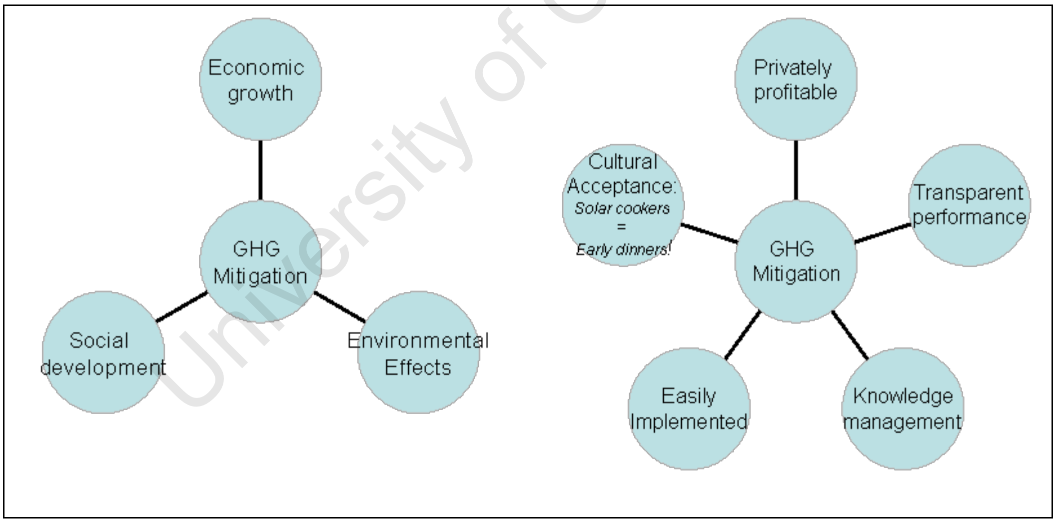

Figure 3.7: Greenhouse gas mitigation in the South African social (left) and private (right) context – some thoughts

Energy markets in many countries, including South Africa, are deregulating. The use of market based instruments needs to be carefully considered[91] and may need to be engineered to help realize the optimization of the energy system. Emphasis needs to be placed on increasing the incentives to effectively remove market failures, especially

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[91] At present, electricity is not priced at the marginal cost of production. Therefore the 'cost of saving energy' is not equal to the marginal cost of production. This skews the system toward higher consumption of electricity, which is ultimately more costly to the economy.

where the promotion of 'integrated measures' is concerned. An example would be appropriate incentives to increase the uptake of industrial energy efficiency measures – such as marginal cost pricing of electricity – or marginal rebates for energy efficiency measures.

Some case studies and conclusions

A deduction made from the Integrated Energy Plan modelling is that energy management can induce profitable CO_2 mitigation in the energy system. This is encouraging, especially in the profit driven industrial sector.

Table 3.1 shows the results of several recent case studies carried out by the ERI (now the Energy Research Centre (ERC)) at the University of Cape Town, in partnership with government and leading local industry, to illustrate this point. The case studies are from leading locally based firms who have agreed to allow their dissemination, in order to further the process of energy management.

Table 3.1: Energy efficiency savings potential at three major South African facilities (The 3E strategy program (Kenny et al (2000 a, b & c) and Van Es et al (2002))

Annual cost savings[92]	*CO2 saving*	*Facility*	*Average payback*
R6.5m ($520 000)	33 000 tons/pa	Car manufacture (VW South Africa)	10 months
R5.5m ($440 000)	40 000 tons/pa	Paper and Pulp (SAPPI Mandini)	7 months
R 2m ($1600 000)	13 000 tons/pa	Gold mining (AngloGold Elandsrand)	8 months

These and other case studies, training courses and the South African Energy Management Association (SEMA) (EMN (2002)) were launched by the ERI with the "energy, efficiency and earnings (3E) strategy drive".

Selected limitations and recommendations

Both the model formulated and data used are limited and therefore so is the strength of the conclusions. In particular the data set used to estimate energy savings potentials should be increased and improved. An approach to this end is suggested in Appendix 1 at the end of this thesis (rather than the chapter specific appendix). The model also ignores the effects of price changes on the demand for useful energy services. For example, if energy can be provided more cheaply (while reducing emissions) this may increase the consumption of energy (and ultimately increase emissions - this is termed the 'rebound effect'). Further, increased consumption and activity in industry may lead to changes in activity in other sectors of the economy. Some models approximate changes in a single

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[92] Assuming a current exchange rate of 8zaR to 1US$.

sector by including ‘demand elasticities’. It would be useful, however, to account for changes in all sectors. An attempt to do so is presented in Chapter 9.

Acknowledgments

Special thanks to Eskom and the Department of Minerals and Energy for funding. The following individuals and their organisations must be acknowledged for their assistance in preparing the South African I.E.P.

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- Eskom, Steve McFadzean and Johan Prinsloo,
- ETSAP, Gary Goldstein.

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- The EU and Netherlands government,
- The US Department of Energy and University City Science Centre,
- Local industry: VW SA, SAPPI and Anglogold,
- And The South African Department of Minerals and Energy.

Appendix: Summary of the MARKAL modelling

Mathematical formulation

The MARKAL model objective function, described in Loulou et al. (2004), can be summarized mathematically as follows:

$$\sum_{t=1}^{t=NPER} (1+d)^{NYRS\bullet(1-t)} \bullet ANNCOST(t) \bullet \left(1+(1+d)^{-1}+(1+d)^{-2}+\cdots+(1+d)^{1-NYRS}\right)$$

NPV is the net present value of the total cost to be minimized (the objective function)

ANNCOST(t) is the annual cost for period *t*

d is the general discount rate

NPER is the number of periods in the planning horizon

NYRS is the number of years in each period *t*

The total annual cost ***ANNCOST(r,t)*** is the sum over all technologies $\boldsymbol{k}$**,** all demand segments $\boldsymbol{d}$**,** and all input fuels $\boldsymbol{f}$**,** of the various costs incurred, namely: annualized investments, annual operating costs (including fixed and variable technology costs, fuel delivery costs, costs of extracting and importing energy carriers), minus revenue from exported energy carriers and taxes on emissions. (Note that for the modelling purposes of this chapter the commodities referred to are energy carriers.)

Mathematically, ***ANNCOST(t)*** is expressed as follows:

$$\boldsymbol{ANNCOST(t)} = \Sigma_{k} \{\mathit{Annualized\_Invcost}(t,k) \; *\mathit{INV}(,t,k)$$

$$+\mathit{Fixom}(t,k) \; *\mathit{CAP}(t,k)$$

$$+ \mathit{Varom}(t,k) \; *\Sigma_{\mathrm{s,s}} \mathit{ACT}(t,k,s)$$

$$+ \Sigma_{c} (\mathit{Delivcost}(t,k,c) * \mathit{Input}(t,k,c) * \Sigma_{\mathrm{s}} \mathit{ACT}(t,k,s)) \; \}$$

$$+ \Sigma_{\mathrm{c,s}} \{ \; \mathit{Miningcost}(t,c,l) * \mathit{Mining}(t,c,t)$$

$$+ \; \mathit{Importprice}(t,c,l) * \mathit{Import}(t,c,l)$$

$$- \; \mathit{Exportprice}(,t,c,l) * \mathit{Export}(t,c,l) \; \}$$

$$+ \Sigma_{c} \{\mathit{Tax} \; (,t,p) \; * \; \mathit{ENV}(t,p)\}$$

Where:

Annualized_Invcost(t,k) is the annual equivalent of the lump sum unit investment cost, obtained by replacing this lump sum by a stream of equal annual payments over the life of the equipment, in such a way that the present value of the stream is exactly equal to the lump sum unit investment cost, for technology k, in period t. Note carefully that by stopping the summation over t at the end of the horizon, the objective function automatically accounts for the salvage value of all assets stranded at the end of the horizon.

Fixom(k,t), Varom(t,k), are unit costs of fixed and operational maintenance of technology k, and period t;

Delivcost(t,k,c) is the delivery cost per unit of commodity c to technology k and period t;

Input(t,k,c) is the amount of commodity c required to operate one unit of technology k, in region r and period t;

Miningcost(t,c,l) is the cost of mining commodity c at price level l and period t;

Importprice(t,c,l) is the (exogenous) import price of commodity c and period t; this price is used only for exogenous trade, see below;

Exportprice(t,c,l) is the (exogenous) export price of commodity c and period t; this price is used only for exogenous trade, see below;

Tax(t,p) is the tax on emission p and period t;

Important input data for the industrial efficiency example are summarized below:

Pertinent model input data

In this section I repeat input data which are pertinent to the modelling of industrial energy efficiency options. This includes power station data, costs of efficiency saving, and the derivation of the industrial sector baseline scenario.

Power station costs

Much of the cost and emissions savings are in fact derived from delaying new power station investment and operation. The power station performance data is given below (NER (2004)):

Table 3.2: Energy saving in South African industry

	Units of capacity	*Investment cost, undiscounted*	*Fixed O&M cost*	*Variable O&M cost*	*Life-time*	*Lead Time*	*Efficiency*	*Availability factor*
Type	*MW*	*R/kW*	*R / kW*	*c / kWh*	*Yrs*	*Yrs*	*%*	*%*
Coal								
New pulverized fuel plant	642	9 980	101	1.1	30	4	35	252
Fluidised bed combustion (with FGD)	233	9 321	186	2.9	30	4	37	88
Imported gas								
Combined cycle gas turbine	387	4 583	142	11.5	25	3	50	85
Open cycle gas turbine (diesel)	120	3 206	142	16.2	25	2	32	85
Imported hydro								
Imported hydro	9200 GWh / yr			2.1	40	6.5		
Renewable energy								
Parabolic trough	100	18 421	121	0	30	2	100	24
Power Tower	100	19 838	356	0	30	2	100	60
Wind turbine	1	6 325	289	0	20	2	100	25, 30, 35
Small hydro	2	10 938	202	0	25	1	100	30
Land fill gas (medium)	3	4 287	156	24.2	25	2	n/a	89
Biomass co-gen (bagasse)	8	6 064	154	9.5	20	2	34	57
Nuclear								
Nuclear								
PBMR initial modules	165	18 707	317	2.5	40	4	41	82
PBMR multi-modules	171	11 709	317	2.5	40	4	41	82
Storage								
Pumped storage	333	6 064	154	9.5	40	7	storage	95

Costs of saving energy in industry[93]

As shown by several case studies for individual industries (ERI (2000)[94]) and nationally (Trikam et al. (2003) and Howells (2006)), final energy can frequently be converted into useful energy more efficiently. Energy use can also often be more efficient. Such efficiency-based savings may involve incremental costs[95]. Put another way, energy can be saved, but there may be a cost associated with saving it. In the table below I report the percentage of energy that could be saved by end use. This gives a low end technical potential (Trikam et al. (2003)) and an estimate of both the cost and life time associated with each saving.

Table 3.3: Energy saving in South African industry

Energy efficiency measure	*Cost of measure*	*Life*	*Cost of energy saved*	*Reduction in base case consumption*
	Rm/PJ	*Years*	*Rm/PJ*	*% in year 2015*
Electrical steam system saving	18	3	7.24	0.2%
Other thermal savings from electrical based heating	13	2	7.49	1.8%
Higher efficiency motors	195	8	36.55	3.1%
Variable speed drives	156	8	29.24	3.1%
Lighting	100	5	26.38	2.7%
Compressed air saving	25	4	7.89	4.5%
Heating ventilating and cooling measures	61	5	16.09	0.9%
Refrigeration efficiency	39	5	10.29	0.7%
Saving coal though boiler and furnace optimization as well as steam saving	6	3	2.41	15.2%
Oil saving	22	3	8.85	19.5%

While the costs of saving energy are given in table 3.3, table 3.4 below gives the associated fuel price assumptions.

Table 3.4: Fuel costs (Winkler et al. 2005)

Price for fuel	*Units*	*2001*	*2013*	*2025*
Crude oil price	Real crude oil price local production (R/GJ)	24.8	18.0	21.4
	Real crude oil price imports (R/GJ)	27.6	20.0	23.8
Petrol price	IBLC (R/GJ).	50.3	51.4	60.9
Diesel price	IBLC (R/GJ).	44.9	45.9	54.4
Paraffin price	Bulk (R/GJ)	58.0	59.3	70.3
	Drum (R/GJ)	80.5	82.3	97.6

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[93] This data is listed in Chapter 9 (Howells, In Press a). Unfortunately it is based on a limited set of industrial audit data. Appendix 1 (Howells (2006)) suggests a methodology for improving the sample with an emphasis on electrical use.

[94] See also: Kenny et al (2000 a, b & c) and Van Es et al (2002)

[95] Cost is often but not always incurred. Sometimes energy can be saved through behavior change and may simply require appropriate incentives.

HFO price	Bulk (R/GJ)	35.7	36.4	43.2
LPG price	Bulk (R/GJ).	112.1	114.6	135.8
	Drum (R/GJ).	124.4	127.2	150.8
Coal price	Electricity generation (ZAR/GJ).	3.02	3.02	3.02
	Sasol (ZAR/GJ)	2.54	2.54	2.54
	Domestic/commercial (ZAR/GJ)	3.45	3.45	3.45
	Industry (ZAR/GJ)	3.18	3.18	3.18
Biomass price	Wood (c/l)	30.0	30.0	30.0
	Bagasse (R/GJ)	0.0	0.0	0.0
Natural gas price	LNG (R/GJ)	21.5	21.5	21.5
	PetroSA (R/GJ)	20.0	20.0	20.0
	Sasol pipeline (R/GJ)	22.1	22.1	22.1
Electricity price	Import (R/GJ)	5.5	Endogenous	Endogenous
	Export (R/GJ)	16.3	‘	‘
Electricity price inc. distribution costs	Agriculture (R/GJ)	41.4	‘	‘
	Commercial (R/GJ)	41.0	‘	‘
	General (R/GJ)	57.4	‘	‘
	Manufacturing (R/GJ)	10.5	‘	‘
	Mining (R/GJ)	9.8	‘	‘
	Residential (R/GJ)	44.6	‘	‘
	Transport (R/GJ)	21.8	‘	‘
Uranium price	Import (R/GJ).	3.2	3.2	3.2

In the next section of this appendix, the assumptions and background data used to derive the results of the industrial energy efficiency case study (figure 3.6) are described.

Derivation of the baseline scenario using described public domain data

In order to develop a baseline scenario of future energy demand in the industrial sector, projections were based on assumptions and forecasts used for official national planning exercises (NER 2004 and DME 2003a). Against this baseline various energy efficiency interventions are considered, as well as new power station investments to construct a (limited) mitigation cost curve.

The electricity forecast was taken from the IRP2 exercise of the National Electricity Regulator (NER (2004)). That forecast was based on a simple regression model (Howells (2004a)), which was reviewed by the NER’s Advisory Review Committee.

The basic elements of the electricity forecast, which was based on historical data, were as follows (NER (2004) and Howells (2004a)[96]):

1. The historical output of about twenty four industrial (including mining) sectors of the economy was gathered. This output was either in terms of physical quantity or as

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[96] Note that the forecasting model was run for high economic growth. For this example, we re-run the model (described by the equations above) for the moderate economic growth (4% short term, 3% long term) assumed for the IRP (NER (2004)). This is similar to the IEP (3%).)

economic value added. The former is useful for commodities where price fluctuations affect value added significantly, but these value added fluctuations do not affect the average energy consumption. Electricity consumption data was divided by output for each industrial sector. This gives a measure of each industry's "energy intensity". Changes in energy intensity over time were projected based on historical data with a simple logarithmic function, normalized to an index where their value in the year 2000 is 100. This is reproduced in table 3.5. A detailed discussion of which measure is most appropriate for the South African energy sector is given in Hughes et al (2002).

Table 3.5: Indexed energy intensity changes by sector

Sector/Sub-sector	*Year*	*1990*	*1995*	*2000*	*2005*	*2010*	*2015*	*2020*
	Measure of production (Physical or value added)	*Industrial Production Index (IPI) relative to value in 2000 (=100)*						
Industry (Mining)								
Gold	Physical output	75	88	100	112	125	137	150
Platinum	Physical output	107	102	100	99	98	97	96
Coal	Physical output	105	102	100	99	98	98	97
Iron ore	Physical output	104	102	100	99	99	98	98
Copper	Physical output	87	95	100	103	105	106	107
Diamond	Physical output	169	126	100	86	76	69	63
Chrome	Physical output	126	110	100	95	91	88	86
Asbestos	Physical output	58	84	100	109	114	119	123
Manganese	Physical output	102	101	100	100	99	99	99
Rest of mining	Value added	103	101	100	99	98	98	97
Industry (other sectors)								
Food bv & tbacc	Value added	79	92	100	104	107	110	111
Textile, cloth & leather	Value added	10	67	100	118	131	140	148
Wood & wood prod	Physical output	92	96	100	102	103	104	105
Chemicals	Value added	109	103	100	98	97	96	95
N M M	Physical output	82	92	100	104	107	109	111
Iron & steel	Physical output	81	91	100	105	108	110	112
Precious & non-ferrous	Physical output	94	97	100	101	102	103	104
Rest of basic metals	Physical output	54	78	100	111	118	123	128
Rest of manufacture	Value added	97	99	100	101	101	101	102

2. Based on historical changes in sector output and economy-wide GDP, a forecast of industrial production was estimated. Therefore the historical decline of certain mining activities continued, while increases in tertiary activities increased. Normalizing this data to the value to the year 2000 was again done (and values repeated in table 3.5). The following equations summarize the sector outputs for the GDP growth rate of the IRP (2.8%) taken from Howells (2004a).

Table 3.6: Index of output by industrial sector relative to 2000

Year		*1990*	*1995*	*2000*	*2005*	*2010*	*2015*	*2020*
	Basis of output	*Output index relative to value in 2000 (=100)*						
Industrial sectors								
Industry (Mining)								
Gold	Physical output	171	135	100	88	73	55	35
Platinum	Physical output	62	79	100	122	148	178	213
Coal	Physical output	79	90	100	111	120	129	140
Iron ore	Physical output	89	95	100	114	129	146	165
Copper	Physical output	143	111	100	96	87	77	66
Diamond	Physical output	76	76	100	118	138	160	185
Chrome	Physical output	69	70	100	118	134	153	176
Asbestos	Physical output	1230	418	100	94	86	76	65
Manganese	Physical output	96	86	100	109	116	125	135
Rest of mining	Value added	83	90	100	122	144	170	199
Industry (other sectors)								
Food bev & tobacco	Value added	92	97	100	122	156	194	239
Textile, cloth & leather	Value added	402	79	100	109	128	151	176
Wood & wood products	Physical output	82	94	100	119	143	172	205
Chemicals	Value added	76	99	100	119	141	168	198
Non Metallic Minerals	Physical output	98	101	100	125	164	209	261
Iron & steel	Physical output	88	87	100	117	136	157	181
Precious & non-ferrous	Physical output	48	58	100	119	143	170	201
Rest of basic metals	Physical output	108	72	100	109	117	126	136
Rest of manufacture	Value Added	75	90	100	116	134	155	179

3. The electricity forecast was calculated by:

$$E_{y,x} = (IPI_{y,x}/100) * (EII_{y,x}/100) * E_{y,2000}$$

Where

$E_{y,x}$ is the electricity consumption by sector y in year x

$IPI_{y,x}$ is the industrial production index for sector y in year x

$EII_{y,x}$ is the Energy Intensity Index for sector y in year x

$E_{y,2000}$ is the electricity consumption of sector y in year 2000

$E_{y,2000}$ values are given in the table below:

Table 3.7: Electricity consumption in 2000

Sector/sub-sector	*Year 2000*
	Electricity consumption by sector in GWhr
Industry (mining)	
Gold	18 705
Platinum	6 695
Coal	2 823
Iron ore	353
Copper	1 051
Diamond	716
Chrome	177
Asbestos	20
Manganese	144

Rest of mining	854
Industry (Other sectors)	
Food Bev & Tobacco	2 675
Textile, cloth & leather	148
Wood & wood prod	7 184
Chemicals	13 378
Non Metallic Minerals	4 438
Iron & steel	14 286
Precious & non-ferrous	8 028
Rest of basic metals	96
Rest of manufacture	3 463

In order to replicate the *all energy* (and end use or useful energy) forecast of the Integrated Energy Plan (IEP), with public domain data, the following steps were taken:

1. Following the IEP baseline assumptions, it was assumed that fuel shares would be consistent with those of recent history (DME 2002) and that recent history prices trends would continue: i.e. comparatively low cost coal, limited natural gas usage, low cost electricity (based on average – not marginal cost pricing), and high liquid fuel prices. Overall fuel consumption by fuel in the industrial sector is thus estimated and illustrated in figure 3.8. Note that changes, though small, are primarily due to changes in industrial energy intensity, as well as changes in industrial output. With recent capacity shortages, attempts to coerce electricity savings from mining and heavy industry and to raise the price of electricity to cover the cost of expanding generating capacity have begun.

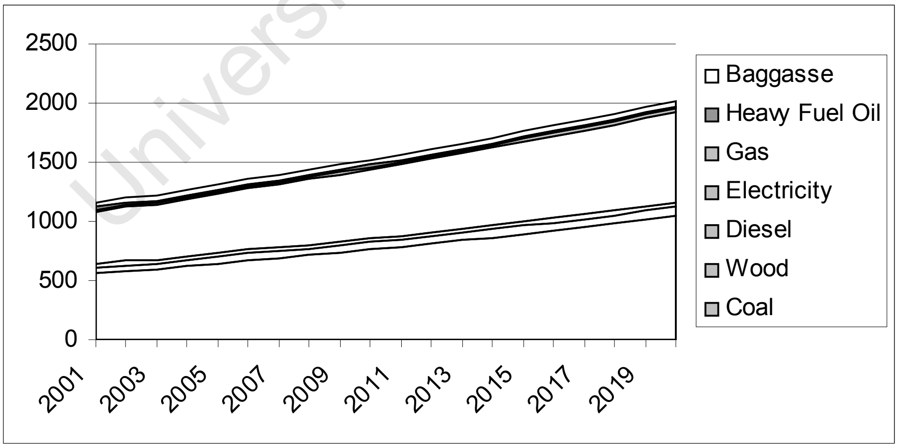

Figure 3.8: Industrial energy consumption by fuel

2. End-use data were estimated from limited local studies as well as international profiles for similar economic sectors. (This data is summarized in Appendix 1: ‘Improving Data – Targeting Industrial Energy Efficiency’ of this thesis.)

It is important to note that this data is simply a scenario of the future, based on assumptions with broad stakeholder and official endorsement and repopulated with public domain data. Many of the assumptions are not necessarily robust, for example:

- Energy prices and technology prices may change significantly, as seems increasingly likely.
- Market incentives or management practice may change and affect the uptake of more efficient technologies, as also seems increasingly likely.
- Industrial growth may change and with those, fuel forecasts.
- New technologies may radically affect existing processes and with those, demand.

There are many more examples that could be cited. These not withstanding, having a scenario that is reflective of current practice is useful simply to contrast it to different future scenarios based on what might be achieved by better management of existing or likely options. As I do not consider long term futures, such an analysis can by useful for drawing short to medium term policy. This is the philosophy for the development and use of scenarios in this and future chapters of the thesis.

Selected MARKAL detail

For the special example reported in Figure 3.6, the above data is entered into MARKAL, which is used to determine:

- the least cost power station and other energy supply requirements to meet energy needs (subject to increasing limits on the quantity of CO_2 permitted to be released); and
- the uptake of the most appropriate energy efficiency investments.

In this example I consider only energy efficiency measures as mitigation options on the demand side and concentrated on electricity generation on the supply side.

In the MARKAL model used for this chapter, each year is modeled. Each year is divided into six average consumption (inter-temporal) periods, or ‘time-slices’. These are: a summer, winter and intermediate (season) day and night. The length of and the energy demand in each time slice determines the ‘load characteristics’ of the system. More electricity is consumed during the day than the night. For each time slice the cost of supply and demand is balanced in order to determine the least cost system. The supply curve (the relation between the quantity of electricity that can be supplied and the price at which it could be supplied) is illustrated below. This is done indicatively as no attempt is made to represent quantities. Note that each step along the curve relates to specific technology options.

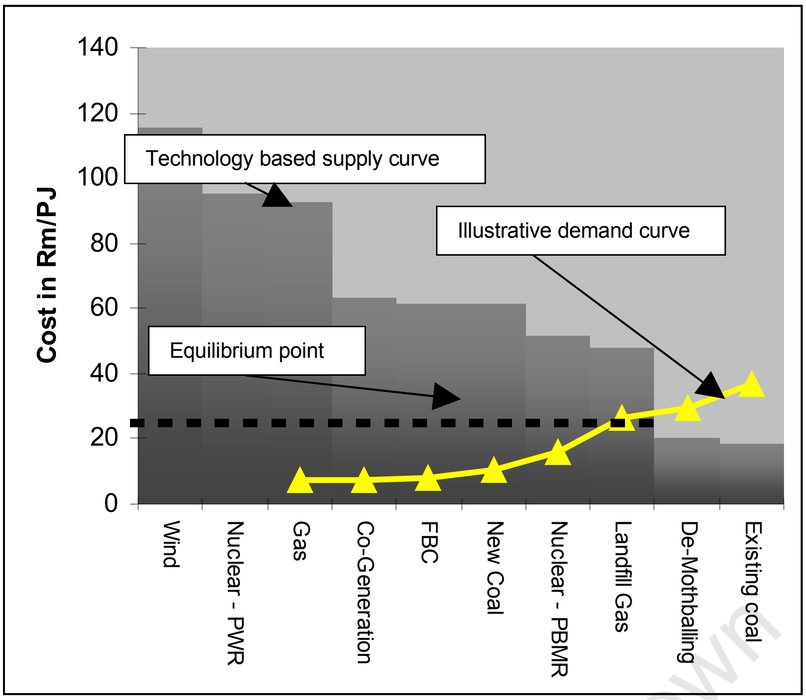

Figure 3.9: Electricity supply curve in MARKAL

Similarly, the demand curve for industrial electricity demand is derived from potential investments in energy efficiency options. This is indicatively illustrated in the figure below.

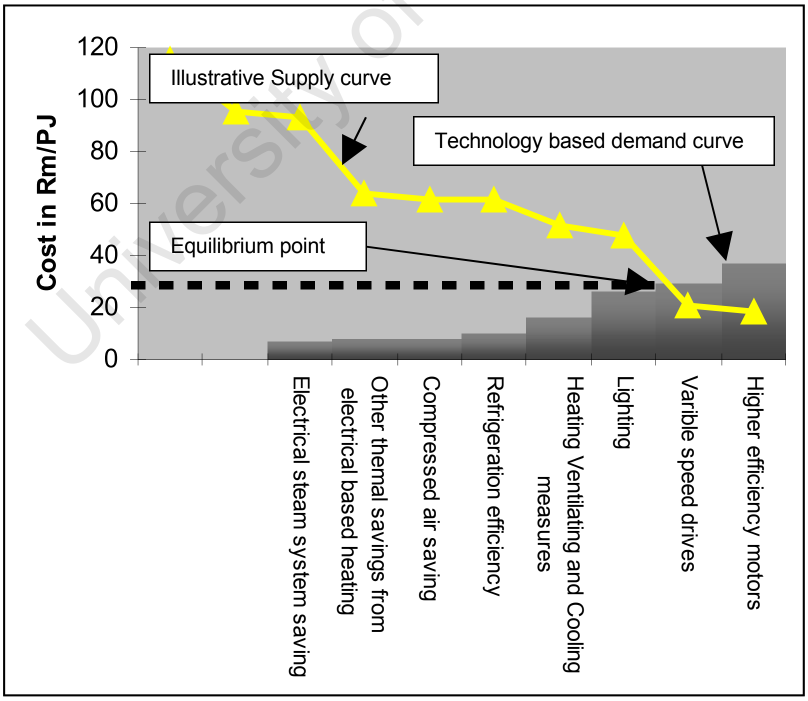

Figure 3.10: Industrial electricity demand curve in MARKAL

In economic terms, where the supply and demand curve intersect, they are in equilibrium. MARKAL is dynamic as it solves all time steps (each of the six time-slices and each year) simultaneously. In an ‘ideal’ world, with marginal cost pricing, perfect knowledge and foresight, (but with some of the underlying assumptions adopted here) the result given by MARKAL would be the outcome one would expect of the perfect (energy) market. However as the market is not ideal, the results are used to indicate what this ideal market might look like, which is in turn useful for policy formulation. I also constrain the introduction of new technologies so that the results generated might be achievable. (In our case important constraints include for example the lead times of new power stations and the penetration rates of energy efficiency investments.)

Section 3: Energy Supply to the poor: considerations and models

In the next section the focus is low income consumers. It begins with a non- modelling piece that describes aspects of certain market inefficiencies in low income rural areas. This helps set the scene for the modeling applications that follow. In the first model application, a very simple model - suited to illustrate the inefficiency of an energy subsidy - is developed and applied. It is used to indicate that scenarios (of subsidies for alternative fuels) may improve the policy's efficacy. The final chapter in the section shows the benefit of developing sophisticated modelling of rural households. This improves the suitability of optimization modeling of energy provision policies for poor rural households. Various scenarios of "how to" better provide energy for a poor rural village are expounded.

Chapter 4 Calabashes for kilowatt-hours – Rural energy and market failure

Introduction

Following the macro analysis of Chapter 3, this chapter begins a more focused discussion of household fuel consumption in low income rural areas dependent on traditional biomass fuels.[97] No modelling is employed and the aim of the chapter is to form a context for modeling chapters which follow.

This chapter describes how information failures can retard transitions from the traditional use of biomass fuel by low income rural consumers and micro-producers. Traditionally biomass is used to meet the bulk of the user's thermal needs and is often associated with poor ventilation, especially in winter months, when burners are used indoors with no chimney. "Traditional biomass use" also implies that the biomass is harvested directly by the user.

The results of the information "failures" are distorted fuel choices. In general, societies move away from traditional biomass use as economic development takes place. Individual energy users move to less polluting and more convenient fuels as their incomes rise. If one accepts the doctrine of revealed preference (built on initial the work of Samuelson 1938), then these trends imply that such transitions provide net gains in utility if properly timed. The chapter shows how distorted markets[98] entrench existing fuel use patterns – hindering the transition to new fuel use patterns. In order to qualitatively discuss how these transitions may take place, an indicative neo-classical description of consumer and producer behavior is used. Simple examples are used to show the effect of electricity in retarding uptake of relatively clean commercial fuels such as LPG.

This chapter identifies three types of fuel-transition "drivers". It then discusses the effects on the drivers of information failures involving consumers, micro producers and government. Often these information failures simply dull the effect of the "driver". Several examples are considered, largely based on a field study in Nkweletshini, a South African rural village. In this village, a partial transition from fuel-wood to LPG occurred after specific attempts to correct for failure in environmental governance. The chapter

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[97] The section is based on the author's contribution to an earlier paper: Howells M., Jonsson S., Käck, E., Lloyd, P., Conradie B., and Bennett K. Calabashes for Kilowatt-hours – Energy Transitions and Market Failures in Low Income Rural Areas, *Energy Policy*, Submitted.

[98] Markets considered are in a rural low income setting. The market distortions occur due to various information and governance failures.

concludes that policies to encourage transitions to cleaner sustainable fuel use may need to recognize and address such information and governance failures.

Fuel transitions

Services derived from fuel and appliances are often termed 'useful-energy-services' (see Loulou et al (2004)) and include for example: lighting, cooking, crop-drying etc. Fuel provides a service when it is used in an appliance (such as a kettle or fireplace) or productive technology (such as a lathe or fridge used to preserve foods for sale). There may be apparent anomalies in fuel and appliance selections. While utility flows from the service, some status goods also provide utility in themselves (the designer samovar or pot-belly stove). Moreover, a wealthy household may use an "inferior" woodburning fireplace or barbeque for heating and cooking. Such options provide "recreational" utility, rather than meeting basic needs.

A fuel transition has been described (Elias & Victor (2005)) as a change from one fuel source to another. In this chapter the description is augmented to include changes in fuel use *and, or* appliance use, i.e. it is not limited just to fuel switching. Examples of this expanded definition of a fuel transition would include:

- No change in the *type* of fuel used for a particular service, but a change in the *way* it is used (e.g. replacing a traditional fuel-wood stove with a more (thermodynamically) efficient wood-stove. Though the stove is changed, wood is still consumed. However the transition may result in the consumer using less wood and consuming a similar quantity of cooking service, or the consumer using similar quantities of wood, but consuming greater quantities of the cooking service.)
- The consumption of a new energy service. An example includes the purchase and use of a battery powered radio for the first time. A new fuel is used, a new appliance owned and a new energy service consumed.
- The substitution of one fuel and appliance for another. e.g. heating water in an electric kettle, rather than in a pot on the stove. The same service is derived and consumed, but a different appliance and fuel used.

Often only fuel switching is considered in the literature, but to do so clearly excludes other important aspects of fuel use.

Fuel transitions are an integral part of socio-economic development[99] as well as development's impact on the environment. In poor rural areas, households can spend several hours collecting fuel-wood daily – often the unenviable chore of women and children. Over a million people die annually due to indoor smoke (WEC/FAO 1999) associate with poorly ventilated biomass use. To this one can add the greenhouse gas implications of destroying forests which act as carbon sinks. Amongst other causes, deforestation takes place from over-harvesting fuel-wood (WRI 2000). Without energy, industrial or commercial activity cannot take place and income generation limited. Without access to, and the transition to, affordable forms of clean appropriate energy, many of the world's poor are 'locked into' livelihoods which are often unnecessarily environmentally damaging, unhealthy and uneconomic. Producers may be unable to increase their competitiveness and economic development may also be obstructed.

Conversely, after economic development, households and economies generally move away from freely harvested biomass to cleaner[100] and more productive forms (Victor & Victor (2002)). I am going to assume that consumers and producers wish to use more convenient, cleaner, less costly and more productive forms of energy –from which more utility can be derived. Certainly this is the trend of history (Nakicenovic et al. (1998)). This is not to say, for example, that households will not in the future derive utility from fuelwood, or that multiple fuel use will not continue, given choice. However, it is assumed that for the *bulk* of basic needs the household desires to move from one end of the so-called energy ladder[101] (Eberhard & van Horen (1995)) towards the other.

When discussing the dynamics of fuel transitions, it is convenient to use the terms "primary", "circumstantial" and "informational" to identify the drivers of fuel transition.

The primary 'driver' of energy transitions

Neo-classical economics describes consumers/households and producers/firms as "maximizers", either of utility or profits. Energy sources provide utility in differing degrees and at different costs to the consumer. Maximizing utility therefore creates a

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[99] Without electricity, for example, lighting is poor, thereby retarding conditions for good education and limiting the supply of other services associated with social transformation such as communication, computation and refrigeration.

[100] While few fuels are more hazardous to health than "traditional" biomass (see Eberhard & van Horen (1995)), it should be noted that during much industrialization, energy-use was not 'clean'. (Consider for example deadly smog events in London during the early 20th century – fueled in part by "commercial" coal.)

[101] The term 'energy ladder' is often used to describe the generally observed trend of households moving from the use of biomass and candles, to kerosene, to electricity and gas, when meeting basic heating and lighting needs.

"desire" for transitions, albeit subject to a household budget constraint. Utility maximization is taken as the 'primary driver'. Limited by circumstance and fueled by information it is in a sense the "independent variable"[102]

The neo-classical system uses perfect competition as its benchmark. This is a system in which there is full and symmetrical information, a single homogeneous product, no market power and frictionless exchange,while both production and consumption are free of externalities. Since these properties are hardly characteristic of the real world, markets do not always work 'as they should'. Collectively, evidences of such instances are called 'market failures' or market "distortions". This chapter refers to information and governance failure as such a cause of observed market failure. It does not argue that a market simply "fails".

Energy and utility in production

In the neo-classical description, the *producer* in a cash or barter market will favor fuel-technology options that minimize costs and or provide new services from which profit can be derived. For example, if boiling water is required to make tea in an eating house, the choice between a cooking pot on an open fire or an electric kettle depends only on which of the two can be operated most cheaply (in terms of both money and time). If the eating house owner wants to serve cold beverages, biomass burning technologies are no longer relevant. In this case the purchase of a fridge is not related to cost minimization as much as it is to do with the profitability that could be derived from the new service. Then the choice rests between paraffin, gas or electric refrigerators. All are commercial products. If the services are equivalent the decision is made on the basis of simple monetary cost efficiency alone.

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[102] Though the desire for new services or appliances may change as a function of advertising, peer pressure or cultural changes it is, in a sense, the 'independent variable'. Limited due to circumstances, it drives what is consumed or owned. Or, in terms economic, it determines, subject to constraints such as budget, the "demand correspondence". (The "demand correspondence" is a common micro-economic term, describing the choice of goods and services purchased to maximize utility under various constraints.)

Energy and utility in consumption

Unlike firms, where only profit maximization is assumed to matter in adopting a new technology, a consumer can derive satisfaction just from ownership and may value the status of an electrical fridge even if other cheaper options exist. Such "utility" is difficult to measure. It is assumed here, however, that cleaner more convenient energy and appliances which provide new services (associated often with the richer or developed country user) are probably desired.

Circumstantial 'drivers'

Consumers (and producers) attempt to maximize their utility (or profitability) subject to constraints. As these constraints change, so may their purchases of energy consuming appliances and their energy usage patterns. Constraints that affect the fuel transitions of households and producers are termed '*circumstantial drivers*'. These can include:[103] income, access to markets, market form, climate and custom.

Income plays a clearly observed role in fuel-appliance purchase and use (or energy transition) (Victor & Victor (2002)) and is the first circumstantial driver identified. As incomes increase, budgetary constraints relax and demands for new goods and services, including non-agrarian products, increase. The appeal of new appliances and new production technologies induces energy transitions.

Clearly energy and economic transitions are restricted by poor access to appropriate energy. Without it desired new technology-appliance combinations become unattainable, limiting potential production activities regardless of new demands for product. For the consumer, the welfare gains to be had with new energy forms including savings in time budgets may not be realized. The second circumstantial driver is therefore access to appropriate energy (as well as the corresponding appliances and technologies.)

Barter economies are common market forms in many parts of Africa (OECD (2004)). While barter secures production and consumption opportunities, it also limits choice (Martin et al. (2000)). Barter-based markets may also therefore limit penetration of new energy forms, appliances and technologies. This is because they are based on a dual coincidence of wants and because many of the goods and services involved in an energy transition have to be purchased from suppliers outside the immediate area using cash. This slows the energy transition. The third circumstantial driver identified here is therefore monetised trade – the absence or decline of barter.

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[103] For a list of circumstantial factors which affect micro-enterprise as well as the uptake of commercial fuels in rural developing country settings, see Kebetcha (1999).

A fourth circumstantial driver is the extent of access to undervalued biomass. Such access is a feature of commercially unexploited[104] communal land. There are examples, locally and internationally, of well governed land uses that include community woodlots and regulated commercial fuelwood growing (Williams et al. (1996)). However, access to arable communal land which is not used for income- generating crop-growing can provide biomass that is freely harvested and effectively under-priced. Note that much deforestation – and with that access to free fuelwood[105] - is the result of agricultural expansion as land is used for commercial crop growing (Hyde & Seve (1993) and Allen & Douglas (1985)). Ironically there are also instances where access to free biomass leads to a temporary dependence on it until it runs out[106] through over-harvesting. A fuel transition is then forced. (Examples of the over-harvesting of fuel-wood are included in: Hosier & Bernstein (1992), Bluffstone (1998) and Williams et al. (1996), amongst others.).

In certain instances, institutional intervention can affect fuel usage, ranging from communal banning of dangerous fuels (Mehlwana & Qase (1999))[107] to subsidized electrification programs (Gaunt (2002)) to international protocols (UNFCCC (2008)) which affect the use of GHG intensive fuel use. This is the *fifth circumstantial driver*: active (rather than inactive) institutional intervention.

Sixth, location and climate affect demands for the useful energy service of heating and cooling, as can, *seventh: household size*, in both persons and space. (See Afrane-Okese (1998), the ESKOM National Load Reseach Program (Dekenah (2002) and (2004)) and Louw et al. (2006) for a detailed regression analysis of how these factors affect historical consumption of electricity, as well as by Mehlwana & Quase (1999).

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[104] Note that there may be and often are reasons which make land unattractive for many kinds of production, though it is fertile and arable. These can include: missing or no access to markets, restrictive trade policies, barter economics etc. It is an interesting thought that restrictive trade policies such as international import protection and farmer subsidies in some markets could in fact be halting the transitions of many to more healthy forms of energy use. That said, unless the fuel users benefit economically from the commercial exploitation of the land, new fuels may be unaffordable and a situation of fuel poverty can result. A transition from biomass may occur, but may less than beneficial.

[105] (As per previous footnote:) that said, unless the fuel users benefit economically from the commercial exploitation of the land, new fuels may be unaffordable and a situation of fuel poverty can result. A transition from biomass may occur, but may be less than beneficial.

[106] While those who save ecological treasures see utility in having them around which transcends their market price, if no such relative utility is seen in a communal wooded country side – perhaps dwarfed by desperate circumstance, poverty and poor governance (Garrett (1968)) – its over consumption in that circumstance can simply be tragic, but quite rational.

[107] Mehlwana & Qase (1999) describe the banning of paraffin/kerosene after a series of fires in a South African slum.

Finally and *eighth* in this superficial discussion, cultural custom and norms potentially affect the manner in which services, and the manner in which the services themselves are required. (Consider different cooking requirements for different foodstuffs as an example. Appliance and fuel choices in cooking are discussed in Prasad & Visagie (2006) for South Africa for the cooking of maize. By Berrueta et al. (2008) for cooking Mexican tortillas. In both cases, the culturally preferred foodstuff determines the type of energy service required.)

To summarize, the following *circumstantial* drivers have been mentioned: (1) Income and affordability; (2) access to energy-appliance – or production technology - options; (3) barter economics; (4) management of communal land as well as access to it; (5) institutional and policy intervention; (6) location and climate, (7) dwelling size and (8) cultural norms.

The circumstantial drivers have been discussed in terms of their direct effect on the purchaser of energy and appliances. However, these drivers have important secondary effects. These are particularly important where they affect income generation. The micro producer may purchase and use more productive appliances and fuels. The wages and wealth of his employees may increase. As a secondary effect, they may in turn purchase new appliances etc.

Informational 'drivers'

Information can change the consumer's attitudes, customs and aspirations (Shiffman and Kanuk (1997)). Changing position on the demand curve, information can affect the utility associated with fuel/appliance usage. Further, as consumers and producers in the real world will not have access to full information all of the time, the information at hand will likely 'bound' the behavior of the otherwise "rational agent" (Lazonick 1993). Even when information is available, it may take time for this to be assimilated and acted on, depending on a number of factors including societal adoption rates and the prevalence of "early movers" (Shiffman and Kanuk (1997)). Less than full information, however, can result in distorted markets and some examples are summarized in the table below.

Market failures and drivers

In the preceding section "drivers" of energy transitions were described as primary, circumstantial and informational. In the next section, the effects of information and government "failure" on the driver and the slowdown of the transition is sketched. In the footnotes, anecdotal common examples are included. Examples are given of how failures have entrenched the use of traditional biomass.

Table 4:1 Summary of failure causes and effects

Failure types	*Instances*	*Driver*	*Implication*
Poor consumer information	Consumers unaware of the long term health effects of biomass smoke	Informational	Deflates the full cost of biomass, as full health costs are not internalized[108].
	Consumers exaggerate dangers associated with new fuels, such as LPG[109].	Informational	Until use is common, this causes an (irrational) 'aversion' to new fuels.
Poor supplier information	Suppliers unaware of consumer needs, such as 'stove design' requirements for customary food.	Informational	Reduces the potential 'utility' that would otherwise be gained with the use of the new fuel-appliance combination relative to traditional use[110].
	Inappropriate project management, including poor knowledge management and key performance indicators. (This is often associated with 'supply driven' interventions, such as off-grid electrification.)	Informational	Inappropriate behavior is rewarded. The emphasis is often on 'aspects of delivery' that do not necessarily relate to the sustained *consumption* of the new fuel. The user is often eventually left with unreliable energy.[111]
Poor government information	Inappropriate pro-poor fuel interventions.	Informational	Eligible alternatives to traditional biomass may be under- or – inappropriately subsidized[112].

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[108] In a study of a rural community in Kwa-Zulu Natal, South Africa local residents were asked about health effects associated with fuel-wood burning. Over three quarters reported knowledge of short term effects such as coughing and sore eyes, but none cited any knowledge of long term effects (Lloyd et al. 2002).

[109] Again, that is not to say that new fuels are not without risk. However, relative to the risks associated with traditional biomass, they are often significantly lower.

[110] The introduction of solar cookers in Africa, though apparently rational due to savings in time budgets, did not result in the expected transition from biomass. It is reported that this was primarily due to the poor "supplier information". Various local customs, including, amongst other things, demands for night-time cooking, were simply not accounted for (Eberhard 1993).

[111] Several studies relate the failure of the provision of clean fuel options for social upliftment. In particular there is failure reported due to inappropriate measurement of 'supplier' performance. Typically the focus is on the provision of some aspect of supply, rather than ensuring sustained consumption of new fuels. In South Africa, early rural off-grid electrification programs failed, as the key performance indicator was the number of schools provided with PV systems. Surveys months later showed that many of the systems no longer worked – as proper service delivery was not a KPI of the program. Currently the revised off-grid electrification program includes mandatory servicing of PV panels. Similar studies relate poor unreliable grid based electricity supply (Mehlwana & Qase (1999)) to customers 'back switching' to old fuel usage – though reliable electricity was preferred.

[112] In South Africa, the government developed a subsidy to supply a quantum of free basic electricity for social and health reasons (Gaunt (2002) and Gaunt (2003)). This was intended to encourage consumers to move from traditional fuels (including biomass), as well as relatively hazardous fuels such as coal and kerosene. It was shown that a market friendly alternative could provide consumers (for cooking needs) with several times more utility at the same cost by allowing consumers the option of alternatives such as LPG (Howells et al. (2005) and the next chapter). Inappropriate subsidies and interventions such as this will result in alternatives to biomass effectively being 'under-subsided' limiting their penetration.

Government intervention	Under-investment in transport infrastructure, providing access to markets.	Circumstantial	Limited access to markets dampens local potential producer profit to be made from productivity increases with new fuel-technology combinations. This retards demand for new technology-energy combinations.
Land mismanagement	Poor 'communal management' preventing any organized agriculture.	Circumstantial	Land and therefore the fuelwood (only in instances where it is in competition with the cash growing crop to be harvested) may be undervalued[113].
	No local ecological accounting, especially where deforestation is a risk of over harvesting.	Circumstantial	Undervaluing of biomass-harvesting - where harvesting leads to (sometimes irreparable) ecological damage[114].
Barter economics	Prevents potentially efficient alternatives that may not be easily traded, replacing local production norms.	Circumstantial	Entrenches the fuel-use (and production possibilities) status quo[115].
No accounting for climate change related carbon costs	Destruction of carbon sinks due to over-harvesting[116] of fuel-wood where deforestation is a risk of over harvesting.	Circumstantial	Undervaluing of unsustainably harvested biomass[117].

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[113] In many rural developing country instances, land is communally owned or at least communally available. Such land is often poorly managed (Gander (1994)). Where wood harvesting on such lands could be profitably replaced by other activities, fuel-wood is effectively undervalued. Although land conversion may mean deforestation, increased agricultural production may increase the potential biomass (as crop residues) available for fuel. However, as this is likely to correspond to a change from traditional biomass fuel use to a commercial crop residue, using our broad definition an energy transition would occur. Where arable land is not organized effectively, it will hinder organized agriculture and associated transitions.

[114] Due to poor management, land is often degraded by the fuel-wood demands of growing rural and peri-urban settlements (Eberhard (1992)). In Botswana, desired species of biomass were over-harvested, though other undesirable species remained. In India it was noted, as well as in many other areas, that local ecological damage is not 'included' in the cost of biomass harvesting (Dasgupta 1996). This failure results in the under pricing of biomass – and price difference to alternatives higher.

[115] Many of Africa's Least Developed Country's rural communities are part of barter economies (OECD (2004)). In several examples in Africa it has been observed that these conditions tend to retard the consumption of electricity post electrification (Ranganathan (1992)). Such economies have been noted to limit the penetration of any new goods or services (Marin et al. (2000)) - including commercial energy and new technology, therefore limiting shifts to new economic 'frontiers of production'. Further, if economic growth is hampered, so too is commercial energy consumption required for new equipment,and any further consumption of energy associated with increasing local income.

[116] We note however, that in some instances, increased use of biomass would in fact be preferable from a carbon balance point of view – where it is not over-harvested *(our point of concern)* this is certainly the case. Where increasing the sustainable consumption of biomass is an economic GHG mitigation option, it is likely this will not be consumed 'traditionally'. i.e. without ventilation and at low efficiencies.

[117] Apart from local ecological damage, global damage occurs with the unsustainable over-harvesting of biomass. (Clearly this is not to say that all fuel wood harvesting is "wrong", used sustainably it is both an important renewable fuel and the growing biomass an important carbon sink. Nor is this to say that deforestation is the result of only biomass harvesting.) However, when net biomass is depleted from fuel wood harvesting, so is an important 'sink' for the greenhouse gas Carbon Dioxide (IPCC (2001)). Damage costs for the reduction of these sinks are not accounted for in developing, non-Annex 1, countries. Their non-inclusion will again result in the under-pricing of unsustainably harvested biomass unless policy tools such as the CDM are effective.

Non-inclusion of external health costs in prices	Third parties pay for the effects of biomass usage.	Primary	Biomass usage, which is often associated with high levels of indoor air pollution, is under-costed
Monopoly power of fuel-appliance suppliers	Available appliances are over-priced and new entrants disadvantaged	Primary	Biomass may remain the significantly lower cost option, while competition may have reduced the cost of alternatives.
Poor knowledge on the part of micro producers	Producers unaware of potential profit gains to be made with new fuel/appliance combination.	Informational	Suppresses profitable gains associated with a transition[118].
Lack of financial services	Inability of micro-producers to finance high capital purchases	Circumstantial	Suppresses the purchase of expensive productive technologies with associated transitions[119].
Failure of labor markets to clear	Increased un- and under-employment in local communities	Primary	Suppresses potential economic activities with associated demand for new services requiring new commercial fuels.

Next, a short case study is examined. A rural village in South Africa is the target of an intervention designed to correct market failure and promote a shift from the overuse of biomass. The state of the rural community before and after the intervention is discussed. There is a qualitative attempt to interpret some changes in energy use patterns in terms of governance and information failure on the part of consumer and fuel-appliance suppliers.

A short case study: Nkweletsheni

Households in the community of Nkweletsheni were harvesting biomass at an unsustainable rate. More fuelwood was harvested than regrown as it was free to harvest. Effectively, households were reducing the net quantity of biomass and a carbon sink and the global environmental damages not included in the transactions. With external funding an intervention was made to correct this failure. There were other market-related-failures which may have affected the consumption of fuels both pre- and post-intervention. In both cases, these failures would have the effect of encouraging the use of biomass (if the villages intended to move away from this source), but it is difficult to quantify the relative extents of this "encouragement".

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[118] In Kenya, Kabetcha (1999) reports various gaps in entrepreneurial (producer) knowledge that limit gains made by the introduction of modern energy and related technologies – even where opportunities for profitable enterprise were apparently available.

[119] Meadows et al. (2003) cites lack of functioning credit markets and banking facilities as a critical barrier to the adoption of any relatively 'capital intensive' new technology. It is in this context that micro-finance has found itself a powerful niche as a development enabler. In Zimbabwe, in an effort to address this formally, the national electrification program was faced with the prospect of low sales and pressure to increase grid connections. In an effort to address several common market failures, the utility deliberately targeted entrepreneurs. It is hoped that their access to markets and business knowledge would make them higher volume consumers. Further, attempts to provide "appropriate" technologies as well as low interest financing having been made available (Mpako (2005)).

Methodology

The Nkweletsheni community in Kwa-Zulu Natal, South Africa, is typical of some developing country rural communities in several ways. Preliminary studies (Howells et al. 2005) showed that there were several market-related failures identified in the village which would affect a transition from traditional fuel use. These included the observed reduction in available biomass – with no associated penalty. It was being overharvested for use as fuelwood – and a carbon sink was being reduced while the cost of this loss was not included in the cost of biomass harvesting. An attempt was made to correct this by the introduction of subsidized LP Gas. PV solar home systems were included in the intervention to provide households with electricity. Following the intervention, initially promising uptake of new cleaner fuels, consumption levels continued, but dropped, resulting in a 'partial' fuel transition. On investigation it appears that new and uncorrected failures were identified and that these would act to suppress the demand for new fuels from wood – were such a transition desirable to the consumer.

This case study was deliberately chosen as the data, thought limited, could be interrogated. Data was collected by four methods. An initial survey[120] with detailed results was designed (Lloyd et al. (2002a)) and reported by Lloyd et al (2004b). A second survey and analysis (Howells & Dick (2003)) was conducted post the intervention and this was later followed by a series of interviews to ascertain the effectiveness of the intervention (Jonsson & Käck (2005)). Finally, sales and the organization of the implementing company were analyzed (Jonsson & Käck (2005)).

Nkeweletsheni pre-intervention

The initial survey of domestic energy use in the community of Nkweletshini in south-western Kwa-Zulu Natal took place during 2002. About 150 households were surveyed. According to Lloyd et al (2004b), the community has a low housing density, below the 50 households per km^2 measure used by Eskom and the DME as the limit for future electrification. Houses were modest, with a median number of 3 rooms, and built of either clay or cement blocks. Houses were generally thatched although some had corrugated iron roofs. Figure 4.1 shows such a picture. Many in the community are employed, but it was relatively unskilled employment, with a median income of about R660/month/household.

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[120] This survey incorporated novel aspects in order for the data to be used in detailed economic modeling.

Figure 4.1: Nkweletsheni households and location

96% of all households cooked (and a similar proportion heated water) with wood collected free of charge in the vicinity – though some of the older folk in the village collected and sold some wood. 3% cooked with paraffin and 1% with LP gas. The primary appliance was a wood stove; 4% of the households use an open brazier (‘imbaula’).

Households showed no awareness of any long term health affects associated with fuel-wood usage and LPG was considered a dangerous fuel, due to its perceived ‘explosive potential’. Both of these were significant information failures (on the part of the consumer), only one relating to LPG safety was addressed in the subsequent intervention. (See Lloyd (2002) for an assessment of LPG and Kerosene safety.)

Following questions regarding changes in biomass collection it was estimated that between 5% and 14% of the wood collection was done unsustainably (Howells & Dick (2003)[121]). It was this reduction in woodland and carbon sink, not accounted for in the collection of wood, that was targeted by the intervention and related studies. (It is helpful to think of the reduction of the carbon sink as a net emission of CO_2. In the context of

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[121] From the questionnaire employed folk claimed wood collection required 50-70% more time than in previous years in terms of time and effort. Based on the interviewers, that referred to knowledge of 5-10 years prior at the most. Assuming an equal distribution of biomass and other factors being equal such as type of biomass grown and harvested, equal harvesting rates during harvesting, this loosely implied that between 5 and 14% of the wood collected is done so in an unsustainable manner. (I.e. Taking the extra time required as a proxy for extra distance to walk for wood collection/deforestation: if it takes 50% more time than it did 10 years prior then the average annual increase in time collection is 5%.) According to the participants, loss of wooded ground cover (in their collection area) was not due other reasons, such as clearing for agriculture. This crass estimation was used in the absence of measured time series data and perhaps satellite mapping which would eliminate the need for conservative assumptions and an inordinate number of assumptions, which were perhaps reasonable, but not tested by Howells & Dick (2003).

trading schemes, reductions in CO_2 emissions can have significant market value. An attempt to include this value to help maintain this carbon sink was made.)

The intervention – preserving a carbon sink

In order to reduce the destruction of the woodland, an energy package was provided which was hoped would encourage a transition from and therefore a slowing down of traditional biomass use. It was subsidized at a level which would be less than the "external health cost" associated with the emissions from biomass burning (discussed later) and close to the market price associated with the "net emissions" of CO_2 which were observed. Villagers could acquire PV panels[122], lights, LPG cylinders, a 2-plate LPG cooker[123] and a 6kg monthly supply of LPG, leaving them to pay a monthly installment of $25 (R150) for the service. The project team visited the community twice, once before and once after the intervention, surveying the selected households on their energy consumption patterns.

Care was taken in order to introduce the intervention in a manner that was sensitive both to the needs of the inhabitants of Nkweletsheni, as well as to local governance. Only after both community and local government acceptance was attained did the project proceed.

For implementation, a team of four local people were employed to form a local energy business: 'Switch On'. The business is registered as a not-for-profit company and all employees were bilingual in English and Zulu (the local languages).

The 'Switch On' NGO was responsible for the installations and maintenance of both the solar and the LPG part of the package; they collected LPG from the supplier in a nearby town (Highflats) and refilled the customers' LPG cylinders. (Initially Switch On delivered LPG 'refills' to the households concerned). They were further tasked with educating consumers about LPG usage. For transportation, an open-back half-ton truck was used, since the roads are poor and the terrain is rough. A technical manager visited the site monthly in order to address any complex technical problems. The salaries of the team depended on the monthly costs of the business as well as on the amount of repayments collected each month. Thus, a low payment rate one month would imply that the team's salaries would be lower.

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[122] The PV panels themselves were responsible for little CO_2 mitigation (displacing fossil fuel 'charged' lead acid car batteries in many cases). However, as the projected saving due to LPG use was high, the PV panels were included in the 'package' in order to increase its desirability. Approximately 2.1-2.3 tons of $CO_{2\ \text{equivalent}}$ was mitigated for the ninety households per annum due to the introduction of PV (Howells and Dick (2003))

[123] Essentially a small camping stove suitable for many quickly prepared 'Western Style' foods.

Household response immediately after the intervention

Households adopted the PV and LPG systems. Following the intervention, a random sample of twenty-two households with the systems were surveyed[124]. The sample size represented over 30% of the 71 installations which were in place at that time. 90 installations were eventually installed under the program.

There were advantages and disadvantages associated with conducting the second survey relatively soon after the intervention. A disadvantage was that people's behavior may still have been affected by things such as the novelty value of their new systems, and therefore their responses were not representative of their long term usage patterns. On the other hand, an advantage was that effects of the recent displacement of old fuel and usage patterns were easily recalled. For example, households were still aware of how many hours they used to spend collecting wood and how this had changed since they started using LPG[125].

The results of the survey were striking, and I focus on the effects of LPG[126] uptake. All of the households questioned were using LPG, and less wood, for cooking and water heating in particular, as reported in Figure 4.2 below. Less efficient (and more polluting) paraffin was also displaced.

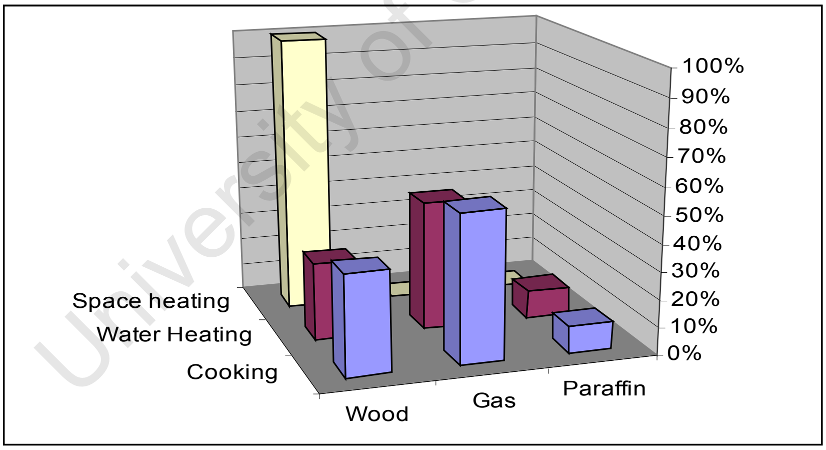

Figure 4.2: Fuels used per activity post intervention (Howells & Dick (2003))

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[124] While at the time this sample was thought to be random, there was a key independent variable which was not accounted for. This was accessibility. The team carrying out the questionnaire interviewed households which could be reached by road. Later trends relating LPG consumption to accessibility were revealed (Jonsson and Käck (2005)) This means, that the extrapolation of this 'random' survey may have led to overstating the benefits associated with LPG, as it was not associated with negative distribution problems.

[125] This data was used to confirm the baseline initially estimated.

[126] We note however that the uptake of the PV systems was a clear example of an energy transition according to the definition adopted earlier.

It was estimated that if all 90 households were to partially displace wood collection at the rate observed during this survey, for 16 years between 1.0 and 1.7 thousand tons of $CO_{2\ \mathrm{equivalent}}$ would be mitigated (Howells & Dick (2003)). Further, were this project to be replicated, this would be at a cost of between 7$ and 12$ per ton[127]. This is well within the estimated externality cost range associated with CO_2 emissions (Blignaut 2003) and market prices of emissions bought through the CDM. Further estimates of health cost savings (supposing the treatment was sought and paid[128] for) were significant[129]. Much of these costs would simply be borne in terms of poor health by household members - under "normal" circumstances.

Household response months after the intervention

Implementation took place over the period November 2002–November 2003 and the maintenance of the PV systems as well as LPG supply was ongoing. The transition from fuel-wood use to increased LPG usage is of interest. In particular for households who paid[130] their monthly contribution for the energy package and their LPG collection habits.

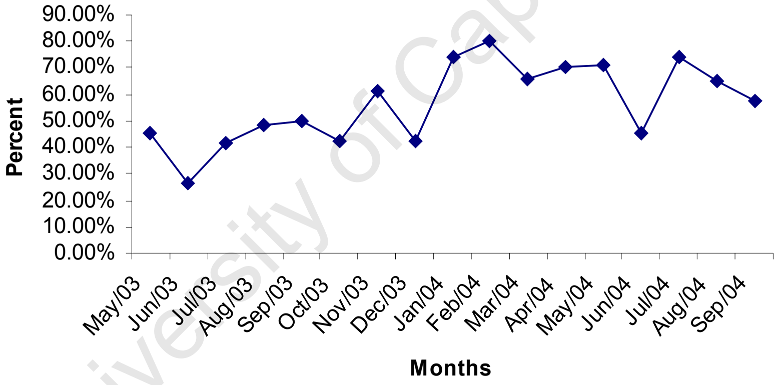

Figure 4.3: LPG 'non-collection' for eligible households (Jonsson & Käck (2005))

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[127] Much of the initial cost involved scoping, international project promotion and initial research. Were all costs to be included, the total cost of CO_2 mitigated would be between $65 and $111 per ton. In Howells & Dick (2003) emphasis was placed on the fact that these estimates were based on survey rather than scientifically monitored data.

[128] These costs could be born either by government through rural clinics or by households directly.

[129] Howells and Dick (2003) estimate a saving of over $500 per household per annum. This is based on reduction of indoor air emissions as a result of increased LPG to wood-fuel burning. 'Low-end' externality costs relate tons of emissions to treatment costs. The values used are repeated in the Appendix of chapter 6.

[130] Due to the sporadic income of many in the case study, most have been in debt, at some time or another, to the Switch On business. This observation implies that methods such as flexible "micro-finance" may play and important role in this context.

Figure 4.3 gives the percentage of eligible households who did not collect their LPG refills. The figure clearly shows a significant increase in the non-collection of LPG. After conducting several interviews with the Switch On team and with a limited number of consumers (Jonsson & Käck (2005)) the following reasons were given for increased non-collection. (Both are instances of market-related–failure, however, this time due to poor incentive structures within the Switch On business and poor understanding of the consumers needs):

- The Switch-On team limited the number of LPG deliveries, as this extra effort (and cost) was not rewarded, neither was this a key performance indicator (KPI). This represented a failure in the incentive structure of the Switch On business. At the onset of the project, LPG deliveries were carried out during the maintenance cycle for the PV systems.
- Many of the LPG appliances provided were inappropriate. These were essentially small stoves that were not suitable for large pots used for long cooking periods. In this case, customary food is a maize-based starch dish which is typically cooked for long periods in heavy pots which damaged the stoves (Households on average reported cooking over several hours per day.) This represented a failure in terms of the knowledge of the needs of local consumers.

Some considerations

Were there utility to be gained by transitioning from biomass, the informational market failures reported would likely have resulted in increased dependence on biomass. “Pre intervention”, these failures included: (the non-accounting of) the reduction of a carbon sink, poor consumer information of the long term health hazards of biomass smoke, poor land management and exaggerated fears of the dangers of LPG. When measures were put in place to reduce non-accounting for the carbon sink, a partial transition to a ‘cleaner’ energy package (LPG and PV) was observed. One of the changes associated with this transition tackled by the implementers was improving consumer knowledge of the relative safety of LPG.

Many of the reasons limiting a more complete transition to LPG might be attributed to some extent to yet other “failures”. These include: poor knowledge of local needs - manifest in the provision of inappropriate appliances - as well as poor KPI selection and incentive schemes set up in the Switch On business.

It is difficult to attribute the relative importance of the specific market failure and their effect on the fuel transition – assuming that a transition from biomass as the only significant heat providing fuel would increase utility. However, there was market failure reduction and there was a partial fuel transition away from biomass to LPG.

Conclusions

In this chapter an energy transition is defined and three drivers are identified. The primary (and independent) driver for energy transitions is the increase in utility that the new appliance or service brings. Other drivers relate to the circumstance and information that the energy users have at hand. Causes of institutional and information failures and their role in energy transitions were discussed. These relate to: imperfect information, poor land management, barter economics, erosion of the global commons, externalities, the abuse of monopoly power and others. In all cases there is a propensity for these market failures to suppress the uptake of new fuels-appliance use and encourage traditional biomass usage – were we to assume that there is greater utility to be had from moving to so-called modern fuels. (The trend of moving away from traditional biomass use is common to most now modern economies.)

The result of these failures would tend to retard both the potential economic growth effect to be gained by the uptake of new fuel/technology combinations and uptake of new fuel/technology combinations themselves. This is especially the case where gains are to be had by new technology in the case of the producer.

Were transitions to new fuel use patterns to be hastened, this work implies conditions under which energy transitions may be more likely to take place. Some key aspects include:

- effective institutional land management;
- effective institutions;
- clear information relating to the effects of biomass and effective subsidy;
- access to markets; and
- monetized economies.

In a short case study it was reported that correcting for market failure encouraged a transition away from biomass. The market failure in question related to climate damage. However, the full effect of this transition is probably not realized due to poor supplier and, in effect, institutional arrangements associated with the implementation of the corrective intervention.

Increased economic growth, improved market efficiency and removal of market failure are axiomatic[131]. Studies show a relationship between growth and the fuel transition away from traditional use of biomass[132]. However, it is not clear how much of this transition could be due to reduced market-related-failure and how much due to increased efficiency of markets. In this chapter it has been found qualitatively that the casual effects may be associated with the efficiency of the market and certain types of market failure.

Recommendations

Much of what is cited is location and situation specific. It is therefore risky to generalize, moving away from inferring that a relationship is likely. A detailed inventory of case studies and drivers should be examined in the context of transitions and market failure. Where possible, it would also be of use to try and quantify 'changes in utility' during transitions: A task that is perhaps easier to undertake for micro-producers than consumers. Efforts should focus on the following, amongst others things:

- careful study of the needs of energy users and the economics of their energy use;
- systematic study of the role of institutions and energy transitions;
- market situation of producers before and after electrification, testing for market failure and the development of a database of 'success factors' (including, if possible, some quantification of those factors to their effects);
- changes in energy consumption during transitions to more monetised economies;
- the effects of more economically efficient subsidies versus less sensible subsidies with the same aim;
- understanding the role of cultural issues and preferences, in particular as it relates to behavior changes and the effects of those changes on energy use.

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[131] Removing market failure results in a more efficient economy – implying faster economic growth and greater welfare.

[132] Ruttan (2004) argues that an energy transition can be both the cause and effect of economic growth. In the case of producers, electricity and the new technology options that it brings can help increase profitability and growth. Producers move to a new 'production frontier'. Meadows et al. (2003) quote a significant number of such instances where this has occurred. In the case of consumers, as incomes increase, modern appliances and fuels become more affordable (Victor & Victor (2003)). Increased electricity consumption is the effect of economic growth. While a potential energy transition may be the cause of economic growth in our framework, it requires the correct conditions to do so. The afore-discussed causes of market failures may slow or halt producer profit that may be gained by access to new fuels and appliances/technologies. Furthermore, electrification may lead to improvements in various human development indicators (HDIs) such as literacy (Kanagawa & Nakata (2005a)) which in turn (over longer periods) affects human capital and its profitability. It is therefore suggested that both increasing the use of appropriate energy services and reducing market failure are causal factors of economic growth. Reducing market failure and increasing income are causal factors for energy transitions.

A weakness in the study is the estimation of "unsustainability" of biomass harvesting where perhaps changes in lifestyle or population growth or other reasons have accelerated this trend. This warrants further study into appropriate methods and estimates of data accuracy.

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Chapter 5: Beyond BEST – The efficient provision of pro-poor energy subsidies

The previous chapter indicated that market distortions could lead to mis-allocation of resources. An example mentioned was the (South African) state electricity subsidy[133] . The Basic Electricity Support Tariff (BEST) was designed to advance the welfare of poor households (Gaunt (2002)) by supplying 50kWh Free Basic Electricity (FBE) per month per household. It was not clear, however, that this was the most cost-efficient use of resources. In this section a less costly alternative is described and evaluated.

Introduction

For a decade the South African government has steadfastly supported energy policies that advance the welfare of the poor. These have included one of the world's most effective policies for electrifying low-income areas in urban and rural regions alike (Gaunt 2003). In this tradition, the government has introduced a 'Free Basic Electricity (FBE)' scheme offering 50 kilowatt hours per month at no cost to each household connected to the national grid. Such a subsidy naturally has displacement effects among substitute energy sources. A free monthly supply of 50 kWh is likely to influence energy choices, particularly among low income households. Detailed surveys of energy budgets in extremely poor electrified households – including urban shack dwellers – show that at current prices household electricity consumption averages 20 kWh per month. Electricity is more expensive than traditional alternatives such as coal or firewood for cooking and heating (Williams (1994)); the rational household uses it sparingly. Typically, purchased electricity is used for television, lighting, electric irons and a few other applications for which fuel substitutes are inferior or absent. For the most energy-hungry applications, however, traditional fuels continue to dominate (Afrane-Okese 1998). Ceteris paribus, free electricity is likely to affect a household's equilibrium bundle of energy-appliance options or use.

In a trial run in 2002, government offered 50 kWh of free electricity to households for a one year period. The response, documented in detail through Eskom's Load Research Programme, was a rapid rise in pervious average monthly consumption of 30-35 kWh per household (Prasad & Visagie (2006)). Long run effects are expected to exceed these short

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[133] This chapter draws heavily from: Howells. M., Victor, D. G., Gaunt T., Elias, R., Alfstad T., (2006). Beyond free electricity: The costs of electric cooking in poor households and a market-friendly alternative, Energy Policy 34 (2006) 3351-3358

run impacts; the trial survey was recognized as finite in duration; investment in white goods was therefore limited. However, once the policy is in place nationally, households will gain confidence in the continued availability of free electricity. When free electricity was offered in the Khayelitsha township of Cape Town a survey (Cowan & Mohlankoana (2004b)) revealed that households were responding by purchasing and using electric cookers, and in some cases hot water cylinders.

There is little doubt that free electricity has improved the livelihoods of poor households. It has reduced household expenditures and also expanded the use of a clean fuel at the expense of mainly dirty alternatives. Two questions arise however: what were the unintended consequences. Could the same outcomes have been achieved at lower cost?

Methodology

In this section the approach to the analysis is described. It is shown that free electricity has a greater cost than might be expected. If used at peak times, users consume high cost electricity. This analysis focuses on estimating selected marginal infrastructural costs. It compares them with the costs if households were provided with an alternative energy source that placed no burden on the grid during peak load periods and therefore changed the need (and cost) for infrastructural expansion. (By being selective in the infrastructural costs for electricity analyzed, the full costs of electricity provision are underestimated. This allows the analysis to be simplified: producing useful information for comparing alternatives in a transparent manner.) The approach is described in South Africa-specific detail below, and abstracted in the appendix to this chapter.

The primary impact of the free electricity supplied is the increased use of electricity for cooking. The electricity subsidy makes it more difficult for unsubsidised alternatives such as LPG stoves to survive in the marketplace. Importantly, most cooking occurs during periods when electricity is already in peak demand. At the margin, this electricity is particularly costly for society since electricity is difficult to store[134] and thus the entire electric power system must be sized for adequate supply during peak periods. This peak-load effect lies at the heart of this analysis.

The South African electric power system is short of peak capacity during winter months. NER (2004) estimated that if all demand management targets were realized and all

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[134] Typically, electricity is produced at peak times using a so called “peaking plant”. These include open cycle gas turbines (OCGT) which run on oil. When there is potential, pumped storage plants are also used. The latter are the only plant which effectively store electricity (by pumping water uphill at off peak times and then generating electricity as it is released during peak times.).

mothballed power generating plants were restored to operation, peak demand would be 36000MW and total installed capacity 40000MW. New demand will require the construction of new power plants. Plants (and transmission and distribution lines) are needed not only to supply the quantity of power consumed but also to preserve the buffer of about 15% (NER (2004)) extra capacity – known as the 'reserve margin,' which sits on call ready for dispatch should another generator or power line in the system fail. South Africa will require new power plants even without the roll-out of free basic electricity; however, there is no doubt that its introduction will accelerate that need. To ensure commensurability in the calculations that follow, the analysis utilizes the assumptions and models deployed in the National Electricity Regulator's most recent National Integrated Resource Plan (NER (2004)).

Following Cowan (2004a), the model assumes that the hot plates introduced in response to FBE will operate 45 minutes per day, with a 70% chance that this use will occur during peak periods. It further assumes that on average hotplates operate at 50% of their maximum level. Consider boiling food in water. When heating water, hot plates will be consuming close to maximum power. However, once brought to a boil the power will be reduced and the average power consumed will be less than maximum. During operation, these plates use electricity from, amongst others, baseload coal plants This is extremely inexpensive: about 0.08 R/kWh (NER (2004)), including the cost of maintenance, fuel, and losses (including theft) that are typical of electric service in low-income areas. The cost of connection to the grid is largely 'sunk' and does not include the costs of transmission and distribution. These simplifications will lead to conservative estimates of the cost savings that would accrue from switching fuel use away from electricity.

Assume that incremental (marginal) demand for electricity will be met by an average blend of two types of plants: large coal-fired power plants typical of South Africa's present power system (which are 'on the margin' 80% of the time) and pumped storage facilities such as the Braamhoek scheme (which are 'on the margin' 20% of the time). Given this assumption the incremental cost would be 0.09 R/kWh consumed. This estimate is conservative if, as expected cooking occurs when the system is near peak. The role for the costly pumped storage may be even larger than assumed above.[135] .

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[135] According to available Eskom statistics, historically, pumped storage plants have run at an annual load factor of 20% (Eskom 1996). If pumped storage stations operate only at maximum power these stations will be on the margin for 20% of the time for steady consumption though a 24 hour period. Cooking tends to take place closer to peak than off peak periods and pumped storage stations need not operate at full power. This implies the assumption that pumped storage stations are on the margin for 20% of the time that energy is required is conservative.

Using a more realistic blend of plant including open cycle gas turbines (OCGT) and marginal operating time, the model yields a marginal generation cost of about 0.17R/kWh consumed. Table 5.1 shows the operating and maintenance costs and fuel costs for these options.

Table 5.1: Operating and maintenance (O&M) and fuel costs for the three main options for generating peak power (NER (2004))

Plant type	*Pumped storage*	*Open cycle gas turbine*	*Coal fired*
Units	*R/kWh*	*R/kWh*	*R/kWh*
Operating & maintenance	0.05	0.14	0.02
Fuel costs	0.06	0.81	0.04
Losses (T&D)	0.03	0.24	0.02
Total	**0.13**	**1.18**	**0.08**

The results are particularly sensitive to the assumptions about the relative contributions of pumped storage[136] and OCGT. As a general rule, pumped storage schemes are costly to build and require long lead times but have low operating costs compared to OCGT. South Africa has built 1400MW of pumped storage plant and has begun the process to build more – once these facilities exist there will be strong incentives to use them. However, and critically, further expansion of pumped storage plant is limited[137] by the physical constraints of a relatively arid South Africa (NER (2004)). Gas turbines, by contrast, are relatively inexpensive to build but extremely expensive to operate (If the plant burns oil-based fuels then, during periods of high oil prices, power generation is especially costly). These units are much smaller in size and require less lead time for construction; thus OCGT investments are easier to scale to the exact demand. In most of the world – where demand for peak power is rising sharply – these properties help to explain why such gas turbines are occupying an increasing role in the power system.

To illustrate what is at stake, assume that power is provided on South Africa's power system at the least possible cost. Thus coal plants are constantly in operation; during non-peak periods extra electricity from these plants is used to pump water in pumped storage facilities. During peak periods the pumped storage is used to the maximum extent

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[136] A pumped storage system is used to consume and store electricity when demand is low (and the marginal cost of production low) and discharge electricity when demand is high (and the marginal cost is high). To store the electricity, the system pumps water uphill into a dam. As it is pumped uphill electricity is consumed, and effectively 'stored'. To generate electricity the water in the dam is released downhill and as it runs through a turbine. As the turbine runs, the 'stored' electricity is discharged.

[137] To about 2300 MW while demand grows at over 1000MW per annum.

possible and any residual need for power supply is satisfied with OCGT. Using such a method when looking at the next decade, OCGT plants will probably supply little of the extra demand for cooking power that the provision of free basic electricity creates. During most peak periods the OCGT plants will nonetheless be needed to maintain the reserve margin. This means that they will incur the cost of construction and maintenance but not the actual cost of operation[138]. All told, for every kilowatt of capacity required by low income consumers at peak time there is a once-off cost of R5949 required[139]. (This is the per kilowatt cost of an OCGT plant inclusive of transmission and distribution costs. These are assumed constant despite the increased capacity, further suggesting the conservatism of the estimate). Given these assumptions, one can estimate the minimum cost of supplying the incremental electricity for cooking. This has two components: the incremental cost of supplying the electricity actually used and the cost of maintaining the reserve margin. The cost of supplying the electrical energy used is a function of what plants are running 'on the margin'[140] while cooking is taking place. The cost of the reserve margin is the cost of installing the cheapest capacity on the grid, namely OCGT plant[141].

If the free electricity described above were not available LPG would be an alternative source of heat energy available to households. For cooking purposes it is comparable to electricity, providing quick heating with essentially zero indoor air pollution (Williams 1994)[142]. Already many low income households select LPG for cooking where it is available. From those markets – which are served mainly by private enterprise – we

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[138] It should be noted that this is an assumption that is extremely conservative. Knowing that the South African grid is behind its construction time table for new plant means that open cycle gas turbine (OCGT) plant will now be running at peak times. This inflates the marginal costs of peak generation significantly. In the short term this is again of special importance as the fuel used to generate peak electricity is now also based on the international price of oil. Therefore, if the alternative to using electricity for cooking is based on oil, it may still be significantly cheaper. Cooking directly with liquid petroleum gas (LPG) would require less than three times the quantity of oil if electricity generated from an OCGT plant were used.

[139] NER (2004) suggests that pumped storage plant (where available) may be more than twice as expensive as OCGT Per kW of installed capacity.

[140] In order to be conservative, we do not consider the capital cost component of new plants required to produce electricity.

[141] In the NIRP analysis carried out by the national regulator, OCGT plant are build at various intervals during the twenty year planning horizon considered and OCGT plant built during times of capacity requirement are not decommissioned. It is therefore reasonable, according to the NIRP activity, to assume that the minimum cost incurred to maintain the reserve margin is the capital cost of OCGT's.

[142] We do not consider kerosene as an option due to health effects associated with the way in which kerosene is commonly used. In South Africa, several thousand people die annually from kerosene related poisoning and burns - by comparison ten died after LPG related accidents. Kerosene is also expensive; the running costs of the popular kerosene wick stove are about 20% higher for the same quantity of useful heat for cooking.

derive estimates of the actual costs for LPG services. When compared with electric stoves, LPG systems[143] (stove, valve and tank) are about R50 more costly but have twice the life time: 10 years, rather than 5. The valve systems have a short lifetime of about 3 years. At the time of writing the retail cost of filling a six kilogram LPG cylinder was R36[144] (Tatham (2004)). Since LPG distribution and servicing offer economies of scale and scope these costs should decline if LPG usage increases. The LPG business has yet to secure a foothold in these new markets and probably incurs higher costs than would prevail at larger scale.

Results

The key finding is that LPG is less costly than peak load electricity. This suggests that the opportunity costs of free electricity may be greater than the incremental costs of the current alone. During times when there was considerable excess capacity in the system this may not have been true - but it is certainly true and extremely relevant given the current peak period undercapacity in the grid. Consider the cost of maintaining 1.5 kW of electric cooking capacity and the cost of 1.3kW LPG hotplates over a twenty year period, which is the economic life time of the new OCGT plant. According to our assumptions, 1.5kW of electric hotplate on average will consume 0.75kW, and only 70% of these hotplates will be consuming electricity during peak periods. This implies that 0.525kW, or R3123, of reserve margin will not be needed for the LPG option. Over the period the household would have invested in four electric hotplates and these would have consumed on average 205kWh per year, not all at peak times. The discounted (i.e. present value) cost of the hotplates, reserve margin requirements and electricity (with our conservative assumptions and a 10% discount rate) is R3522. The total cost of supplying the same cooking requirement using LPG systems, with two LPG stove/cylinder systems, seven valve systems and similar quantities of fuel consumed the total cost is R1109. This means there is a (present value) difference of R2413 over the twenty year period. This conservative estimation process yields an average annual levelized (i.e. expressed in present value terms) saving of R258 per year if households use LPG instead of electric

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[143] Data was obtained from the Afrox-Wild Orchard pilot project (Tatham (2004))., The cost of an LPG system is R156 and the equivalent single plate electric hotplate taken from a local supermarket cost, at the time of writing, about R110.

[144] This was for a crude price of $50 per barrel. The Rand Dollar exchange rate of six was assumed and the oil price was presumed constant during the period. We do however report the effect of increasing the LPG price used in this study by 80% in the sensitivity analysis in table 2. The savings are still significant. It is worth noting that the LPG costs are a function of crude price and not of new capital required for refinery investment.

hotplates. (Again I emphasize that this figure relies on conservative assumptions; higher savings are likely. This is particularly the case where OCGT plant will in fact be generating electricity on the margin. In that case, even with extremely high oil prices, electricity generated from OCGT (requiring over three times the oil for generation) will be more expensive than using LPG directly at peak times.

Conclusions

The estimated saving of R258 per household per annum is not trivial. The estimated household income of the poorest decile in 2005 was R4300 per annum (Statistics South Africa (2008)) [145] The opportunity cost of "free" electricity is therefore roughly 6% of such a household's income. Importantly, the net saving involved would be sufficient to meet the total cost of the LPG stoves and giving every household 3.3 free kilograms of LPG per month. This would more than provide for the very basic cooking requirements considered in this experiment. The savings (of R258/year/household) described would accrue to the state and hence ostensibly to society as a whole. Thus, even if the net benefits to the target households were kept unchanged, the cost of basic energy provision would have been reduced.[146]

These estimates are clearly sensitive to the underlying assumptions. The first of these is the peak coincidence factor – that is, the assumption that 70% of the cooking activity occurs during peak periods[147]. It is thought that this assumption is robust and that without real time pricing of electricity, it will be difficult to shift cooking behavior away from peak periods.

The second (and more crucial assumption) concerns the technologies that will be used to supply peak power and maintain the reserve margin. As South Africa has already committed to build new pumped storage, I have assumed that actual power generated by OCGT plant(s) is 0% of the total marginal power consumed by these hot plates. OCGT is used *only* to preserve the peak reserve margin. There are three reasons to be skeptical of this assumption, each of which further underscores the conservatism of the estimates obtained. The first is that as households gain confidence that FBE is indeed a permanent policy, they will optimize their investment in electric appliances (including stoves) to

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[145] This figure is approximately 6%, considering that the poorest 10% of the population earn approximately R4200 per annum.

[146] It should be noted that a similar analysis should be carried out to establish the viability of LPG as a cost cutting measure more broadly than simply for low income consumers.

[147] The losses that we have assumed are also conservative. In fact, much of the demand for electricity is far from its generation (situated near South Africa's central coal fields. Extra savings would accrue). in costal areas due to reductions in the need to strengthen that grid.

make fullest use of the free power. A second is that the 50 kWh[148] free allowance may well increase, there are already agitations to raise it – such an additional load would require additional operation of OCGTs unless a substantial commitment were made to building pumped storage facilities. A third is that, with time, the rest of the economy is likely to shift to a more ‘peaky’ load profile; as that happens, the marginal kWh consumed through FBE increasingly require dispatch of OCGT. (The economy is likely to shift to a more peaky profile as household and commercial consumption increases at the expense of primary – and generally less peaky, baseload - industry. (NER (2004)))

Other assumptions to which the results are sensitive include the price of LPG[149] and the prices of appliances. Table 5.2 below shows the outcomes of sensitivity analyses to annualized savings as a function of peak co-incidence factor, LPG[150] increases and increased appliance[151] costs.

Table 5.2: Key assumptions and their effect on the annualized saving to society

Peak co-incidence factor	*Annualized saving in 2005 Rand*	*Appliance costs in 2005 Rand per system (% increase in costs)*	*Annualized saving in 2005 Rand*	*LPG costs in 2005 R/kg (% increase in costs)*	*Annualized saving in 2005 Rand*
100%	401				
90%	353	375 (140%)	225	11 (83%)	180
80%	305	175 (12%)	255	9 (50%)	211
70%	258	156	258	6	258
60%	210				
50%	162				

Interestingly, even with the high appliance and LPG cost assumptions there is still a net saving of R147 per system to be had by moving to LPG for a twenty year period.

Discussion – implementation

These calculations illustrate the potential for substantial savings. They also make a case for urgent reform since expectations (and capital investments, such as electric stoves) are

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[148] It should be noted that the 50kWh mentioned is a nominal figure - many poor live in municipalities that cannot organise the billing to achieve the ideal.

[149] We assume that changes in the price of crude oil induce directly proportional changes in the LPG price.

[150] We assume a delivered cost of 9R/kg and 11R/kg, a 50% and 83% increase over the case study costs used for this calculation. The increase could be taken to represent an increase in distribution costs or a similarly proportioned increase in crude prices.

[151] The sensitivity analysis used the costs of standard but more expensive appliances available on the market, namely CADAC and Easigas cylinder combinations, available at R375 and R175 respectively. We reiterate that the costs assumed for our primary calculations are based on field rather than hypothetical data and that the costs assumed for this analysis are high.

solidifying around the promise of free electricity. Once such promises become cemented in place it may be politically difficult to change course.

For a more market-friendly allocation of the subsidy it may be sensible to start by introducing time-of-use electricity pricing. Qualifying consumers would be given a flexible grant to be spent on energy. Such a grant could be used for the purchase of *any* appropriate fuels and appliances. It could be for increased LPG usage, lower cost off peak electricity consumption or higher cost electricity at peak times. In an earlier paper (Howells et al. 2006) co-author David Victor specifically recommends the distribution of ‘energy tokens’ which could be used at approved vendors for alternative fuel purchases. The vendors would be limited in the selection of fuels that they could offer so as to maintain the original motivation for the subsidy - which was to improve living standards by effecting a transition to cleaner fuels.

Appendix: Calculating the “floor cost” of generating electricity

In this appendix the equations and methodology for calculating the “floor cost” of generating electricity are described. The “floor cost” of electricity generation as is an artificial cost. It is calculated based on some of the costs incurred when producing an increment of electricity at peak times. It is artificial as it is always lower than the actual cost. It is useful, however, as it is simple and transparent to calculate yet it is meaningful. In this paper it was shown (under the assumptions given) that an alternative was less expensive than the equivalent electricity “floor cost”. Since we know that the “floor cost” is lower than the actual cost, we know that the alternative was more economic than that also. The floor cost calculations are based on an estimate of the peak coincident factor. Thus assuming this is correctly estimated it is valid for the situation in which the incremental demand for electricity has either a “peaky[152]” or “flat” “curve” or “profile”. At the same time new demand for electricity should be creating a shortage of electricity supply capacity (such as in the case of South Africa at the time of writing)[153].

The cost of generating an increment of electricity is a function of the cost of the new capacity required as well as the “production” cost of fuel, operations and maintenance of the plant used to generate the required electricity. These (capital and production) costs are then escalated by the transmission and distribution losses which are incurred when

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[152] That is, more electricity is demanded during peak than during off-peak times.

[153] This method could be used to estimate a “below minimum” cost for meeting new electricity demand as well as estimating minimum cost differences of supplying new demand with differing peak coincidence factors. This would be needed to evaluate the minimum benefits of demand side management (DSM) activities.

transmitting the electricity to its intended consumers (i.e. If 10% of the electricity is lost as it is transmitted, an extra 10% must be generated). The "floor cost" calculation rests on two simplifying assumptions:

1. the marginal capacity required will at least be equal to the portion of the new demand occurring during peak time plus an extra fraction required to maintain the system reserve margin. The cost of this capacity is at least equal to the cost of the plant available with the lowest capital cost. In South Africa's case that is Open Cycle Gas Turbine (OCGT) peaking plant.
2. the marginal cost of electricity "production" - i.e. all of the costs *not* including the capital costs at the peak time are assumed to be the same as an estimate of the average marginal production cost for the entire electricity system for a year's generation. The production cost is assumed to be equal to the cost of running baseload power plants plus a small contribution from peaking plant. It is assumed that peaking plants are run on the margin at least in proportion to load factor of the most run peaking plant. In the case of South Africa, that is that pumped storage plant which is run at a load factor of 20% and coal fired baseload plant is assumed for the rest[154].

For any new demand in electricity consumption we can therefore compute the floor price PF as
follows:

$$P_F = \frac{\sum (CI_t + P_t)(1+r)^{-t}}{\sum \frac{E(1+r)^{-t}}{(1-D_L)}}$$

Where
PF = Floor cost of meeting increases in electricity demand [R/kWhr]
CIt = Capital investment cost required in time period t [R]
Pt = Marginal running cost to meet an increase in time period t [R]
r = Discount rate [fraction]
DL = Distribution losses to the customer [fraction]

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[154] Note that at these times the more expensive peaking power plant will be run at a higher load factor, ensuring that this estimates a cost that is below the actual marginal cost at this time. If with this deflated cost an alternative is cheaper, then it will be cheaper than the actual cost.

CI = Marginal capacity investment due to increased demand [R]

Where CI:

CI = ND*(1+VM) * PCF * CCOCGT

ND = Marginal increase in demand [kW]

VM = Reserve margin requirements as a fraction of peak demand [fraction]

PCF = (Peak coincidence factor) giving the proportion of new demand during peak time [fraction]

CCOCGT = Per unit of capacity capital cost of new OCGT plant [R/kW].

Where P:

P = [Pps * LFps + PPF*(1-LFps)]*E

Pps = The running cost of a pumped storage plant per kWhr [R/kWhr]

PPF = The running cost of a coal fired power plant per kWhr [R/kWhr]

LFps = The annual percentage load factor of the most run peaking plant [fraction]

E = The marginal increase in energy demand [kWhr]

Chapter 6 Modelling Energy Use in Low Income Settings

In Chapter 5 it was shown that a block subsidy for the provision of free electricity might restrict the amount of clean energy that could be provided by offering alternative schemes and fuels. In this chapter[155] an optimization model (using the TIMES framework) is compiled to investigate options to meet environmental, health and economic goals. The village investigated is the case study of Chapter 4.

The work contributes to knowledge by showing that previous efforts to model the dynamics of low income rural energy users can be significantly improved. The application of the standard optimization modelling technique is novel and includes some special adjustments made to simulate some specific dynamics.

Introduction

Energy use is closely linked to quality of life in rural Africa. The gathering of fuel-wood and other traditional fuels is a strenuous and time consuming task mainly performed by women; indoor exposure to particulate matter, mainly from cooking and heating with traditional fuels, causes about 2.5 million deaths each year in developing countries (Bruce et al. (2002)). Modern fuels and appliances allow households to reduce their exposure to smoke from biomass cookers and heaters. Yet modern fuels are costly for income-poor households and often carry their own external costs. For example, numerous children are poisoned after ingesting paraffin and whole villages have burned from fires triggered by paraffin stoves and lamps.

This paper reports on efforts to extend a MARKAL[156] energy model for South Africa to include rural energy choices, allowing for computation of optimal energy systems in a typical (non-electrified) rural village. A previous study (Howells et al. 2003) highlighted deficiencies in earlier efforts to build models of rural household energy behaviour, such as inadequate calibration against surveys of actual energy use in rural settings as well as limited representation of time resolution within the model. The present study incorporates a new village energy survey. It also deploys TIMES[157], an extension of the MARKAL computational framework that allows explicit modelling of time-of-day load curves (for demand side management analysis) and the representation of storage devices and end-use

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[155] This chapter draws heavily from: Howells, M., Alfstad, T., Victor, D., Goldstein, G., and Remme U. 2005, A model of household energy services in a low-income rural African village, Energy Policy, Volume 33, Issue 14, September 2005, Pages 1833-1851 and presented at the International Energy Workshop Vienna, July 2003

[156] For an overview of the MARKAL family, please see Loulou et al (2004).

[157] TIMES is a new model under development by the IEA-ETSAP that possesses all the features of MARKAL plus added flexibility in the definition of time periods, time slices, and technologies.

technologies ('appliances') that meet more than one energy service concurrently. With TIMES, for example, it is possible to account for the fact that open braziers are typically used in a flexible manner to supply hot water, cooking and household heating in low-income rural settings. Past failures to model the multi-functional nature of such appliances may explain why earlier studies often over-stated the rates at which new single-function energy-use devices, such as electric appliances, would diffuse and displace the old. Not accounting for the multi-service supply from appliances results in understating the services met by the appliance and understating its economic performance.

This paper reports load curves for energy demand activities such as cooking, heating and lighting and identifies least cost supply options. The model reproduces the phenomenon, known anecdotally from household surveys, of declining total fuel use that accompanies the shift from traditional to modern, more efficient appliances – for example, the switch from inexpensive candles and wick kerosene devices to much more efficient (lumens per fuel use) but more capital-intensive pressurized stoves and lanterns. It also investigates scenarios in which villagers are able to procure electricity (via grid connection, decentralized stand-alone generators and photovoltaics), and examines the effects on energy choices if household pollution from appliances is incorporated as health-related externality costs. Internalisation of such pollution costs increases households' inducement to electrify for lighting; implying that when grid connections are available the shift to electricity is more extensive and less costly to both households and society. An early product from a collaborative international effort, this model establishes a framework that allows for substantially improved future models based on recent and planned energy surveys in South Africa; the framework is also extendable to neighbouring countries and perhaps other world regions. This tool may also be useful in aiding efforts to establish baselines and counter-factual scenarios that are essential to making workable such schemes as the Kyoto Protocol's Clean Development Mechanism (CDM).

A principal objective of the government of South Africa and many other developing countries is to alleviate poverty through the economic empowerment of their people. In practice ambitious development strategies such as South Africa's Reconstruction and Development Programme (RDP) usually include substantial investments in energy services and infrastructures. Indeed, access to safe, reliable and affordable energy is crucial to development, as virtually all potential economic activity will be dependent on some form of energy service (WEC/FAO 1999; UNDP 2000). Modern energy services can improve the quality of living through better health, better environment and relief from activity that is literally back-breaking. For these reasons the South African government has pursued a vigorous electrification programme, cross-subsidised by higher income users (industry and wealthier residences) and by grants from government. The government is also encouraging a shift to other modern fuels – such as LPG – especially in areas with low population densities where electrification is impractical (DME 2003b).

Apart from a lack of funding, one of the main obstacles facing this energy 'transition' towards modern fuels is the policy makers' poor understanding of the factors determining rural consumers' energy choices. This population group has been recognised in South African energy planning only recently, thus time series data on energy choices are largely unavailable. Moreover, most of the primary fuels used in these households and small firms are collected and traded informally, with few records or statistics (DME (2002), Golding (2002)), making it difficult to determine the level of demand. In turn, poor documentation of existing energy choices has confounded efforts to estimate the demand for future energy carriers (e.g., electricity). Indeed, Eskom, the parastatal electricity utility responsible for the electrification programme in South Africa, has perennially over-estimated the demand for electricity in newly electrified villages, leading in turn to excessive estimates of capital spending on generation, transmission and distribution capacity needed in such areas (McFadzean (2002)). This sub-optimal allocation of resources has probably led to over-estimates of the total system cost of an optimal electrification policy. Since this could exacerbate the political difficulty in sustaining support for low-income electrification programs, a better understanding of the energy requirements and choices in low-income villages is clearly needed.

This chapter presents a new model of the energy system dynamics in a low-income rural community in South Africa. It identifies deficiencies in earlier efforts to model energy choices in rural villages, presents a new model and summarizes a new survey of a non-electrified village (Nkweletsheni) used for calibration. A baseline scenario for future consumption of energy services in the village is computed and I also explore scenarios that envision access to grid electricity as well as internalisation of pollution costs. The model framework, an early product of a long-term research programme, is a tool that can be used for system planning and evaluation of the costs and benefits of policies for rural energy services; it is also useful in analyzing environmental policies, such as measures within the Clean Development Mechanism (CDM) that are designed to reduce emissions of greenhouse gases below a baseline while not reducing (or even enhancing) a village's level of economic activity or access to energy. The modelling framework could also help to improve the quality of household energy survey by focusing survey methods on the core data that must be collected systematically in order to allow policy analysis.

Background to rural energy use in Africa

About 2.4 billion people worldwide rely on biomass fuels – such as wood, dung and agricultural residues – as their main source of energy. This is typical of the situation in the rural areas of Africa, where low incomes and lack of accessibility prohibit the use of modern alternatives. These fuels are collected around the village or are bought from other villagers. Harvesting, collecting and transporting these fuels is often a time consuming and strenuous activity, especially in areas where resources are scarce or being depleted. The fuels are burnt in stoves, open fires or braziers to provide heat for cooking, space heating and water heating, often with direct severe implications on health (IEA (2002), UNDESA (2002)).

Most rural villagers have a low and sporadic income which affects their selection of energy services in at least three ways. First, and most simply, households with low levels of income are unable to afford costly fuels and energy carriers or even modern end-use appliances, such as efficient and low-pollution stoves. This can be seen in South Africa, where numerous poor households have been given access to electricity through the electrification programme, only to be disconnected at a later stage because, despite the price subsidies present, they have been unable to pay their bills (Gaunt (2003)). Second, in the competition for market share, those services that are available in small, discrete quantities will be favoured. Thus fuels such as paraffin often diffuse more rapidly (*ceteris paribus*) than LPG because the latter is economic only when purchased in full tanks. Third, the capital requirements for modern energy appliances – such as modern stoves and lanterns – can be prohibitively costly. Absent are the institutions for financing and collective savings – such as 'microfinance'. The barriers to the introduction of such devices may be high, delaying diffusion.

One of the characteristics of low incomes and the uneven availability of fuels is that these households often meet the same energy service, such as cooking, with a variety of energy carriers (Lloyd et al. (2002)). Models must therefore estimate energy services separately from appliance and fuel choices. In the village survey that is used to calibrate the model in this paper, for example, biomass and paraffin are the most common fuels used for cooking. Most households used both, with wood as the primary fuel, and paraffin as a second choice for quick-start and small batch cooking (e.g., afternoon tea). Even in other villages where (non-grid) electricity is available, expensive battery or PV based electric energy is rarely used for cooking by households in the lowest income group. The choice and quantity of fuel also varies with appliance. Households in the case study typically deploy two fuels for lighting – wax (as candles) and paraffin (in wick lamps) – but they are given the freedom to switch to other devices. For example, paraffin could be used in a standard 'hurricane' (wick) lamp or in a more efficient pressurized 'primus' lamp. The switch allows the same energy service (lumens) to be supplied even as the total fuel consumed (joules) declines.

The choice of service, appliance and fuel also causes many externalities, including pollution and other hazards that analysts have not studied systematically. Most low-income households in South Africa burn wood, coal and other fuels within or near the home dwelling, which exposes occupants to damaging emissions such as carbon monoxide and particulates. The second highest cause of infant mortality in South Africa is respiratory disease, of which the major cause is indoor air pollution from fuel burning (Eberhard & van Horen (1995)). The use of fuels such as paraffin and candles in the household can also cause accidents that result in injury or death, such as poisoning youngsters who drink fluid fuels and whole blocks of flammable shacks that can be set alight from a single household fire triggered when a paraffin stove tips over[158]. Electricity is widely viewed as the cleanest fuel for households (Howells & de Villiers (1999)), although poor wiring and tampering for illegal connections take their toll. Emissions are released when coal is burned to generate electricity, but the sulfur content of South African coal is relatively low and central power stations have electrostatic precipitators or particulate filters and other technologies to limit airborne emissions that are affordable at scale. Moreover, the effluent from central power stations is dispersed into the atmosphere through relatively tall stacks so that their concentration drops to low levels before they reach people – especially in South Africa where vast airspace is available for the dilution of pollution. The social costs associated with the local use of fuels are major concerns for energy planners; yet they are not fully internalized in the market and non-market selection of appliances and fuels.

Analysis of rural energy systems has suffered from the lack of appropriate models and from limited availability of hard data. Modelling frameworks that have been widely applied to rural energy systems are often limited to accounting packages (FAO (2001), Trollip (1994)), but such frameworks do not include a means to estimate energy demand

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[158] It is worth noting that the stove has to contain paraffin heated to above the flashpoint to create an immediate, fierce fire. In this case it acts as an approximately 1MW igniter and makes the home uninhabitable within 40 seconds. If the paraffin remains cold, it can take 15 minutes for the fire to become fierce. Fires caused by candles similarly take quite a long while to develop, for similar reasons.

in the light of changes in critical circumstances (e.g., access to electricity) nor deal with the complexities of flexible multi-use devices or storage. Accounting approaches also, typically, focus on estimating aggregated annual fuel consumption rather than disaggregated energy services and appliances; thus they are not able to probe with any resolution the factors linked to the demand for particular services and appliances. Crude resolution has also confounded efforts to examine indoor pollution and other externalities within energy models. Some studies have examined particular technologies in sophisticated detail (e.g., Duke et al. (2002)), but whole system energy modeling requires examination of all fuels and appliances that compete to supply energy services. Such models typically suffer not only from lack of appropriate modeling detail but also from the lack of systematic data sets. Methods deployed in one rural energy survey are often not repeated in others – thus data from some samples can be exhausted in the calibration of a model, leaving no additional data that could be used for truly independent tests of a model's explanatory power. Some papers have examined macro trends and behavioral patterns (e.g., WEC/FAO 1999; UNDP (2000); Victor & Victor (2002)), but they rarely quantify energy consumption to the level required by energy modelers.

The modelling framework

Building on previous work (Howells et al (2003)), a model is developed for a typical rural South African community using the TIMES model – an extension of the widely applied MARKAL energy modeling system. (That previous work also set the framework for the survey questionnaire applied here in conjunction with the new TIMES model.) MARKAL and TIMES were both developed by the International Energy Agency's Energy Technology Systems Analysis Programme (ETSAP). The initial development of the South African rural MARKAL model, the precursor to this study, was pursued with the Program on Energy and Sustainable Development (PESD) at Stanford University.

TIMES is a multi-period least-cost linear program optimization model that supports rich detail on technology cost and performance and assumes perfect foresight by agents. It evaluates energy and technology choices evenhandedly based upon total lifetime costs of the competing alternatives, taking into consideration constraints imposed on the system (e.g., limits on resource availability and potential market penetration of technologies, emission caps). Its strengths – consistent and integrated representation of technologies in a 'bottom up' framework – are particularly attractive for this study, although I am mindful of the weaknesses in this approach, such as the lack of equilibrium with non-energy aspects of the economy that affect household income and thus ultimately determine income, the demand for energy services and affordability of alternative technologies.

The model driver is the assumed demand for *energy services* – also known as 'useful energy demands' – rather than for particular *fuels,* commonly referred to as '*final*' energy. In the context of studying rural energy needs, six of these energy services (with the associated short name used in the model) are considered in this study:

- cooking (CKG);
- space heating (SHT);[159]
- water heating (WHT);
- lighting (LGT);
- refrigeration (REF), and
- other (radios, TVs, etc. – OTH).

It is assumed that a set of end use appliances (see Table 6.2: List of 'end-use' appliances) satisfy these services and that many of these appliances are capable of supplying multiple services. In turn, the model estimates demand for fuels and energy carriers – such as electricity – from the quantities of final energy required by these appliances to provide the requested level of useful energy services (as a function of the device efficiency). The supply of fuel for these appliances comes directly from the source in the case of renewable energy (such as solar, biomass and wood), from 'imports' to the village (such as grid electricity, paraffin, LPG and coal) and from conversion technologies that are able to transform some locally available fuels into alternative forms (for example, local generators that transform diesel fuel into electricity). A list of the supply options available in this model is shown in Table 6.3. These supply and end use technologies are linked by energy flows as depicted in the Reference Energy System (RES) network diagrams in the appendix (see Figures 6.1 & 6.2). Table 6.2 also notes which energy service each appliance can serve.

The purpose of this modelling exercise is to move away from accounting frameworks that focus on overall levels of fuel consumption to a more comprehensive approach based on energy services. A particular interest that motivated the effort presented here was the need to rectify problems that have plagued earlier efforts to model technological choice in low-income villages; in the next section we focus briefly on those aspects of the modelling

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[159] Space heating also includes open fires used for social purposes –often concurrent with another activity such as cooking – and waste disposal. Therefore there is a significant production of this service also during the warm summers. This is taken into account in our modelling and the production of heat surplus to requirements is illustrated in the results.

framework that are novel. First I examine 'load curves' that allow for computation of energy services and fuel consumption by their time-of-use during the day, along with the role played by storage and other demand side management (DSM) options to influence the shape of the load. Second, I examine the problems associated with multiple services supplied by single appliances. Having thus outlined this model and its novelties, I then turn to calibration and finally to presentation of results. Third, I explicitly allow for inclusion of pollution and other hazards that are external to the prices and calibration. This third aspect is less innovative yet crucially important for policy analysis.

Inclusion of load curves

Analyses of low-income villages are usually limited to aggregate daily consumption of energy; they do not disaggregate energy-consuming activities according to the time of day – the so-called 'load curve' or energy demand 'profile' (see, for example, Williams 1994). Yet load curves matter since they affect the capital requirements for energy supply and utilization technologies. Notably for electricity, which is very costly to store, system requirements and costs are especially sensitive to load curves. Various schemes are available to reduce peak load requirements by limiting total demand for energy supply (e.g., via improved system efficiency), also known as demand conservation. Schemes are also available for 'peak shaving' – the shifting of loads from peak periods to other times of the day. Both these strategies – energy conservation and peak shaving, collectively often called demand-side management (DSM) – must be modeled in order to understand the prospects for rural electrification. Of particular interest is the effect of DSM when one considers that the cost of producing electricity varies at different times of the day.

In MARKAL it is only possible to simulate aggregate load curves since the time slice resolution is fixed at annual, seasonal and diurnal levels. The TIMES extension of the MARKAL modeling system allows the modeler more flexibility in selecting temporal resolution, allowing for computation of services, appliance usage and fuel demand as load curves. However, calibration of such a model is much more demanding of the background data. For this study, I rely on a new energy survey[160] that offers load curves with hourly resolution; for computational simplicity I average and adopt six 4-hour time-slices (2am-6am, 6am-10am and so forth) for each day; I also divide the year into four seasons (summer, autumn, winter and spring), resulting in the monitoring of twenty-four time-slices for a year within the model.

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[160] Developed in previous work (Howells et al. (2003)), may be downloaded, as an annex from http://ldml.stanford.edu/cesp/pdf/rural_energy_modeling.pdf

In outlining our approach to modeling load curves the focus is on electricity, since electricity systems are sized for the peak during the load curve. Although the aim in this chapter is to build a model for a non-electrified village, I also explore scenarios that involve electrification and have therefore given particular attention to the task of modeling load curves for electric appliances.

Estimating load curves requires information on the daily patterns in the demand for energy services, which I derive through calibrating our model against a rural energy survey (a subject I address in the next section). That alone, however, is not sufficient because the modeler must also estimate the daily pattern in the usage of energy appliances in supplying those services. Typically detailed energy models assume a many-to-one mapping for energy devices to useful services. If cooking (an energy service) is demanded for one hour then devices being used for cooking will be used for that hour.[161] In fact, different appliances have different demand profiles. For example, the conditional demand analysis (CDA) that is part of Eskom's load research programme reveals that electric stoves have a different load curve (demand profile) from electric hotplates, even though both supply the service of cooking. (Dekenah (2002).[162]

Thus the current survey of energy services can yield a load curve that is different from the load curve that is actually experienced when the village is later electrified. In this initial effort to address this problem, I use the appliance load curves drawn from Eskom's CDA. The figure below illustrates how this was modeled for a cooking appliance. Typically, curves from actual pre-electrification surveys –in this case, the demand for cooking – are smoother than for CDA predictions of consumption. The CDA suggests that the actual use of electrical appliances is very peaky - and thus electrification brings a general increase in the peakiness of energy. Given that TIMES is driven by the amounts and profile of the projected useful energy demand and that the model must be able to operate in both pre-electrification and post-electrification environments, I address this shift to a more peaky load profile by adding availability constraints to the usage patterns for electrical appliances. In addition, I map the output (a dummy commodity) to a dummy 'storage' device. This dummy commodity was converted into useful cooking energy by a dummy device with the same profile as required by the actual pre-electrification village survey. Thus the electrical appliance is able (in the model) to meet the same profile as the

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[161] The amount of energy used per hour, however, differs according to the efficiency of the appliance being used. We therefore model efficiency as a function of the appliances considered.

[162] CDA is a method that combines surveys with estimation, based on known total demand for electricity, of demand for individual types of appliances. This programme has recorded readings from data-loggers over the past decade and CDA has produced estimates of electrical appliance load curves as a function of time since electrification. Data from this program are used to inform the shape of the load profiles of electrical devices used in this study.

smooth demand for cooking in the survey but, at the same time, have a more peaky electrical consumption.

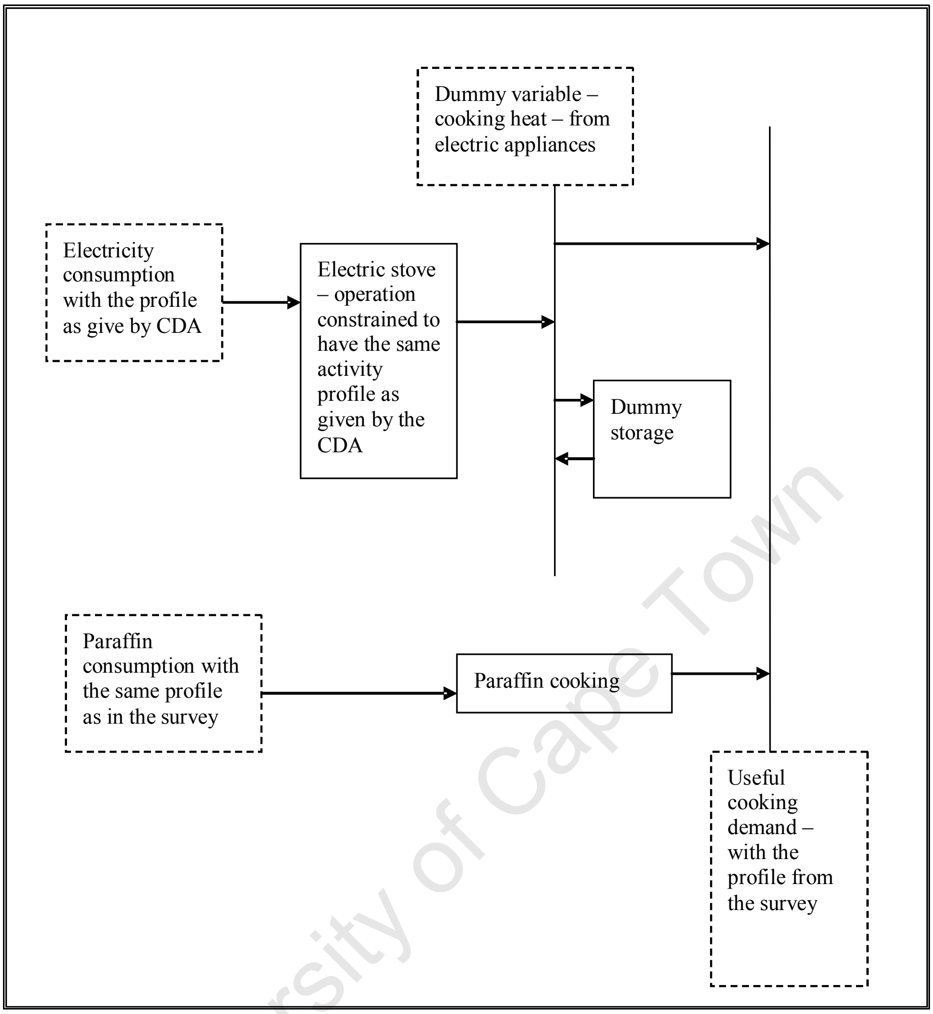

Figure 6.3: Modelling a device-specific profile in TIMES

The improved time-slice resolution and the establishment of true load curves for electricity appliances can help to predict more accurately the required supply capacity for electrification projects.

Modelling energy efficiency DSM is done by simply characterizing the appliance efficiency. If the model chooses the efficient appliance, then the system is more efficient. The timing of the demands is not affected and therefore shape of the load curve is unaffected, although the overall level will be reduced.

Peak shaving DSM policies can be modeled with a storage device that mimics the effect of shifting electrical energy consumption to an off-peak period when spare capacity is available. The cost for shifting electric loads between time-slices was assumed to be the same as for a conventional pumped storage plant.[163] Such actions do indeed change the

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[163] Depending on the application, this is likely to be higher than for several standard DSM options, and the costing of DSM in low consumption and income areas should be the focus of further study.

shape of the load curve by smoothing the peaks and valleys. This aspect is indicative. There are DSM options that are lower cost than pumped storage options, such as geyser ‘ripple control’ or behavior changes.

By capturing these effects I can estimate the load curves for individual appliances and then aggregate them to the load curve for a particular fuel (e.g., electricity). This framework thus also allows estimation of how the load curves would vary with changes in the characteristics of electricity supply – for example, variation in the costs of electricity with time of day (e.g., peak vs. off-peak), which in turn could make it possible to determine the optimal mix of appliances and behaviors that would occur with electrification if time-of-day pricing were available.

Multiple fuels, single appliances, multiple services

In rural energy use some appliances supply more than one energy service. A wood brazier, for instance, serves as a source for cooking, space- and water- heating. If this is not taken into account it will lead to an underestimation of the economic value of such appliances, which may help explain why pre-electrification studies have overestimated the potential replacement of traditional with electrical appliances (Gaunt 2003).

It is necessary to model appliances so that they can supply more than one energy service and it is essential not to fix the output splits from these appliances as users typically have a measure of flexibility in deploying the technology. Furthermore, the multi-service appliances often can utilize multiple fuels in a flexible manner, a fact that also must be reflected in the model structure. An open fire, for example, can be supplied with coal or biomass (or a mixture of the two) and the device can be used to cook or to heat water while at the same time (in both modes) providing space heating. A schematic of this multi-fuel, multi-service platform is illustrated, with the example of an open fire, in figure 6.4 below.

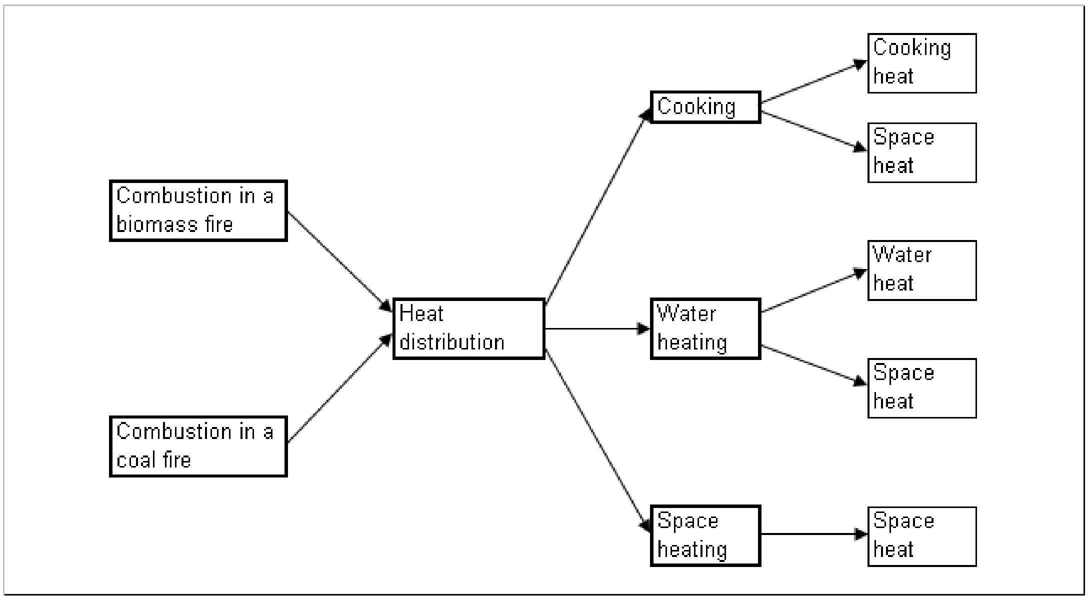

Figure 6.4: Modelling flexible appliances

In the approach employed, flexibility is ensured by letting the model choose the mix of energy forms (inputs) as well as the output splits in satisfying the total demand for energy services. However, as shown on the right set of boxes in figure 6.4, when providing one energy service (e.g. cooking or water heating) other services (notably space heating) are an intrinsic byproduct and thus often over-supplied, such as when cooking on a hot summer day. The flexibility in allocating outputs makes it possible to model the consequences of, for example, providing solar water heaters, which would reduce the demand for hot water and thus shift the allocation of energy services from the open fire from water heating to cooking – while also reducing the amount of surplus space heat that had been supplied incidentally to water heating. Anecdotal evidence from surveys suggests that, in some cases, supplying such specialized appliances leads to no systemic change in household energy choices because traditional appliances are still needed for other functions that, incidentally, also supplant the need for the specialized appliance[164].
This approach contrasts with most other studies which have focused on strategies for estimating total fuel consumption rather than disaggregating services, appliances and fuels. It also differs in that our approach allows explicit modelling of multiple service appliances and thus does not automatically assume, as is common, that total system efficiency will rise with the introduction of modern appliances. Efficiency may actually decline when energy services supplied by a single appliance are replaced by several modern appliances (for example, when a biomass stove is replaced by an electric hotplate for cooking and water heating purposes and an electric heater for space heating).

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[164] While we attempt to accurately model the ‘status quo’ of current behavior, changes could affect fuel use significantly. In areas where wood has historically been scarce villagers are often observed building more efficient fires!

Collectively the new appliances are at times less efficient, especially during a period of transition when the old multi-purpose appliance and the new single-purpose appliances co-exist in the household. A relatively open fire for instance provides an equal amount of space heat regardless of whether it is used for cooking or water heating concurrently. Using the activity profiles from the Nkwetetsheni survey I have linked fuel use to end-use energy surveys, which allows computation of the supply of incidental space heat at times when there is no heating demand as households deploy appliances such as open fires that have this multi-service characteristic.

Inclusion of social and environmental costs of energy use

In addition to the capital, operating costs and performance of particular appliances in supplying energy services, a wide range of other factors such as convenience, trendiness and pollution are also relevant when making energy choices. Some of these factors may be known and valued by users and thus affect choices, yet are not visible in the prices for fuels and appliances. Surveys suggest that villagers include some of these effects in their energy use patterns as they appear to avoid unhealthy and dangerous fuels. Other effects may be true externalities – not known or valued by individual agents yet the cause of societal effects such as collective pollution and neighbourhood fire risks associated with particular dangerous appliances.

In the MARKAL/TIMES modelling approach used for this project, cost minimisation is the objective. Behavioural aspects are incorporated in the model by applying constraints to the system (e.g., requiring the model to deploy an appliance at some minimum level that is known to reflect user preferences that do not appear to correspond with observed costs and performance) or influenced by imposed additional costs (e.g., the estimated health costs associated with indoor air pollution). This study gives particular weight to quantifying indoor air pollution related to fuel use and the associated effects on health. When energy is converted from one form to another, gaseous emissions are often produced. The model uses standard emission factors for appliances (Howells & de Villiers (1999)) and tracks several emissions from fuel conversion and consumption including:

- carbon dioxide;
- carbon monoxide;
- methane;
- nitrogen oxides (including the GHG emission nitrous oxide);
- non-methane volatile organic compounds;

- particulates;
- particles smaller than 10 microns (PM10); and
- sulfur dioxide.

One of the scenarios that I present later illustrates this approach, with particular attention paid to indoor air pollution. Because health effects from emissions related to electricity generation are relatively small in Africa, power plant emissions are only tracked in terms of their global warming potential. This is examined cursorily in another scenario. The externality costs associated with the local pollution are calculated based on the products of emission intensity (kg/GJ), energy output (GJ) and unit costs of emissions ($/kg). These values were taken from Howells & de Villiers (1999), summarized in table 6.4. These costs are then added to the objective function (total discounted costs) and are included in the least cost optimization.

Calibration and village surveys

Calibration requires measured energy use data. Given the state of knowledge about energy choices and the myriad ways that households can meet their need for energy services within a given constraint of income and location, it is not yet possible to build a full model of energy choice from first principles without calibration. Two methods of collecting data that could be used for calibration have been deployed in South Africa: (i) surveys of households and, (ii) a technique known as conditional demand analysis (CDA), which relies on electricity usage data for electrified villages and then employs statistical techniques to estimate total demand for different energy services. For the main calibration of the model I utilize the former approach, although our treatment of load curves for electricity appliances (discussed earlier) uses CDA.

The survey

Typically survey data on usage of energy and appliances for rural households has been spotty and consistency across surveys has been low. Variability in methods and lack of investment in time series surveys explain, in part, this deficiency (Prasad (2002)). The specific weaknesses in available surveys include the following:

- Lack of disaggregated data on the major energy uses – cooking, space heating, and water heating – including duration, time-of-day and fuel used per task.
- Embedding of energy surveys within larger surveys that covered many other topics, with the result that energy-specific questions may be few in number and data useful for energy modelling (e.g., fuel per task) may need to be computed from other

secondary and often subjective statistics that are of interest to the organization conducting the survey (e.g., fraction of household income devoted to energy purchases).

- Lack of data on transaction costs, such as the time or money needed to move fuels from their primary location (e.g., a forest) to the point of local use, which is especially problematic for fuels that are not traded in transparent markets.
- No data on 'hire purchase' (rental, leasing, collective purchase) arrangements for capital-intensive energy-using appliances.
- Lack of information needed to compute statistical uncertainty, which contributes to the larger problem in energy modelling: the failure to treat uncertainties that propagate through models in a systematic manner.
- Failure to integrate modelling and data collection activities, with the result that neither is tuned to the opportunities and limitations of the other.

A previous study (Howells et al. (2003)) developed a customised survey that addressed most of these problems, with the aim of generating data that would be useful for calibrating models of the type described in this paper.[165] Notably, the survey includes questions on appliance use during discrete daily time periods, allowing computation of load curves. The survey was refined and tested with the modelling framework in mind; the format was revised to comply with standard field testing for product marketing in order to make it more effective and easier to administer; and finally, the survey was translated into the local language, namely Zulu (Lloyd et al. (2002)). The survey was then applied to the village of Nkweletsheni and the data modeled and reported in this work.

There was also an attempt to gather information on people's energy use preferences in order to establish whether there are hidden social costs associated with the use of certain energy use patterns.

Village description

The village is described in more detail in Chapter 4. The data gathered through initial surveys provided the basis for this study.

As is common in rural African communities, several fuel types are used to meet one energy service requirement and several requirements are often met by a single appliance. This was primarily due to fuel availability, fuel costs, service requirements, and cultural aspects. The majority of respondents used wood in an *imbaula* as fuel for the three most energy-intensive services – cooking, space and water heating. (An *imbaula* is an informal

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[165] The survey may be downloaded, as an annex, from http://ldml.stanford.edu/cesp/pdf/rural_energy_modeling.pdf.

wood stove, often constructed from a 25l metal paint drum.) Most respondents used the fuel because it was easily available or because they were familiar with it. Other reasons for using the fuel were the absence of alternatives and the relatively high cost of other fuels such as paraffin or LPG. Of the people who used wood, many preferred paraffin as their secondary fuel. The reasons for this are not clear from the survey, but it is the least expensive option after wood. LPG is also difficult to transport and purchase in small quantities. Paraffin was used when conditions such as rain made it difficult to collect wood the day before it was needed – wood stockpiling and dry storage did not appear to be significant activities. Many households reported that they were unhappy with the wood-fuel they used. Most of these cited coughing, smoke and smelliness as the primary problems with the fuel. They considered the fuel to be dangerous, since it produces high quantities of ash and made them 'sick'. This observation indicates that villagers were aware of some of the externality costs of fuel use. This underscores the need to quantify relevant externality costs and the degree to which they currently influence (or are internalised into) people's energy decisions.

In some households different appliances were used for water heating and cooking. Typically, one would find that space heating and cooking are carried out on an *imbaula*, while water heating is done with a paraffin stove – at different times. It is not clear if this is typical. However, if this is the situation, it would be an indication of convenience as a driver of energy use patterns. A paraffin stove is much quicker and easier to use for water heating than a wood fire. It is inconvenient to start a fire just to supply an energy service that requires only a small amount of heat over a short period of time, such as water heating.

Lighting services were supplied by candles or by paraffin wick-devices. The rationale for the proportional split[166] of candle to paraffin use is probably related to appliance costing, fire hazard risks and/or convenience.

Most households owned a radio and about one-third had a TV; 22 households (one-fifth of the total) reported having a cell-phone. These appliances (predominantly electrical) are powered by batteries (rechargeable car batteries and disposable batteries). Total energy demand for this activity category is small but the relative cost is much higher than grid electricity due to the high per unit cost of electricity delivered by batteries.

Hourly activity data was gathered from the survey for cooking, water heating, space heating, radio listening and lighting. This was used to quantify the amount of useful energy needed, per household, as the profile of the demand.

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[166] About one unit of lighting is supplied by candles for every nine units supplied by paraffin.

Scenario analysis

Characterization of the scenarios

With the calibrated model a reference Base case and several alternative scenarios are developed. All scenarios begin with the simplified assumptions that relative prices for fuels and appliances do not vary over time, but the demand for all energy services grows at 2% per year. The scenarios are:

Reference scenario: 'Base case' (BC): I assume that electricity is unavailable in the village and there is no government intervention through subsidies or other policies for other (non-electric) fuels and appliances. The villagers are allowed to move towards least cost options within market penetration limits and the current mix of available technologies and appliances.

Stand-alone generation only (SAG): Much of rural Africa is unlikely to be grid connected in the short term. However, in many areas the means to generate electricity exist locally, such as with mini-grid systems, local generators and photovoltaic panels with batteries. In this scenario the villagers are given the option of purchasing such systems without connecting to the national grid.

Grid electrification (GE): For this scenario the villagers are allowed access to the national grid from 2005 onwards[167] and villagers are also allowed to invest in distributed generation systems or stand alone photovoltaic systems as in the SAG scenario.

Electrification with cost reflective electricity prices (EREP):[168] While all the scenarios include the availability of demand side management measures, this scenario also includes a time dependent energy cost for grid generated electricity. The actual cost to the system for generating and supplying electricity should vary over time because electric systems are sized for peak load and some uses are economically more valuable (command a higher price) than others that can be shifted with little penalty to other times of day. However, the inability to bill small customers by time-of-use introduces distortions as these users impose a load, yet are charged only the average cost per unit of energy consumed. (If they were charged the peak price the outcome, also, would be inefficient as users would be paying too much for the electrons they consume during most of the day.) In this scenario I envision the application of time-of-use generation costs in order to evaluate the potential of DSM measures to accompany grid electrification.

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[167] i.e. two years later

[168] Marginal grid electricity costs – marginal cost pricing means rising electricity prices as new generators tend to be more expensive than existing ones. The existing stock of generators have their capital costs mostly amortized, hence prices increase with national grid power station expansion. Further, hourly electricity costs differ. As discussed in the previous chapter, the marginal cost of peak supply is different to average daily costs.

Externalities (EX): In the externalities scenario costs were applied to activities and emission releases that do not normally represent direct costs to the consumer. The emissions penalties used in this study are summarized in Table 6.4 and phased in over a 3-year period. I also assumed a cost of one US cent per kilogram for wood collection (Lloyd et al. (2002a)). This is based on a market cost for rural wood supply, which is marginally cheaper than local coal prices (Lloyd et al. (2002a)) – 1.4$/GJ (or 34$/ton). The various scenarios are summarized in Table 6.1 below.

Table 6.1: Scenarios

Scenario (ID)	*Key constraints and features*
1. Base case (BC)	No access to electricity, conventional existing technologies/appliances only
2. Stand-alone generation only (SAG)	No access to grid electricity, local electricity options, includes BC
3. Grid electrification (GE)	None, access to the national electric grid, includes DG
4. Electrification with cost reflective electricity prices (EREP)	Same as GE, with time dependant grid electricity pricing.
5. Externalities (EX)	Same as GE, with inclusion of indicative health costs of emissions

Model results

This section focuses on a few key implications of each scenario. The MARKAL/TIMES optimization framework provides results that indicate economically optimal outcomes for the assumptions used in each scenario

Reference scenario: 'Base case' (BC)

In the Base case only current technologies and appliances are available to the model. As can be seen in Figure 6.5 below, wood continues to dominate the final energy picture (and its use grows with village population) since there are few substitution possibilities. (There is no upper bound considered on wood supplies. That hypothetical assumption may be challenged in the longer term though with continued overharvesting.)

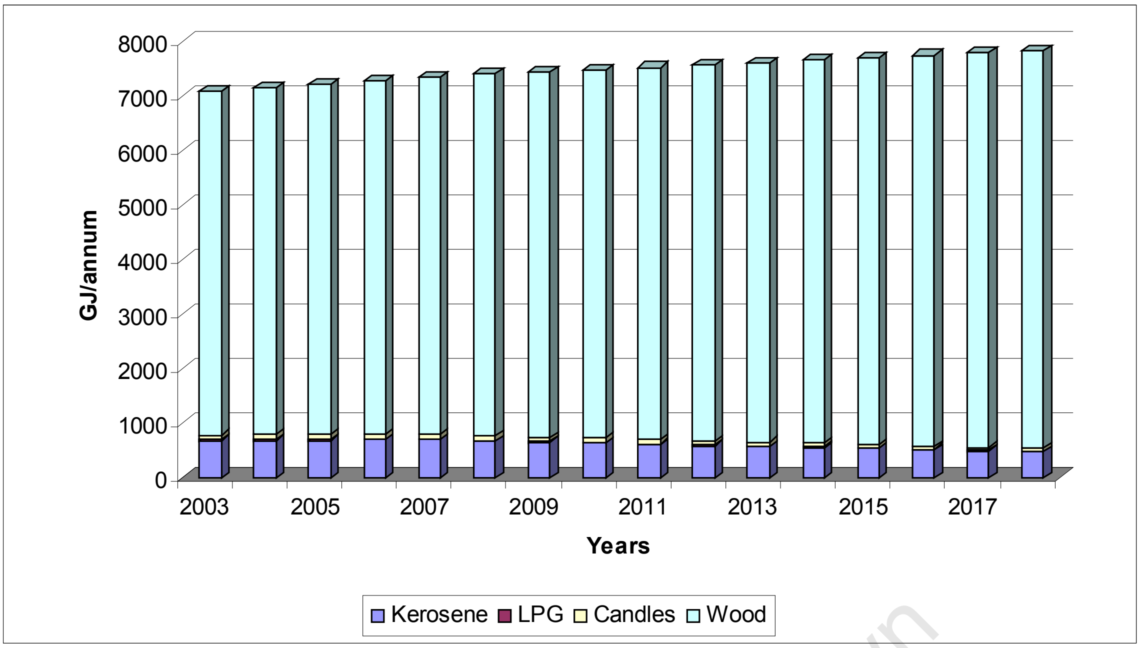
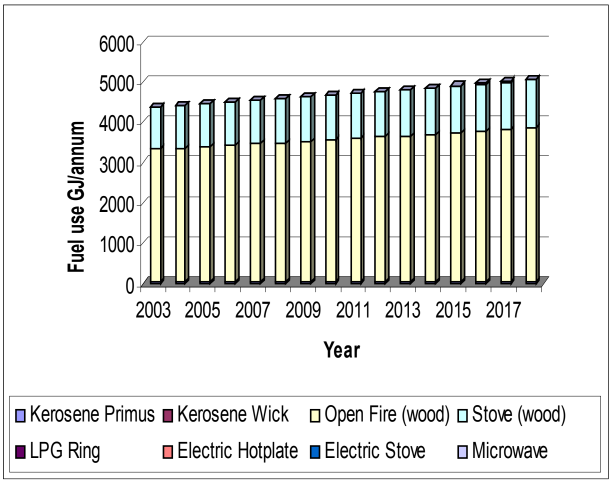


Figure 6.5: Final energy demand by fuel in the base case

Biomass stoves and open fires are the main suppliers of cooking services; open fires contribute roughly 75% to final energy demand and 70% to useful energy demand. LPG and paraffin serve as secondary or back-up fuels and continue to supply a very small part of the cooking energy service requirement. They are stand-by fuels when wood is not available but they are not economically competitive choices for households when wood is present.

Final energy used for cooking



Useful energy required for cooking

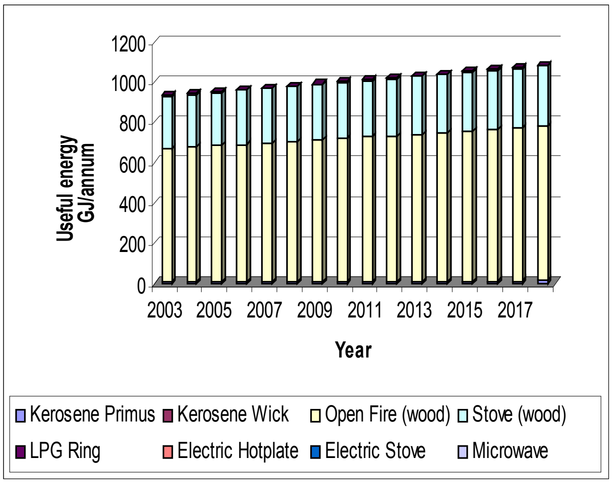
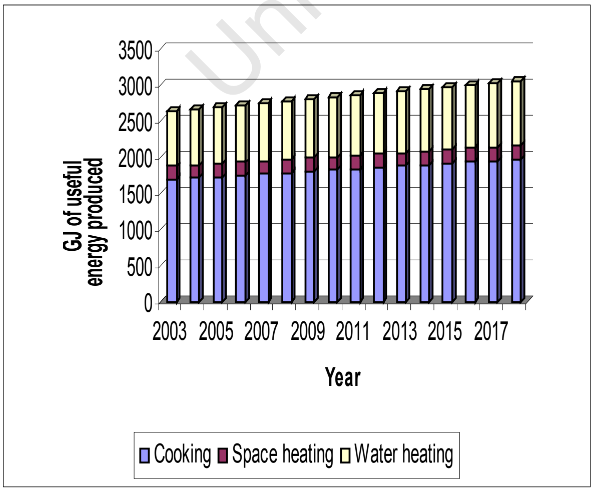


Figure 6.6: Cooking devices used in the base case

Water heating demand is met in much the same way as cooking, with biomass being the dominant fuel and paraffin playing a minor role, mainly as a backup. This is indicated in Figure 6.6. Cooking and, to a lesser degree, water heating also contribute to space heating. Biomass is the only fuel that is also used specifically for space heating, although the largest quantity of space heating is supplied ancillary to other services (cooking or water heating). Averaged throughout the year, total associated surplus heat production (from cooking and water heating) exceeds the actual demand of space heating by 40-45%, as illustrated in Figure 6.7.

Space heating as a function of activity



Requirements and over production of space heat

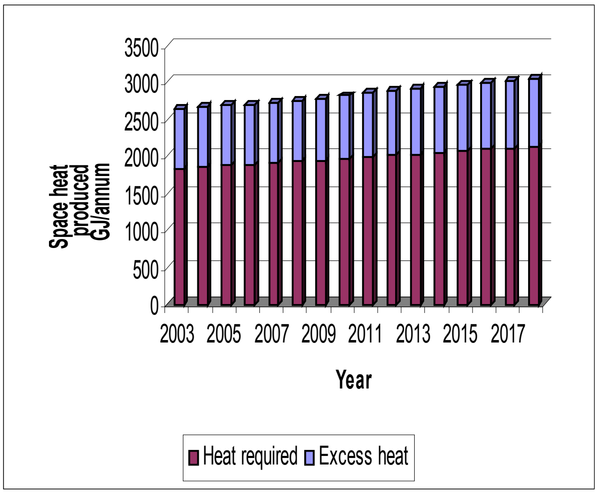


Figure 6.7: Space heating in the base case

Over the modelling period the total final energy consumption for lighting drops significantly due to a technology transition from kerosene wicks to the more efficient paraffin pressure lantern. In 2003, paraffin wicks provide about 80% of the lighting, the rest being met by candles (Figure 6.8). By the end of the period, pressurised paraffin lanterns provide half of the useful energy but consume less than 25% of the fuel that is burned for lighting. Candles supply about 10% of the lumen hours throughout the period. Paraffin lanterns are the least cost supply option, so market penetration limits were assumed and imposed on the model to prevent it from totally dominating the sector.[169]

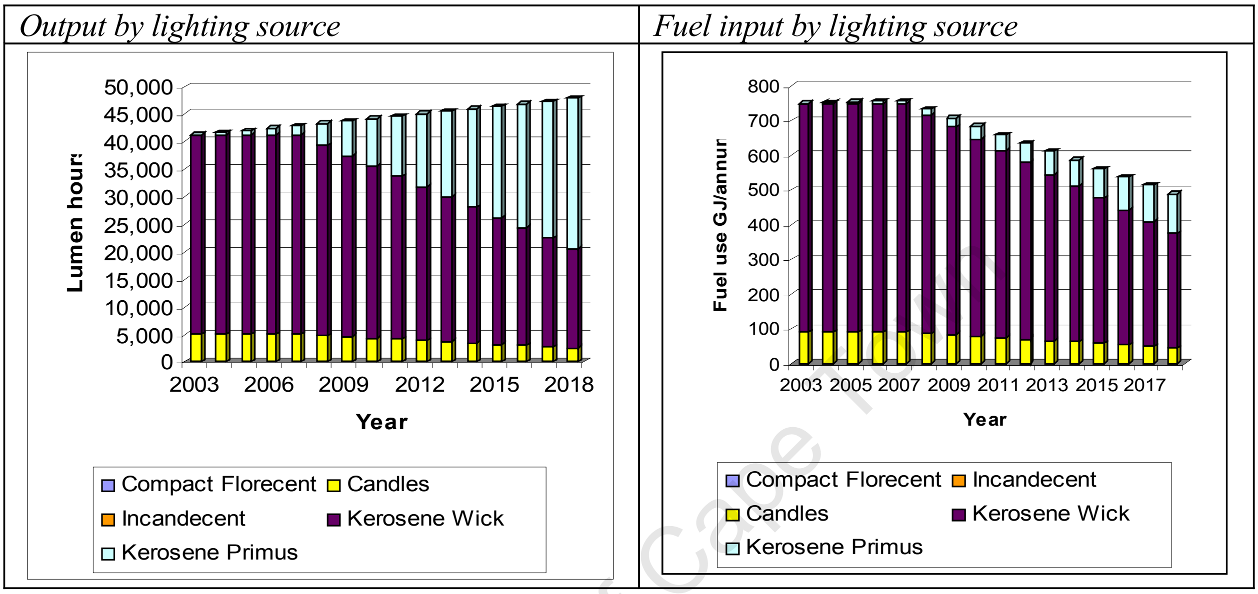


Figure 6.8: Lighting and fuel consumption in the base case

Energy supply to other demand devices (TVs and radios) is exclusively from batteries[170], the only available source of electricity in the reference scenario. These batteries are either charged at a nearby grid connection and then brought back to the village or are disposable and bought from local traders.

The Stand-Alone Generation only (SAG)

In this scenario the most significant change from the Base Case is that diesel generators and a mini-grid system can be installed. Indeed, the model selects installation of such generators, but only with capacity adequate for lighting where they displace paraffin and for 'other' services (e.g., television and radio) where they supplant expensive batteries. These uses consume relatively small amounts of electricity, but price per kWhr of this electricity from these sources is high.[171]

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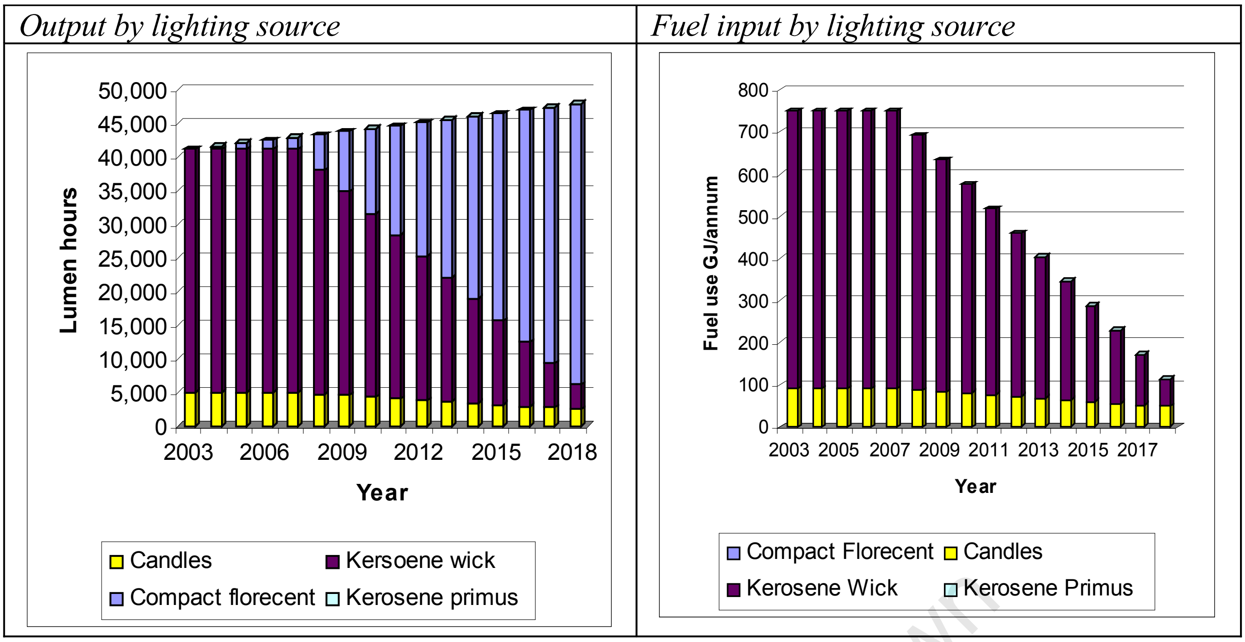
[169] Further to the deficiencies noted, in rural energy data from a surveys, is that the survey only reports 'snapshots' and monitoring with time is difficult. Were time series available, penetration rates could be better calibrated. In the case of electrical appliances penetration rates were taken from the Load Research Program (Dekenah 2002).

[170] Including dry cell and lead-acid batteries.

[171] Estimated at 200-300c/kWhr vs. about 150c/kWhr from a diesel genset. Note that the former cost is very sensitive to the cost of remote battery charging services (or local PV-based charging) as well as the cost of disposable batteries.


Output by lighting source

Fuel input by lighting source

Figure 6.9: Lighting and fuel consumption in the stand-alone generation only scenario

Cooking and space heating are still primarily performed by burning wood. The flexibility and abundance of this traditional fuel prevent the distributed generators and mini-grids from making more than a small contribution to total final energy supply. Such situations commonly exist in remote areas, where diesel generators are used for lighting, radios and televisions (Williams (2003)). Nonetheless, electricity plays an important role, as seen in figure 6.10, where the substitution of appliances is even more dramatic than in the base case. The availability of electricity means that households shift to Compact Florescent Lights (CFLs) rather than investing in Kerosene pressure lamps – the CFLs have an extremely high light output and yet are extremely efficient. In consequence total fuel use for lighting is only one-fifth of that estimated in the base case (as shown in Figure 6.9).

Grid Electrification (GE)

In this scenario a modeled village is given the option to invest in both distributed generation and connection to the national electricity grid. (In the previous scenario, only distributed generation options were allowed.) Contrary to the assumption that electrification would not be economic for Nkweletsheni the modeled village actually chooses grid electrification.[172] Note, however, that the model only chooses electricity at low consumption levels for services such lighting and entertainment where current has special value. The electricity demand for these activities is extremely price inelastic: the cost of electricity could be increased six-fold and the modeled electricity consumption

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[172] The costs of remote grid connection were taken from Gaunt (2003) & Gaunt (2002). Average capital costs for the grid connections are given as $260/kW and an electricity cost from the grid of 11$/GJ (4cUS/kWhr).

from the grid for these specialized applications would not vary. The model calculates that supplying these low volumes of electricity from a new grid connection would remain less costly than purchasing or charging batteries for radios etc., or the use of kerosene for lighting. It also prefers the economics of grid connection compared with distributed generation. Such strategies – grid connection with only low volume consumption – have been followed in some countries, such as Zimbabwe. However, while this is an economic option it does not promote a more complete move to electricity. The possible motivations for more complete electrification are discussed under the externalities scenario.

As with the distributed generation scenario, wood continues to dominate the supply of cooking and space heating services. Indeed, surveys in South Africa (e.g., Afrane-Okese (1998)) show that poor households, once electrified, continue to use more affordable fuels, such as wood or coal, for the most energy-intensive activities.

This model's ability to account for continued use of multipurpose wood- burning devices should be noted. It is this aspect of the model that enables the relative economic value of the older technology to be correctly captured and in which its projections differ from other studies (McFadzean (2002), Gaunt (2003)) where higher penetration and use of electric appliances post-electrification were expected.

Electrification with Cost Reflective Electricity Prices[173] (EREP)

In this scenario, the marginal cost of generating and delivering electricity from the national grid rises in the future, when new capacity is needed beyond the current (largely amortized and therefore low cost) national electric power system[174]. This scenario also uses peak load pricing, i.e. prices that vary by time of day and season in a manner consistent with cost-optimal demand side management of household grid connections. If optimal, this would minimize the cost to the electricity system– an important aspect of resource allocation in a developing country context. This approach to electricity pricing shifts electricity consumption from peak to off-peak times. In the setting of a low income village much of the shift occurs through batteries that are charged during off-peak periods and used in entertainment devices during peak[175]. The overall effect, however, is an 8% increase in total consumption (Figure 6.10) due to the losses from the storage process.

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[173] Marginal grid electricity costs – increasing with national grid power station expansion.

[174] The average cost increase for this scenario is assumed to 4% per annum. The cost profile assumed is based on the national energy model marginal costs and, for the last year modelled, given in figure 6.15.

[175] Though the leads of these devices are low in absolute terms.

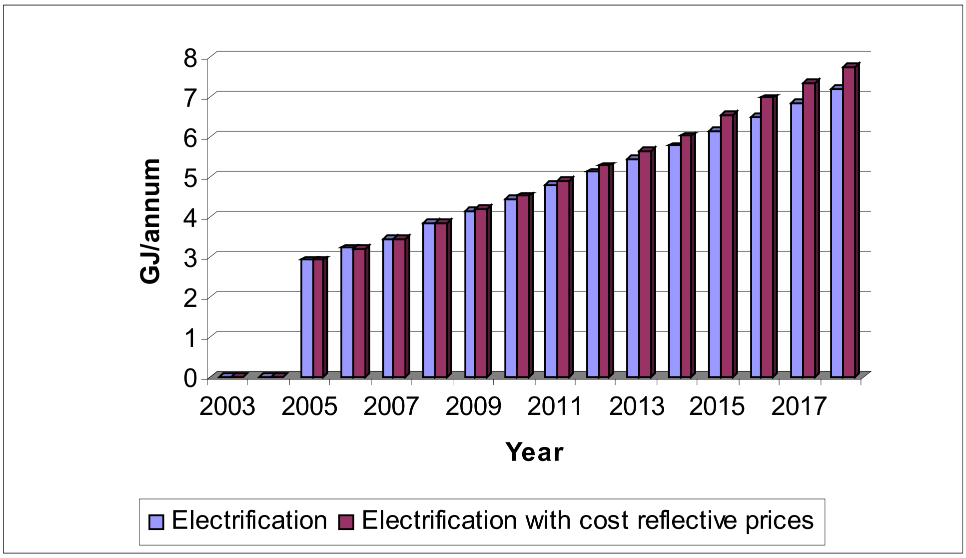


Figure 6.10: Comparison between the grid electrification and the EREP Scenarios: increased total consumption due to greater reliance on storage

In the EREP scenario, demand side measures become cost-effective. Figure 6.11 displays the electricity consumption during a summer day for the GE and EREP scenario and the effects of including accounting for a time-dependent grid electricity cost. The figure, used for illustration, is for a summer day near the end of the modelling period. In this particular snapshot, consumption is lower in the EREP case. It is used due to its accentuated shape. It shows a clear reversal of the shape of the demand curve when compared to the Base Case. That is, when the electricity costs are high, the electricity demand in the EREP case is suppressed and, when the cost is low, they are inflated. In the electrification case (where a flat energy charge is assumed) the demand follows a standard morning and evening peak shape. Were electrification to take place without accounting for varying electricity cost, the profile of electricity drawn from the grid would add to the overall 'peakiness' of current national demand and increase the system costs. (The Electrification case has its peak times in the morning and evening, which is similar to national demand). The change in shape in the EREP case is accounted for by the model increasing the share of DSM over the Base case.

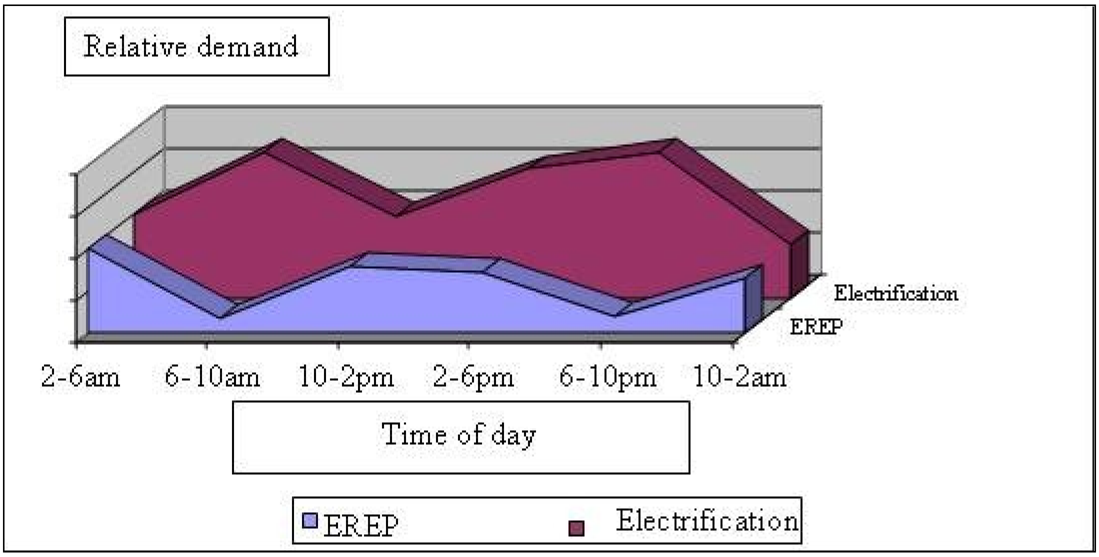
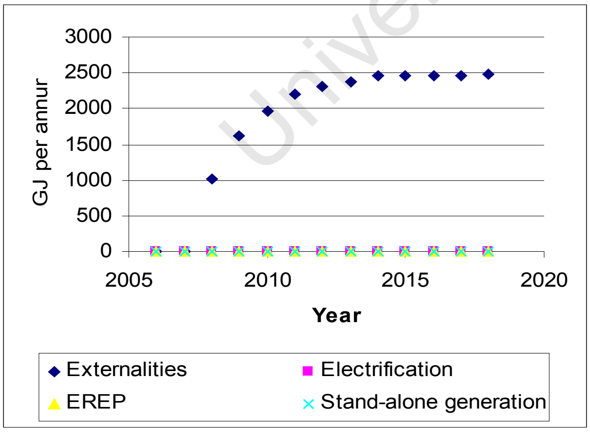
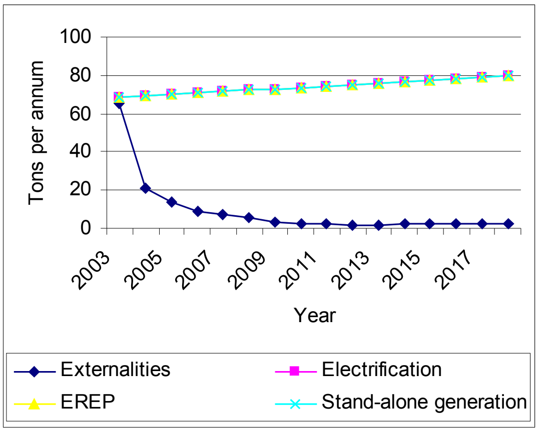


Figure 6.11: Summer electricity consumption by appliances in the EREP case versus the electrification (GE) scenario

Externalities (EX)

The externalities scenario builds on that of grid electrification (GE), yet also includes the cost to health and other externalities from local combustion emissions; Table 6.4 summarizes the assumptions that were used for these externalities. However, one should be mindful of the implicit uncertainties and the need to explore sensitivity analyses in future formulations and scenarios. The net effect, shown in figure 6.12, is a shift to greater use of electricity and thus a sharp reduction in local pollution.

Electricity consumption per scenario	*CO emissions per scenario*
	
NMVOC emissions per scenario	*Particulate emissions per scenario*

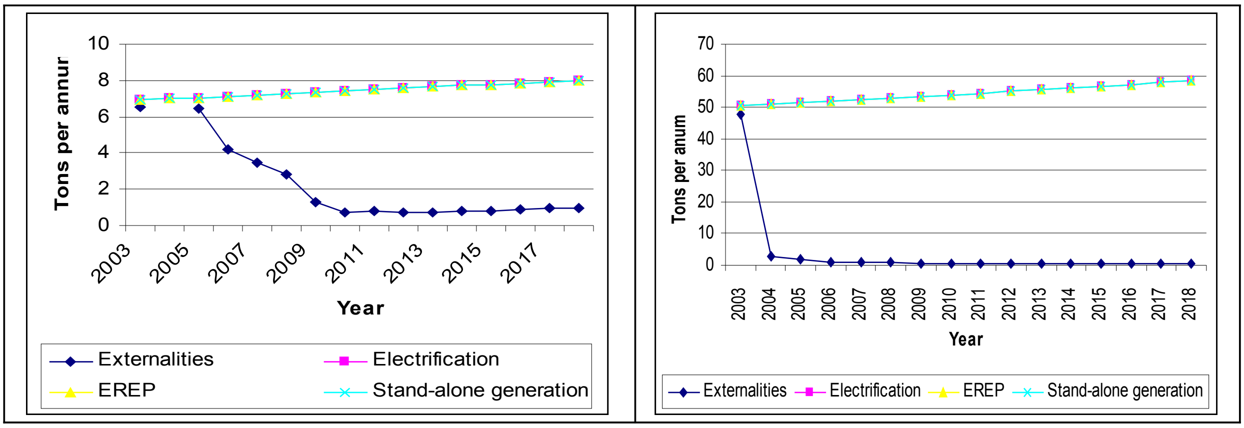
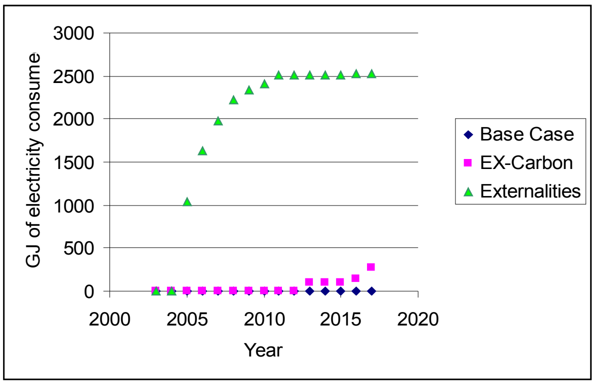


Figure 6.12: Electricity consumption and emissions

A special case of this scenario was run to encompass the cost of carbon emissions –(sub-scenario EX-Carbon). This sub-scenario prices CO_2 emissions at (a relatively low) 5$/ton CO_2 (see Blignaught 2003). The principal effect of this scenario, when compared with the EX scenario, is to dampen the shift to electricity (as seen in Figure 6.13). The high CO_2 emissions due to coal-fired power plants raise the net cost of electricity and hence its price. Normally the model would show a return to wood-fired devices and away from electricity. However, sensitivity analysis shows that a $5/ton tax on firewood would be enough to induce consumers to use LPG devices and solar hot water heaters ahead of firewood.

The policy implication is that real attempts to control greenhouse gas emissions in developing countries – such as the Clean Development Mechanism (CDM) of the Kyoto Protocol and related schemes such as the World Bank's Prototype Carbon Fund (PCF) – will need to make careful but extensive use of energy system models (and sensitivity analysis) in order to calculate baselines and to avoid unintended consequences. In the case analyzed here, the option that would generate the most robust CDM credits appears to be a combination of non-electrical renewable energy supplies (solar) along with oil-based energy (LPG); outcomes that would not be obvious without the modelling.

Electricity consumption



Carbon dioxide emissions

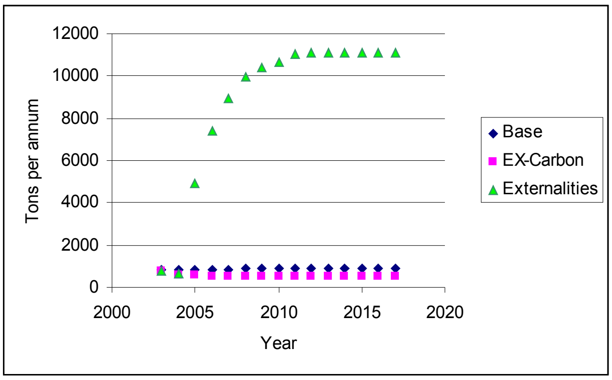


Figure 6.13: Electricity consumption and CO_2 production for the base case and the externality scenarios

Total energy consumption

Finally, the total energy consumption in each of the scenarios is compared. As shown in Figure 6.14, when compared with the base case each scenario envisions a reduction in total consumption. This is not surprising, since the electrification scenarios (SAG, GE and EREP) provide the model with additional (electricity-related) flexibility to meet energy services and, in general, that flexibility is utilized to invest in appliances that have lower total costs and higher performance – and that are, all else equal, are more efficient. However, the shift to electricity is limited only to particular high-value services. Only in the externalities scenarios does electricity play a larger role outside lighting and entertainment services. Villagers attempt to avoid the cost of pollution externalities, with the result that total energy consumption is the lowest when externalities are included in the calculation.

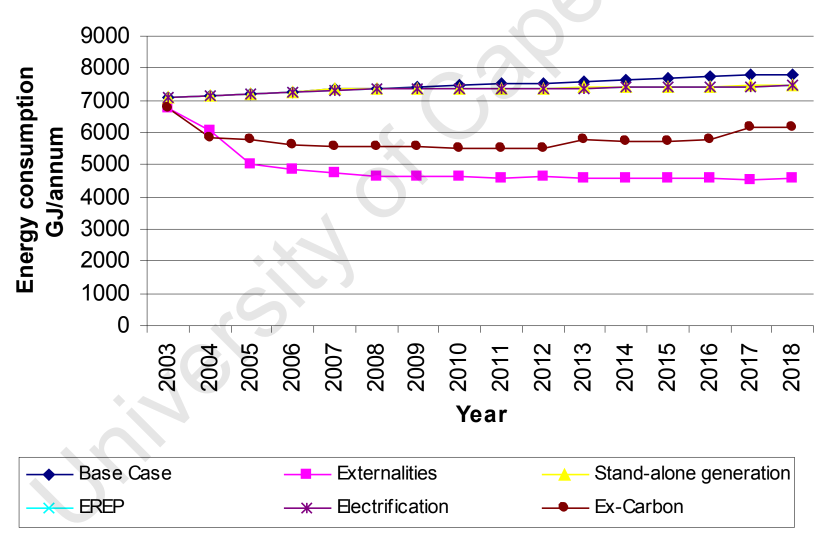


Figure 6.14: Total energy consumption: comparison of base case with the five main scenarios

Conclusions

Although the vast majority of energy models have focused on large users in urban areas (or whole countries) purchasing appliances and fuels in commercial markets, in this chapter. Ways are illustrated to apply the tools of modern energy modelling to a rural village in Africa. It has been shown that appropriate surveys as well as advanced modelling techniques are needed for this task. A framework within the MARKAL optimization family of models for further work is offered. Improving the MARKAL system through the TIMES computational system has allowed us to both increase the time resolution to reflect daily load curves and to address the single appliance-multiple service attributes of rural energy systems. Using a higher time slice resolution allows for a more careful estimation of peak system requirements and also allows for better modelling of the possible effects of demand side management programs that encourage shifting from peak to non-peak periods, such as time-of-day pricing of electricity.

Among the many results, the model suggests that time-of-day pricing may actually encourage greater use of electricity because of the premium placed on storage devices (batteries in our model, but possibly other devices in the real world as well) that shift load from peak to non-peak periods. In all scenarios except the Base case (in which the model was barred from investing in electrification) small amounts of electricity were used for special purposes such as illumination and entertainment devices. However, the explicit inclusion of local pollution effects encouraged a shift to grid electricity – the most cost effective fully clean energy carrier available to the village. The benefit of electrification in reducing local pollution and allowing for special high value services helps to explain why the South African government and Eskom have long engaged in an active program for electrification of poor areas. The current national government in South Africa has argued that it is in the national interest to subsidize an initial volume of electricity for poorer consumers (Gaunt (2003)).

One of the major factors limiting the uptake of commercial energy forms – such as paraffin, LPG and electricity – is the very low private cost of locally gathered wood fuel. Field research also confirms that local fuel wood slows the diffusion of new energy sources and technologies (Williams et al. (1996), Williams (1996), Gander (1994)).

Interestingly, inclusion of a carbon dioxide externality in the model retards the shift to electricity but does encourage the greater use of some fossil fuels, notably paraffin for lighting and LPG for cooking and heating. That result depends, in large part, on how the carbon emissions from local fuel wood are treated in the model – an area needing further work if such models are to be used in the context of the CDM or other efforts to determine baselines and credits for carbon emission reductions. Other local environmental damage such as top-soil erosion etc. could be considered in future work.

Much remains to be done to improve the model. Among the factors known to affect actual energy use but not included in the model is the ability of many appliances to service more than one person, which in turn would affect total demand. For example, when a candle used by one person for reading is replaced by a light bulb that illuminates a whole room, more than one can read at night. It is also clear that factors beyond economics and simple externalities affect household patterns of energy use (Qase (2000)). Among the other improvements to the modelling framework would be the application of a goal programming variant of MARKAL to allow for optimizing across factors beyond simply system costs. This would allow for the testing and calibration of the hypothesis that other factors influence consumer's willingness to pay for energy services. However, the necessary survey data and theories for how to do this do not presently exist.

We have not investigated the many interactions between the energy systems computed in the model and the broader economy. Among them is the possibility, known anecdotally, that the availability of electricity or other modern fuels and carriers could promote the creation of small cottage industries in villages to market and service the appliances that utilize these sources of final energy. More work is needed – especially with other modelling frameworks such as agent-based models and equilibrium models – to investigate such multiplier and rebound effects.

More work is also needed to integrate surveys into the model. At present this model can't be tested and refined with survey data from villages other than that used for calibration, precluding any real test of the model's robustness. Improved surveys may also make it possible to compute appliance-specific as well as income elasticities, allowing future models to estimate village behavior by income level (which surveys suggest is an important determinant of energy choices).

Finally, as shown, the inclusion of externalities and peak load issues into electricity pricing can affect energy usage. More progress is needed in modelling both. For externalities, much work is needed to identify (as uncertain ranges and not as simple point estimates) the values of such externalities to different key actors. For electricity pricing a more sophisticated system could be built around the actual cost of time-of-day metering or perhaps time-of-day DSM (peak shaving) programs that have already been the subject of some experimentation in South Africa and other developing countries.

Among the model's many implications for policy are the roles it reveals for electricity and fossil fuels in developing village economies. Electricity's role appears particularly robust, especially when it depicts full cost pricing of non-electric energy carriers.

With the merits of this new advanced modelling framework now demonstrated, an important next step will be to expand the demand services to include fledgling, but growing, small scale rural agriculture and industrial needs (see WEC/FAO (1999) & ESMAP (2000)). Similar principles of dual use and timing of demand are likely to be central to planning for these needs appropriately. However, the present chapter was not an exercise in forecasting total rural demand – it is focused rather on household behavior.[176]

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[176] Which often accounts for the bulk of demand in rural settings (see Afrane-Okese 1998 & Williams 1994).

Appendix: Charts and figures

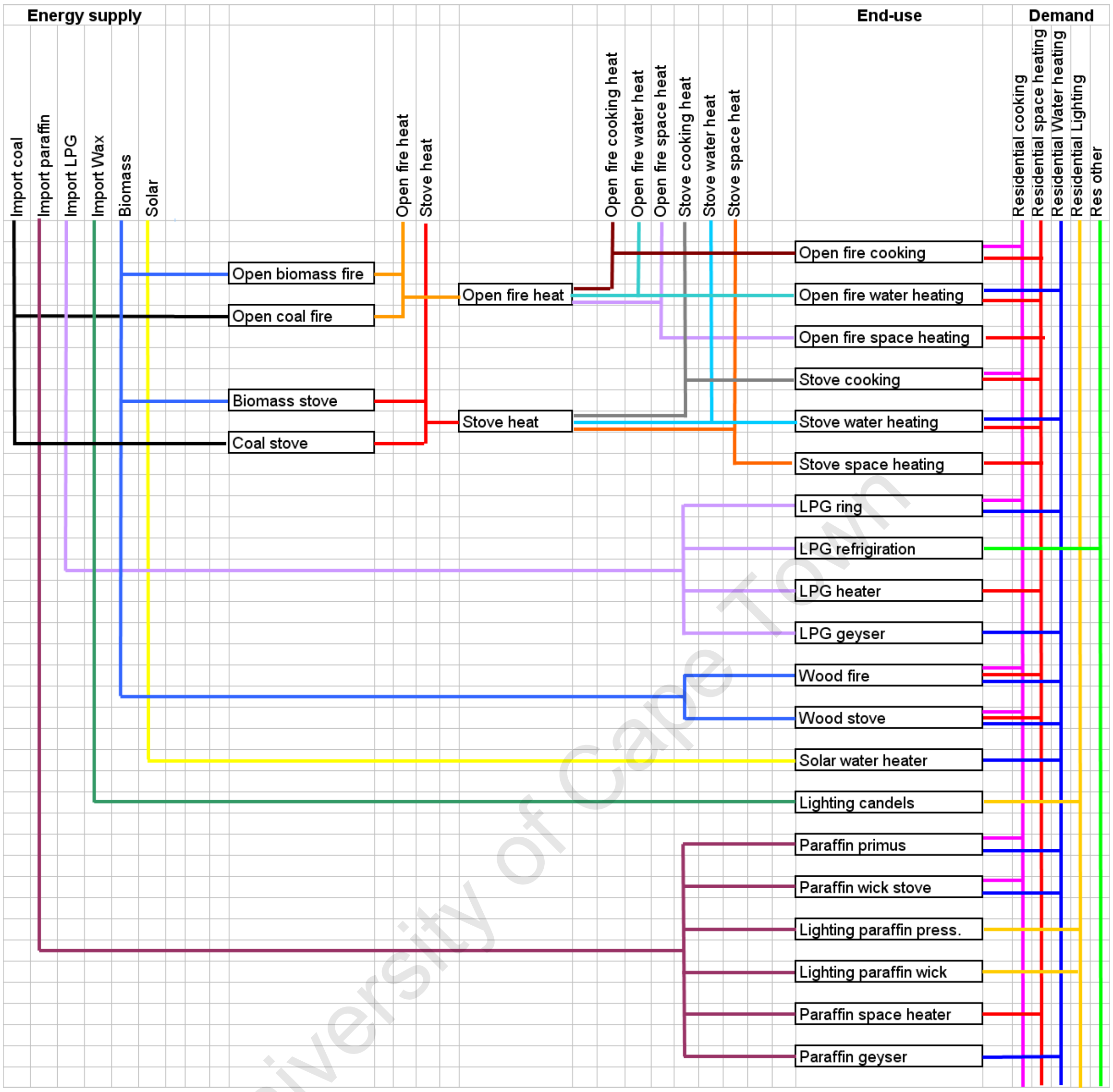


Figure 6.1: Reference energy system for non-electrified community

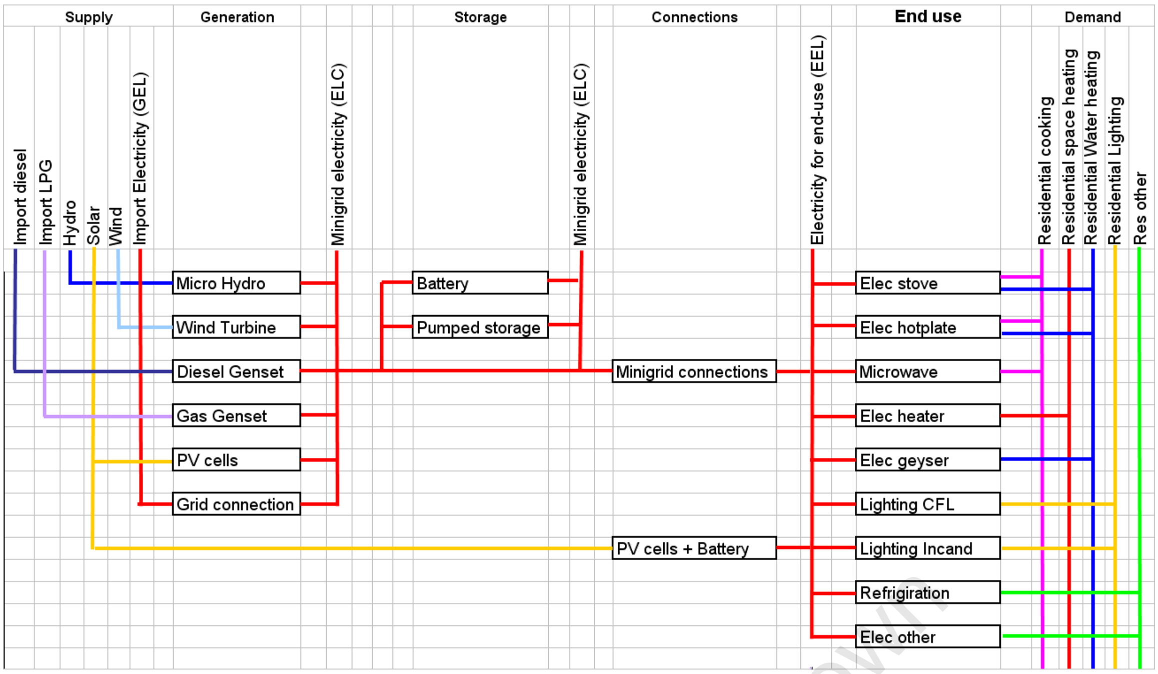
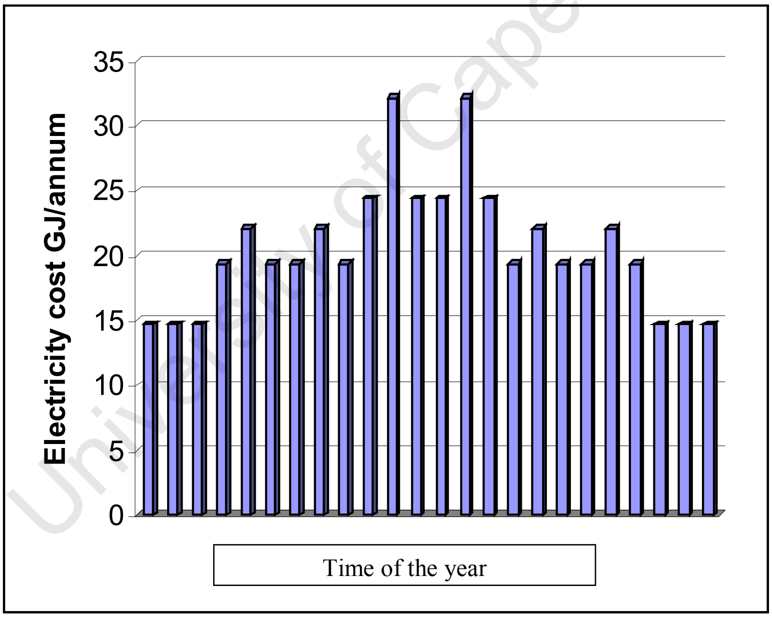


Figure 6.2: Reference energy system for electrification options



(Two bars represent one month starting in summer (January))

Figure 6.15: Electricity assumed electricity cost profile for 2018

Table 6.2: List of 'end-use' appliances

	Fuel used	*Demand met*					
Technology		*CKG*	*SHT*	*WHT*	*LGT*	*REF*	*OTH*
Demand devices							
Open fire	Biomass, coal	X	X	X	-	-	-
Stove	Biomass, Coal	X	X	X	-	-	-
Electric hot plate	Electricity	X	-	X	-	-	-

Electric stove	Electricity	X	-	X	-	-	-
LPG ring	LPG	X	-	X	-	-	-
Paraffin primus	Paraffin	X	-	X	-	-	-
Paraffin wick stove	Paraffin	X	-	X	-	-	-
Microwave	Electricity	X	-	-	-	-	-
Electric geyser	Electricity	-	-	X	-	-	-
LPG geyser	LPG	-	-	X	-	-	-
Paraffin geyser	Paraffin	-	-	X	-	-	-
Electric heater	Electricity	-	X	-	-	-	-
LPG heater	LPG	-	X	-	-	-	-
Paraffin heater	Paraffin	-	X	-	-	-	-
Incandescent lighting	Electricity	-	-	-	X	-	-
CFL lighting	Electricity	-	-	-	X	-	-
Candles	Candle wax	-	-	-	X	-	-
Paraffin press.	Paraffin	-	-	-	X	-	-
Paraffin wick	Paraffin	-	-	-	X	-	-
Electric fridge	Electricity	-	-	-	-	X	-
LPG fridge	LPG	-	-	-	-	X	-
Other devices (TV, radio etc.)		-	-	-	-	-	X

Table 6.3: Energy supply technologies

Electricity supply technologies	*Fuel used*
Diesel generator	Diesel
Gas generator	LPG
Grid connection	Electricity
Photovoltaic generator	Solar
HAWT	Wind
Electricity storage technologies	
Pumped storage	Electricity
Battery	Electricity

Table 6.4: Externality costs[177]

$/ton	*US range*[a]	*UK*[b]	*(1996)*[c]	*This study*
Carbon monoxide – low level	95 – 946			946
Sulphur dioxide – low level	165 – 82500	368	120 – 204	713
Nitrogen oxides – low level	935 – 9790	125	15 – 25	88
NMHCs[d] – low level	352 – 5830			339
Particulates – low level	572 – 4598	21 330	57 – 97	339

Notes:

a. Sarkar and Wolter (1998), and Sorensen (1992). No distinction is made between low-level and high-level emissions. Those externality costs calculated on the basis of cost of control are excluded.

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[177] It should be noted that these costs, though referenced, are purely indicative, and should be seen as such.

b. The Royal Society (1995), which considers damage costs to the UK only and not to the rest of Europe.

c. Low/high range. Applies only to the Mpumalanga region and to human health effects. Van Horen (1996b) determined the combined health impact of sulphur dioxide, oxides of nitrogen and particulates. He identified sulphur dioxide as being the dominant health risk, but its effect is enhanced by oxides of nitrogen and particulates. Total externality costs were apportioned based on a weighting of 10 for sulphur dioxide, 1.0 for nitrogen oxides and 0.5 for particulates. It should be noted that these were for emissions that were not released indoors. These underestimate indoor air pollution values.

d. Non-methane hydrocarbons.

Section 4 Development and GHG mitigation in industry

This section of the thesis focuses on greenhouse gas (GHG) mitigation in industry by industrial energy efficiency and its role in development. Recall that the theme of the thesis is to show how suitable modeling can not only warn of inefficiency in development policies, but indicate technical scenarios of how such inefficiencies are best remedied. With this in mind the first two chapters focus on the application and development of a suitable tool. The first chapter (7) uses an "off the shelf" multi-criteria analysis approach. This sheds light on what may constitute more efficient policy industrial GHG mitigation policy. While it specifically illustrates what technical scenarios may be more robust than others, it has limitations. Some of which are addressed in the subsequent chapter. The second chapter (8) in the section applies a hybrid model developed to solve for multiple goals, while also take into account selected energy-economy interactions. Finally using the insights gained, a development-policy, the Clean Development Mechanism, is shown to be inefficient.

This first chapter (7) was written in response to an observation. Namely that there were many fragmented studies which focused on different aspects of energy efficiency interventions in industry. Some focused on job creation, some energy saving, some on mitigation potential. (As well as others.) Further different voices amongst government, civil society and private enterprise were calling for different objectives to be prioritized in related policy. For the green lobby that was improved environmental performance, for industry - increased profitability and for government - improved job creation. The study was undertaken to establish if there were energy efficiency options which would satisfy all voices.

In order to account for different studies (of differing accuracies), and finally rank different industrial energy efficiency options, a simple method was employed. A Monte Carlo[178] multi criteria analysis (MCDA) was undertaken. In this analysis different attributes of different industrial energy efficiency options were assessed by different criteria. The weighting of the criteria formed the basis of scenarios. In each scenario criteria had a different weighting for the present and the future. If certain energy efficiency options were common to all scenarios, then they were assumed to be robust.

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[178] It was necessary to use a monte carlo approach as each option (and weighting) was estimated to different accuracies. Therefore the score of each energy efficiency option would be generated as a function of some randomization. The degree of randomization was a function of the level of accuracy estimated. After several model runs a spread of scores for each option were generated (as a function of the accuracy of the input data). From this inferences could be made about how the different energy efficiency measures ranked against each other.

Given that potential outcome, deliberately extreme scenarios were chosen. If the solutions were common to those, then it would likely feature in a less extreme more plausible scenario.

While useful[179] the MCDA approach has clear limitations. Another approach was applied and developed to address some of those in Chapter 8. An optimision model (similar to that of chapter 3) was used to solve for several rather than one objective. Rather than solving to only minimize cost, it would now solve also for reducing the environmental burned as well as other goals. Further, in order to account for economic changes brought about by new investment in the energy system, aspects of an Input Output model were incorporated. This new approach is useful as it allows us to consider the dynamic change of the energy system over time, were it to meet different goals. (The multi objective optimization is a form of analysis known as Goal Programming (GP).) This provides more integrated and useful dynamic information for policy formulation, though again it has limitations and those are mentioned[180].

Finally, the model of Chapter 8 was applied in Chapter 9 to evaluate (rather than sculpt) a future scenario. That scenario was one of the successful implementation of a national energy efficiency policy. The scenario was evaluated in terms of different development goals. Doubt exists about whether that policy would be successfully implemented. However, it is shown to be both useful for meeting greenhouse gas (GHG) mitigation objectives as well as for other important goals. As this is a policy which should conceivably happen for development reasons, it is not clear if this would conform to conditions of the Clean Development Mechanism (CDM). CDM, a powerful multinational tool for mitigation, is mechanism aimed to encourage only “additional” greenhouse gas (GHG) saving.

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[179] And at the time of publication of that work was innovative in the specific context of evaluating industrial GHG mitigation option in terms of different criteria and scenarios.

[180] Perhaps most notably the static nature of a standard IO analysis.

Chapter 7 A simple framework for analyzing GHG mitigation options

This section begins a move away from the micro and household models of the previous chapters towards the macroeconomic impacts of mitigating sector wide emissions and an evolution of methodologies for their analysis. In this chapter[181] a multi-criteria-decision analysis technique is used and demonstrates a method for determining best fit solutions to an apparent dilemma: how to reduce emissions whilst spurring development.

Introduction and problem statement

Industrial energy efficiency measures offer the potential to reduce greenhouse gas (GHG) emissions, affect job creation and influence other sustainable development goals (Spalding-Fecher et al. (2004), Geller et al. (1992), Laitner (2004) and Laitner (1998)). These measures also affect industry in terms of implementation difficulties and profitability (Kenny et al. (2000a), Kenny et al. (2000b), Kenny et al. (2000c), van Es (2002), IEA (1996)). In this chapter a hypothetical case study is developed to show how certain industrial electrical energy efficiency measures can both meet national development goals and reduce green house gas (GHG) emissions. It uses a very simple Multi Criteria Decision Analysis (MCDA) framework to examine GHG mitigation under extreme (and hypothetical) scenarios and shows that the framework can provide robust solutions that meet multiple policy and development goals. As stakeholder views are likely to be less extreme than those presented in the hypothetical scenarios, significant solutions identified are robust. (Future work could focus on quantifying accurate descriptions of stakeholder weightings). An advantage of the MCDA approach used here is that it provides a consistent framework that can use data from studies. Using Monte-Carlo simulation, an attempt to include data or other parameters of varying levels of accuracy is made.

South Africa is a developing country that currently has no obligation to reduce GHG emissions under agreements such as the Kyoto Protocol. Moreover, the effectiveness of emissions trading mechanisms as incentives for developing countries to reduce GHG emissions is unclear and there are well recognised limitations[182] to Clean Development

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[181] This chapter draws heavily from: Howells, M & Laitner, J (2003). A Technical Framework for Industrial GHG Mitigation in Developing Countries. In Proceedings: Summer Study: Industrial Energy Efficiency. New York, July.

[182] Please note that the limitations to CDM, mentioned here and in subsequent chapters, are themselves limited. There is no intention of implying that the full CDM mechanism is lacking, nor that CDM

Mechanism (CDM) projects (see e.g. Wara (2006)). It may therefore be sensible to investigate mitigation options that would both promote development and reduce GHG emissions - and then to evaluate these in terms of national development or government policy goals including the effects of their implementation within industry.

For governments of developing countries, benefits such as job creation may be more important than GHG mitigation. However, the correlation between GHG mitigation measures such as the efficient use of industrial energy and benefits such as job creation (Spalding-Fecher el al (2004)) warrants further study and is described here.

Scenarios

This section of the thesis follows earlier studies such as Trikam et al. (2003) and Trikam (2001) in having as its focus electrical energy efficiency measures that would reduce GHG emissions by industry. The scenarios chosen for this analysis are:

1. A **base case** in which government development goals such as job creation are emphasised; this scenario also recognises issues such as profitability and ease of use, although these are given a lower priority,
2. An **environmental interest case**, in which aspects such as water conservation are the focus, and
3. A **profit-driven case** in which profitability and ease of implementation are favoured above development goals such as job creation.

Each scenario involves at least one objective of importance to stakeholder groups. For example, in the base case listed above, job creation (an important government goal) competes against profitability and ease of use. A shortcoming of most standard economic analyses and models is that they tend to focus on a single objective – either to minimize cost or to maximize profit, welfare, or consumer utility (Laitner and Hogan, 2000; and Hobbes and Meier, 2000). Although the need for multicriteria decision models increases as climate change issues grow more complex, current policy tools do not always have the capacity to solve for multiple objectives. This chapter demonstrates how a multi criteria decision analysis (MCDA) framework[183] can be adapted to do a goal-programming analysis of emission reductions and to investigate the scenarios listed above.

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projects which have been established not also meet urgent development goals.

[183] Hobbes and Meier (2000) provide an in-depth review of a variety of multicriteria decision tools that would also be useful in policy analysis.

Method of solution

This analysis compares the effects of 11 different energy efficiency measures. These are assessed according to 10 'criteria'. These criteria are then grouped to form the three scenarios evaluated, wherafter conclusions are drawn. The scenarios are imposed on the data in the framework by assigning present and future impact scores to the attributes that reflect the characteristics of each scenario. For example, in the profit-driven case, the attributes *profitability* and *ease of use* are given higher present impact scores than in the base case where *job creation* is emphasized instead.

The attribute values used in the model may be expressed in different units, such as South African Rand[184] per kilowatt-hour (*R/kWh)* or kilograms per cubic meter (*kg/m*^{3}). In an attempt to make the values commensurable they are normalized, each set of attribute values being scaled according to the range of values for that attribute.

To cater for uncertainty in the attribute values, each normalised value is randomised[185]. The premise behind the randomisation is that the attribute values for each measure may be unreliable. The effect of errors in the values is simulated by applying random adjustments to each impact score and attribute value. This is done over multiple runs of the model, and the results of each run are then averaged. In this way both the average values of the impact scores and attribute values can be determined, as well as a confidence range[186] for each value. This confidence range allows estimation of the potential errors in the input data, and hence provides a measure of overall confidence in the results (Cartwright, 1993). Once the results are obtained, if the final score of a candidate solution is standardised and randomised to within a 95% confidence interval and still lies unambiguously above that of another solution, it is concluded that the first solution is better than the second. If the confidence ranges of the two alternatives overlap, no such conclusion may be made (Cartwright, 1993). (That is not to say that overlaps of the confidence intervals are devoid of statistical inference. At differing confidence intervals the range or spread of the solution for each candidate would be smaller. If differing confidence intervals are chosen, statistical inferences may be drawn from the

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[184] At the time of writing one U.S. dollar was worth approximately six South African Rand.

[185] The randomization is performed with a uniform distribution. Therefore if: n is the normalized value, r is a random variable (with a uniform distribution) between 0 and 1, and u is the uncertaintly level between 0 and 100%, then the randomized normalized value for each model run becomes: n-(u/100%) +2*(u/100%)*r. Future work could focus on statistical forms the likely shape of that error distribution and inferences on the results.

[186] The confidence range is a function of the mean and the standard error of the set of reasults for each candidate. The standard error is function of the standard devation divided by the square root of the number of model runs.

overlaps associated with the 95% confidence interval overlaps. That is avoided in this chapter, only inferences with high confidence are reported. Further, details of data uncertainty in the input variables are not available[187].)

In this study the method was adapted by allowing the magnitude of the randomisation applied to be specific to each attribute. This adaptation is important since it allows data from different surveys (that have different levels of accuracy) to be combined in one study.

The multicriteria framework

The multicriteria framework used in this paper consists of entities, attributes and data. The entities comprise the energy efficiency measures, the attributes are the guidelines for the assessment and the data consist of attribute values and their scores. These are described in more detail below.

Measures considered

Following the analysis of chapter 3 "A least cost mitigation pathway for South Africa", improved electricity use in the industrial sector is clearly important for cost effective emissions reduction. The industrial electrical energy efficiency measures considered here had already been identified as targets in current national planning (Trikam et al. 2003). They represent 'big hits' in terms of the potential GHG savings accruable to South African energy. They also produce complex effects observable in more than one field of study. Previous evaluations of them had been limited - consider de Villiers (2000) and de Villiers and Matimbe (2000). Both were sectoral studies designed specifically to inform South Africa's national GHG policies and IPCC communication. Both considered the cost of implementation – but ignored further development impacts.

The following measures were considered and these are either characterized by technologies or management approaches adopted (bracketed abbreviations in ***bold italics*** refer to labels used in the results table):

Variable speed drives (***VSD1 & VSD2***) – These drives reduce unnecessary power consumption in electrical motors with varying loads.

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[187] Most of the assumptions reached are based on initial data such as fuel consumption. In the studies used to compile this data there is no attempt to assign certainty to these values (see NER (2004), DME (2003a), and DME (2004a) for official data). The approach in this chapter is to show that an MCDA framework can be used to reconcile estimates even with (as in the final scenario of the study) high levels of uncertainty. The implication is that in order to improve the accuracy of policy making, specific uncertainties which may have a bearing on the outcome can be identified. This can then be revisited in policy formulation.

Efficient motors (***Motors1 & Motors2***) – These motors are available at higher cost. Efficient motors can reduce power consumption, but may require modifications because running speeds are generally higher than for inefficient motors.

Compressed air management (***CA***) – This measure is easily achieved and often results in significant savings at low cost.

Efficient lighting (***Lighting1 & Lighting2***) – These measures take advantage of natural lighting, more efficient light bulbs and appropriate task lighting.

Heating, ventilation and cooling (***HVAC1 & HVAC2***) – These measures are for maintaining good air quality and temperature and can commonly be improved through better maintenance and the installation of appropriate equipment.

Thermal saving (***Thermal1 & Thermal2***) – Thermal saving refers to more efficient use and production of heat.

Variations in local content have important implications for both job creation and technology transfer, and are considered in the analysis. Certain components of these measures could be produced locally or imported. In the above list the suffixes '1' and '2' indicate, respectively, measures with 80% and 20% local content. Compressed air management is assumed to have 100% local content because of the way in which this measure is implemented. (Fixing leaks, for example, which often provides the biggest saving, is normally carried out by local artisans).

The above list is not exhaustive, but all of the measures on it have been specifically identified as important (Trikam et al. 2003) and are used in the MCDA framework to show how multiple objectives can be met while GHG emissions are mitigated. At a policy level it also shows how GHG emission reduction, rather than necessarily competing with development, can complement it.

Criteria for policy setting

The manner in which GHG mitigation is handled reflects the positions and priorities of the parties concerned. Each priority determines a set of criteria by which the mitigation options should be assessed. A set of criteria which could be affected by energy efficiency measures was established for the South African Department of Minerals and Energy (Hughes et al 2002). These include (bracketed ***bold*** abbreviations are used in the table of results):

- greenhouse gas mitigation (***GHG***);
- resource (fuel saving/system ***efficiency***);
- water saving (***Water***);
- mitigation of local environmental loading (specifically:

    - sulphur dioxide $\boldsymbol{SO_2}$,
    - nitrogen oxides $\boldsymbol{N_2O}$ and
    - total suspended particulates ***TSP***);
- technology and technology transfer (***Technology***);
- job creation (***Jobs***)

Following Howells & Solomon (2002), further important criteria included were
Profitability (***Profitability***) and
Ease of implementation (***Ease***)

The importance of each criterion varies according to priority. The priorities in turn depend on the party involved, such as a government department and its associated objectives. The significance of the criteria are reflected by their present, and future impacts, and scores assigned to these.

Of course GHG mitigation may not be viewed as a priority in developing countries. The MCDA framework allows the policy maker to consider its significance relative to other priorities.

Data used for this study

Data for the study was gathered from both previous work and from specific modelling carried out for this analysis. The three categories of data required for the analysis are: attribute data, uncertainty data, and the weighting of the development criteria. The attribute data capture the contribution that each energy efficiency measure makes to the specific objective or criteria, uncertainty data reflect a confidence interval about the attribute data, and the development criteria weightings reflect specific stakeholder concerns.

Attribute data

Attribute values for each measure are expressed as the unit contributions to each development objective or criterion. These are summarised in Table 1. Parameters for the modelling are documented in Hughes et al (2002). In this work the impacts – in terms of energy saved – for different electrical energy efficiency measures is estimated. Other attributes of these measures are gathered from other studies. The ***job creation*** estimates were extracted from an input-output economic model (Laitner 2002 and Laitner 2001). This model was re-run for an eleven year period from 2003 to 2013 and the profitability of the various measures were considered. The proxy used to determine profitability is the payback[188] of the measure. Foreign content is used as a loose indicator of ***technology*** transfer.

An energy model of South Africa developed using the LEAP 2000 energy modelling/accounting software (Howells et al 2002) was re-run for this study in order to estimate changes in local environmental loadings for the period 2003 to 2013[189]. The mitigation levels of CO_2 equivalent for the following attributes were determined for each measure:

- Greenhouse gases[190] (***GHG***): carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O);
- Local pollutants: sulphur dioxide (***SO_2***), Nitrogen Oxides (***NO_X***) and total suspended Particulate (***TSP***);
- Power station water requirement (***water***).

Several local industrial case studies (Kenny et al 2001a; Kenny et al 2001b; Kenny et al 2001c and Van Es 2002) have evaluated 'ease of implementation' for selected measures within local industry. These studies further quantify profitability and "ease of implementation" for electrical energy efficiency measures, and the values derived in these studies are used in this chapter.

'Balance of trade' attribute data (considered a priority in Hughes et al. 2002) were considered negligible, as the fuel savings (mainly coal consumption in the power sector) are expected to affect trade significantly only in the longer term (van Horen 1999)[191].

Uncertainty data

A central feature of this model is the notion that individual estimates of attributes have different uncertainties. This is often the case in developing country analyses, where data is available only from *ad hoc* studies. The differing uncertainties make direct comparison difficult unless an approach that accounts for the uncertainty is adopted. For this reason error ranges for the attributes are included. Thereafter, the energy efficiency measures are

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[188] Payback is a simple ratio of the cost divided by the annual saving of an energy efficiency measure in real terms.

[189] For each measure implemented at a national level, changes in electricity consumption were computed and in turn quantities of fuel burned and emissions released.

[190] GHG emissions were combined into a single indicator, namely carbon dioxide equivalent, using the respective global warming potential of the individual species.

[191] The coal used is of such poor quality that it has low opportunity costs: washing would be expensive and the coal cannot be used for other industrial purposes. (Though, in a sense, it is not strictly true to say that coal washing would be expensive. Much of the power station feed has already been washed to extract a high-grade fraction that is then exported. The poor quality washed middlings often form the power station feed. To further wash those would be impractical or expensive.)

evaluated in the MCDA framework. The uncertainty values used are summarised in Table 7.1. These hypothetical values are used illustratively in the scenarios discussed below. A sensitivity analysis that uses increased levels of uncertainty is included in order to account for the possible effects of data with large uncertainty on the final results.

The following assumptions were made for the scenarios:

- Estimates of emissions and water consumption levels are considered accurate to 5%. The estimates are consistent with assumptions that are typical of large-scale local planning programs (See NER 2003b and NER 2004).
- Estimates of job creation potential were derived using a large array of assumptions. The relationships between these assumptions are expected to change with the economic and labour characteristics of the South African economy. The estimates are thus assigned a high uncertainty of 30%.
- Profitability values are derived from limited case studies of well-managed, high profile firms in local industries. It is not clear that the same is true of “lower profile” industry in South Africa – it is possible that savings associated may be higher due to lower maintenance levels. The uncertainty associated with these figures is assumed to be 20%.
- Ease of implementation may, as with the previous assumption, depend on the measure and circumstance of the plant considered. An uncertainty of 20% is assumed.
- Technology transfer is estimated by the foreign content in the measure. This does not distinguish between ‘advantageous’ and ‘neutral’ transfer. A high degree of uncertainty (60%) is thus associated with the indicator.

Importance and weighting

The importance of each development criterion relative to the development priorities of government is often not explicitly quantified. These are captured via hypothetical extreme scenarios. A similar approach was used by the Intergovernmental Panel on Climate Change (IPCC 2000) for its long term mitigation scenarios. In that case, scenarios of global GHG emissions were modeled based on extremes in likely technology adoption (amongst other things). It was argued that this helped determine the “solution space” for more realistic development scenarios. In practice, these scenarios should or could be determined by debate amongst policy makers. This was presented to stakeholders for comment at national workshops and meetings and the outcomes (from using relatively extreme scenarios to obtain robust solutions) accepted.

Of the two sets of weightings proposed below, one is for the present (period one) where environmental concerns are relatively low, and the other is for a longer term (period two) in which environmental effects are more important. However, given the current urgent planning priorities of the South African government, it is not likely that future priorities will be considered as important as those of the present. For this case study, it is assumed that future development criteria are only 20% as important as current development criteria. The weights are set accordingly. The attribute values for the hypothetical scenarios for energy efficiency measures considered are presented in Table 7.1.

Table 7. 1: Attribute data for the multi-criteria analysis

	GHG mitigation	*Job years (and technology transfer: 100%-local content)*		*Water saving*	*Fuel saving*	*SO_2 mitigation*	*TSP mitigation*	*NO_X mitigation*	*Ease of imple-mentation*	*Profitability (Payback)*
Unit	*Thousand tons*	*80%*	*20%*	*M Liter*	*PJ*	*Thousand tons*	*Thousand tons*	*Thousand tons*	*Index*	*years*
Compressed air	22 829	7 500	-	229	247	224	6.9	89.2	1	1
HVAC	547	270	60	5.5	5.9	5.4	0.2	2.1	2	1
Lighting	9 639	3 200	900	96.7	104	95	2.9	27.7	3	3
Motors	14 393	7 600	-1,300	149.9	162	147.2	4.5	58.4	3	5
Thermal saving	13 478	4 400	3,200	135.2	146	132.8	4.1	52.7	1	0.5
VSDs	3 794	3 700	-1,500	38.1	41.2	37.4	1.2	14.8	3	4
Uncertainty	5%	30%	60%	5%	5%	5%	5%	5%	20%	20%
Near term weighting	0	100		26	32	3	2	1	50	50
Medium term weighting	6	100		53	63	6	4	1	10	10

The Base case scenario

In the Base case, job creation is treated as the most important criterion, and the weights of the remaining attributes are positioned relative to it. To derive the attribute weights for the base case, the following assumptions were made:

- The relative weightings of emissions are calculated using low-end externality costs for power station emissions (van Horen 1996b). The externality data are derived primarily from health impacts, which inform local environment strategy (DEAT 2003). The weighting on GHG emissions was assumed to be zero during period one and to become as important as SO_2 emissions during period two. The importance of other emissions doubles in the future the future since it is assumed that clear links are established between sustainability and growth, and also because of increased influence from a larger, middle-class 'green' lobby.

- Profitability was considered to be as important as job creation in the longer term as the industrial lobby gathers momentum. Initially it is taken to be only half as important.
- The importance of GHG mitigation increases significantly. It is assumed that South Africa develops into an Annex 1 (or equivalent) country.
- Ease of implementation increases in importance with the growth of the industrial lobby, which resists direct government involvement in production. Initially it is assumed to be half as important as job creation, whose importance remains constant.
- The scarce water resource of South Africa are further prioritized by government over time, thereby doubling the importance of reducing water consumption in period two.

Technology transfer increases in importance from the first to the second period. The relationship between development and transfer becomes better described. The need for technological edge is maintained[192].

Other scenarios: Environmental interest and Profit-driven

These scenarios are permutations of the base case and represent extreme departures from it. They are designed so that solutions that are common to these "extremities" are likely to be robust. The **Profit-driven** scenario reduces the importance of job creation by 75%, and at its expense doubles the importance of profitability and ease of implementation. In the (extreme) **Environmental interest** scenario the importance of profitability and ease of implementation is reduced by 80%, while environmental concerns such as emissions savings are amplified to between 10 and 20 times of their original values[193]. Job creation is reduced to 25% of its importance in the base case.

Results

A Monte Carlo simulation was run in a custom built application (described in Jeftha (2003), but based on Cartwright (1998)). Results for the scenarios are given in Figure 7.1. For each measure there are two scores, indicating a range of confidence for the measure.

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[192] That data in the table is related to local content and job creation in data columns 2 and 3.

[193] Recall that, in the base case, environmental emissions savings have little importance relative to job creation.

This confidence interval is affected by aspects such as the uncertainty associated with the input data. It also allows the better mitigation options to be identified from within the group, since options with higher scores are better at fulfilling the policy reflected in the criterion weighting structure.

Scenario 1 - Base Case

In this case, jobs, profitability and "ease of use" were given the largest significance weightings for the present and future scenarios. Three groups of candidates emerge:. those with preference scores of more than 2, those with scores between 1 and 2 and those with scores of less than 1. Amongst the last group, there appear to be three sub-groups.

The first group contains the three potential winners: Compressed air (CA), Thermal measures with high local content (Thermal1) and high foreign content (Thermal2). These are unambiguously better than the other candidates, but cannot be ranked apart from each other because their confidence intervals overlap. These three perform particularly well because of their profitability and ease of use.

Motors1 is the only candidate in the second group. Although this option has a high score for job creation, it has poor scores for profitability and ease of use. Thus it is easily distinguished from members of the first group on the basis of these discriminants.

The third group consists of three sub-groups: 1.{HVAC measures with a high foreign content (HVAC2), Lighting measures with a high local content (Lighting1), and high foreign content (Lighting2)}, 2.{Efficient motors with a high foreign content (Motors2), installing variable speed drives (VSDs) with a high local content (VSD1)} and 3. {Heating, ventilation and airconditioning measures with a high local content (HVAC1), and VSD's with a high local content VSD2}. Amongst the first sub-group, Lighting1 does not fare significantly better than its peers despite having a larger job creation score. In this case it appears that the distinguishing features of the candidates are profitability and ease of use. In the case of {Motors2, VSD1}, job creation appears to be a very strong feature, since although Motors2 has significantly higher scores on most other attributes, VSD1 still manages to perform as well as Motors2 on the basis of its score for this attribute.

Scenario 2 - Environmental Interest

In this scenario water consumption, followed by efficiency and then total suspended particulate matter (TSP) (or smoke) were given the highest combined weightings in order to reflect an 'environmentally friendly' disposition in this scenario. Given these weightings, Compressed air measures (CA) emerges as the clear winner. High local

(Thermal1) and high foreign (Thermal2) thermal measures, followed by efficient motors with a high local content (Motors1) are the next best options.

In terms of confidence intervals, all four of these options are distinguishable from each other, and it further appears that the candidates may be grouped together as {CA}, {Thermal2, Thermal1, Motors1, Motors2}, {Lighting2, Lighting1} and {VSD2, VSD1, HVAC2, HVAC1}. Somewhat surprisingly, technology, ease, profitability and jobs seem to be the discriminants accounting for the order of preference amongst the second group, the scores for the other attributes being identical for each pairing. In the third group, technology also plays a strong role. In the fourth group, technology transfer and jobs seem to play distinguishing roles. Technology transfer appears to be the stronger factor, often appearing to compensate for poor job creation levels.

In relation to the policy reflected in the weighting structure of this scenario, the attributes are not as clearly demarcated as in the base case. There is not a clear correspondence between the policy and the candidate groupings and attributes other than those most favored by the policy appear to dictate the rankings of the options. This inference is important. It implies that future work should carefully consider the full range of criteria for targeting interventions.

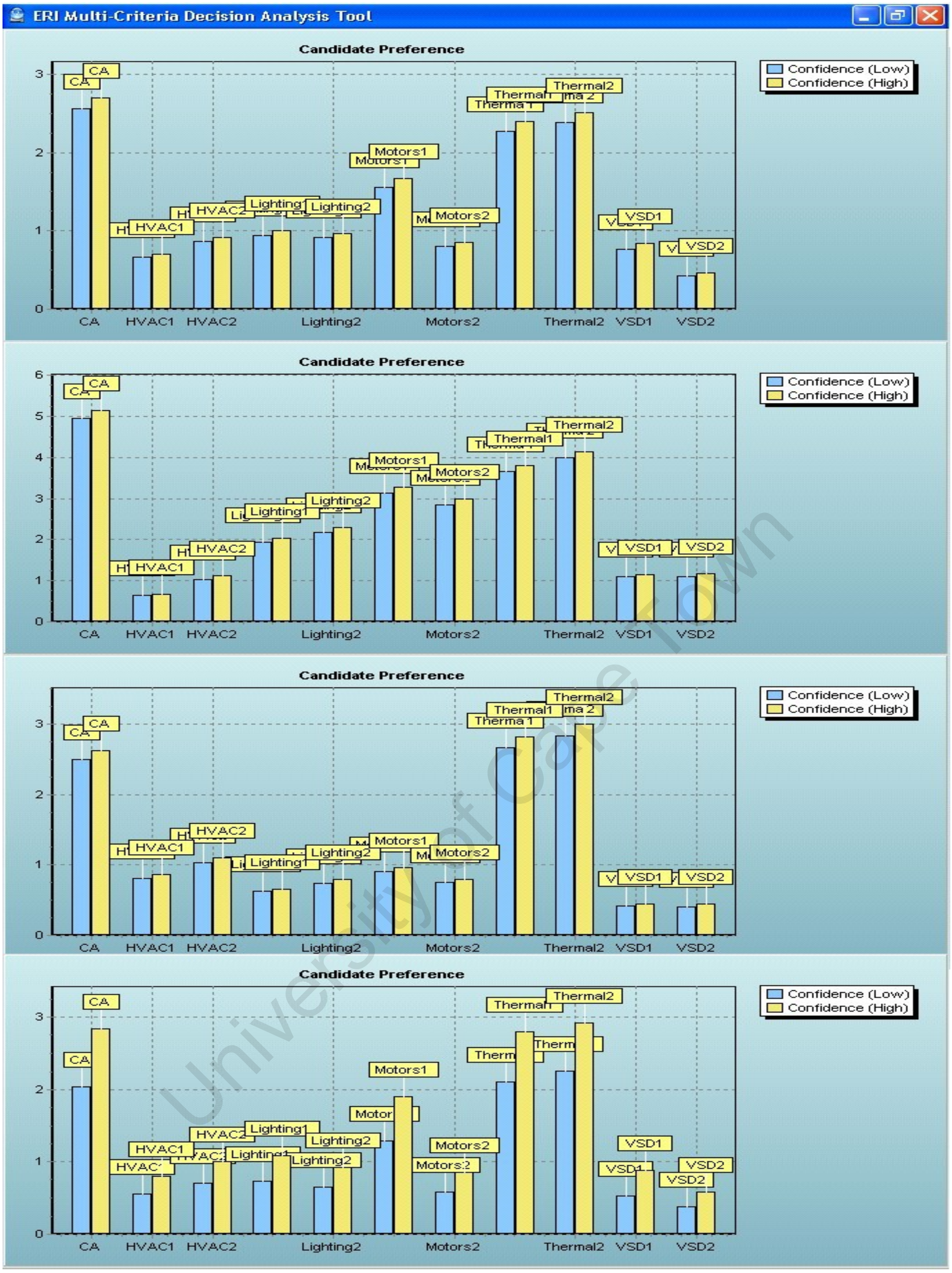

Figure 7.1 Results of the MCSA, showing (top to bottom) confidence intervals for the base, environmental interest, profit-driven & an uncertainty case study[194].

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[194] The results from the high uncertainty case are of interest as they indicate a level of robustness in the interventions chosen. Compressed air (CA) and thermal measures (Thermal1and Thermal2) are unambiguously the highest scoring measures. This is the case even with high uncertainty in the data. These are followed by motor measures with a high local content (Motors1). However, after those three there is no clear winner. This would imply two things. Firstly, if only three measures were to be targeted for implementation, they would be thermal, compressed air and motors (with a high local content). Secondly, if more measures were to be targeted, more accurate information on their attributes etc is

Scenario 3 – Profit Driven

Here ease of use and profitability were weighted ahead of other attributes. Given these weightings, thermal measures with high foreign content (Thermal2) and then high local content (Thermal1) were rated most highly, followed closely by compressed air (CA) measures. Of these three options, the technology score dictated the observed ordering more strongly than jobs created; Thermal1 and Thermal2 being equal on all the other scores.

Implications for the energy efficiency policy

With the exception of the base case, each of the scenarios investigated produced a clear winner and solutions were similar. Thus a framework is in place for decision making in accordance with different policies. The study further illustrates how uncertainty can be handled and allows accurate characterisation of current and future scenarios. In addition, government can assign weightings that are appropriate and consistent with national prerogatives. This study does not attempt to accurately quantify what those priorities will be, though the base case is consistent with development objectives at the time of writing. The multi-criteria approach also provides insights into the relative merits of non-environmental criteria which are likely to support GHG mitigation measures. This illustrates the need for an approach such as this to GHG mitigation analysis. In each scenario, different groups of options emerged. Certain attributes distinguished the members of each group from the rest. In this regard, the base case differs from the other two scenarios since it yields no clear winner, but produces a set of three potential candidates. Moreover, the distinguishing attributes were those with the high weightings. In the other cases, attributes other than determined by the policy were found to define the groupings.

For future work it would be of interest to assess the role of the uncertainty value in the final preference scores in a more definite fashion, *i.e.* it would be interesting to determine whether there is a point after which the results remain the same irrespective of the uncertainty settings. Alternatively, to establish whether or not there is a point beyond which the results become unstable (producing completely different preference orderings with each run). This would be useful not only for policy making (e.g. whether to support a compressed air savings program rather than importing high efficiency motors), but also to direct data collection overseen by government (see DME 2005b and NER 2005). By

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needed.

working backwards from the goal of deriving policy through available frameworks, important datasets can be distinguished.

It would also be interesting to account for more than one policy at a time. It would also be useful to know what policies may be immediately useful (reducing fuel consumption), and what may be useful in the future when they may affect the building of new power stations.

The technique, as demonstrated here, will simply find an optimal solution to the problem. There is no direct means of filtering out less suitable candidates by means of constraints, such as stipulating that NO_x emission levels should be below a certain limit. There is also no direct way to tailor the solutions by means of criteria, such as stipulating that in addition to meeting the constraints, the final solution is to be such that the employment score is maximised. These aspects can be addressed by means of other optimisation techniques. It would be of interest to investigate how these may be incorporated into the existing framework presented in this chapter.

Data accuracy is a limitation. Both that it is uncertain and that the shape of its uncertainty is not known. Clearly some data cannot be known. Work which would better quantify the uncertainties in the data – and how these would play out in policy making - would be useful.

A number of potential improvements to this initial effort have been highlighted. In the next chapter, a framework is used which can asses the potential role of several mitigation measures simultaneously and consider their timing. To do this, an optimization tool is programmed to solve for several goals.

Acknowledgements

The chapter uses a custom made application which was compiled by Lindsey Jeftha. Lindsey was also intimately involved in aspects of the analysis in the original paper but was not included as an author. Skip Laitner is also thanked for introducing the notion of both the IO modelling and MCDA analysis for energy efficiency evaluations as well as reviewing the original work.

Chapter 8 Mapping out climate friendly development

In the previous chapter, a methodology was discussed for the assessment of GHG mitigation options. That methodology allowed different data, or data sets of varying accuracy and based on differing assumptions, to be collated and compared. However, it did not provide a means to determine the optimal deployment of GHG mitigation measures either in terms of timing or extent. In this chapter[195] I present the first application of an integrated model. It is a technology rich optimization model integrated with an input-output model set up to solve for multiple goals. (It builds on previous work which is included in Appendix 2, entitled 'Modelling multiple goals' (Howells & Laitner (2005).)

Introduction

Having described the South African energy sector in previous sections, this chapter discusses goals which government hopes to meet by implementing appropriate energy policy. It extends the case study and focuses on industrial energy efficiency measures (in the previous chapter) as well as limited (wind-generated) renewable energy (see Appendix 11.2). In particular, the economy-wide effects of job creation and any changes in fuel consumption associated with these measures are computed. These effects are integrated into a single energy systems model to help with calculation consistency. The model is programmed to solve for various goals (rather than simply minimizing cost as was the case in chapter 3). Scenarios are developed by varying the weightings of these goals; the effects and roles of industrial energy efficiency measures (and renewable energy) are then observed.

Background

The use of relatively low-cost energy in South Africa is inefficient and there are significant opportunities for cost saving through energy efficiency measures. (Trikam (2001), Trikam et al. (2003) ERI (2000a)). Without the implementation of these measures, energy is under-utilized. Importantly, these measures would not necessarily change the economy's energy-intensive structure (Trikam (2001)), but rather move it

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[195] This chapter draws heavily on Howells, M., In Press, Mapping out development pathways for climate friendly economic growth in a developing country, *International Journal of Energy Technology and Policy*. The modeling component is also used in Winkler et al (2007).

towards better practice and closer to its efficient frontier (Laitner (2004)). The effect would be to reduce the 'end-use' cost of energy[196].

Several studies (summarized in DME (2004a)) have documented reasons for the non-realization of such energy savings. Recently, the South African Department of Minerals and Energy (DME) developed an energy efficiency strategy to help realize the potential for such savings. Prior to this, although it had supported improved energy efficiency (DME (1998)), the DME had only embarked on very limited active policies.

Energy efficiency and policy goals

The goals which the current DME policy (DME (2004a)) aims to meet, by the adoption of energy efficiency measures are summarized in the table below. The government's target is to reduce energy consumption by 14% in the next eight years relative to a reference scenario (DME (2004a)), and by so doing to meet some of its stated goals. While the next chapter will discuss this ambitious target with reference to the Clean Development Mechanism, this chapter will demonstrate how various measures can best meet government's stated goals.

Table 8.1 repeats the stated goals of government. In order to incorporate these into the modelling, the attribute of the energy system which proxies each goal is stated.

Table 8.1: Goals to be met by energy efficiency

Goal description (DME (2004a))	*Attribute modelled as proxy for goal*
Social sustainability **Goal 1: Improve the health of the nation** Energy efficiency reduces the atmospheric emission of harmful substances such as oxides of sulphur, oxides of nitrogen, and smoke. Such substances are known to have an adverse effect on health and are frequently a primary cause of common respiratory ailments.	**Goal 1**: Tons of sulphur dioxide, nitrogen oxides and total suspended particulates
Goal 2: Job creation. Spin-off effects of energy efficiency implementation; improvements in commercial economic performance; and uplifting the energy efficiency sector itself, will inevitably lead to nationwide employment opportunities.	**Goal 2**: Thousands of jobs created
Goal 3: Alleviate energy poverty Energy efficient homes not only improve occupant health and wellbeing, but also enable the adequate provision of energy services to the community at an affordable cost.	**Goal 3**: NA[197]

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[196] This increases economic activity and fuel consumption (which is modeled in this analysis), however, the changes are small and the rebound effect limited. (This is discussed later).

Environmental sustainability	
Goal 4: Reduce environmental pollution Energy efficiency will reduce the local environmental impacts of its production and use	**Goal 4**: As per 'Goal 1'
Goal 5: Reduce CO_2 emissions Energy efficiency is one of the most cost-effective methods of reducing GHG emissions, thereby combating climate change. Addressing climate change opens the door to utilizing novel financing mechanisms, such as the CDM, to reduce CO_2 emissions.	**Goal 5:** Tons of CO_2 emitted
Economic sustainability	
Goal 6: Improve industrial competitiveness It has been demonstrated that one of the most cost-effective ways of maximizing commercial profitability is the adoption of appropriate energy efficiency measures. Nationwide, this will improve South Africa's export performance and improve the value that her economy derives from indigenous energy resources.	**Goal 6**: Cost of energy supply in millions of (real) Rands[200]
Goal 7: Enhance energy security Energy conservation will reduce the necessary volume of imported primary energy sources, crude oil in particular[198]. This will enhance the robustness of South Africa's energy security and will increase the country's resilience against external energy supply disruptions and price fluctuations.	**Goal 7:** Energy imports in (real) Rands and imported energy as a proportion of total energy consumed
Goal 8: Defer the necessity for additional power generation capacity It was[199] estimated that the country's existing power generation capacity will be insufficient to meet the rising national maximum demand over the period 2007-2012. Energy efficiency is integral to Eskom's Demand Side Management programme in so far as it contributes 34% towards the 2015 demand reduction target of 7.3GW (NER (2004)).	**Goal 8:** Power station investment timing

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[197] A broader analysis may include aspects relating to the provision of energy and lower cost to the poor. In this case however this analysis focuses on increased employment.

[198] There are potential shortcomings in the national Government formulation: there is both expensive (oil) imports and cheap (Cahora Bassa hydro electricity) imports, and one would be prudent to differentiate between them

[199] Note that shortages were being felt before 2007. However, the most significant of those were due to transmission constraints. Those constraints were felt worst when ESKOM's nuclear power plant in the Western Cape required extensive unplanned maintenance as the capacity of the grid carrying power to the Cape was not large enough to meet that demand. Since then, the situation has changed radically, and the shortage is definitely one caused by generating capacity restraints. As predicted by this and previous modeling attempts.

[200] Note that as the supply of useful energy is kept constant between scenarios, this proxy is similar to considering costs per unit of energy supplied between scenarios.

Methodology

In this chapter the methodology used to compute and incorporate attribute data for various interventions and consistently solve for several goals is described. The use to which energy is put, and specific efficiency measures to be considered, are summarized. The calculation of job creation and other indirect or 'rebound' effects, and other attribute data, is discussed . The MARKAL model employed is then described. The model uses multipliers from an Input-Output model. The Goal-Programming (GP) extension of MARKAL is used to solve for multiple goals including job creation and environmental mitigation. Finally the scenarios adopted are described, defining them in terms of stakeholder goals and hypothetical weightings (which follow from the previous chapter).

Industrial energy efficiency measures and renewable energy (Wind)

Energy is used in industrial technologies to supply a service, such as high temperature heat, motive power, or lighting (see Figure 8.2). The services for which the energy is used are called the end-use services, and the energy used for these services is termed the end-use or final demand for energy. The energy efficiency measures considered are those that supply the same quantity of service using less energy. They reduce the end-use or final demand. Although these energy efficiency measures may cost more than their business-as-usual equivalent, these costs are often recouped over time from savings in the energy bill. (Consider the difference between a compact florescent light bulb (CFL) and an incandescent. In general, the CFL has a higher capital cost, but uses less energy to supply the same number of lumens. Over time (depending on the life time of each bulb) the extra cost of the CFL may be recouped by the savings on the energy costs[201].) The time taken to recoup the (real) cost of the initial outlay is referred to below as the payback period.

In order to determine the potential savings that may accrue to energy efficiency measures it is necessary first to determine the demand for energy end-use. Typically, coal is used either for thermal purposes (boilers and furnaces), and oil for a mix of thermal and motive (ERI 2001). The apportionment of electricity is more complex and I estimate an end-use demand for electricity by industry – summarized in the table below (Howells (2006) and at the end of this thesis in: Appendix 11.1).

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[201] For industry it is assumed that many factors associated with energy efficiency in the household can be ignored. In the case of CFLs, households choices may depend on much more than simply supplying the same number of lumens as their less efficient equivalent. They may be concerned about the hue of the light, the form of the bulb etc. While in industry it is assumed that the criteria is sufficient light of enough quality for the production requirements.

Table 8.2. Percentage end-use of electricity by industrial sector (Appendix A and Howells 2006)

	Food and beverages	*Textiles*	*Wood and wood products*	*Chemicals*	*Iron and steel*	*Non ferrous metals*	*Rest of basic metals*	*Rest of manufacture*	*Non metallic minerals*	*Gold mining*	*Other mining*
Indirect uses-boiler fuel	2%	1%	3%	1%	0%	0%	0%	1%	0%	0%	0%
Process heating	4%	5%	6%	3%	39%	1%	17%	10%	8%	2%	2%
Process cooling and refrigeration	24%	7%	0%	6%	1%	0%	0%	5%	0%	7%	7%
Compressed air	8%	10%	38%	10%	8%	0%	11%	9%	14%	20%	20%
Other machine drive	44%	50%	38%	53%	40%	2%	56%	47%	72%	45%	45%
Electro-chemical processes	0%	0%	0%	18%	2%	95%	17%	11%	0%	0%	0%
Other process use	0%	1%	1%	0%	1%	0%	0%	1%	0%	10%	10%
Facility HVAC	8%	15%	4%	4%	3%	1%	0%	8%	3%	8%	8%
Facility lighting	7%	10%	7%	3%	4%	1%	0%	7%	3%	4%	4%
Facility support	2%	2%	1%	1%	1%	0%	0%	2%	0%	4%	4%
Onsite transportation	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

The end-use splits are combined with a detailed industry-by-industry sector energy forecast (NER (2004); Howells (2004)) in order to determine a forecast for the end-use of energy for the industrial sector as a whole. With assumptions about the savings potential of each energy efficiency measure by end-use, it is possible to estimate the total potential savings. The specific measures I consider are described in the previous chapter (Howells and Laitner (2003) and Trikam (2001)). I distinguish between measures that have (hypothetically) high (80%) and low (20%) local contents in order to later derive policy implications (following per Hughes et al. (2002) and Howells and Laitner (2003)) and assume (an illustrative) cost difference between these (as per Howells (2004b)). This data is summarized below (as in the previous chapter) in terms of: payback[202], proportion of fuel saved and assumed cost-ratio (CR[203]) of high local to high foreign content and is listed below:

- Variable speed drives: These drives reduce unnecessary power consumption in electrical motors with varying loads (ERI (2000c)). Typical payback periods are 3.6 years. Conservatively 2.2% of industrial electricity can be saved and the cost-ratio (CR) is 1.4.
- Efficient motors (ERI 2000c): These motors are available at higher cost. Efficient motors can reduce power consumption, but may require modifications since running speeds are generally higher than those of inefficient motors. Typical payback periods are 7 years, conservatively 2.3 % of industrial electricity can be saved and the cost-ratio (CR) is 1.4.
- Compressed air management (ERI 2000h): This measure is easily achieved and often results in significant savings at low cost. Typical paybacks are 0.9 years, conservatively 3.2 % of industrial electricity can be saved and the CR is 0.9.
- Efficient lighting (ERI 2000c): These measures take advantage of natural lighting, more efficient light bulbs and appropriate task lighting. Typical paybacks are 3.6 years, conservatively 1.9% of industrial electricity can be saved and the CR is 1.2.
- Heating, ventilation and cooling (ERI (2000b, d & g)): These measures are for maintaining good air quality and temperature and can commonly be improved through better maintenance and the installation of appropriate equipment. Typical paybacks are 2.2 years, conservatively 0.6 % of industrial electricity can be saved and the CR is 1.1.
- Thermal saving (ERI (2000 d, e & f)): Thermal saving refers to more efficient use and production of heat. For steam systems (in particular) condensate recovery and improved maintenance is considered. Typical paybacks are 0.8 years, conservatively 1.4 % of industrial electricity, 10% oil and 15% coal can be saved and the CR is 1.2.

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[202] It should be noted that the payback periods used are indicative and based on average savings, average equipment usage rates etc.

[203] As South Africa is not a significant provider of many potential interventions, local alternatives are assumed to impose a cost premium. This is significant, as while jobs are created directly providing the interventions, it will not be competitive if done at a much higher cost to industry,.

We also consider the effect of introducing renewable energy supply to industry as an option to meet various development imperatives. Wind generation as a bulk renewable energy supply of choice (DME (2003c) & (2004b)) and its detailed costing for South Africa is provided in the national integrated resource plan (NER 2004). Wind-generated electricity, though more expensive than coal-fired electricity, uses no fuel nor does it emit greenhouse gases directly.

MARKAL is used to determine "shocks" or changes to business as usual industrial practice. This is required to bring about an optimal system with the focus on industry. The choices (for "shocks" or changes) that we have given the model are: industrial energy efficiency investments, investment in new coal fired power station or investment in renewable wind generation capacity to meet the growing demand for electricity.

These shocks are likely to have economy wide effects. The effects may be direct, such as lower fuel consumption in industry with the adoption of an energy efficiency measure. Such direct [204]effects are captured in a standard representation in MARKAL. However, there may be indirect effects as well. Thus, a reduced industrial fuel bill may lead to increased economic activity, increasing economy-wide requirements for energy or increasing employment. Such "indirect effects" and are estimated using an Input Output (IO) model. Previously, MARKAL had been run for the South African energy sector with an exogenous unchanging projection of useful energy demand to be met. The changes were estimated and their inclusion is described later. Where direct savings through energy efficiency are offset by indirect increases, the increases are sometimes referred to as a type of "rebound effect"[205]

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[204] And some indirect effect, where these are linked by the fuel chain concerned.

[205] A rebound effect is an increase in energy use in response to some measure that is implemented to improve the efficiency of energy use. Commonly noted rebound effects include:

- Possible increases in production due to lower tariffs in consuming sectors (it is assumed that this saving could be translated into increase final demand)
- Increased indirect requirements due to the higher local content associated with the nuclear electricity production
- Increased consumer spending due to lower household fuel bills

This work (including its first iteration – included in Appendix B at the end of the thesis) represents the first time aspects of an IO model have been integrated with MARKAL in order to estimate rebound effects.

Job creation and rebound effects

Job creation effects related to energy efficiency investments have been extensively described in the recent literature (Jeftha (2003); Laitner (1998); Geller et al. (1992)), and specifically for South Africa (Laitner (2001); Hughes et al. (2002); Spalding-Fletcher et al (2004) and Howells (2004b)). Following Spalding-Fletcher et al. (2004), a demand input-output analysis is adopted to determine economy-wide changes to expenditure on labour due to the changes in purchasing per unit of energy saved by an energy efficiency measure, and per unit of capacity investment in new power stations (wind or coal). Similarly economy wide expenditure changes for fuel consumption by sector are determined to estimate rebound effects.

The methodology is now summarized. An Input-Output model[206] summarizes the flow of revenue between economic sectors (Robinson (1989)). Along the rows of the Social Accounting Matrix (SAM) intermediate and final demands are given and in the columns the outputs. Using an aggregated national matrix (as per Spalding-Flecher et al. (2004)), this analysis considers eight key sectors (see Table 8.3). (Note that this methodology could be expanded to include more sectors.) From this matrix, the direct[207] requirements of each sector can be calculated by dividing each cell by its respective Total Gross Output (TGO). Considering payments, the column total for TGO is used. This gives the "A matrix", in which payments by sectors are recorded down columns, while receipts by sectors flow across the rows.

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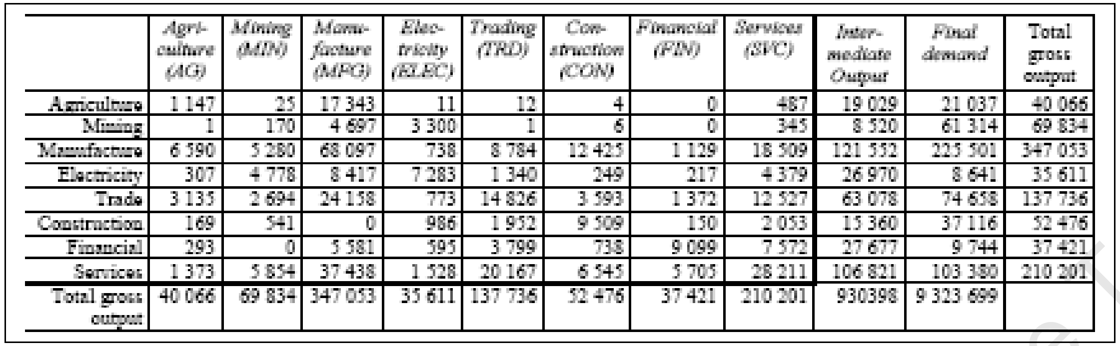
[206] In this analysis, the measures that are considered are likely not to change into the future. However, the structure of the economy will. This is not reflected in the SAM used, which is a historical snapshot, as is the IO model that is derived. Accounting for that change is outside the scope of this study, however, a methodology to incorporate this has been proposed by Jeftha (2003).

[207] Direct in the sense that it indicates the express level of input for one unit of output, not yet taking into account indirect effects in other sectors of the economy.

Table 8.3: Summarized input-output table for South Africa (Millions of Rand) (TIPS 2001)



	Agri-culture (AG)	*Mining (MIN)*	*Manu-facture (MFG)*	*Elec-tricity (ELEC)*	*Trading (TRD)*	*Con-struction (CON)*	*Financial (FIN)*	*Services (SVC)*	*Inter-mediate Output*	*Final demand*	Total gross output
Agriculture	1 147	25	17 343	11	12	4	0	487	19 029	21 037	40 066
Mining	1	170	4 697	3 300	1	6	0	345	8 520	61 314	69 834
Manufacture	6 590	5 280	68 097	738	8 784	12 425	1 129	18 509	121 552	225 501	347 053
Electricity	307	4 778	8 417	7 283	1 340	249	217	4 379	26 970	8 641	35 611
Trade	3 135	2 694	24 158	773	14 826	3 593	1 372	12 527	63 078	74 658	137 736
Construction	169	541	0	986	1 952	9 509	150	2 053	15 360	37 116	52 476
Financial	293	0	5 581	595	3 799	738	9 099	7 572	27 677	9 744	37 421
Services	1 373	5 854	37 438	1 528	20 167	6 545	5 705	28 211	106 821	103 380	210 201
Total gross output	40 066	69 834	347 053	35 611	137 736	52 476	37 421	210 201	930398	9 323 699	

The Leontief inverse of the direct requirements $(I-A)^{-1}$ gives the "output multipliers" for each sector, which capture both the direct and indirect effect for a change in payment. The introduction of measures such as industrial energy efficiency will have both direct and indirect effects on the economy (Spalding-Flecher et. al. (2004)).

This output multiplier matrix can be interpreted (in the form $X = (I-A)^{-1} \times F$) as a series of linear equations from which one can derive how much of each sector output is required directly and indirectly to support a R1.00 increase in final demand of product from that sector. Each element shows the required production levels to meet the specified demands from different sectors in the economy.

Therefore, if we know the direct changes that result from implementing an energy efficiency measure in industry or in building a new power station, the direct and indirect effects on other sectors can be calculated. In turn, changes in expenditure on fuel and salaries can be derived per sector. Expenditure on energy or wages is then translated back to job-years (dividing by a national average wage of R20 000 per annum) or into GJ of fuel consumed (dividing by an average tariff by sector). In order to manipulate this data for input into MARKAL, changes are derived in expenditure on wages and on fuel (by consuming sectors) as a function of a unit of energy saved by energy efficiency measures. To determine investment in new coal-fired or wind generation, I calculate the effect per unit of capacity added (and in the case of wind power, savings in coal used for electricity generation).

To save one unit of energy by implementing an energy efficiency measure, the following changes need to be accounted for (and estimated for each measure described earlier):

- increased savings in industry (*MFG in the SAM above*) due to reduced fuel bills over the life of the measure;
- decreased expenditure on fuel supply (*ELC for electricity*, *MIN for coal*[208]) to industry over the life of the measure. (In the standard formulation of MARKAL, the direct effect of reduced electricity generation, as well coal supply to industry and as electricity production are captured. However, indirect effects of fuel purchases as well as expenditure on salaries are not. These are calculated using the IO model.);
- expenditure from industry (*MFG*)(equity) and from the financial sector (*FIN*)(debt) to purchase and implement the energy efficiency measure (50% debt equity contribution is assumed (Spalding-Flecher et al. (2004)). the cost of debt is assumed to be 12%) ;
- the quantity of money spent on implementation in construction (*CON*) that is seen by the South African economy is in turn dependant on the 'local content' of that measure;
- debt repayments from industry (*MFG*) to the financial (*FIN*) sector (a five year loan is assumed);
- the relative cost of a measure with a high local content compared to that with a lower local content is considered (the ratio of the cost of high local to low local content is referred to as a 'Cost Ratio' or CR.).

To invest in a new power station, the following changes need to be accounted for:

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[208] Savings in oil use are limited in this analysis, but would accrue to refining included in MFG.

- increased payment to the electricity (*ELEC*) sector from industry (*MFG above*) and other consuming sectors for the requirement of new generating capacity over the life of the power station. (Note that considering this as a "marginal increase" is an important enabling assumption[209]);
- changes in expenditure on fuel supply (*MIN for coal*[210]) to the electricity (*ELEC*) sector are captured directly in a standard MARKAL formulation. Direct and indirect changes in expenditure on wages are calculated using the IO model. (Indirect changes in electricity demand are calculated resulting of the construction of new coal power plants. Only construction and investment are assumed to cause indirect changes. Operation and maintenance costs for new plant are assumed to be similar to existing plant. Conveniently, the SAM which is used represents a time when little construction in the power sector was taking place. Little capital recovery is included in the tariff (represented by payments to ELEC from other sectors). At that time the capital costs were amortized. However, fuel, operating and maintenance costs were included (NER (2004)). Details of the assumptions regarding construction follow.
- retained earnings of the electricity supply industry (*ELEC*)(equity) and loans from the financial sector (*FIN*)(debt) are used to purchase and implement the energy efficiency measure. A twenty year economic life is assumed, with 60% of the investment being

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[209] Note that the payment for electricity from new investment is explicitly separate from payment for electricity from existing power stations on the grid. This done is for two reasons. First, it removes the necessity for recalculating the entire SAM used for deriving the multipliers. The new electricity sold at a higher price is explicitly modeled as a "shock" to the system, with all of its associated direct and indirect effects. This is a valid approach for the South African system where electricity pricing is based on average costs of production - the sum of the cost of production of new as well as existing power stations. The effect of considering the existing tariff as expressed in the recent SAM plus a marginal increase for the new power station is equivalent to considering an average increase in tariff for our calculations. Recall also that there is no attempt to model behavior, but rather determine an optimal economic outcome. If I were attempting to model behavior, then it would be necessary to simulate the effects of an average tariff as new capacity is added. The second reason is that, by so doing, we can decouple the complication of having to work out future expenditure on fuel which would otherwise be a function of the load factor of the plant, which (with the exception of wind and oil (see next footnote)) is calculated by MARKAL. Coal prices will not change significantly (NER (2004)), and they are currently included in the average cost of electricity. The load factor for wind is entered exogenously based on the available (non-dispatchable) resource. This saving can be calculated outside of MARKAL.

[210] Note that oil-fired generators used to maintain the reserve margin should run at extremely low load factors, and therefore fuel consumption is negligible.

funded from debt at a cost of 6% (to ESKOM). The cost of equity is taken as 16%. Taken together, there is an average return from the tariff of 10% (NER (2004));

- the proportion of the money spent on implementation in construction (*CON*) that initially accrues to the South African economy is in turn dependant on the 'local content' of that measure;
- debt repayments from electricity supply industry (*ELEC*) to the financial (*FIN*) sector over twenty years;
- the relative cost of a measure with a high local content compared to that with a lower local content is considered (the ratio of the cost of high local to low local content is referred to as a 'Cost Ratio' or CR).

Once these elements are accounted for, multipliers for fuel or salary expenditure are calculated for an investment in a unit of new power station capacity or for saving a unit of energy by means of an efficiency measure. These are then translated into changes in average fuel consumption by sector or changes in employment (as estimated job years) throughout the economy. Fuel consumption is estimated by multiplying changes in fuel expenditure per sector by the fuel tariff for that sector, while job years are calculated by dividing salary expenditure changes by an average annual wage. Final multipliers are now derived which determine indirect changes in fuel consumption and total changes in employment. These multipliers show three distinct phases for each measure: construction, operation while repaying debt, and operation post debt repayment. The differences in expenditures over the life of the measure are illustrated in the solid bars of figure 8.1.

Note this approach could be refined by including more detail. It should also be noted that the IO approach is based on average values and approximations while new operations take place at the margin (though some attempt to include marginal representation has been made). Also, although the measures described here are likely not to change into the future, the structure of the economy will. This is not reflected in the SAM used, which is a historical snapshot, as is the IO model derived. Accounting for this is outside the scope of this study, however, a methodology to incorporate this has been proposed by Jeftha (2003).

Entry in MARKAL

Aspects of the IO model are integrated into the MARKAL model by adding selected multipliers. Job creation multipliers are added to track job creation changes, while indirect fuel consumption changes are included by adding their multipliers. The latter are then linked to total fuel production and consumption.

For multiplier entry into MARKAL, only two phases, rather than the three mentioned earlier can be adequately represented. These are for the construction phase and for the period of operation with repayments. Therefore, inputs are averaged and simplified to those shown in figure 8.1 (this is due to constraints in the MARKAL formulation). The transparent bars indicate the simplified job creation multipliers included in MARKAL, while the solid bars show the results from the actual IO modelling. Adding these allow the changes in job creation to calculated over the model run period, much as emissions might be tracked (in the standard formulation of a MARKAL model).

Note: This is for thermal energy efficiency saving with both a low payback and high local content. Using the IO model approach, this figure accounts for both the loss in revenue to coal mining and the effective gain in revenue from the money saved to industry.

Figure 8.1: Jobs created per unit of coal saved

Fuel consumption multipliers are also included in the MARKAL model[211]. This is done to estimate indirect changes in fuel consumption and to track their effects on related parameters. These indirect effects are leakage, or “rebound”, effects. Essentially, GHG mitigation measures that reduce the effective cost of energy may encourage increased consumption and thereby negate some of the projected savings.

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[211] Changes in fuel consumption are achieved by adding dummy import and export processes into the MARKAL model, whose activity are set to vary according to implementation of new energy efficiency measures or power stations.

From the IO analysis, rebound effects are shown to be limited, but important. In figure 8.2 the indirect effects are shown by sector for an electricity efficiency measure. By entering them into this model I account for increases (or decreases in the case of relatively costly wind generation) in fuel consumption and production. This allows the estimation of indirect changes in costs and emissions since energy production requirements only change slightly while emissions are a function of the production and consumption of energy which are tracked.

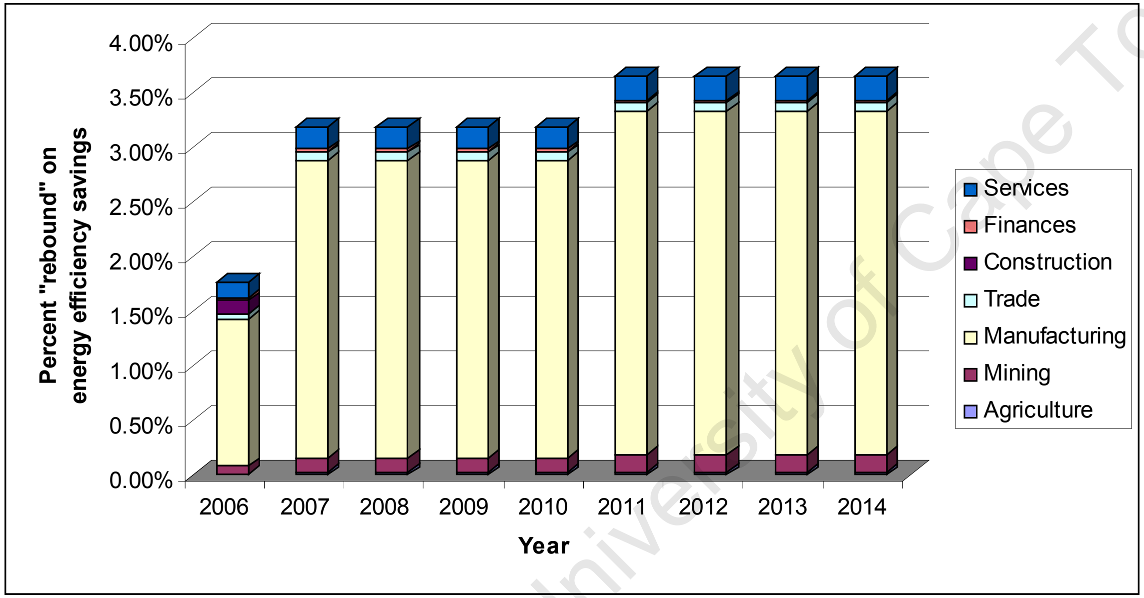

Figure 8.2: Rebound effect per unit of electricity saved

This approach is novel, as it allows for cross-sector relations that would otherwise not be captured using standard approaches. In particular, it allows the inclusion of a form of price elasticity (i.e changes in electricity price are related to changes in demand for electricity, via various changes in activities captured in though the IO). In standard MARKAL, elasticities may be limited to a single sector (Loulou et al

(2004)). Variations over time which relate to changes in activity, such as during a construction phase and an operation phase, would not be included.

The energy systems model: Goal programming MARKAL with input output integration.

In order to consistently account for the attributes of the energy system and the role that energy interventions play in that system, the MARKAL energy model (ETSAP (2005)) is used. The application deviates from the standard formulation of MARKAL to incorporate rebound effects as well as to allow it to solve for multiple-criteria in order to meet development 'goals', as well as including cross-sector indirect effects. Normally, MARKAL's single goal is to minimize the cost of the system modeled. This single goal is akin to the economic notion of 'satisficing', and if mimicking behavior, of 'bounded rationality'.

The model is calibrated using detailed sector-by-sector demand projections (See Appendix to Chapter 3) and identify a limited set of power investments based on recent electricity sector planning (NER (2004)). Based on this, it is assumed that open-cycle gas peaking plant and coal-fired power station investments will be used to meet increasing electricity demand on a least cost basis[212]. Other energy supply investments are considered to increase in line with 'business as usual': oil demand being met by increasing crude refining capacity, and coal by local coal mining increases.

In order to calculate the attributes of the system, coefficients gathered from a variety of sources are used to relate energy use to the attribute considered. Gaseous emissions per unit of fuel burned are taken from IPCC (1996) and van Horen (1996a), water emissions data from van Horen (1996b), particulate emissions from Howells & de Villiers (1999), and indicators for the 'difficulty of implementation' from Howells & Laitner (2003). Job creation and the effects of indirect fuel consumption changes are calculated using the IO approach discussed earlier. I assume that fuel switching is limited over the scenario period (DME 2003a).

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[212] This may change if more expensive wind generation is chosen over other options due to optimization parameters.

The goal programming variation of MARKAL (GP-MARKAL) which is employed is described in Goldstein & Hobbs (2003). Goal programming, in its various incarnations, is a subset of multicriteria analysis (MCDA). The technique attempts to bring the solution as close as possible to the various goals of the analyst[213] (Lee (1972)). In GP-MARKAL, individual goals are weighted relative to each other. The form of goal programming employed here is 'non-preemptive'. The model is run with the goal to maximize (or minimize depending on the goal) the model attributes that constitute policy benefits to be derived from deploying energy efficiency. Similar analysis has been carried out to assess economic and environmental development and has been discussed both internationally (see, for example, Huang et al. (1995) and Greening and Bernow (2004)) and in South Africa (Howells & Solomon (2002) (Chapter 3); Howells and Laitner (2003) (Chapter 7)). This analysis differs from the latter for South Africa as it considers multiple objectives in a dynamic model while earlier studies considered either only single objectives subject to constraints in a dynamic model or compared the effects of discreet investments. It also includes detailed rebound effects.

Sector specific rebound effects are included by adopting a non-standard (Howells (2004b) and Figure 16 of appendix B.) model structure (see Sato et al. (2000) for an example of a standard structure). While changes in energy demands (and the resulting changes in attributes) have been accounted for in variations of MARKAL (such as MARKAL-MACRO and MARKAL-MICRO (Loulou et al. (2004)) this represents novel use of fuel demand multipliers in response to changes in the energy sector within the MARKAL reference energy system.

Scenarios

Five scenarios are developed. The first is a *reference* scenario which is used to measure the success of the multi-objective scenarios.[214] This scenario assumes that there is limited uptake of energy efficiency. It provides the benchmark against which the other scenarios are

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[213] These could be the goals of interested and affected parties.

[214] The solution space we investigate with the other four scenarios is between the inefficient frontier represented by the reference scenario. The reference scenario is based on business as usual practice. These scenarios are adapted from (Hughes et al (2002), DME (2003a) and Howells & Laitner (2003)), and described in some detail in Chapters 3 and 7.

compared. For employment purposes, direct jobs in the energy sector were considered. IEA (1996) indicated that approximately 30 000 people were directly employed in the electricity sector. It was assumed that even with efficiency gains this number would be non-declining.[215] If the total number of jobs in a scenario is higher than in the reference scenario, these are reported (as with emissions) as a percentage of the reference scenario value[216]. However, if both calculated indirect and direct jobs losses are lower than on average 30 000 job-years per year, then compared to the reference case the result will be a negative percentage.

A *least cost* scenario is presented that determines the lowest cost configuration of the energy efficiency measures.

An *industry goals* scenario develops the least cost scenario by addressing the *ease by which the energy efficiency measures can be adopted* .

The fourth scenario reflecting elements of *government goals* emphasizes job creation.

Finally an *extreme green* scenario is presented. This weights heavily the need for GHG mitigation at the expense of other economic imperatives. All scenarios are run for the period 2005 to 2020.

Table 8.4: Criteria weighting of the system relative to the reference scenario

Scenario	*Extreme green*	*Government goals*	*Industry goals*	*Least cost*
Criteria				
Jobs created	4%	15%	0%	0%
Carbon dioxide reduced	37%	0%	0%	0%
Water use reduction	9%	4%	2%	0%
Nitrogen oxide	6%	0%	0%	0%

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[215] This assumption in particular is worth increased study. Interestingly, policies have encouraged dispersed coal supply, thereby empowering new black owned businesses. However, this was done at a time of excess capacity in the fuel supply for power generation.

[216] Therefore, if there is a loss of 15 000 job years in one year, a value of 50% would be reported. If there were a loss of 45 000 jobs in a year, a value of -50% would be reported. If there were 30 000 job gains in a year, there would be a gain of 200%.

reduced				
Sulfur dioxide reduced	37%	0%	0%	0%
Ease of implementation	2%	5%	23%	0%
Cost minimized	5%	76%	75%	100%

These scenarios are used to investigate the role and effect of energy efficiency interventions. Of particular interest are GHG emission levels.

Results

By comparing the results of the scenario runs to the reference case, the effects of energy efficiency investments are quantified. These outcomes are shown in Table 8.4. It should be noted that CO_2 emissions are mitigated in all cases, though this is not an explicit goal in any but the extreme green scenario.

Table 8.4: Attributes of the system relative to the reference scenario

Scenario /attribute	*Jobs*[217]	*Carbon dioxide*	*Water*	*Nitrogen oxide*	*Sulphur dioxide*	*Cost*
Extreme green	-110%	83%	85%	78%	80%	144 %
Government goals	119%	93%	95%	89%	93%	99%
Industry goals	112%	93%	95%	90%	93%	99%
Least cost	103%	98%	98%	97%	97%	98%
Reference case	100%	100%	100%	100%	100%	100 %

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[217] It was assumed that the energy sector employed approximately 30 000 people. This was used in order to develop a reference against which to show economy wide changes by scenario.

An aim of analyzing several scenarios, all with different goals taking on different levels of importance, is to determine if any particular technology or set of technologies are chosen in all scenarios. If so, then these are probably low regret options and could form part of a robust 'development pathway'. (These scenarios may be interpreted as representing different views / scenarios of development.) The results of the various scenarios are discussed next. Note that these provide the sensitivity analysis needed to determine robust energy choices.

Interestingly, all scenarios, other than the extreme green scenario, show significant increases in jobs and a small reduction in the cost of supplying energy to the economy. Thus energy efficiency (EE) helps move the economy closer to its 'efficient frontier' discussed in the single objective study of chapter 3.

4. In the case of the *extreme green* scenario, high investments in non-economic, but more environmentally benign technologies, increase costs and cost the economy jobs.
5. The *government goals* scenario achieves the highest job creation effects by investing in high local content and relatively low cost energy efficiency measures, such as compressed air saving.
6. *Industry goals* also shows a marked, but slower, increase in job creation. Importantly, this is done at a lower cost to the economy than the *government goals* scenario. It extends the investment style of government goals, but at the expense of local manufacturers since the cheaper measures introduced involve lower local content. An aspect of this scenario is that the need to build a new power station is delayed by two years (also delaying electricity price increases).

In all cases there is an increase in investment in energy efficiency technologies, which are therefore an integral component of these views of development. Only in the extreme green case is wind chosen, displacing coal.

Conclusions

This chapter reports the development and application of a model that optimises the energy system of a developing country to meet goals of development. The modelling technique chosen is a partial equilibrium; energy systems model that accounts for various attributes of the energy and economic system of South Africa. Also integrated into this model are aspects of an economic I/O model. I use the GP-MARKAL framework, which allows one to minimize several attributes of the system. These are reported as 'development goals'. I examine a limited set of potential interventions to a business as usual energy future, their effect on the energy-economy and the role that they may play in different development scenarios. This analysis allows the specific investments required and their effects to be identified. The case study is limited and there is significant scope for its expansion, both in terms of application and improved data "granularity".

A key finding, however, is that certain energy investments reduce costs (improving productivity), improve the development indicators modeled and co-incidentally reduce emissions. Were these investments to be implemented for GHG reduction reasons they would, in effect, drive development. Clearly there is a role for technology transfer and a play-off exists between increased local content and potentially increasing costs.

Further, there are investment options which cost the economy. In our simplified case, this happens with large investments in wind generated electricity. In such cases there is merit in the development of markets (such as CO_2 trading) to minimize the collective costs.

The conclusions have a potentially profound effect in terms of the international climate change debate. The pro-mitigation lobby's anecdotal arguments for clean development are transformed into quantifiable terms. The implication is that developing countries (in the short-to-medium term) could focus their mitigation measures which also meeting urgent development imperatives

Appendix

The following appendix, taken from Goldstein & Hobbs (2003), summarises the MARKAL GP formulation. The MARKAL model adapted to a GP construct would have a formulation as described here:

Minimize

$$\sum_{t\geq gpstart, e\in GPENV}\left[(1/cap_{e,t}) * escal_e * (ewt_e^- d_{1e,t}^- + ewt_e^+ d_{1e,t}^+)\right] +$$

$$\sum_{t\geq gpstart}\left[(1/least\_cost_e) * cscal * (cwt^- d_{2t}^- + cwt^+ d_{2t}^+)\right]$$

(1)[218]

subject to:

$$\sum_{i,t} c_{i,t}x_{i,t} = total\,system\,cost$$

(2)

$$\sum_{i} a_{i,t}x_{i,t} \leq b_t$$

for all *i* (3)

$$\sum_{e\in GPENV,\, f\in F} e_{e,f}\,x_{f,t} + d_{1e,t}^- - d_{1e,t}^+ = cap_{e,t} * (1 - cappct_e)$$

(4)[219]

$$\sum_{i} c_{i,t}x_{i,t} + d_{2t}^- - d_{2t}^+ = least\_cost_t$$

(5)[220]

$$x_i, b_i, d_1^-, d_1^+, d_2^-, d_2^+ \geq 0$$

(6)

where

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[218] EQ_GPOBJ in the MARKAL-GP model code.

[219] The *cap* parameter and constraint is provided/generated for each period. The value for *cap* in each period should be taken from the row in ANSWER Table T27ENV = EMISSION.L of the "reference" or emission constrained run to which the GP runs are to be compared. The constraint is built for each period beginning from the *gpstart* period. It is important that *cap* and *least_cost* be simultaneously infeasible for the model, otherwise the resulting solution can be an inferior (dominated) point. The *cappct* parameter, which is under user control, enables this by forcing the emission goal to be reduced to a level lower than that achieved in the reference case. (EQ_GPCAP in the MARKAL-GP model code.)

[220] The *least_cost* parameter and constraint is provided/generated for each period. The value for *least_cost* in each period should be taken from the total discounted system cost row in ANSWER Table T02 = D.TOTCOSTS of the "reference" or emission constrained run to which the GP runs are to be compared. The constraint is built for each period beginning from the *gpstart* period. (EQ_GPCOST in the MARKAL-GP model code.)

MARKAL components:

$c_{i,t} =$ cost associated with each component or technology, i, of the energy system for time period t

$a_{i,t} =$ matrix coefficient associated with each variable and row in the LP representation of the energy system

$b_t =$ the right-hand-side of the various equations of the LP for period t.

$e_{e,f} =$ emission coefficient associated with the technologies/fuel types in the energy system

$x_{i,t} =$ variables associated with each component of the energy system

$F =$ all energy system activities associated with a GPENV emission

GP Parameters[221]:

$GPENV =$ list of emission indicators subject to evaluation $[GPENV]$
$escal_{\mathrm{e}} =$ scaling factor for each emission (default $=1$) $[GPEMSCL]$
$cscal =$ scaling factor for total cost (default $=1$) $[GPCSTSCL]$
$ewt_{\mathrm{e}} =$ weighting factor, above/below, for each emission (default $=1$) $[GPEMWTA/B]$
$cwt =$ weighting factor, above/below, for total cost (default $=1$) $[GPCSTWTA/B]$
$cap_{\mathrm{e,t}} =$ emission levels from the reference case $[GP\_CAP]$
$cappct_{\mathrm{e}} =$ fraction by which to reduce cap_{e} $[GPEMPCT]$
$least\_cost_{\mathrm{t}} =$ cost of least cost solution from the reference case $[GP\_LC]$
$gpstart =$ year from which the GP emissions & cost limits are applied $[GPSTART]$

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[221] The [input] value at the right of each parameter indicates the name of the input parameter to be provided by the analyst, or generated from the reference scenario.

Chapter 9 Beyond the Baseline: Kyoto, mitigation and development

In this, the final substantive chapter[222] certain lessons learned from Chapters 3, 7 and 8 are applied: namely that there are large emissions reductions to be had from undertaking activities that should be undertaken anyway. That is, they can be either or both *financially and privately* rational or they are *socially* rational. Where these local benefits are compelling it plausible that some of these would be undertaken irrespective. For others however, inertia, or a gap between private and public benefits may delay take-up. With this in mind it is now asked whether the Clean Development Mechanism (CDM) set up under Kyoto will markedly help South Africa reduce carbon dioxide emissions[223].

Introduction

In many countries of the world, economic development is proceeding along paths that are not 'climate-friendly'. This chapter investigates the barriers to a more climate-friendly development path in South Africa and assesses the climate and other socio economic benefits that could accrue from a change in the country's current strategy. . Using the analysis of the previous chapter, it is shown that significant emissions could be saved while doing little harm to, or even encouraging, economic development. It is impossible to assert that these savings could be achieved under current emissions mitigation mechanisms, and therefore, they may not be realized until the cost of adaptation is higher than the cost of mitigation.

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[222] This chapter shares material with two earlier papers; Howells, M. I., House, J., and Laitner, J. (2005a). Beyond the Baseline – Large Scale Climate Friendly Development. International Energy Workshop Kyoto; and Winkler, H., Howells, M., and Baumert K. (2007). Sustainable development policies and measures: institutional issues and electrical efficiency in South Africa, Climate Policy, Volume 7, Number 3, 2007, 212–229

[223] While intentionally provocative, this criticism of this analysis on CDM is clearly limited. There is no attempt to argue that CDM is fundamentally flawed across the board. I argue only from the case of industrial energy efficiency in South Africa. Further there is no argument that CDM projects by nature do not contribute to national development goals. Indeed they have to confirm to nationally determined "sustainable development" criteria.

The goal of climate action in developing countries should be simple: to significantly lower the trajectories of greenhouse gas emissions growth. While an eventual aim is to reduce emissions in absolute terms, a constraint is that the policies used should promote development rather than hinder it. To date, however, the maze of political hurdles has defeated all multinational efforts.

Under the Kyoto Protocol, the international community adopted the Clean Development Mechanism (CDM), which allows developed countries to invest in greenhouse gas mitigating projects in developing countries that would not have otherwise gone ahead – in other words, projects that are 'additional.' This requirement precludes investments and policies which could significantly reduce emissions but could have gone ahead under different circumstances for other reasons. However, though argued to be in its infancy (Winkler et al. (2007)), progress (other than political) has been poor (Wara (2006)).

This chapter investigates industrial energy efficiency and identifies a development pathway that reduces emissions, but is arguably not additional (recent work by Winkler et al (2007) shows the changes required to make it so). As shown in the previous chapter, this policy would both reduce emissions and encourage development. Despite being an effective policy, however, the definition of additionality may mean that it may not go ahead under CDM[224].

The challenge

A major challenge in reducing greenhouse emissions in developing countries is showing that such reduction can be achieved simultaneously with development. Mitigation need not hinder social development. Historically, developed economies have moved through phases of economic activity that were necessarily energy and CO_2 emissions intensive. Many developing countries are approaching or undergoing such industrialisation, and view the prospect of emissions reduction as a threat to their economic evolution.

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[224] The idea is that 'additional' projects should be those that are worth-while but will not go ahead without support. If a project would not happen without the support, then ipso-facto it must be additional. However, while the notion is elegant and sound, it is clearly difficult to argue what constitutes a baseline and what is additional - or not - in many cases, including this.

South Africa presents a good example of the challenge posed by attempts to simultaneously reduce greenhouse gases and promote economic growth. The country's development needs are stark and industrial competitiveness – which is supported by the supply of cheap coal – is of the utmost importance in its open economy. To South African politicians, global emissions reduction policies that threaten the country's competitiveness or cause job losses in heavy industry or fuel supply are an anathema. This attitude is not uncommon. As indicated by Aldy and Frankel (2004), this has been a key objection to developing countries taking on GHG mitigation targets: "First, they believe it would be unfair for them to sacrifice their economic development for a problem created by the industrialized countries. The developing countries have contributed only about 20 percent of the carbon dioxide that has accumulated in the atmosphere from industrial activity over the past 150 years. Second, they have more pressing development concerns and, in contrast to richer industrialized countries, they do not have the ability to pay for emissions abatement. Developing country governments consider the raising of their people's economic standard of living the number one priority."

In many ways South Africa is an extreme case because of its high energy intensity relative to its economic development. However, unless emissions reductions on a relatively large scale can be achieved in a development-friendly way, it will prove difficult for any developing country to agree to take on an emissions target. Given that developing countries are likely to account for over 50% of emissions by 2020 (IPCC 2000), they must be included in any serious effort to meet the challenge posed by climate change. By some measures, China is already in the process of overtaking the USA as the worlds largest emitter of GHGs.

The opportunity

Improved energy efficiency has the potential to improve economic competitiveness while significantly reducing emissions per unit of economic output. Even in the absence of climate-specific policies, such improvements could have been implemented if their effects were understood and if the institutional capacity existed to carry them out. However, for various reasons this has not happened. Key obstacles identified by the Department of Minerals and Energy (DME 2004a pp16-24) are listed below:

- *Energy Pricing*. Current South African electricity pricing is not based on ESKOM's marginal[225] generation costs, but rather on average costs. This results in a new electricity producer being paid more to produce an extra unit of electricity than the single consumer would save by reducing a unit of consumption (i.e. were one consumer to reduce his electricity consumption, the reduction in tariff would be shared amongst all consumers – diminishing that consumers individual incentive). (Having said this, however, as indicated in Chapter 7, many Energy Efficiency measures have low payback periods, even with current prices.) [226]
- *Lack of knowledge and understanding of energy efficiency*. Ignorance may mean that opportunities to improve energy efficiency are overlooked by industry and other consumers who are unaware that they exist.
- *Institutional barriers and resistance to change*. Institutional barriers often stem from a fear that outsiders will identify previously overlooked opportunities, thereby uncovering apparent incompetence. There is also a frequently encountered misconception, particularly within industry, that energy efficiency will disrupt production processes and that changes should not be made unless absolutely necessary.
- *Lack of investment confidence.* Achieving optimal energy performance may require the installation of costly imported plant and equipment. Investment in such long-term projects is vulnerable to economic uncertainty, in particular regarding exchange rate fluctuations.
- *The practice of 'Bounded Rationality'*. The concept is related to H. Simon's notion of "satisficing" (Simon (1982)). Decision making with limited management resources requires the use of imperfect, or incomplete, information and less than fully rational procedures.

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[225] The national energy regulator determines the tariff. This is based on the average cost of electricity generation from the national stock of electricity generators. In this context, were electricity to be priced on the margin at any given time, the tariff would be based on the cost of generating electricity from the most expensive power plant running to produce electricity at that time.

[226] It should be noted, that moves are afoot to increase the price of electricity to cover the cost of new capital investment requirements. (That is simulated in this analysis.) However, the price of electricity will increase on average enough to recover the capital cost of the new power stations. This price will not increase to the marginal price of generating electricity from the most expensive new plant (at the time it is needed).

> This is significant as the majority of energy consumers currently have imperfect information regarding the range and performance of energy efficient products. This fact inevitably results in poor decision-making when purchasing goods or specifying equipment.

Effective government policy on energy efficiency has been limited, with an historical focus on securing the supply of energy (Eberhard & van Horen (1995) and Dutkiewicz (1994)). A new policy designed to address these barriers has been formulated: the specific instruments adopted are will be discussed (under the "Policies" section of this chapter). This case study looks at the implications of an effective energy efficiency policy in South Africa. It focuses specifically on electricity, which holds a key place in the economic mix because it affects employment both directly (in the power generation sector) and indirectly (from the competitive advantage low-cost electricity provides). Interestingly, under the Clean Development Mechanism (CDM), it can be argued that if non-financial barriers exist, these may result any Greenhouse Gas (GHG) savings in this environment being additional. This can no longer be clearly argued in the South African case, as specific policy has been developed to overcome these barriers. It remains to be seen if it does, or how effective it will be. It may not be very effective, it may be effective, but it can not be clearly argued as additional. Thus in this situation of uncertainty, the Clean Development Mechanism (CDM) is of little help to encourage large scale savings.

The South African government plans to embark on an ambitious energy efficiency program motivated by a concern for the three dimensions of sustainable development: economic, social and environmental sustainability. (DME 2004a) The strategy is to pursue energy efficiency not simply as a goal in its own right, but because it contributes to major energy policy objectives (DME (1998) (White Paper on Energy Policy). Using the model of the previous chapter, this chapter considers various environmental, social and economic effects of meeting government energy efficiency targets and compares them to a reference case scenario.

The extent to which the objectives are met depends considerably on the policy specifics and the vigor of its implementation. At present the government has neither allocated the necessary funds or institutional capacity to implement the policy.

The Department of Minerals & Energy (DME) recently published a 'draft energy efficiency strategy'. The strategy sets its goal as a 12% improvement in energy efficiency relative to consumption by 2014 (DME 2004a). The rationale behind the target is that increased energy efficiency will help the country meet a series of development goals. Presently, the emphasis is on national rather than global goals (such as GHG mitigation), but according to the draft strategy carbon funding should be taken advantage of when it can be used to encourage energy efficiency. This underscores the need for GHG mitigation regimes to be consistent with development goals if emerging nations are going to be engaged (Heller & Shukla 2003). The goals South Africa hopes to meet through the adoption of energy efficiency measures can be grouped according to the following sustainable development themes: social, environmental and economic. Specific goals are reported in table 9.1.

Analysis

Previous work has taken estimates of the energy savings derived from historical evaluation of other national energy efficiency policies and adapted the results to South Africa (Hughes et al. (2003)). Using the model developed in the previous chapter, we apply it to this target to quantify the effects in terms of attributes (other than fuel saving) associated with the DME's stated development goals, as specified in Table 9.1. In the previous chapter the model was programmed to meet these goals. In this chapter the same model is used to calculate the development attributes associated with meeting the national energy efficiency target.

Table 9.1: Goals to be met by energy efficiency (DME 2004a)

Goals	*Metric / proxy for this goal in the analysis here*

Social sustainability Goal 1: Improve the health of the nation Goal 2: Job creation. Goal 3: Alleviate energy poverty	Goal 1: Tons of sulphur dioxide, nitrogen oxides and total suspended particulates Goal 2: Thousands of jobs created Goal 3: NA
Environmental sustainability Goal 4: Reduce environmental pollution Goal 5: Reduce CO_2 emissions	Goal 4: Tons of sulphur dioxide, nitrogen oxides and total suspended particulates And specific water use Goal 5: Tons of CO_2 emitted and abatement cost (R / t CO_2)
Economic sustainability Goal 6: Improve industrial competitiveness Goal 7: Enhance energy security Goal 8: Defer the necessity for additional power generation capacity	Goal 6: Cost of energy supply in millions of South African Rands Goal 7: Level of energy imports in rand and per unit of energy[227] Goal 8: Power station investment timing expressed as MW of supply avoided

The model is described in the previous chapter. It is used to quantify two scenarios: the first is a reference scenario reflecting the continuation of current development trends, the second is an electrical energy efficiency policy scenario called the 'efficiency scenario'. The difference between the two shows the potential impacts of energy efficiency on local sustainable development and on emission reductions. The model uses the MARKAL energy model generator[228]. A description of the model is contained in Howells & Laitner (2005) and in the previous chapter. This model incorporates limited macro-economic[229] effects such as economy wide employment and rebound effects,

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[227] This result is, however, not reported as we consider only the displacement of locally mined coal, which is used to generate the electricity saved. Nor is this policy likely to increase volumes of electricity exported as a result of reduced local demand, seeing that regional demand is limited.

[228] ETSAP (Energy Technology Systems Analysis Program). 2005. www.etsap.org

[229] These are incorporated from an input-output analysis (see also Spalding Flecher et al. (2004)). The interventions considered are based on limited technological changes at the margin of relatively intensive industry. In this instance, one is not considering, and cannot consider changes in the structure of the economy as mitigation options.

which are unusual[230] in standard MARKAL models. This is done by considering the effect that improved efficiency has on economic activity[231]. The increase in economic activity results in "direct" and an 'indirect' increase in fuel consumption (and therefore emissions). Increased fuel usage due to lower fuel costs is known as the 'rebound effect'[232]. While emissions are reduced, there is a rebound in emissions due to the positive economics of the measure. These emissions are generally less than 5% of the direct emissions saving, assuming that the structure of the economy does not change significantly (Howells In Press). Using the same IO approach, the effects on changes on employment are estimated.

The model was calibrated using detailed sector-by-sector demand projections (see Appendix to Chapter 3), emissions and economic data[233], and by identifying a limited set of power investments based on recent electricity sector planning (NER (2004)).

The **reference scenario** describes 'business as usual', without the energy efficiency policies described in the DME's draft energy efficiency strategy and summarised in chapter 8. It uses assumptions of electricity demand growth taken from the recent National Integrated Resource Plan (NER (2004)) of the National Electricity Regulator. These assumptions are consistent with the previous Integrated Energy Planning exercises of the Department of Minerals and Energy (DME (2003a))[234].

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[230] See Sato et al. (2000) for an example of a standard MARKAL generated model.

[231] There are two effects considered: the first is a general lowering of the cost of industry's energy bill and the second is the effects associated with implementing the measure.

[232] There are several possible reasons for the rebound. These can include: (1) Increases in production due to energy bills in consuming sectors (it is assumed that this saving could be translated into increase final demand); (2) Changes in indirect requirements due changes in investments in energy efficient and power generating technologies; (3) Changes in consumer spending due to changes in wages (associated with changes in economic activity). The latter is not included in this analysis.

[233] Gaseous emissions per unit of fuel consumed are taken from IPCC (1996) and van Horen (1996a), water emissions data from van Horen (1996b), particulate emissions from Howells & de Villiers (1999), and indicators for the 'difficulty of implementation' from Howells & Laitner (2003), which is derived from Kenny et al. (2000 a, b, c) and van Es et al. (2002).

[234] The 'primary planning assumptions' are summarised as follows:

- A net discount rate of 10% is assumed
- An average medium term economic growth rate of 2.8% is expected

The **efficiency scenario** assumes the successful adoption of the policies listed earlier. To realise the goals, in order to reach the 12% energy savings, specific technological measures are "forced" into the model to the required levels.

The specific measures considered are described by Howells & Laitner (2003) and Trikam (2001), Trikam et al (2003) and are listed in Table 2 below. Assumptions related to the characteristics of these options including aspects such as economics, job creation potential, rebound effects and cost differences associated with local content are described earlier in the thesis in the previous chapter.

The savings accruing from each measure to meet the efficiency scenario of the DME are adapted from Hughes et al (2003) as well as Trikam et al (2003) and are summarised in Table 9.2. Using attributes calculated from the model runs as proxies, the effects in terms of the development goals listed in Table 9.1 are compared to the base case.

Table 9.2: Savings by measure for the policy scenario Adapted from Hughes et al. (2003)

Technical energy efficiency saving measure							
Steam system	Other thermal measures	Efficient motors	VSDs	Efficient lighting	Compressed air saving	HVAC	Refrigeration
Percentage of industrial electricity saved to meet DME targets by 2014							
0.16%	1.26%	2.21%	2.21%	1.89%	3.16%	0.63%	0.47%

The efficiency scenario is now compared to the reference case and differences reported. Firstly, system costs, a measure of competitiveness. These decrease over the scenario period by about 8.3 billion South Africa Rand[235] at the 10% discounted rate used. This is due to two

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- A low penetration of DSM is expected and this is in line with current commitments
- The horizon of the scenarios is from 2005 to 2020
- Structural changes from energy intensive industry continue at historical rates.

[235] One dollar is equal to approximately six South African Rand.

factors. The first is fuel saving in industry itself and the second is the postponement and reduction of about 4GW of new investment in the power sector. (Power station investment in coal baseload plants is delayed by approximately three years.) Along with decreased electricity generation due to more efficient use of electricity, there are reductions in local emissions from the power sector. Recall rebound effects are accounted, and these offset savings only slightly. (As discussed in the previous chapter, less than 5% of savings are lost due to increased economic activity due to the efficiency scenario's negative cost nature.)

During 2014, when the energy efficiency target is reached, significant inroads have been made in terms of meeting the stated local development goals. Four hundred million fewer litres of water are used annually and there are reductions of 200 000 tons of SO_2, 23 000 tons of particulates and 80 000 tons of nitrogen oxides. About 40 000 new jobs are created.[236] For comparison, the entire coal mining industry in South Africa in 2000 employed approximately 51 000 people.

Table 9.3: Impacts of industrial energy efficiency on costs, pollutants and jobs

	2014	*% saving in total energy system*	*2020*	*% saving in total energy system*	*Units for absolute numbers*
Annual energy savings	76	3%	93	3%	PJ
Annual cost savings	4.1[237]	est. 8%	1.2	est. 2%	Billion Rand
Avoided investment in power stations	3600	est. 7%	4400	est. 7%	MW saved
Pollutants avoided					
Carbon dioxide	20	est. 4%	24	est. 5%	$MtCO_2$
Oxides of nitrogen	84	est. 5%	102	est. 5%	kt NOx

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[236] These are only for electricity consumption within industry and do not include the savings that would accrue to other fuel use and to mining. The economy wide (and all fuel) effects of these measures are hundreds of thousands of jobs created.

[237] Of which approximately three hundred million is attributed to a reduction in fuel costs.

Sulphur dioxide	204	est. 6%	252	est. 6%	kt SO_2
Total suspended particulates	23	est. 4%	28	est. 4%	kt TSP
Water savings	455	est. 5%	558	est. 5%	Gl (10^9 litres)
Additional jobs created	40 000		60 000		Jobs
Cost of abatement	-34[(238)]		-8		$ / tCO2-eq
Note: The 'cost of abatement' is a benefit, since efficiency measures have negative cost over the life of the intervention.					

Co-benefits of realizing these policy goals include significant greenhouse gas mitigation. Figure 9.1 shows CO_2 savings relative to the reference case as well as to additional jobs created.

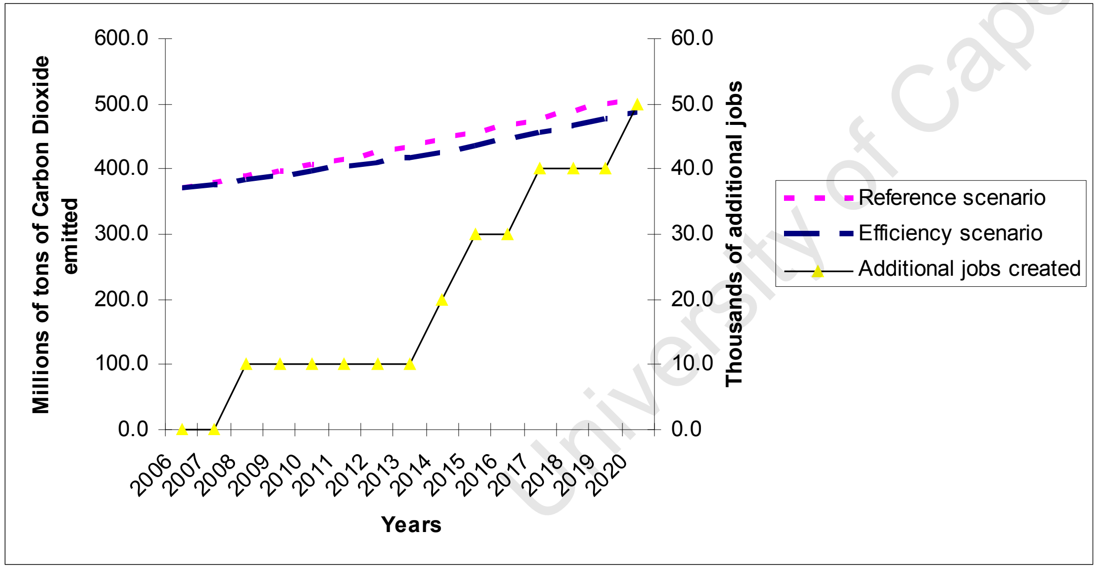

Figure 9.1: CO_2 savings by scenario and jobs created[239] through industrial electrical energy efficiency

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[238] Cost savings are great in this year due to the postponement of investment in new baseload power stations, which are expected to be invested in at this time.

[239] Note that these are extra jobs created that result from cash flows through the economy as a result of lowered energy costs and new investments in energy efficiency.

At present, a total 21 million tons of CO_2 are expected to be mitigated in South Africa via climate-motivated mechanisms such as CDM (DME 2005c). Importantly, these reductions involve net positive costs. In contrast, over the whole scenario period, there is a reduction of approximately 230 million tons of carbon dioxide at a negative cost per ton of CO_2. If all sectors and all energy carriers are considered, the total saving may be close to a billion[240] tons of CO_2 . This represents a change in the CO_2 development trajectory of the country that could not be achieved by project specific activities.

Policies

Even though these policies pay for themselves, some form of energy efficiency policy is required as its autonomous uptake has proven slow. The government cites several reasons for this (DME 2004a): the lack of information about energy efficiency costs and benefits, lack of investor confidence in related technologies and practices, as well as institutional barriers. The latter relates to a mismatch between key performance indicators and accounting for changes in energy bills. There are also market imperfections, in particular tariffs that do not reflect the marginal price of fuel supply (NER (2005) and NER (2004)).

Standard policy measures (described in detail in DME (2004a) being considered as part of the South African policy to meet the 12% target include:

- energy efficiency standards;
- appliance labeling;
- education, information and awareness;
- research and technology development;
- support of energy audits;

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[240] This is based on a loose estimate that nationally a reduction of about 25% of the national fuel bill could be mitigated (DME 2004a).

- monitoring and targeting;
- green accounting.

By definition, energy efficiency measures like those described above are not ‘additional’ in an economic sense because at some point in the future they begin to save money. While South Africa has the institutions and finances to support such policies, there are other arguably more urgent requirements for the government. Domestic resources are limited and needs are great. As such energy efficiency policies may not receive appropriate levels of funding and support despite the climate and development benefits they offer.

Potential international interventions and incentives

The use of international donor funding to support energy efficiency policy initiatives is common in developing countries. However, as yet, there is little incentive to be gained by donors for the emissions that might be mitigated as a result. The current regime for engaging developing countries on climate change – the Clean Development Mechanism (CDM) - offers developed countries no incentive that they can offer to persuade South Africa to adopt aggressive yet development-friendly energy efficiency policies. This is because it is impossible to determine the ‘additionality’ of emissions reductions created through policies that improve industrial productivity

However, there are mechanisms available to developed nations seeking incentives for low-carbon development paths outside of the CDM. One of these is subsidized loans for the capital costs of low-carbon infrastructure, efficient appliances or policy support. Another is the subsidized export of low- carbon energy and infrastructure technology via the export credit agencies of developed countries (U.S. Export-Import Bank, etc.). If emissions baselines are altered by foreign assistance, perhaps approximate savings may be used as ‘soft’ credits. These credits would have limited applications, but could be used for setting mitigation targets, or as a ‘safety valve’ to reduce the excessive pressure exerted when meeting mitigation targets.

While discussed only notionally, such real emissions reductions could encourage flexibility in the multinational process and accelerate technology transfer. The reductions would be more likely to encourage development in the host country than to retard it . However, if a pre-condition of climate change assistance to developing countries is that assistance must create discrete, identifiable emissions reductions, investments that fundamentally shift the emission baseline and lock-in lower carbon growth paths may not be realized. It is therefore necessary to consider new mechanisms or change existing ones.

Conclusion

This chapter used MARKAL modelling to demonstrate that greenhouse gas emissions can be reduced without retarding development. In particular, it demonstrated the merits of adopting a progressive energy efficiency strategy in South Africa.

While the Kyoto Protocol may have been '*a historic step forward in the world's efforts to combat a truly global threat.'* (Annan 2004), it has been indicated that it may miss important opportunities to reduce emissions and promote development. Indeed, the case study in this chapter indicated that current mechanisms such as CDM may encourage neither.

There are incentives suggested that could encourage the GHG mitigation. These incentives are currently outside of the CDM[241]. It is concluded that it is necessary to urgently review the CDM or to develop new mechanisms to accommodate such non-additional, large scale, development-friendly mitigation measures.

Appendix

In order to estimate economy wide effect of employment as well as changes in electricity needs, an Input-Output approximation was used. The approach was based on Spalding-Fecher et al. (2004), which considered energy efficiency investments. Their approach is expanded to include investments in new coal fired power stations. The expanded approach is used to calculate economy wide requirements for labor and

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[241] From a donor or developing country standpoint, they may act to encourage exports and increase flexibility in emissions targets.

electricity, with investments in energy efficient measures in industry as well as new power stations. The appendix to this chapter summarizes these economy wide changes following a change in sector output in terms of income (wage) and electricity multipliers as well as economy wide changes in output following the new investments.

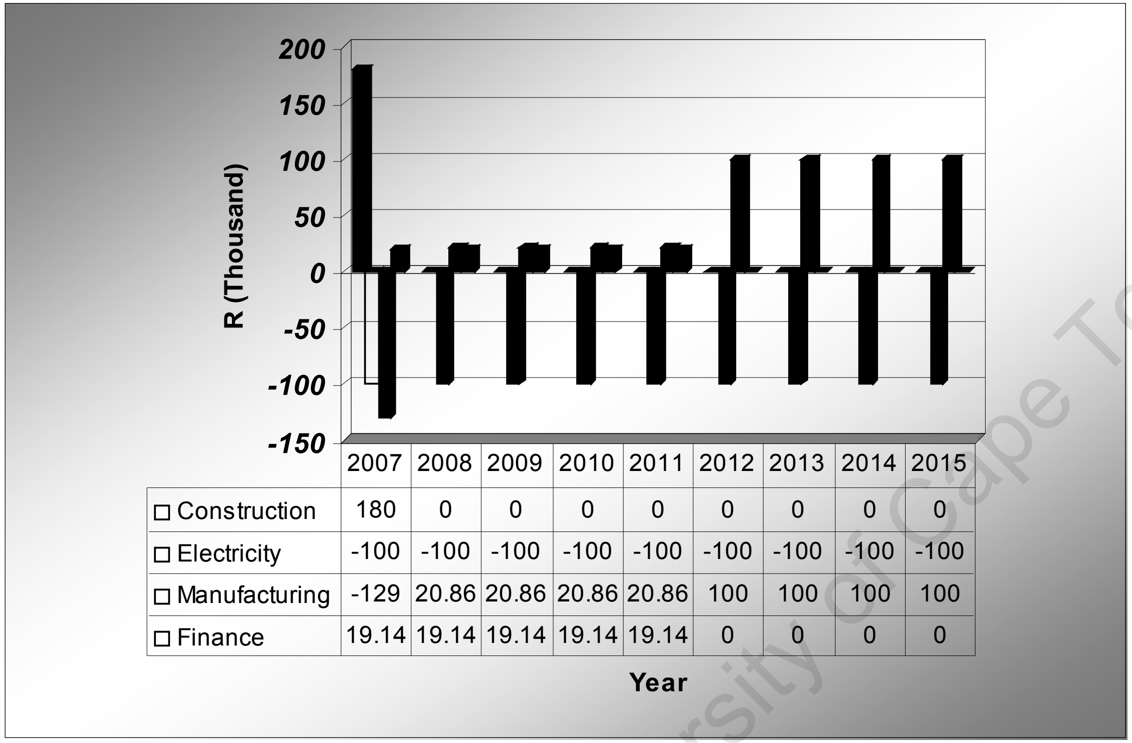
The multipliers (GWhrs and jobs per million rand) for an increase in sector output are summarized in the table below sector by sector (a more detailed description of how the multipliers were calculated from the national social accounting matrix can be found in Spalding Flecher et al. (2004)). By combining these with changes in required output per sector, changes in electricity and job year needs can be calculated.

Table 9.4 Economy wide Job years and GWhrs required per million rand of sector output

Sector	**Economy wide Job years per million R**	**Economy wide GWhrs per million R**
Agriculture	14	1.1
Mining	21	4.8
Manufacturing	19	2.5
Electricity	16	
Trade	27	1.2
Construction	25	1.5
Finances	48	1.0
Services	19	1.9

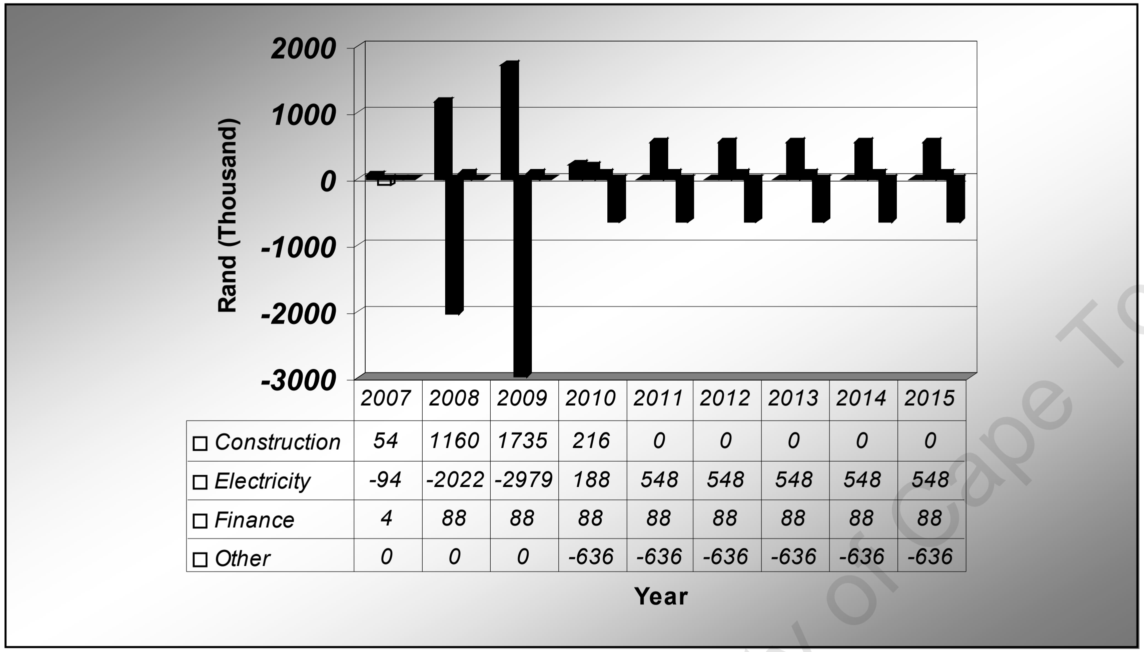
Income and electricity multipliers were calculated as a function of changes in income in the energy system from a "business as usual" pattern which characterize the SAM used. (During this period South African electricity prices were mostly based on running costs at a time when excess capacity reduced the need for new investments in generation capacity.)

New power station investment and industrial energy efficiency options are associated with changes in output from several sectors. Expenditure patterns change over time: initially negative as capital is expended and then recouped through energy savings or through increases in the electricity tariff. (For power plants, the tariff is based on allowing a fixed rate of return for new investments (NER (2004)). These expenditure changes are summarized for typical investments in the graphs below – for the saving of one GWhr (with a pay back of 3 years and 60% local content) or investment in one MW of coal capacity (with assumptions given in NER (2004) and assumed 60% local content). From these, summarized coefficients are derived and included in MARKAL. Note that changes in requirements in the electricity sector are calculated using MARKAL explicitly rather than using the multipliers from the IO model. Economy wide employment effects are captured by incorporating a 'job-year' co-efficient into the model.



	2007	2008	2009	2010	2011	2012	2013	2014	2015
□ Construction	180	0	0	0	0	0	0	0	0
□ Electricity	-100	-100	-100	-100	-100	-100	-100	-100	-100
□ Manufacturing	-129	20.86	20.86	20.86	20.86	100	100	100	100
□ Finance	19.14	19.14	19.14	19.14	19.14	0	0	0	0

Figure 9.2 Changes in income by sector for a saving of 1GWhr of electricity.



	2007	2008	2009	2010	2011	2012	2013	2014	2015
☐ Construction	54	1160	1735	216	0	0	0	0	0
☐ Electricity	-94	-2022	-2979	188	548	548	548	548	548
☐ Finance	4	88	88	88	88	88	88	88	88
☐ Other	0	0	0	-636	-636	-636	-636	-636	-636

Figure 9.3 Income by sector for 1MW of new coal-fired electricity plant

Using these coefficients in the MARKAL model, a “base case” is run and changes are compared to a run where energy efficiency investments are allowed. The differences are reported in terms of jobs created and emissions reduced.

Conclusion and recommendations

This thesis has analyzed a number of energy related issues ranging from macro-level analyses of greenhouse gas mitigation and of energy provision to micro-level analysis of energy use patterns in low rural communities. The methodologies used to analyze these issues ranged from the standard applications of existing tools, to novel hybrid approaches. The main theme has been to show how suitable modelling can not only warn of inefficiency in development policies, but also indicate technical scenarios of how such inefficiencies are best remedied.

The South African energy sector faces a number of challenges that are common to many developing country situations. These include the need to provide affordable energy to the poor and for the development of industry, while subject not only to budgetary constraints, but also to the restriction that the development induced should be environmentally friendly. Regarding the latter, reducing greenhouse gas emissions from a carbon dioxide intensive economy has been a focus of this thesis. Using a standard optimization approach, it is shown that by improving the thermodynamic (and economic) efficiency of energy supply and demand, future emissions and costs can be reduced. There are a number of reasons why this does not happen automatically. These include poor information on the part of energy users, who are unaware of the savings to be made, and ineffective policy implementation, such as failure to price electricity at its marginal cost[242].

Many rural communities in economically underdeveloped parts of the world rely on biomass fuels heavily - fuels whose fumes are estimated to cause over 2.5 million deaths per year. Again, mental inertia is not the sole problem: markets in these regions can also entrench fuel use patterns. Reasons include information limitations, poor policy, restrictive barter based local economies, monopoly power, land mismanagement and non-accounting for environmental damage. Where consumption patterns would otherwise be shifting away from traditional biomass fuels, these failures are likely to suppress that trend. In the case of fuel wood this biomass dependency may mean over-harvesting, that can also affect carbon sinks.

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[242] In other words, the price of electricity is not equal to the cost of production of the most expensive producing power plant at the time when electricity is dispatched.

In order to promote a switch from harmful household fuels, electricity to the poor is often subsidized. In South Africa, the government chose to supply 50kWh Free Basic Electricity (FBE) per month per household. This thesis shows that pre-existing alternatives would have cost less, with arguably larger benefits for the poor. By offering free electricity the state distorted the energy choices of poor households – encouraging them, for example, to cook with electricity when alternatives such as LPG would deliver a similar cooking service at a much lower cost to society, or more service for the same cost to society. This was shown using a simple novel calculation of the *"less-than-minimum"* cost of providing this electricity versus the real cost of an alternative. Similarly, it was shown that the national power system would be further strained were new users locked into using electricity for their cooking loads.

An optimization model was applied to data describing actual energy use in a low income rural village that was surveyed as part of this research process. This provided insights into certain of energy use pattern changes to reduce costs, increase electricity consumption and improve environmental performance. The survey used to develop and populate the model included questions covering the times of energy and appliance usage. A novel aspect of the model developed was that it accounted for the sometimes "concurrent" effect of supplying "space heating" while cooking, or water heating when burning solid fuels. It is postulated that ignoring this effect has lead to previous analyses overestimating post electrification electricity consumption during winter.

It was shown that, while a number of greenhouse gas mitigation options encourage socio-economic development in South Africa, there are also some that do not. A number of "mitigation options" assessed in various studies were combined. A multi-criteria decision analysis (MCDA) was used to determine those that may be in the national interest. In order to simulate possible development priorities, extreme hypothetical scenarios were adopted and possible changes to priorities over time. Uncertainty in the comparability of data gathered from different sources was also taken into account. This was particularly important, as external data sources were of varying qualities and based on differing assumptions.

A novel combination of an optimization model with an input-output model, allowed this research to approximate job-creation and some of the "ripple effects" that energy investments cause through the economy. It focused in particular on the extent to which decreasing the *effective* cost of energy to industry increases the demand for services by industry and the rest of the economy. The model showed the potential for certain apparently perverse outcomes. In particular that green-house gas mitigation measures that also reduce the *effective* unit cost of energy to industry may result in some indirect increases[243] in GHG emissions[244]. After incorporating these effects, the model was programmed to solve for multiple goals. It was shown that the goals of both industry and of government are consistent with environmentally beneficial outcomes. Where their stated objectives are prioritized, emissions can be reduced and jobs created concurrently. By contrast, an extremely strong green agenda could adversely affect both job creation and economic performance. If an economically efficient future is targeted, then emissions are reduced while jobs created. (It is not shown, however, if the emissions are reduced to a sustainable level, nor is a "sustainable level" quantitatively defined. Emissions are lowered, coal use is decreased as is the cost of energy to the economy. This implies that the energy system *tends* to one that could underpin more sustainable development. In a broad sense (used here) the tendency to sustainability means moving to non-declining (national) welfare, output, resource stock including the environment etc.)

In order to meet socio-economic goals, the South African government has embarked on an energy efficiency program. If it is realized, this program will result in increased job creation and reduce close to one thousand million tons of greenhouse gas (GHG) emissions. It is in the national interest, and emissions savings are both significant and co-incidental. This program may occur without any explicit greenhouse gas (GHG) mitigation funding and is therefore not strictly "additional". However, it is unclear whether this program will be realized. Unfortunately, if the program is not realized, the current United Nations "Clean Development Mechanism (CDM)" will provide no

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[243] It was shown, however, that while this "rebound" phenomena exists, its effect is small.

[244] Recall that increased energy use will normally result in increased GHG emissions in South Africa, as energy supply is dominated by coal.

international encouragement for this emissions reduction. If such significant emissions mitigation opportunities are going to be missed by developing countries, the "additionality" criterion of the CDM may call for some form of amending[245].

The thesis is based on a number of papers in which various modeling techniques are used. There are several common themes. One of these is the importance of thinking broadly and beyond immediate causes and effects. In economic jargon: of thinking in general rather than partial terms. An observation associated with increased integration of these analyses is of particular interest. As the analysis attempts greater integration, two inferences follow. The first is that there may be interventions or technology groups which have concurrent benefits to the environment, resources and welfare. As such these interventions or technology groups are more important than may be deduced from isolated partial analysis[246]. (The converse of which may also be true, that an important result in a partial analysis may be less so in a more integrated one.). Another interesting thought is simply that the system and its actors are integrated. Thus the wellbeing of the poor rural dweller is affected not only by national power supply investments, but also by international agreements to reduce GHG emissions. Similarly the choices of the poor, shaped as they are by circumstance and policy, also affect national energy supply investments as well as important environmental assets.

The thesis is important as it applies and further develops common analytical approaches in a novel manner. Further, these approaches are applied to real development challenges yielding non-trivial results. There is no attempt to suppose or argue that the models or results are complete and beyond criticism - far from it. They are based on commonly applied techniques which have faults that are well documented[247]

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[245] Note that this is not to say that the CDM is without merit. For many other projects for which additionality criteria could easily met may be effectively supported with positive development attributes. However, there are a large class of mitigation measures which may not be well supported with CDM in its current state.

[246] This thesis showed that industrial energy efficiency interventions and a less narrowly focused pro-poor energy policy held wide benefits. Those benefits would be missed if GHG mitigation, or increasing the quantity of electricity consumed by the poor, were the only criteria for analysis.

[247] A list of significant applications of approaches and certain limitations are given in chapter 2.

and are noted in this thesis. However, in each case these methodologies have been improved[248] and some of their limitations or faults are addressed. Where this was inappropriate, simple new approaches were developed[249].

These models have also been applied. The applications were specific[250] and showed significant improvement on previous attempts at analyzing those applications. These analyses provided specific policy insights ranging from the supply of energy to the poor, to industrial energy efficiency policy, and to international greenhouse gas mitigation regimes. The results of the case studies also yield insights into the integrated nature of sustainable development, and therefore the need for its analysis to be similarly integrated.

South Africa provides the specific application of the models. It is a country of extremes and therefore a useful analytical target. It has abundant cheap coal, inefficient industrial energy use, insufficient generation capacity, inequitable access to energy, misguided subsidy policy and (in rural areas) high dependence on traditional biomass and kerosene fuel. As a member of the global community it also needs to consider how best to engage in greenhouse gas (GHG) mitigation actions, while not compromising its development. Using the South African example, a summary of some key policy findings includes:

- The need for clear energy information databases including estimates of externality and health costs
- The need to implement an aggressive national industrial energy efficiency program
- The case for pricing electricity at its marginal cost, thereby rewarding measures that affect electricity demand
- The case for assisting rural energy users (in particular) by making available information relating to the health costs and benefits of various common fuels, such as wood, kerosene, LPG and electricity

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[248] In particular Chapters 6 and Chapters 8 improve aspects of (cost-benefit) optimization models. In chapter 6 the focus is on more accurate representation of low income rural households. In Chapter 8, aspects of an input-output model are integrated with an optimization model.

[249] In Chapter 5 a novel, simplified approach is developed for costing the (below minimum cost) of electricity generation at peak consumption times.

[250] The applications include the national energy system in Chapters 3, 8 and 9, energy supply to a rural village in Chapter 6 and to low income grid connected consumers in Chapter 5.

- The need for suppliers of energy appliances targeting low income rural consumers to undertake more appropriate needs analysis to match supply options. This is particularly the case where the suppliers are donors.
- Pro poor energy policy should target sustained service delivery[251] in the most cost effective and flexible manner. Households should preferably be given a choice of fuels if the state commits to fuel subsidies
- Energy policy decision making should be broadened to include other development aspects with simple and transparent decision making tools
- Greenhouse gas mitigation strategies that encourage development should be quantified and chosen on the basis of national development goals

Finally, it is important to emphasize that the strength of this work lies in insights related to the application or development of methodologies. Importantly, these methodologies are shown to be flexible and were designed to take into account changing circumstances. And certainly circumstances are changing! Here in lie challenges faced by both the policy maker and the modeler. One challenge relates to flexible policy development and another to using these tools. A good example of this is illustrated in Chapter 5. It looks at the provision of electricity at peak times and compares it to an alternative. The method was applied to conditions shortly prior to the time of publication (Howells et al 2006). At that time, the alternative considered could provide far more cooking utility at the same cost as using electricity. The policy recommendation was to provide the consumer with greater choice than backing a single option. (That is if an energy subsidy to poor households was committed to in the first place). The policy recommendation remains valid under changing circumstances. The alternative considered to motivate the policy recommendation – the provision of liquid petroleum gas (LPG) - may no longer be viable with

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[251] Rather than, for example, count the numbers of PV panels deployed. While noble, this does nothing to overcome issues related to breakage and non maintenance etc.

current record oil prices[252]. However, other options, such as biomass based gel fuels or low smoke briquettes, by the same logic may be new lower cost alternatives than sticking with electricity. The approach developed is also applicable to assessing new options and changing fuel prices. The recommendation was that a range of alternatives be available to the consumer. Had the policy maker moved from picking electricity to LPG for the subsidy purposes, perhaps the initial folly would have been followed by worse. While higher oil prices may simply reinforce some of the conclusions reached in chapters of this thesis – and indeed other modeling work - changes in technologies, prices and the appearance of new alternatives should not be "locked out" by well meant, but inflexible policy design.

A key challenge to the modeler is to continue developing flexible models, especially as contexts and insights change. The thesis is replete with specific suggestions and recommendations for possible improvements to models. None of the approaches used are beyond reproach. However, and herein lies the challenge for the modeler, at some point decisions must be made. The modelling should be as functionally appropriate as possible for the circumstance, policy assessment and the policy maker.

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[252] However, the current capacity shortage is forcing the production of electricity from oil in open cycle gas turbine (OCGT) plant. It is therefore likely that burning oil directly for cooking in the form of LPG is still cheaper than using electricity for cooking. But that is simply coincidence.

References

ACE (2006), ASEAN Center for Energy (ACE), AAECP Energy Policy and systems analysis project, http://www.epsapforum.com/pdf/3rdRegionalStudy_summary.pdf

Afrane-Okese, Y., (1998). Domestic Energy Use Database for Integrated Energy Planning. Cape Town, Energy and Development Research Centre, University of Cape Town.

Afrane-Okese, Y., (2000) (Personal communication). Energy and Development Research Centre, University of Cape Town.

Afrane-Okese, Y., (1999) "National Domestic Energy Use Database System as a Tool for Integrated Energy Planning." University of Cape Town, Energy and Development Research Centre.

Aldy, E., Barrett, S., and Stavins, R., 2003, Thirteen Plus One: A Comparison of Global Climate Policy Architectures Climate Policy, Vol. 3, No. 4 | pp. 373-397

Aldy, J., & Frankel, J., (2004), Designing a Regime of Emission Commitments for Developing Countries that is Cost-Effective and Equitable, G20 Leaders and Climate Change Conference, Council on Foreign Relations, http://belfercenter.ksg.harvard.edu/files/Aldy%20and%20Frankel%202004.pdf, September 20-21

Alfstad, T., (2004a). Meeting South African renewable energy targets, http://www.energycommunity.org/reCOMMEND/reCOMMEND2.pdf, COMMEND, December, Vol 1

Alfstad, T., (2004b). The application of energy models in the South. COMMEND.http://www.energycommunity.org/reCOMMEND/reCOMMEND2.pdff, COMMEND, December, Vol 1

Alfstad, T., (2005). Development of a least cost energy supply model for the SADC region. Energy Research Centre. Cape Town, University of Cape Town. MSc. Thesis, www.erc.uct.ac.za

Allen, J., and Douglas B., (1985) The Causes of Deforestation in Developing Countries Annals of the Association of American Geographers 75 (2) , 163–184

Annan, K., (2004). (Then) Secretary-General of the United Nations. Commenting on Russia's long-awaited ratification of the Kyoto Protocol, November

ARGONNE (2008), Energy and Power Evaluation Program (ENPEP-BALANCE) , http://www.dis.anl.gov/projects/Enpepwin.html#balance

Banuri, T., & Weyant, J. P. (2001). Setting the stage: Climate change and sustainable development. Climate Change 2001: Mitigation: Contribution of WG III to the Third Assessment Report of the IPCC. Intergovernmental Panel on Climate Change, Cambridge University Press: 74-114.

Barnes, D., (1988). Electric Power for Rural Growth: How Electricity Affects Rural Life in Developing Countries. Boulder, Westview Press.

Berrueta, V., Edwards, R., & Masera, O.R., (2008). “Energy performance of woodburning cookstoves in Michoacán, Mexico”, Renewable Energy, Volume 33, Issue 5, May 2008, Pages 859-870

Binswagner, M. (2001),’Technological Progress and Sustainable Development: What About the Rebound Effect?, Ecological Economics, 36 (1), 119-132

Blignaut J., & King A., (2002). The externality cost of coal combustion in South Africa. Conference Proceedings: Bridging the Economics/ Environment Divide, Forum for Economics and Environment, Pretoria, pp 71-85.

Bluffstone, R., (1998). “Reducing Degradation of Forests in Poor Countries When Permanent Solutions Elude Us: What Institutions Do We Really Have?” Environment and Development Economics 3 (3): 295-317.

Boland, L., (2003). The Foundations of Economic Method, Routledge, UK

Bramert, M., Runeborg, E., 2006, Meeting New Challenges - A Model of the Future Energy Demand in the South African Transport Sector, KTH Stockholm, Report nr: EKV/653

Bruce, N., Perez-Padilla, R., & Albalak, R. (2000). Indoor air pollution in developing countries: a major environmental and public health challenge for the new millennium, Bulletin of the World Health Organization 78: 1078-1092.

Cartwright, T., (1993). Modelling the World in a Spreadsheet: Environmental Simulation on a Microcomputer, John Hopkins University Press 1'st Edition.

CDM Watch (2004), Market failure: Why the Clean Development Mechanism won't promote clean development, www.cdmwatch.org.

Cowan, B., (2004), (Personal Communication). Head of Energy Poverty and Development Program, Energy Research Centre, University of Cape Town.

Cowan, B., & Mohlakoana, N. (2004a). Barriers to access modern fuels in low-income households: Khayelitsha (Cape Town) South Arica, Energy Research Centre, University of Cape Town.

Cowan, W., & Mohlakoana, N. (2004b). Income Related Aspects of Energy Use Workshop on Energy Transitions, www.pesd.stanford.edu/ events.august_2004_workshop_on_energy_transitions/ August, Cape Town.

Cowen, T., (1992). Public Goods and Market Failures: A Critical Examination, Transaction Publishers.

Criqui, P., Mima, S., and Viguier, L., (1999). Marginal abatement costs of CO2 emission reductions, geographical flexibility and concrete ceilings: an assessment using the Poles model. Energy Policy 27, pp. 585–601.

Criqui,, P., (1996). POLES 2.2. JOULE II Programme, European Commission DG XVII—Science Research Development, Bruxelles.

Cullenward, D., & Victor, D., 2006, The Dam Debate and its Discontents, Climatic Change, Vol. 75 no. 1-2, page(s) 81-86, March

Daly, H., (1990) Toward Some Operational Principles of Sustainable Development, Econological Economics 2(1):1-6

Dasgupta, P., 1996. The economics of the environment. Environment and Development Economics,1: 387-428.

Davidso,n O., & Winkler, H., 2003 South Africa's energy future: Visions, driving factors and sustainable development indicators, EDRC.

De Villiers, M., (2000). Greenhouse gas mitigation for the commercial sector. Cape Town, Energy and Development Research Centre.

De Villiers, M., and Dutkiewcs, R., (1994) Development of a draft manufacturing and mining energy effectiveness study for SA Part 2: Pretoria. Department of Mineral and Energy Affairs. Report no ED9210

De Villiers, M., & Matimbe, K., (2000). Greenhouse gas mitigation for the residential sector. Cape Town, Energy and Development Research Centre.

DEAT (2000), Department of Environmental Affairs and Tourism, "South African National Country Study (draft)." (Funded by GTZ and yet unpublished).

DeCanio, S., 2003, Economic Models of Climate Change, NY: Palgrave Macmillian, New York

Dekenah, M., (2002). (Personal communication) Load Research Program, Video conference.

Dekenah, M., (2004). Workshop on Energy Transitions. Cape Town, See http://pesd.stanford.edu/events/august_2004_workshop_on_energy_transitions/.

DeLaquil, P., Wenying, C., & Larson, E. D. (2003). Modeling China's Energy Future. Energy for Sustainable Development, VII(4).

DFID (2005), Department for International Development. Development of the Enpower Energy Appraisal Tool for Poor Communities. Project number: R7662, http://dfid-kar-energy.org.uk/html/projects/e4.htm

DME (1998), White Paper on Energy Policy for South Africa, Department of Minerals and Energy (DME). Pretoria.

DME (2002), Energy Balances. Pretoria, Department of Minerals and Energy. See www.dme.gov.za/publications/project_research/energy/spreadsheet95.htm.

DME (2003a), Department of Minerals and Energy, Integrated Energy Plan for the Republic of South Africa, http://www.dme.gov.za/pdfs/energy/planning/integrated_energy_plan_dec03.pdf, Pretoria

DME (2003b), The promotion of LPG in South Africa. DME Workshop. Pretoria, Department of Minerals and Energy. www.dme.gov.za

DME (2003c), White paper on Renewable Energy. www.dme.gov.za/publications/pdf/policydocs.whitepaperonenergy.pdf

DME (2003d), Electricity Basic Services Support Tariff (Free basic electricity) Policy, Department of Minerals and Energy. www.dme.gov.za/energy/pdf/ebsst fbe policy.pdf , Pretoria.

DME (2004a), Draft energy efficiency strategy of the Republic of South Africa. See http://www.dme.gov.za/pdfs/energy/efficiency/ee_strategy_05.pdf, Department of Minerals and Energy (DME) www.dme.gov.za.

DME (2004b), Draft Renewable Energy Strategy, Department of Minerals and Energy, Pretoria.

DME (2004c), Economic and financial calculations modelling for the renewable energy white paper and strategy formulation. Report no 2.3.4-19 prepared by Conningarth Economists. Pretoria. Department of Minerals and Energy – Capacity Building in Energy Efficiency and Renewable Energy project.

DME (2004e), SAMI –South African Minerals Industry 21'st Edition. Directorate: Mineral Economics. Department of Minerals and Energy. www.dme.gov.za/publications/pdf/annual reports/SAMI2003-4e.pdf, Pretoria.

DME (2005a). Department of Minerals and Energy (DME) http://www.dme.gov.za.

DME (2005b), Energy Balances. Department of Minerals and Energy. www.dme.gov.za/energy/pdf/aggregate%20balance%202001.pdf. Pretoria.

DME (2005c), Department of Minerals and Energy, Designated National Authority (DNA), Pretoria. www.dme.gov.za

DTI (2002), Department of Trade and Industry, Energy Consumption in the UK, http://www.berr.gov.uk/files/file11250.pdf

Duke, R., Jacobson, A., Kammen, D.M. (2002), Product Quality in the Kenyan Solar Home Systems Market. Energy Policy(30): 477 –499.

Dutkiewicz, R. K. (1994), Energy in South Africa: a Policy discussion document. ERI Report NO GEN 171, Energy Research Institute, Diepriver, Cape Town.

Eberhard, A. (1992), Shifting paradigms in understanding the fuelwood crisis: policy implications for South Africa. Journal Energy R&D in Southern Africa 3(2): 19-25.

Eberhard, A. (1993), Dissemination of Solar Ovens in Lesotho: Problems and Lessons. Proc 8th Solar World Congress. Perth p2754-2758 Pergamon.

Eberhard, A., & Van Horen, C. (1995), Poverty and Power, Pluto Press and UCT Press.

EC (1999), European Commission, DGXII-Science, Research and Development, ExternE, Externalities of Energy, Vol. 7: Methodology – 1998 Update, 233 EUR 19083. Office for Official Publications of the European Communities, L–2985

EC (2005), European Commission, World Energy Technology Outlook 2050, WETO – H2, http://ec.europa.eu/research/energy/pdf/weto-h2_en.pdf, Brussels

EDRC (2003), Policies and measures for renewable energy and energy efficiency in South Africa. Prepared for the Sustainable Energy & Climate Change Partnership. Cape Town, Energy & Development Research Centre (ERDC), University of Cape Town.

EIA (1997), Energy Information Administration, 1997. World Energy Projection System: Model Documentation. Office of Integrated Analysis and Forecasting. US Department of Energy, Washington, DC, DOE/EIA-M050(97).

EIA (2003), Energy Information Administration, System for the Analysis of Global Energy Markets - Vol. I, Model Documentation, http://tonto.eia.doe.gov/FTPROOT/modeldoc/m072(2003)1.pdf , Department of Energy.

EIA (2004), Annual Energy Outlook, Energy Information Administration (EIA). http://www.eia.doe.gov/oiaf/archive/aeo04/index.html.

EIA (2004), Energy Information Administration (EAI). http://www.eia.doe.gov/emeu/mecs/mecs94/consumption/mecs5.html#mecs2cb

Elias, R., & Victor, D., (2005). Energy Transitions in Developing Countries: a Review of Concepts and Literature: Publication Number WP-40, Program on Energy and Sustainable Development, Stanford University

EMN (2002), Energy Management News, Launch of the South African Energy. Management Association (SEMA), http://www.erc.uct.ac.za/Energy%20Managment%20News/EMN%20%20Dec%202002.pdf, Vol 8, No 4, December

Engineering News (2008), Areva, Westinghouse submit bids for Eskom's big nuclear expansion, http://www.engineeringnews.co.za/article.php?a_id=125840

ERC (2005), Energy Research Centre, Unpublished Leap Data. Cape Town, University of Cape Town.

ERI (2000a), Energy Research Institute, "The 3e Strategy: Energy Efficiency Earnings." Energy Management News 6(3): 1-2.

ERI (2000b), Electrical energy saving: Refrigeration. Cape Town, Energy Research Institute, University of Cape Town, http://www.3e.uct.ac.za/downloads/refrigeration.pdf

ERI (2000c), Energy Efficiency Guidebooks: Electrical Energy Saving. Cape Town, Energy Research Institute, University of Cape Town, http://www.3e.uct.ac.za/downloads/electricalsystems.pdf

ERI (2000d), Energy Efficiency Guidebooks: Steam Systems Saving. Energy Research Institute (ERI), University of Cape Town, http://www.3e.uct.ac.za/downloads/steam.pdf

ERI (2000e), Energy Efficiency Guidebooks: Insulation. Energy Research Institute (ERI), University of Cape Town, http://www.3e.uct.ac.za/downloads/insulation.pdf

ERI (2000f), Energy Efficiency Guidebooks: Boilers and Furnaces. Energy Research Institute (ERI), University of Cape Town, http://www.3e.uct.ac.za/downloads/boilers.pdf

ERI (2000g), Energy Efficiency Guidebooks: The 3E Strategy. Energy Research Institute (ERI), University of Cape Town, http://www.3e.uct.ac.za/downloads/3estrategy.pdf

ERI (2000h), Energy Efficiency Guidebooks: Compressed Air. Energy Research Institute (ERI), University of Cape Town, http://www.3e.uct.ac.za/downloads/compressedair.pdf

ERI (2001), Energy Research Institute, Preliminary Energy Outlook for South Africa: Prepared for the SA Department of Minerals & Energy. Cape Town, Energy Research Institute (ERI), University of Cape Town.

ESKOM (1996), Eskom Statistical Yearbook 1996, ESKOM.

ESKOM (2004), Annual Report. ESKOM, Johanesburg www.eskom.co.za

ESMAP (2000), Energy Services for the Worlds Poor. Washington, Energy Sector Management Assistance Programme (ESMAP) and World Bank.

ETSAP (2005), Energy Technology Systems Analysis Program. www.etsap.org

FAO (2001), Food and Agriculture Organization of the UN (FAO). See http://www.seib.org/publications/ch4_adb.pdf.

Fishbone, L., Giesen, G., & Goldstein, G., (1983), User's Guide for MARKAL (BNL/KFA) Version 2.0: BNL 51701.

Gander, M., (1994), Status Report on Biomass Resources. Fuelwood Demand and Supply in South Africa: Biomass Initiative Report PFL-SYN-01.

Garrett, H., (1968), The tragedy of the commons, Science 162:1243-48

Gaunt, T., (2002), Options for a Basic Electricity Support Tariff, University of Cape Town, Eskom & Department of Minerals and Energy.

Gaunt, T., (2003), PHD Thesis: Electrification technology and processes to meet economic and social objectives in South Africa. Department of Electrical Engineering. Cape Town, University of Cape Town.

Gaunt, T., (2004), "Meeting electrification's social objectives in South Africa, & implications for developing countries." Energy Policy, (In Press, Corrected Proof).

Geldenhuys, A., (2003), (Personal communication) Senior engineer, Integrated Strategic Electricity Planning (ISEP) Office, ESKOM.

Geller, H., DeCicco, J., and Laitner, S., (1992), Energy Efficiency and Job Creation: The Employment and Income Benefits from Investing in Energy Conserving Technologies. Washington, DC: The American Council for an Energy-Efficient Economy.

Gielen D., (2003), The Future Role of CO2 Capture and Storage Results of the IEA-ETP Model, https://www.iea.org/textbase/papers/2003/eet04.pdf, Paris.

Gielen, D., & Chen, C., (2001), "The CO2 Emission Reduction Benefits of Chinese energy Policies and Environmental Policies: A Case Study for Shanghai, Period 1995-2020." Ecological Economics 39: 257-270.

Gielen, D., (2003), The future role of CO2 capture and storage. Results of the IEA ETP model. Working document EET/2003/04. http://www.iea.org/

Golding, A. (2002), (Personal communication), Department of Minerals and Energy (DME).

Goldstein, G., & Hobbs, B., (2003) MARKAL Goal Programming Formulation. MARKAL-GP Version 5.1 - March 3

Greber, B. (2001), Grenz¨ubergreifende integrierte Elektrizit¨atsplanung ims¨udlichen Afrika, University of Stuttgart, Germany.

Greening, L., & Bernow, S. (2004), Design of Coordinated Energy and Environmental Policies: Use of Multi-Criteria Decision Making. Energy Policy 32(2004): 721-735.

Grubb, M., Kohler, J., & Anderson, D. (2002), Induced Technical Change in Energy adn Environmental Modelling: Analytic Approaches and Policy Implications, Annual Review of Energy and the Environment Vol. 27: 271-308, November

Harnisch, J., Koch, M., Höhne, N. & Blok, K. (2002), Prospects for the Application of Energy Models in the Design of Climate Policies, 6th Greenhouse Gas Control Technologies Conference, International Energy Agency, Japan

Haw M., & Hughes A., (2007), Clean energy and development for South Africa: Scenarios, Report 1 of 3. Energy Research Centre, http://www.erc.uct.ac.za/publications/Report%201-%20Haw-Hughes.pdf, February

Hawdon, D., & Pearson P., (1995), Input-output simulations of energy, environment, economy interactions in the UK Fuel and Energy Abstracts, Volume 36, Number 4, July, pp. 295-295(1)

Hayes, M. (2004), Algerian Gas to Europe: The Transmed Pipeline and Early Spanish Gas Import Projects. PESD Working Paper #27. See http://pesd.stanford.edu/publications/20602/, Palo Alto, Stanford University.

Heller, T., & Shukla, P. R. (2003), Development and climate: Engaging developing countries. Arlington, Pew Center on Global Climate Change.

Higgins, S., & Shanklin, W. (1992), "Seeding the mass market for high technology consumer products." Journal of Consumer Marketing 9(6).

Hobbs, B., & Meier, P. (2000), Energy Decisions & The Environment: A Guide to the Use of Multicriteria Methods. Norwell, MA, Kluwer Academic Publishers.

Hosier, R., & Bernstein, M. (1992), Woodfuel use and sustainable development in Haiti. Energy Journal 13 2, pp. 129–156.

Howells, M., (2006), Targeting of Industrial Audits for DSM Planning. Journal of Energy in Southern Africa 17 (1): 58-65, http://www.erc.uct.ac.za/publications/Howells-17-1jesa.pdf

Howells, M., & Kenny, A. (2001). Energy futures: trends and options for the world and for South Africa, with emphasis on the generation of electricity. Journal of Energy in Southern Africa 7(2): 338-394.

Howells, M., (2000a), Sustainable Energy Development in South Africa, Journal of Energy in Southern Africa 9(4) November, 125-128.

Howells, M., (2000b), Bulk energy baselines and mitigation options. Cape Town, Energy Research Institute (ERC), University of Cape Town

Howells, M., (2001), Sustainable development in South Africa: Optimizing the energy, societal and environmental relationships in the medium and long term" Journal of the Japan Society of Energy Resources 22 (1) 46-50.

Howells, M., (2004a), High-Growth Forecast for the IRP. Cape Town, Energy Research Centre (ERC), University of Cape Town.

Howells, M., (2004b), Modelling multiple goals: Greenhouse gas mitigation and socio-economic development. Cape Town, Energy Research Centre (ERC), University of Cape Town.

Howells, M., & de Villiers, M. (1999), Sustainable Energy – Energy and the Environment. Cape Town, Energy Research Institute (ERI), University of Cape Town.

Howells, M., & Dick A. (2003), Climate change impact of the rural energisation project: Report no. CON 126. Cape Town, Energy Research Institute, University of Cape

Howells, M., & Laitner, J. (2003), A Technical Framework for Industrial Greenhouse Gas Mitigation in Developing Countries, Summer Study: Industrial Energy Efficiency (ACEEE), Proceedings

Howells, M., & Laitner, J. A. (2005), Industrial efficiency as an economic development strategy for South Africa. American Council for an Energy-Efficient Economy (ACEEE), Proceedings

Howells, M., & Solomon, M. (2000), South African Energy Greenhouse Gas Inventory for Wichus Environmental Consulting. Cape Town, Energy Research Institute, University of Cape Town.

Howells, M., & Solomon, M. (2002), An optimal greenhouse gas mitigation path for South Africa in the short to medium term. Journal of Energy in Southern Africa 13(4): 123-129.

Howells, M., & Solomon, M. (2003), An optimal greenhouse gas mitigation pathway for South Africa. Proceedings: Greenhouse Gas Control Technologies 6, Kyoto, Pergamon.

Howells, M., Alfstad, T., Cross, N., Jeftha, L., & Goldstein, G. (2003), Rural Energy Modelling. Working Papers Series no 11, Program on Energy and Sustainable Development.

Howells, M., Alfstad, T., Victor, D., Goldstein, G., & Remme, U. (2005), A model of household energy services in a low-income rural African village. Energy Policy 33(14): 1833-1851

Howells, M., House, J., & Laitner, J. (2005a), Beyond the Baseline – Large Scale Climate Friendly Development. International Energy Workshop Kyoto.

Howells, M. I., Solomon, M., Bennett, K., & Kenny, A. (2002). Energy Outlook for South Africa 2002: National IEP. Cape Town, Energy Research Institute, University of Cape Town.

Howells, M., (2006), Industrial Energy Efficiency Data: Targeting DSM in South Africa. Journal of Energy in Southern Africa, Vol 17 No 1 , February

Howells, M., Jonsson, S., Käck, E., Lloyd, P., Conradie, B., & Bennett, K. (Submitted). Calabashes for Kilowatt-hours - Energy Transitions and Market Failures in Low Income Rural Areas. Energy Policy.

Howells, M.I. (In Press). Mapping out development pathways for climate friendly economic growth in a developing country. International Journal for Energy Technology and Policy (Special Issue: Modeling Technology Characterization).

Howells. M., Victor, D. G., Gaunt T., Elias, R., Alfstad T., (2006). Beyond free electricity: The costs of electric cooking in poor households and a market-friendly alternative, Energy Policy 34 (2006) 3351-3358

Huang, J., Pho, K., & Ang, B. (1995), "Decision Analysis in Energy and Environment Modelling." Energy 20: 843-855.

Hughes, A. Howells, M. & Kenny, A. (2002), Energy efficiency baseline study. Capacity building in energy efficiency and renewable energy (CABEERE) Report No. 2.3.4. Report No. P-54126. Pretoria, Department of Minerals& Energy.

Hughes, A., Trikam, A., & Howells, M., (2003), Energy Efficiency Savings. Cape Town, Energy Research Institute (ERI), University of Cape Town.

Hyde, F., & Seve, J, (1993), The economic role of wood products in tropical deforestation: The severe example of Malawi. Forest Ecology and Management Vol. 57, no. 1-4, pp. 283-300.

IAC (2008), US-DOE, Industrial Assessment Centre Program, http://www.iac.rutgers.edu/

IAEA (2005), International Atomic Energy Agency, Energy Indicators for Sustainable Development: Guidelines and Methodologies, Wien

IAEA (2006), International Atomic Energy Agency, 3E Analysis – Country Case Studies, http://www.iaea.org/OurWork/ST/NE/Pess/3-e_countrycasestudies.shtml

IAEA (2007), International Atomic Energy Agency, Model for Analysis of Energy Demand (MAED-2) , http://www-pub.iaea.org/MTCD/publications/PDF/CMS-18_web.pdf

IEA (2005), International Energy Agency, World Energy Outlook 2005 – Middle East and North Africa Insights, OECD, Paris

IEA (2007c) International Energy Agency Energy Prices and Taxes - Energy End-Use Prices (US/toe, PPP/unit) Vol 2007 release 04 , OECD, Paris

IEA (1996), Energy Policies of South Africa. Organization for Economic Cooperation and Development (OECD), Paris.

IEA (2002), International Energy Agency, World Energy Outlook, OECD/IEA, Paris.

IEA (2004) International Energy Agency, Energy Statistics Manual, OECD Paris

IEA (2007a) International Energy Agency, World Energy Statistics and Balances - Energy Balances of Non-OECD Member Countries - Extended Balances Vol 2007 release 01, OECD, Paris

IEA (2007b) International Energy Agency, Energy Prices and Taxes - Energy End-Use Prices (US/toe, PPP/unit) Vol 2007 release 04, OECD, Paris

IEA (2007d) International Energy Agency, World Energy Statistics and Balances - Energy Balances of OECD Member Countries - Extended Balances Vol 2007 release 01, OECD, Paris

IPCC (1996), Intergovernmental Panel on Climate Change, Revised 1996 guidelines for national greenhouse gas inventories. Intergovernmental Panel on Climate Change, Bonn

IPCC (2000) , Intergovernmental Panel on Climate Change, http://www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf

IPCC (2001), Intergovernmental Panel on Climate Change, Climate Change 2001: Mitigation. Contribution of the WG 3 to the Third Assesment Report of the IPCC, Compiled by Metz, B., Davidson, O., Swart, R., & Pan, J. Cambridge Univercity Press for Intergovermental Panel on Climate Change.

Jank, R., (ed.) (2000). A Guidebook for Advanced Local Energy, Planning (ALEP). Paris: International Energy Agency.

Jeftha, L (2003), Energy Efficiency and Job Creation: An Input-Output Model Approach. Journal of Energy in Southern Africa 14 (2).

Jonsson, S., & Käck, E. (2005), Energy Transitions and Market Aspects of Low-Income Rural Areas:A South African Case Study, MSc Thesis Division of Heat and Power Technology, Department of Energy Technology, Royal Institute of Technology, Sweden.

Kabecha, W., 1999, “Technological capability of the micro-enterprises in Kenya’s informal sector.” Technovation, No. 19, pp.117-126.

Kanagawa, M., & Nakata, T. (2005a), Analysis of the energy access improvement and its socio-economic impacts in rural areas of developing countries. International Energy Workshop. Kyoto.

Kanagawa, M., & Nakata, T. (2005b), Analysis of the Energy Access Improvement in Developing Countries through Rural Electrification. 25th Annual North American Conference of the USAEE/IAEE. Denver.

Kenny A., Howells, M. I., Drummond, R., Chapman, D., & Trikam, A. J. (2000b), Energy Audit Management Summary: AngloGold. http://www.3e.uct.ac.za/downloads/anglo.pdf Cape Town, Energy Research Institute, University of Cape Town.

Kenny A., Howells, M. I., Drummond, R., Chapman, D., & Trikam, A. J. (2000c), Energy Audit Management Summary: SAPPI. http://www.3e.uct.ac.za/downloads/sappi.pdf Cape Town, Energy Research Institute, University of Cape Town

Kenny A., Howells, M., Drummond, R., Chapman, D., & Wamono, P. (2000a), Energy Audit Management Summary: South African Breweries. http://www.3e.uct.ac.za/downloads/sab.pdf Cape Town, Energy Research Institute, University of Cape Town.

Kenny, A., (2002), Background to Energy in South Africa. Cape Town, Energy Research Institute, University of Cape Town.

Koopmans, T., (1960), Stationary Ordinal Utility and Impatience, Econometrica 28:287-309

Kypreos, S., Krakowski, R., (2005), An Assessment of the Power-Generation Sector of China. Http://eem.web.psi.ch/Presentations/2005-04-07_Taiwan_Kypreos_Krakowski.pdf

Labriet M., Loulou R., Kanudia A. (2005), "Global energy and CO2 emission scenarios:analysis with a 15-regions world MARKAL model". In Haurie A. and Viguier L. (Editors): The Coupling of Climate and Economic Dynamics, Advances to Global Change Research.Kluwer Academic Publishers. Dordrecht, Netherlands .

Laitner, J. (2002), Workshop on I/O and MCA modeling sponsored by the US EPA held at the University of Cape Town, Energy and Development Research Centre, Univercity of Cape Town, Cape Town.

Laitner, J. (2004), Analytical insights and a thought experiment. www.erc.uct.ac.za/Projects/nov2004ws/Analytical%20insights%20and%20a%20thought%20experiment.ppt Workshop on Development and GHG emissions, Energy Research Centre (ERC), University of Cape Town.

Laitner, J., & Hogan, K., (2000), Solving for Multiple Objectives: The Use of the Goal Programming Model to Evaluate Energy, Air and Climate Policy Options. Presented at the ACEEE Buildings Summer Study. Asilomar, CA.

Laitner, J., DeCanio, S., & Peters, I. (2000), Addressing Behavioral and Social Relationships in Climate Mitigation Assessments. In E. Jochem et al. (eds) Society, Behavior, & Climate Change Mitigation. Dordrecht, The Netherlands, Kluwer Academic Publishers.

Laitner, J., (2001), Energy Efficiency Investments: A Dynamic Link between Environmental Quality and Positive Job Benefits for South Africa. Cape Technikon South Africa Conference on Direct Energy Use. Cape Town, South Africa, University of Cape Town.

Laitner, S., Bernow, S., & DeCicco, J. (1998), Employment and Other Macroeconomic Benefits of an Innovation-Led Climate Strategy for the United States. Energy Policy 26(425-433).

Lazonick, W. (1993), Business Organization and the Myth of the Market Economy, Cambridge University Press.

Lee S., (1976), Linear Optimization for Management. New York, Mason Charter Publishers.

Lee, S., (1972), Goal Programming for Decision Analysis. Philadelphia, Auerback.

Liebenstein, H., (1950), Bandwagon, snob and veblen effects in the theory of consumers' demand. Quarterly Journal of Economics 65, pp. 183–207.

Lloyd, P., (2002), The safety of paraffin and LPG appliances for domestic use, Journal of Energy in Southern Africa, Vol. 13 No. 2, May

Lloyd, P, van Wyk, D, Cook, A and Prevost, X (2002b), SA Country Studies: Mitigating Options Project; Emissions from coal mining Final Report to Dept. Environmental Affairs & Tourism, Jan.

Lloyd, P., Cowan, B., & Mohlakoana, N. (2004a), Improving access to electricity and stimulation of economic growth and social upliftment. Energy Research Centre, University of Cape Town

Lloyd, P., Dick, A. and Howells, M.I. (2004b), The energy profile of a rural community. Journal of Energy in Southern Africa 15(3): 80-87.

Lloyd, P., Dick, A., Howells, M. I., & Alfstad, T. (2002a), A baseline study for Nkweletsheni. Cape Town, Energy Research Institute, University of Cape Town.

Lloyd, P., & Rukato, H. (2001), The potential of LP gas for household energy in South Africa. Journal of Energy in Southern Africa, 12(1): 329-335.

Lloyd, P., and A. Trikam. (2004). The Determination of Emission Factors for South African Power Stations. Eskom Contract 1RE-000046. Cape Town:Energy Research Centre, University of Cape Town.

Loulou R., Shukla, P., and Kanodia, A., (1997), Energy and Environmental Policies for a sustainable future. AlliedPublishers Limited, Delhi.

Loulou, R., Goldstein, G., & Knoble, K. (2004), Documentation for the MARKAL Family of Models. Energy Technology Systems Analysis Program (ETSAP), www.etsap.org .October 2004.

Louw, K., Dekenah, M., Prasad, G., Cowan, B., Merven, B., & Howells, M., (2006), Determinants of Electricity Demand for Newly Electrified Low Income African Households, http://www.iiasa.ac.at/Research/ECS/IEW2006/docs/2006PPT_Louw.pdf, International Energy Workshop, Cape Town, South Africa, June

Marglin, S., (1963), The social rate of discount and the optimal rate of investment, Quarterly Journal of Economics, Vol 77, 95-111

Marin, D., Kaufmann, D., & Gorochowskij, B. (2000), Barter in Transition Economies: Competing Explanations Confront Ukranian Data, Working Paper 287, William David Institute, University of Michigan.

McFadzean, S., (2002), personal communication, Senior Engineer, Integrated Strategic Electricity Planning (ISEP), ESKOM

Meadows, D., Meadows, D., Randers, D., & Behrens, W., (1972), The Limits to Growth. New York: Universe Books. ISBN 0-87663-165-0

Meadows, K., Riley, C., Rao, G., & Harris, P. (2003), Modern Energy: Impacts on micro-enterprises. Phase 1, Task 1.2 A Literature Review into the Linkages Between Modern Energy and Micro-Enterprise, UK Department for International Development: http://www.etsu.com/energy_voices/Assets/ED03493LiteratureReviewFINALissue1.pdf

Mehlwana, A., & Qase, N. (1999), The contours of domesticity, energy consumption and poverty: The social determinants of energy use in low-income urban households in Cape Town's townships (1995-1997). Cape Town, Energy and Development Research Centre, University of Cape Town.

Metz, B., Davidson, O., Swart, R. and Pan, J. Climate Change (2001), Mitigation: Contribution of WG III to the Third Assessment Report of the IPCC. Cambridge, Cambridge University Press for Intergovernmental Panel on Climate Change.

Mpako, M. (2005). Personal communication, Member of the steering committee of the African Energy Policy Research Network (AFRIPREN).

Muller, F., (1979), Energy and environment in interregional input-output models 137 pp, Martinus Nijhoff, Boston and London

Munasinghe, M. (1990). Electric Power Economics. London: Butterworths.

Munasinghe, M., 1992 Policy for Energy and Sustainable Development, Chapter 7 in Byrne, J., Rich, D., Energy and the Environment, Transaction Publishers, ISBN 1560005734

Nakicenovic, N., Grubler, A., & McDonald, A., (1998) Global energy perspectives: International Institute for Applied Systems Analysis/World Energy Council. Cambridge University Press

NER (2003a), National Electricity Regulator, Energy efficiency and demand side management policy within South African electricity industry, National Electricity Regulator (NER) http://www.ner.org.za/

NER (2003b) National Electricity Regulator, The National Integrated Resource Plan, The National Electricity regulator (NER), ESKOM and the Energy Research Centre (ERC).

NER (2004) National Electricity Regulator, National Integrated Resource Plan 2 (NIRP2) 2003/4. Pretoria, National Electricity Regulator. http://www.nersa.org.za/UploadedFiles/ElectricityDocuments/NIRP2%20compiled%202004.pdf

NER (2005) National Electricity Regulator, Statistical Data, http://www.nersa.org.za/.

NERSA (2008), National Energy Regulator of South Africa, Application for rule change to multi-year price determination (MYPD) for the 2008/2009 financial year by ESKOM holdings limited. http://www.nersa.org.za/documents/Aide%20Memoir%20MYPD%20Rule%20Change%2020%20Dec%202007.pdf

Nyabeze, W. (2001). Linking Productive Activities in Rural Areas to Energy Services: A Case for Micro-Hydro. Presentation at the EC Synergy Workshop, 14-15 February CSIR, Pretoria, South Africa.

OECD (2004), Organisation for Economic Cooperation and Development, African Economic Outlook. OECD Development Centre, June.

Partha, D. (1996), The Economics of the Environment, Proceedings of the British Academy Vol 90: 165-221.

PBMR (2007) Pebble Bed Modular Nuclear Reactor Company, What is the PBMR? http://www.pbmr.com/index.asp?content=4

Pezzy, J., (1992), Economic Analysis of Sustainable Growth and Sustainable Development. World Bank Environment Paper No. 2, Washington.

Phdungsilp, A., (2006), Energy Analysis for Sustainable Mega-Cities, Licentiate Thesis, School of Industrial Engineering and Management, Department of Energy Technology, Royal Institute of Technology Stockholm,http://www.diva-portal.org/diva/getDocument?urn_nbn_se_kth_diva-4097-2__fulltext.pdf. Sweden

Prasad, G. (2002). (Personal communication). Senior Researhcer Energy and Development Research Centre, University of Cape Town, http://www.erc.uct.ac.za/gisela.htm

Prasad, G., & Visagie, E., (2005) Renewable energy technologies for poverty alleviation - Initial assessment report: http://www.erc.uct.ac.za/publications/RET%20South%20Africa%20REPORT%20Final%20Draft.pdf, South Africa, Energy Research Centre, June

Prasad, G., & Visagie, E., (2006) Electricity Access III theme: Explicit focus on the poor. Impact of energy reforms on the poor in Southern Africa, Report for Global Network on Energy for Sustainable Development (GNESD),http://www.erc.uct.ac.za/publications/South%20Africa-ACCESS%20III.pdf , Energy Research Centre, University of Cape Town

Qase, N. (2000), Promoting low smoke fuels for the residential sector in South Africa. World Energy Council Conference on Cleaner Fossil Fuels Systems: A business and investement Agenda for Africa. Dakar, Senegal.

Ranganathan V. (Editor) (1992), Rural Electrification in Africa. London, Zed Bo

Repetto, R., Wells, M., Beer, C., & Rossini, F., (1989). Wasting Assets: Natural Resources in the National Income Accounts. World Resources Institute, Washington DC

Reuters 2006, Firms seal deal to build Botswana coal power plant, http://www.cicenergycorp.com/_resources/in_the_news/2006-10-18-Reuters-article.pdf, October

Robinson, S. (1989), Multi-Sectoral Models. . In Chenery, H & Srinivasan, T N (eds). Amsterdam, North Holland:885-947.

Rodgers, M. (1983), Diffusion of innovations. 3'rd Edition. New York, Free Press.

Rogerson, C. M. (1997), Rural electrification and the SMME economy in South Africa. Cape Town, Energy Research and Develepment Centre, University of Cape Town

Rogner H, Langlois, L., McDonald, A., Weisser D., & Howells, M. (2007), The Costs of Energy Supply Security, 20th World Energy Congress, Rome, Italy, November

Ruttan, V. (2004), Development and electrification: What is cause and what is effect? Electricity and the Human Prospect Conference. http://iis-db.stanford.edu/evnts/3961/Electricity_and_the_Human_Prospect_Agenda_23_November.pdf ,Stanford University.

SADID/DWAF (2002), Baseline Study on Woodlands in South Africa. ENV-P-C 2002-21, SA Department of International Development & Department of Water Affairs, Pretoria.

SADOH (2005), Health Sector Strategic Framework 1999-2004, Department of Health. Available online at www.doh.gov.za.

Samuelson, P., (1938) A Note on the Pure Theory of Consumer's Behaviour, Economica, New Series, Vol. 5, No. 17, pp. 61-71

SAPP (1999), Modelling electricity trade in Southern Africa - Year 3 interim report, Southern African Power Pool. https://www.purdue.edu/dp/energy/pdfs/sAfrica/AIRDsummaryYR2.pdf

Sarkar, A. a. Wolter., N. (1998). "Environmental externalities from energy sources: A review in the context of global climate change." Strategic planning for Energy and the Environment 18(2).

Sato, O., Shimoda, M. et al (2000), Roles of Nuclear Energy in Japan's Future Energy Systems. Progress in Nuclear Energy 37(1-4): 95-100.

Scholes, B., & van der Merwe, M. (2000), South African Country Study: Forestry and Land Use Change Report. CSIR. Pretoria.

Schulz T. (2003), Integrated Environmental and Climatic Strategies for the South African Electricity Sector. Master Thesis, Diplomarbeit (in German). Energy Research Centre (ERC), University of Cape Town (UCT), South Africa and Institute of Energy Economics and Rational Use of Energy (IER), University of Stuttgart, Germany, September

Seebregts, AJ, Kram, T, Schaeffer, GJ, Bos AJM (2000), Endogenous learning of technology clusters in a MARKAL model of the Western European energy system. Int. Journal of Global Energy Issues, 14: 289-319

Shelby, M., Fawcett, A., Smith, E., Hanson D., and Sands, R., (2006), Representing Technology in CGE Models: A Comparison of SGM and AMIGA for Electricity SectorCO2 Mitigation. International Energy Workshop ERC, EMF, IEA, IIASA. Capetown, 27-29 June.

Shiffman, L., Kanuk, .L., (1997), Consumer Behaviour, Prentice-Hall,, Englewood Cliffs, NJ, .

Simmonds, G., & Mammon, N. (1996). Energy services in low-income urban South Africa: A quantitative assessment. Cape Town, Energy and Development Research Centre, University of Cape Town.

Simon H., (1982), Models of Bounded Rationality, Vols. 1 and 2. MIT Press 1982

Society, T. R. (1995). Energy for the future, E & N Spoon, London.

Sorensen (1992), History of, and Recent Progress in, Wind-Energy Utilization, Annual Review of Energy and the Environment, Vol. 20: 387-424, November

Spalding Fletcher, R., Winkler, H., Dick, A., Jeftha, L., & Laitner, J. A. (2001), Modelling Economy Wide Impacts of Investments in Industrial Energy Efficiency: A South African Case Study, ACEEE Summer Study: Industrial Energy Efficiency.

Spalding-Fecher R., (2003), Electricity and externalities in South Africa, Energy Policy 31(8): 721-734

Spalding-Fecher, R., Clark, A., Davis, M., & Simmonds, G. (2002), The economics of energy efficiency for the poor - a South African case study, Energy 27(12): 1099-1117.

Spaling-Fecher, R., Winkler, H., Dick, A., Jeftha, L., & Laitner, J.A. (2004), Modelling Economy Wide Impacts of Investments in Industrial Energy Efficiency: A South African Case Study. ACEEE Summer Study: Industrial Energy Efficiency.

Sparrow F, Brian H. Bowen, Zuwei Yu, (1999), Modeling Long-Term Capacity Expansion Options for the Southern African Power Pool (SAPP), Proceedings of the IASTED International Conference, Power and Energy Systems, Las Vegas, Nevada, November 8-10

Strachan N., Kannan R., Balta-Ozkan N., Pye S. and Taylor P. (2006), Development of the UK MARKAL Energy Systems Model, 2nd Interim Report, Policy Studies Institute, http://ukerc.ac.uk/Downloads/PDF/06/06112ndMARKALnoresults.pdf

Subramoney, J. (2004),Integrated Energy Centres(IeC) in SA, (Director: Energy Planning and Development Department of Minerals and Energy), Workshop on Energy Transitions 18th-20th August, Convened by PESD Stanford University and ERC University of Cape Town, Cape Town South Africa

Tatham, G. (2004), (Personal communication). Chief Strategist - Wild Orchid .

The Royal Society, (1995), Energy for the future. Published by E & N Spoon, London

Thillairajah, S. (1994), Development of Rural Financial Markets in Sub-Saharan Africa, World Bank Publications.

Tierney, T. (1993), The Value of Convenience: A Genealogy of Technical Culture, SUNY Press.

TIPS (2001), Trade and Industrial Policy Secretariat (TIPS), Social Accounting Matrix (1997) for South Africa. IDRC.

Treasury (2003), Budget 2002 – National medium terms expenditure estimates, See at www.treasury.gov.za.

Trikam, A. (2001), "Industrial Greenhouse Gas Mitigation." South Africa Journal of Economic and Management Sciences 5 (2): 473-498.

Trikam, A., Hughes, A., Howells, M.I., & Aberg, M. (2003), Energy Efficiency Savings Projections: Report no. P-54126 for the Department of Minerals and Energy (DME), South Africa, Energy Research Institute (ERI), University of Cape Town.

Trollip, H. (1994), Energy Demand Information for Integrated Energy Planning. Cape Town, Energy for Development Research Centre, University of Cape Town.

UCT (2002), Options for a Basic Electricity Support Tariff, University of Cape Town, ESKOM and The Department of Minerals and Energy.

UNDESA (2002), Energy for Sustainable Development of the Least Developed Countries in Africa: Scenarios for Energy and Agriculture for Africa. Food and Agriculture program of the United Nations, New York

UNDP (2000), United Nations Development Program, World Energy Assessment: Energy and the Challenge of Sustainability. New York, United Nations.

UNDP (2001), United Nations Development Program, Impact Study of the Multifunctional Platform on the Living Conditions of Women, Mali. New York, United Nations. Available at: http://www.ptfw.net. .

UNEP (1997), Tools and Methods for Integrated Resource Planning, http://www.uneprisoe.org/IRPManual/IRPmanual.pdf, Riso National Laboratory, Denmark.

UNFCC (2007) United Nations Framework Convention on Climate Change, Project 0545 : Durban Landfill-gas-to-electricity project – Mariannhill and La Mercy Landfills, http://cdm.unfccc.int/Projects/DB/TUEV-SUED1154520464.04

UNFCCC (2005), United Nations Framework Convention on Climate Change, CDM Project 0079 : Kuyasa low-cost urban housing energy upgrade project at Khayelitsha (Cape Town) South Africa. http://cdm.unfccc.int/Projects/DNV-CUK1121165382.34/view.html.

UNFCCC (2006), United Nations Framework Convention on Climate Change, Submitted National Communications from Non-Annex I Parties, http://unfccc.int/national_reports/non-annex_i_natcom/submitted_natcom/items/653.php

UNFCCC (2008), United Nations Framework Convention on Climate Change, Clean Development Mechanism, http://cdm.unfccc.int/index.html

United Nations 2005, The Millennium Development Goals Report 2005, United Nations Publications, ISBN 9211009723

USAID (2007), http://www.usaid.gov/our_work/environment/climate/ Washington

Van der Riet (2003), Senior consultant, Technology Services International, ESKOM

Van Es, D., Fawkes, H., & Howells, M.I. (2002), Energy Audit Management Summary: Volkswagen South Africa. Energy Management News. Energy Research Institute, University of Cape Town.

Van Heerden, J., Gerlagh, R., Blignaut, J., Horridge, M., Hess, S., Mabugu, R., Mabugu, M.,(2006), "Searching for triple dividends in South Africa: Fighting CO2 pollution and poverty while promoting growth", The Energy Journal, Vol.27, No.2, pp113-141.

Van Horen, C. (1996a), PHD Thesis. Energy and Development Research Center. Cape Town, University of Cape Town.

Van Horen, C. (1996b), Counting the Social Costs, Electricity and Externalities, Industrial Strategy Project. Elan Press & UCT Press.

Vaughan, A., & Xaba, T. (1996), Building a framework for understanding micro enterprises in KwaZulu Natal. Westville, Durban, Unpublished report, University of Durban.

Vessia, Ø., (2005) Biofuels from lignocellulosic material-In the Norwegian context 2010–Technology, Potential and Costs - Norwegian University of Science and Technology

Victor, D., & Victor, N. (2002), Macro Patterns in the Use of Traditional Biomass Fuels. Working Paper Series no 10, Program on Energy and Sustainable Development. Stanford University

Wara, M., (2006). Measuring the Clean Development Mechanism's Performance and Potential. Working Paper #56, Program on Energy and Sustainable Development. The Center for Environmental Science and Policy, Stanford University.

WEC/FAO (1999), The Challenge of Rural Energy Poverty in Developing Countries. London: World Energy Council; New York: United Nations.

Williams A., Eberhard A. & Dickson, (1996), Synthesis report of the Biomass Initiative, Biomass initiative Report PFL-SYN-01, Department of Minerals and Energy Affairs

Williams, A. (1994), Energy supply options for low income urban households, Energy for Development Research Centre, University of Cape Town.

Williams, A. (2003), (Personal communication). Department of Electrical Engineering, Univercity of Cape Town.

Winkler H., (2005), ERC Determines Cape Town's Energy Future, Energy Management News, Vol 11 No 1, 1

Winkler H., (2006), Energy Policies for Sustainable Development in South Africa’s Residential and Electricity Sectors, PhD thesis, EBE UCT

Winkler H., Alfstad T., & Howells M., (2005), South African Energy Policies for Sustainable Development, http://www.erc.uct.ac.za/publications/IAEA%20ESD%20Nov%202005,%20final.pdf Energy Research Centre, November

Winkler, H., Howells, M., & Baumert K., (2007). Sustainable development policies and measures: institutional issues and electrical efficiency in South Africa, Climate Policy, Volume 7, Number 3, 2007, 212–229

World Energy Council (2000), Energy for Tomorrow's World - Acting Now!, Atalink Projects Ltd, London

WRI (2000), World Resources Institute Global Forest Watch. http://www.wri.org/powerpoints/gfw_2000/index.htm

WRI (2005), World Resources Institute, Climate Analysis Indicators Tool (CAIT), version 2.0. Washington DC. http://cait.wri.org/

Xingawa, L. (2004). Keynote Address:Deputy Minister of The South African Department Minerals and Energy. Workshop on Energy Transitions, www.pesd.stanford.edu/events.august_2004_workshop_on_energy_transitions/ August, Cape Town.

Appendix A[253]: Improving data – targeting industry in South Africa.

Much of the work in the second section of this thesis reports the benefits of improved industrial energy efficiency. However, while these studies are based on a limited set case study data. In this section, I propose a targeted approach to improve this data, given that a limited number of sites may be visited. The piece focuses on industrial demand side management.

This section of the study aims to establish which industries to target for energy audits and demand side management projects (DSM) in order to improve data for future analysis. As only a limited number of audits might be conducted, it is important to establish how to maximise the return on the invested efforts and resources. The aim is thus to develop a ranking of industries based on their potential for savings from DSM interventions.

A.1 Introduction

In order to derive an approach for targeting demand side improvements in industry, this section considers the following criteria:

1. Electricity consumption and potential DSM savings from retrofits at existing plants.
2. Electricity consumption and potential DSM savings for new plants.
3. Potential DSM interventions by industry.
4. The costs of a suite of DSM interventions by industry.
5. The technical ease with which DSM may be implemented by industry.

The potential for DSM savings for different industrial sectors is evaluated based on these criteria, using aggregated values sourced from local and international studies. DSM measures are applied to the various 'end uses' of electricity within each industry.

From these I suggest a shortlist of 10 industries to target for energy audits and data gathering. I consider both industry and mining and refer to the group collectively as industry.

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[253] Howells, M., (2006), Industrial Energy Efficiency Data: Targeting DSM in South Africa. Journal of Energy in Southern Africa, Vol 17 No 1 , February

The data gathered in the energy audits will be used to refine estimates of the potential for DSM savings in each sector. Data loggers will be installed to measure electricity consumption and demand profiles (kW load as a function of time), which will be used to estimate the impact of DSM interventions on national demand for energy and power. This can provide valuable input to power system planning and analysis in the future.

A.2 Electricity consumption

In this section I list the industries that will be considered as well as their current and projected electricity consumption.

"Current" electricity consumption

Figure A. illustrates the proportion of electricity consumption in the industrial and mining sectors, as well as total national consumption.

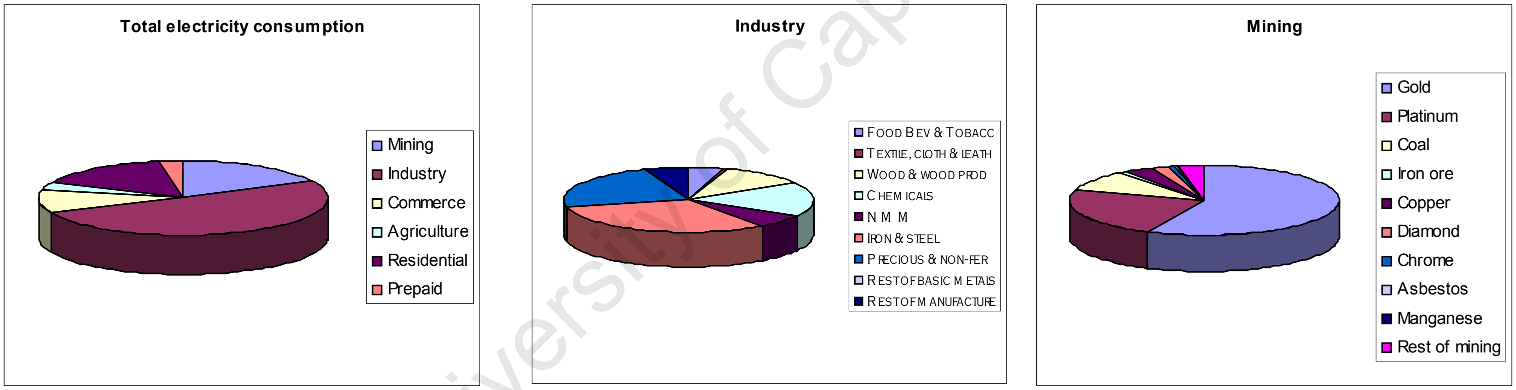


Figure A.1 National electricity consumption 2003

Table A.1 ranks industrial sectors according to total electricity consumption.

Table A.1: Ranking of sectors by current electricity consumption

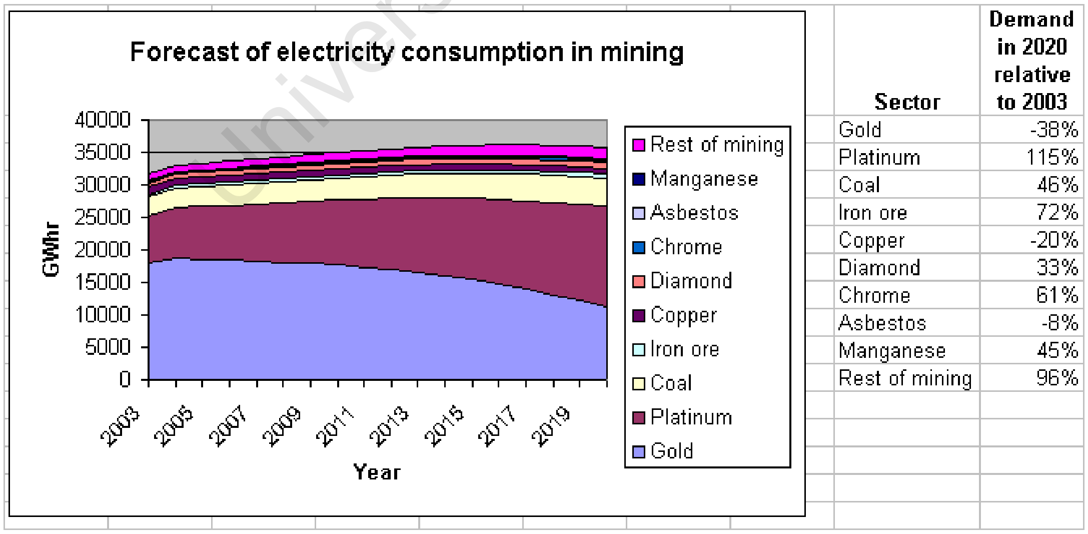
Sector	*Consumption (GWhr)*	*Percentage of total industry consumption*	*Ranking*
Iron & steel	26 923	22.91%	1
Precious & non-ferrous metals	19 447	16.55%	2
Gold mining	18 051	15.36%	3
Chemicals	14 736	12.54%	4
Wood & wood products incl. paper and pulp)	9 613	8.18%	5
Platinum mining	7 209	6.13%	6
Non metallic minerals	5 899	5.02%	7

Rest of manufacture	4 837	4.12%	8
Food bev & tobacco	3 759	3.20%	9
Coal mining	2 964	2.52%	10
Copper mining	1 037	0.88%	11
Rest of mining	945	0.80%	12
Diamond mining	709	0.60%	13
Textile, cloth & leather	445	0.38%	14
Iron ore mining	372	0.32%	15
Rest of basic metals	217	0.18%	16
Chrome mining	187	0.16%	17
Manganese mining	149	0.13%	18
Asbestos mining	20	0.02%	19

This information is useful as it indicates current levels of electricity consumption and can be used to select the industrial sectors that have the greatest potential for savings from DSM retrofit options.

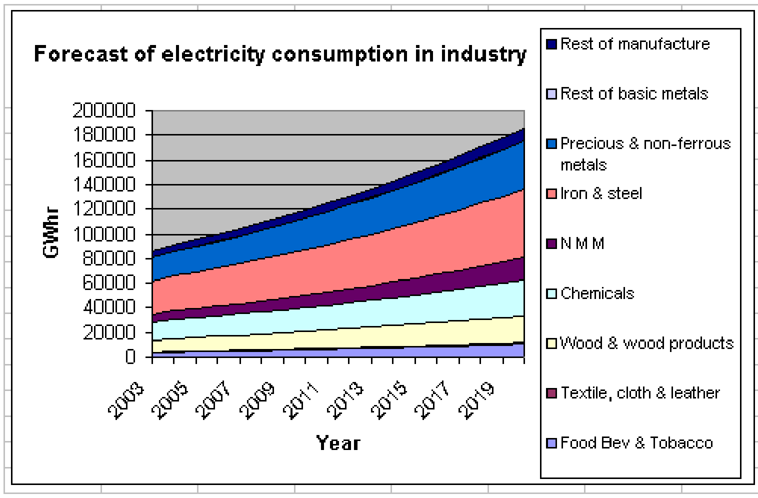
Future electricity consumption

It is important to consider future growth of industries, as including DSM interventions during the construction and design of the new plant may help reduce costs. That is, the economics of DSM may favour a wider range of options for new plant, than for retrofits. Figure A.2 and Figure A.3 below give a forecast of moderate growth in electricity demand for different mining and industrial sectors. (This is derived from the ERC electricity forecasting tool for a moderate GDP forecast of between 3-4% growth.)



Sector	Demand in 2020 relative to 2003
Gold	-38%
Platinum	115%
Coal	46%
Iron ore	72%
Copper	-20%
Diamond	33%
Chrome	61%
Asbestos	-8%
Manganese	45%
Rest of mining	96%

Figure A.2: Forecast of electricity consumption in mining



Sector	Demand in 2020 relative to 2003
Food Bev & Tobacco	180%
Textile, cloth & leather	175%
Wood & wood products	127%
Chemicals	98%
N M M	204%
Iron & steel	105%
Precious & non-ferrous metals	104%
Rest of basic metals	76%
Rest of manufacture	91%

Figure A.3: Forecast of electricity consumption in industry

Table A.2 is a ranking of industrial sectors according to the total (absolute) increase in electricity consumption.

0-29 Table A.2: Ranking of electricity demand growth by sector

Sector	*Growth (GWh)*	*Ranking*
Iron & steel	28 316	1
Precious & non-ferrous metals	20 218	2
Chemicals	14 485	3
Wood & wood products	12 209	4
Non Metallic Minerals	12 017	5
Platinum mining	8 286	6
Food Bev & Tobacco	6 767	7
Rest of manufacture	4 425	8
Coal mining	1 372	9
Rest of mining	911	10
Textile, cloth & leather	778	11
Iron ore mining	269	12
Diamond mining	233	13
Rest of basic metals	166	14
Chrome mining	114	15
Manganese mining	68	16
Asbestos mining	-2	17
Copper mining	-207	18
Gold mining	-6 82	19

A.3 Potential interventions

The next aspect to investigate is the potential for various DSM interventions in each industry. An assumption of what end-uses (motors, process heat, lighting etc.) electricity is actually used for in the different industries is needed to do this. These assumptions were taken from the US Department of Energy's Energy Information Administration (EIA (2004)) and the British Department of Trade and Industry (DTI (2004)), and, for mining, the South African Department of Energy's Integrated Energy Plan (Howells et al 2002). This data is given in Table A.3 which shows the consumption by end-use as a percentage of total consumption for each industry sector. It is important to note that these values are indicative and based on international, not local practice.

Table A.3: Percentage usage of electricity by industrial sector

	Food and beverages	*Textiles*	*Wood and wood products*	*Chemicals*	*Iron and steel*	*Non ferrous metals*	*Rest of basic metals*	*Rest of manufacture*	*Non metallic minerals*	*Gold mining*	*Other mining*
Indirect uses-boiler fuel	2%	1%	3%	1%	0%	0%	0%	1%	0%	0%	0%
Process heating	4%	5%	6%	3%	39%	1%	17%	10%	8%	2%	2%
Process cooling and refrigeration	24%	7%	0%	6%	1%	0%	0%	5%	0%	7%	7%
Compressed air	8%	10%	38%	10%	8%	0%	11%	9%	14%	20%	20%
Other machine drive	44%	50%	38%	53%	40%	2%	56%	47%	72%	45%	45%
Electro-chemical processes	0%	0%	0%	18%	2%	95%	17%	11%	0%	0%	0%
Other process use	0%	1%	1%	0%	1%	0%	0%	1%	0%	10%	10%
Facility HVAC	8%	15%	4%	4%	3%	1%	0%	8%	3%	8%	8%
Facility lighting	7%	10%	7%	3%	4%	1%	0%	7%	3%	4%	4%
Facility support	2%	2%	1%	1%	1%	0%	0%	2%	0%	4%	4%
Onsite transportation	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Table A.3 shows the potential savings from DSM measures for a list of end-use processes. These savings are conservative estimates based on Howells et al (2002).That report based its results on findings from energy audits conducted at local plants. Again, it is important to note that the number of studies from which these estimates were drawn are limited, there is no guarantee that they are representative. The data is also limited in that it considers only a narrow set of interventions whose selection was related to the average payback period. The interventions should be disaggregated further in the future.

Table A.4: DSM interventions and their potential (stand alone) savings by end use

Use of electricity / measure considered	*Steam system*	*Other thermal measures*	*Efficient motors*	*VSDs*	*Efficient lighting*	*Compressed air saving*	*HVAC*	*Refrigeration*	*Load shifting*
Indirect uses-boiler fuel	15%	5%							
Process heating		5%							
Process cooling and refrigeration				10%					20%
Machine drive (inc compressed air)			5%	5%		15%		15%	
Electro-chemical processes									
Other process use									
Facility HVAC			5%	10%			30%		20%
Facility lighting					40%				
Facility support									
Onsite transportation									

The savings estimates of Table A.5 represent a conservative estimate of savings potential. These measures are not independent. If one measure is implemented in an end use category this will reduce the energy consumed by that end use. If another DSM measure is subsequently implemented to the same category, there is less energy being consumed by this end use and therefore less energy that can be saved by the second measure, and so on. Thus the savings by end use, by measure are revised downward to consider the potential savings were all measures to be introduced. This could lead to an underestimate of the potential of individual measures. In this study the assumption is that a suite of DSM measures is implemented in each industry sector.

From this I derive a saving potential (expressed as a percentage of total energy consumption) for each of the end uses. The percentage saving is multiplied by the energy consumed by each end use to give an estimate of potential DSM savings for the individual sectors. From this a ranking of DSM potential by industrial sub-sector is established. This is shown in Table A.5.

Table A.5: Energy saving, DSM potential and ranking of industries based on current electricity consumption

Sector	*GWhr equivalent saved*	*% of DSM*	*Ranking*
Gold mining	2311	21%	1
Iron and steel	2289	21%	2
Wood and wood products	1458	13%	3
Chemicals	1370	12%	4
Platinum mining	927	8%	5
Food and beverages	605	5%	6
Rest of manufacture	542	5%	7
Non metallic minerals	524	5%	8
Coal mining	381	3%	9
Non ferrous metals	184	2%	10
Copper mining	133	1%	11
Rest of mining	121	1%	12
Diamond mining	91	1%	13
Textiles	67	1%	14
Iron ore mining	48	0%	15
Chrome mining	24	0%	16
Manganese mining	19	0%	17
Rest of basic metals	13	0%	18
Asbestos mining	3	0%	19

In order to derive the total DSM savings potential for each measure, the quantity of energy consumed for each end use was determined for all industry and mining. For each DSM measure the potential percentage savings (for each end use they affect) are multiplied by the total energy consumption by end use. The percentage savings are adjusted as described above. From this, the total energy savings are estimated per DSM measure and the DSM interventions are ranked accordingly. The ranking derived for these sectors represents an estimate of savings from retrofit at existing facilities, and is given in Table A.6.

Table A.6: DSM saving by measure and ranking for current electricity use

Measure	*GWhr equiv savings*	*% of DSM*	*Ranking*
Compressed air saving	2900	26%	1
VSDs	1977	18%	2
Efficient motors	1902	17%	3
Efficient lighting	1384	12%	4
Load shifting	1018 (equivalent)	9%	5
HVAC	710	6%	6
Other thermal measures	697	6%	7
Refrigeration	415	4%	8
Steam system	107	1%	9

When considering new installations (assuming similar end use splits) the ranking of industries will change, as shown in Table A.7. It is useful to separate new installations from existing ones as the implementation of DSM may be possible during the commissioning of new plant at different costs from retrofitting. This means that DSM implementation costs (associated with a measure implemented on an existing industrial plant) would decrease. It is also useful to consider that some industries may see a reduction in output over time and consequently so will the potential for DSM.

Table A.7: Energy saving, DSM potential and ranking of industries based on future (2020) electricity consumption

Sector	*GWhr equivalent saved*	*% of DSM*	*Ranking*
Iron and steel	1 885	24%	1
Wood and wood products	1 483	19%	2
Chemicals	1 045	13%	3
Food and beverages	900	11%	4
Non metallic minerals	891	11%	5
Platinum mining	844	11%	6
Rest of manufacture	381	5%	7
Non ferrous metals	149	2%	8
Coal mining	114	1%	9
Textiles	97	1%	10
Rest of mining	91	1%	11
Iron ore mining	25	0%	12
Diamond mining	16	0%	13
Chrome mining	10	0%	14
Rest of basic metals	7	0%	15
Manganese mining	6	0%	16
Asbestos mining	0	0%	17
Copper minng	-38	(-6%)	18
Gold mining	-1040	(-15%)	19

Further considerations: Ease of implementation and cost

Howells and Laitner (2003) describe average payback periods (based on Howells et al (2003), and therefore consistent with this analysis) for the measures considered. If these estimates of payback periods are multiplied by the percentage attributable to each DSM measure and the products summed for each sector, I get an estimated payback period for the full range of interventions. The ranking of sectors under this approach is given in Table below.

Table A.8: Payback period of a suite of DSM interventions applied to and ranked by industry

Sector	*Payback*	*Rank*
Wood and wood products	2.2	1
Textiles	2.6	2
Rest of manufacture	2.6	3
Rest of basic metals	2.8	4
Other mining	2.4	5
Non metallic minerals	2.9	6
Non ferrous metals	2.6	7
Iron and steel	2.3	8
Gold mining	2.4	9
Food and beverages	2.4	10
Chemicals	2.7	11

Howells and Laitner (2003) and Kenny et al (2000 a, b,& c) and van Es et al (2003) describe the technical ease of implementation of each DSM measure. The lower the index, the less technically complex the implementation of the particular suite of DSM measures is. By considering the spread of savings by measure for each industry, industries are ranked in terms of the ease of technical[254] implementation of a range of options in Table A.9

Table A.9: Technical ease of implementation of a suite of DSM interventions applied to and ranked by industry

Sector	*Ease of implementation*	*Rank*
Wood and wood products	1.9	1
Rest of basic metals	2.0	2
Iron and steel	2.2	3
Non metallic minerals	2.3	4
Gold mining	2.4	5
Other mining	2.4	6
Chemicals	2.5	7
Rest of manufacture	2.5	8
Textiles	2.7	9
Food and beverages	2.7	10
Non ferrous metals	2.7	11

It is interesting that ‘Wood and wood products’ is both most cost effective and requires the least technical effort. It is also interesting to note that sectors which score well in terms of

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[254] It should be noted that this does not account for ‘ease of behavioral change’ which may be required.

payback and technical ease of implementation also have the greatest potential for DSM savings.

A.4 Conclusions

Table A.10 gives an indication of DSM saving potential by industry based on the literature survey and analysis undertaken. The table shows the ranking of industries both in terms of current consumption and future. Cells shaded in dark grey indicated industries in the top five ranking for both time periods and cells shaded light gray those (remaining) in the top ten of both periods. The sector 'Rest of manufacture' is not considered as this 'sector' effectively includes many industrial processes, while I expect some similarity within other defined sector groupings.

Table A.10: Summary of DSM savings potential for current and future industries

Existing industries year 2004				*Industries of the future year 2020*			
Sector	*GWhr equivalent saved*	*% of DSM*	*Ranking*	*Sector*	*GWhr equivalent saved*	*% of DSM*	*Ranking*
Gold mining	2311	21%	1	Iron and steel	1885	24%	1
Iron and steel	2289	21%	2	Wood and wood products	1483	19%	2
Wood and wood products	1458	13%	3	Chemicals	1045	13%	3
Chemicals	1370	12%	4	Food and beverages	900	11%	4
Platinum mining	927	8%	5	Non metallic minerals	891	11%	5
Food and beverages	605	5%	6	Platinum mining	844	11%	6
Rest of manufacture	542	5%	7	Rest of manufacture	381	5%	7
Non metallic minerals	524	5%	8	Non ferrous metals	149	2%	8
Coal mining	381	3%	9	Coal mining	114	1%	9
Non ferrous metals	184	2%	10	Textiles	97	1%	10

Work in gold mines is important in terms of retrofit processes to include DSM. However, energy consumption in this sector is expected to fall in the future. This could mean that interventions in this sector may be short lived and their effectiveness would decline with the mines' decline in electricity demand.

The importance of including DSM from the onset in new industrial growth projects is in part related to the new process that will be taken up in the future. These processes may be different from current processes used in the sector concerned. Therefore, for a DSM strategy that would to target new industrial growth, it may be sensible to quantify and examine potential new process and design DSM specifically ‘into’ the growing industrial sector. From this, DSM strategies specific to that process for growing sub-sectors should be derived. This may reduce energy consumption by new plants. It may, therefore, be inappropriate to simply extrapolate the findings of current energy audits. Combined with energy audits, this knowledge may also provide strategic insight into the planning of potential interruptibility of electricity supply agreements.

The current work is primarily aimed at developing a strategy for DSM based on audits of existing plants, and not on the impact of new plant layout or process design which may affect future energy use. The focus is therefore on assessing existing plant, with the possible exclusion of gold mines which have declining production output and whose consumption has been described in detail in previous, albeit dated work (Geldenhuys (2003)).

A.5 Recommendations

It is recommended that audits are conducted at sites representing the industries with the greatest potential for DSM savings. The audits should be distributed among these industries according to their proportional contribution to total DSM potential as established in the above analysis. Within the industries, customers with the largest electricity consumption should be selected.

As an example I consider a case where the total number of audits is 10. Table A.11 shows the recommended number of audits for each industrial sector for this scenario.

Table A.11: Allocation of audits

Sector	*With gold mining*	*Without gold mining*
	Number of audits	
Gold mining	2	
Iron and steel	2	3
Wood and wood products	1	2
Chemicals	1	2
Platinum mining	1	1
Food and beverages	1	1
Non metallic minerals	1	1
Coal mining	1	

Non ferrous metals		

Increasing the number of audits will have two main benefits: it will improve the accuracy of the projected potential for savings in each sector and produce statistics for a larger number of sectors.

Further it is suggested that work be carried out considering the potential processes to be used by growing industries. This should be carried out in order to scope the potential for DSM interventions to be included in the commissioning of new industrial plant. For example, A special focus area, not considered here, would be assessing the potential for inturruptibility of supply agreements in planned industrial investments. The latter, securing inturruptibility of supply agreements, has been identified as an imperative by the most recent National Integrated Resource Plan for electricity (NER (2004)).

Appendix B[255]: Modelling multiple goals

This appendix presents work which predates that described in Chapter 8. Chapter 8 presents a model which can be run for multiple goals and determine emissions and fuel usage effects for multiple sectors. The model reported here is limited to identifying electricity related emissions and other attributes. While there is much repetition, this appendix provides the background information that is cited to this paper in Chapter 8.

In developing countries such as South Africa, greenhouse gas (GHG) mitigation is generally viewed with suspicion. Economic development and resulting energy use often increases emission levels. As a result, strategies to reduce these levels are viewed as impeding development and thus as contrary to government policy. Because of pressing development needs such as poverty alleviation, greenhouse gas mitigation is generally not high on the list of government imperatives. GHG mitigation measures often have attributes that affect several different development objectives and therefore government departments. This makes coordination and ranking of the options difficult. It is therefore sensible to develop a model to determine how GHG mitigation measures, sets of measures and optimal pathways[256] affect development. Further, it would be helpful to determine optimal strategies in terms of these competing goals. This would help indicate where best to spend limited resources and to develop a case for these measures to be implemented.

B.1 Background and motivation

Greenhouse gas emission levels can be mitigated through application of industrial electrical energy efficiency measures. These measures relate greenhouse gas mitigation to economic development. They can increase jobs and profits but have implementation difficulties.

Strategies such as fuel switching, use of renewable energy, more efficient methods of energy transformation and supply, and improved manufacturing processes can also reduce emission levels. In South Africa, a sub-set that has been identified as a national planning priority (Trikam et al. (2003)) is the accelerated uptake of electrical energy efficiency

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[255] This section draws heavily from the paper: Howells, M. (In Press), Modeling Multiple Goals: GHG Mitigation and Socio-economic Development**,** Journal of Energy in Southern Africa, submitted

[256] GHG mitigation pathways include the extent and timing of mitigation measures in the system considered.

project in industry. As South Africa's electricity is predominantly coal based, another recent emphasis has been placed on an increased uptake of renewable energies (DME (2003c)). As with several countries, much recent analysis in South Africa, has been undertaken using the least cost modelling framework, MARKAL (DME (2003a))

Most analysis of greenhouse gas mitigation strategies in modeling frameworks has looked at single objectives, such as least cost. A typical analysis will use a model that determines how to meet various lower than expected emissions targets[257] (The model could have linear programming or partial equilibrium.) According to Goldstein and Hobbs (2003), such modeling is often undertaken without consideration of other important goals that should be included in the decision process. A recent assessment of the state of the art of modeling in the area of environmental policy (Laitner et al., (2000)) has strongly suggested the need for the application of multi-criteria analyses in this area.

Motivated by this, a formulation (GP[258]-MARKAL) of the MARKAL linear programming model has been adapted to include more than one objective in its objective function (Goldstein and Hobbs (2003)). Recent work, with South Africa as a case study (Howells and Laitner (2003)), developed a multi-criteria decision analysis framework to evaluate various industrial electrical energy efficiency measures against development goals. The latter work evaluated each GHG mitigation options in isolation and did not consider their combined effects[259], nor did it consider the optimal timing of implementing them. An application of GP-MARKAL is therefore developed for South Africa to overcome these short comings.

B.2 Methodology

We take as our starting point the system defined by Howells and Laitner (2003), and adopt South Africa as a case study. South Africa is a coal-intensive[260], developing country that currently has no obligations to reduce greenhouse gas emission levels under agreements

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[257] For a South African application, please see Howells and Solomon (2003).

[258] An abbreviation for 'Goal Programming'.

[259] Such as increased economy wide consumption of electricity that would result from increased industrial efficiency and its economic growth effects.

[260] Coal account for over 90% of electricity generation and more than 30% of total final energy consumption.

such as the Kyoto Protocol. Moreover, the role of emissions trading mechanisms is unclear as an effective incentive for developing countries to reduce emission levels. South Africa's electricity costs are the lowest in the world, which is a disincentive to certain interventions in the South African energy sector, such as the uptake of energy efficiency or renewable energy. (DME (2004a)).

We limit our attention to interventions that affect electricity use in industry and the emissions that are associated with its production. I consider a range of energy efficiency measures and the purchase of carbon free[261] renewable electricity. I wish to consider a short to medium term time frame (that is from 2004 to 2022) and not consider structural change in the economy as a greenhouse gas mitigation option. The measures considered are such that their uptake could be easily encouraged by national policies (Trikam et al. (2003)).

The uptake of these measures will affect various aspects of the country's development and coincide with various energy and non-energy related national goals (Hughes et. al. (2002), and DME (2004a)[262]). The model is developed to optimize for these goals. The weighting, or importance of these goals in terms of national development, will be determined over time as priorities change. A series of scenarios are therefore analyzed to determine features of development pathways for different priorities and weighting.

B.3 Measures considered

We consider measures that could be implemented through targeted programs. These change the standard use of energy and equipment in South African industry or replace it. The change brings about a reduction in electricity consumption, however it usually requires upfront payment. The following measures were identified (Howells & Laitner (2003) and Trikam et a.(2002)):

Variable speed drives – These drives reduce unnecessary power consumption in electrical motors with varying loads.

Efficient motors – These are available at higher cost. Efficient motors can reduce power consumption, but may require adaptation as running speeds are generally higher than for inefficient motors.

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[261] We do not consider carbon emitted during the manufacture of the technologies we consider.

[262] Note that these are "development goals as defined by the South African Department of Minerals and Energy.

Compressed air management – This is an easily achieved measure that often results in significant savings at low cost.

Efficient lighting – These measures take advantage of natural lighting, more efficient bulbs and appropriate task lighting.

HVAC – These measures maintain good air quality and temperature. They include better maintenance and the installation of appropriate plants.

Refrigeration – Often, after a few years of operation, the performance of fridge plants can be improved by better maintenance. This is often a better measure than getting new plant as new plant often does not make use of its reject heat and cooling and is often 'oversupplied'. These measures target the resulting inefficiencies.

Thermal saving. – Heat can be produced and used more efficiently. I consider two sets of thermal saving measures: those for electrode boilers and steam systems, and those for other heating processes such as furnaces and in-line heating.

We also consider the option of industry purchasing carbon free electricity by entering into a power purchase agreement with producers. Due to its low cost relative to other renewable generation options, I consider wind-generated electricity.

Several consequences of these measures directly affect the development goals. Attribute values (either directly attributed to the measure or via its effect through the system) are discussed further in the 'modeling' section of this paper.

B.4 Development goals

Next we consider the effect that the energy system has on various policy objectives (DME (2004c)). We shall term these objectives, 'development goals'. The development goals that are considered here are mapped to attributes of the economy over which the energy system has a clear influence. Meeting these goals would therefore include, for example, minimizing attributes such as local air pollution, or minimizing the energy system cost etc. A list of 'development goals', influenced by the energy system were identified by the Department of Minerals and Energy (Hughes et al. (2002)). A subset[263] that would be affected specifically by the measures chosen are modeled. Issue of importance to industry, such as the ease with which a measure could be taken up and its affects on profitability (see

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[263] It is worthwhile noting that solving for this subset, rather than all aspects simultaneously, may result in a less than optimal system.

Howells & Solomon (2002)), are also considered. The GP-MARKAL model formulation allows the modeler to optimize attributes values (such as minimizing cost to derive a 'least cost' solution). For consistency, the objectives[264] are stated as attributes to be minimized:

- **Gaseous emissions** such as carbon dioxide, an important greenhouse gas emission[265], and local pollutants such as sulphur dioxide, nitrogen oxides and particles.
- **Water usage** is a key consideration for South Africa's development, as resources are limited.
- **Total system cost** reduction is an imperative of the National Electricity Regulator (NER 2004). Minimizing the cost of supplying electricity, as well as the service derived from electricity (DME (2004c)) is modeled.
- Increased technology transfer is an option which could help increase local productivity. In this modeling framework, it is equivalent to reducing **reliance on local technology**. To accommodate this, I develop two cases for each measure: one with a high proportion of local content (80%) and one with a low content (20%). This is a proxy for technology transfer.
- Job creation currently receives of the highest attention in terms of government spending, Minimizing **job losses** is thus important (Treasury 2004).
- We wish to consider the ease with which the measure should be implemented. This attribute is termed **complexity of implementation**
- Profitability is high on the list of attributes that industry would like to maximize. As the problem is formulated in terms of attributes to be minimized; the **"un-profitability"** of energy efficient options is modeled.

B.5 Modelling

The modeling framework developed to calculate the attributes of the system, which are then minimized in various scenarios is now discussed. The section begins by discussing aspects related to Input Output (IO) modeling and then issues related to the GP-MARKAL model developed. This is important, as aspects of the IO modelling are incorporated into

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[264] While these objective represent the expressed views of government, they are not exhaustive. Future analysis may wish to incorperate a more comprehensive list.

[265] Other GHG emissions such as methane and nitrous oxides are negligible from South African electricity generation (Lloyd and Trikam (2004)).

the GP-MARKAL model, allowing the model to take into account economy wide effects that it would otherwise not.

Input-Output modeling

From the national Social Accounting Matrix, SAM, an input output (I/O) model can be constructed. The economy wide effects of changes in spending in an energy efficiency investment, for example, can be deduced. This approach has been adopted for several studies relating to energy efficiency programs and is suited to evaluating perturbations in the short to medium term. I adopt aspects of the framework described by Fletcher et al. (2003). Similar approaches have been used elsewhere by Geller et al. (1992) and Laitner et al. (1998), and for the South African context by Laitner (2001) and Jeftha (2003). I also adopt parameters[266] from recent national electricity planning exercises (NER (2004)) for the I/O analysis.

An Input-Output model is used to develop data to be incorporated into the GP-MARKAL model (in the form of coefficients). This is done in order to simulate the effects of the energy efficiency or renewable energy investments through the economy. Two effects are considered. The first is the annual change in energy demand in different sectors as a result of the investment, the second the annual effect on job creation in the whole economy.

Countrywide employment coefficients are derived using the same methodology described by Fletcher et al. (2003) with several special aspects considered. We consider jobs created per kW of electricity saved per year by the energy efficiency investment. For instance, renewable jobs created per kW of renewable energy installed are calculated.

Some notable aspects of the approach are mentioned below:

- Specific changes in spending in the economy included changes in[267]:

1. Payments to construct the energy efficiency or renewable energy intervention.

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[266] Such as the 10% discount rate used.

[267] Please see the appendix for a graphical representation of these for electricity supply, and values used for the analysis. For a detailed account of spending pattern changes, for energy efficiency investments, please see Fletcher et al. (2003). For investments in Renewable Energy we consider the difference in cost between the investment in renewable energy and generating options that are 'displaced'. The relative proportions of peak and baseload stations 'displaced' were derived using MARKAL (assuming least cost optimization) and are indicated in the appendix.

2. Fuel cost changes to industry: Savings for energy efficiency investments and increased costs for renewable energy power purchase agreements.
3. Equity costs for industry or the electricity supply industry assuming a debt equity ration consistent with national planning (NER 2004)
4. Interest on loan payments for to the finance sector over the repayment period (energy efficiency) or economic life (electricity supply) of the investment.
5. Electricity supply industry fuel cost and tariff changes that occur from reduced demand, or the substitution of renewable energy options for business as usual options.

- The work Fletcher et al. (2003) derives total employment figures for the period which was being considered for that study. I estimate annual employment figures.
- In general (for both changes in employment and electricity demand data) I consider effects relating to the investment phase of the measure (accounted for in year 1) and other effects relating to its financing and operation[268](accounted for as an average over the lifetime of the measure).
- Accounting for time dependence[269] allows us to observe the effects of applying different 'discount rates' to the job creation indicator.

Figure B.1, shows average, levelised figures for jobs created as a function per MW of installed wind capacity at two different levels of local content (80% and 20% assuming the same cost). Job creation is shown during investment in year 1, and operation in year 1 and subsequent years. I assume that costs are borne by industry through an effective increase to their overall electricity price over the economic life of the plant displacing a fixed quantity of coal (see appendix).

Job creation with a local content[270] of 20%	*Job creation with a local content of 80%*

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[268] Key parameters required for the formulation are reported in the appendix, including changes in production and investments in the electricity sector as a function of new investment in renewable energy.

[269] Spending over construction is discounted and levelised to derive a single year figure for investments. Similarly, the effects while running the new technology are not smooth over time, yet a single levelised figure is derived to approximate the time dependency of the measure.

[270] Installation and manufacture.

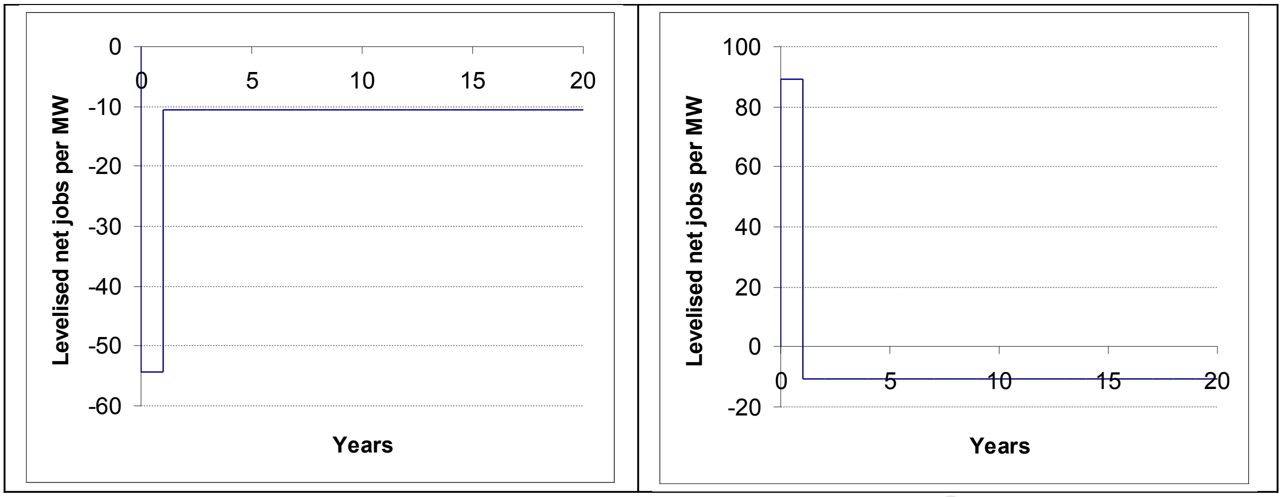

Figure B.1: Jobs and investment in wind

Two dynamics are well illustrated above: the decrease in jobs relating to increased foreign content and increased electricity price. It is interesting to note that, while there may be increased jobs and economic activity during the construction of renewable energy projects such as wind, there may be long term losses resulting from increased electricity prices.

For energy efficiency measures, where the effect is to reduce the effective cost of electricity (as less electricity is consumed at the same price), jobs are increased during the life of the equipment. A similar dynamic to that of Renewable Energy is observed in relation to foreign and local content. The extent to which jobs are lost or created as a result of construction is also dependent on the cost of installation. If the costs exceed the savings that will accrue, it is likely that this will result in job losses. Under certain circumstances, low cost, effective measures with a high foreign content may create more jobs than similar measures that are more expensive, but have a high local content. For illustrative purposes, I therefore consider a price difference, as part of starting set of assumptions, for local versus foreign content in measures (see appendix).

We also consider the effect of changes in spending in the economy on expenditure in other sectors. Of particular interested are changes in electricity demand in different sectors[271]. It is important that these are derived on a sector by sector basis, as electricity use is sector dependent. For example, the service sector has a more peaky time of use profile than industry, which is relatively flat. Thus an increase in services electricity demand will result

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[271] In terms of industry itself, there is an increase in energy demand of about 2% of the savings affected by the energy efficiency measure. An economy wide increase of about 3% is observed.

in a more peaky economy wide electricity demand profile (see Figure B.2). This in turn will change the shape of investment in the power sector and its cost. I therefore capture the effects of changes in electricity demand by sector over time, by determining coefficients for both the construction and operation of the measure considered.

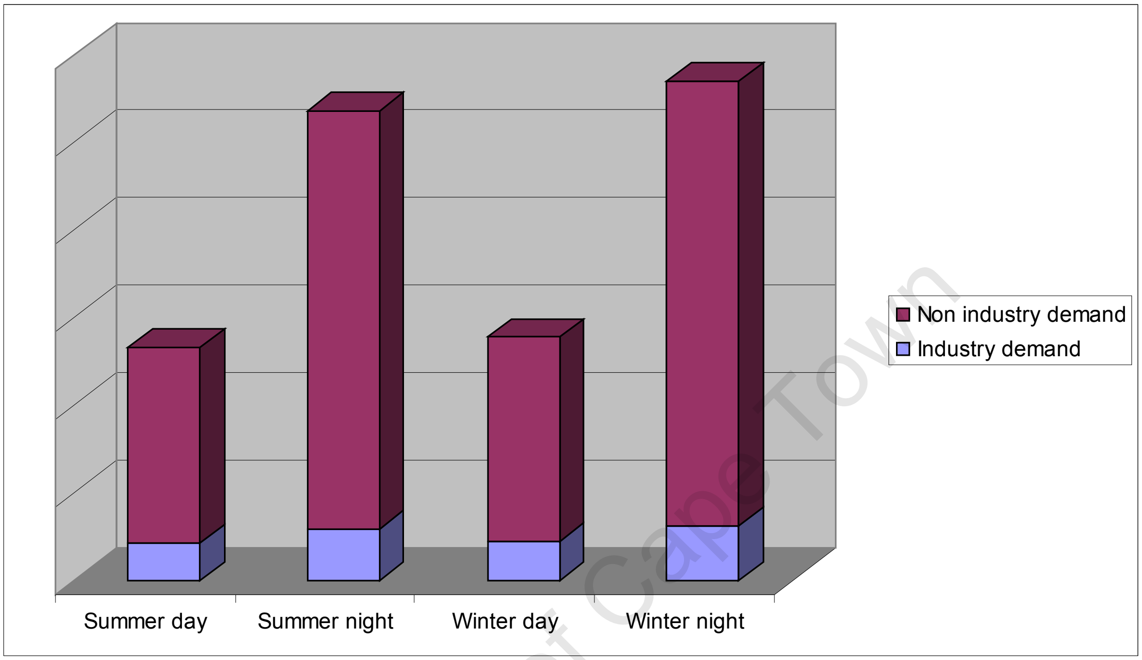

Figure B.2: Simplified industry[272] and non industry electricity consumption patterns

Changes in electricity consumption are related to changes in price and other factors. Thus I account for electricity cost to electricity demand changes (elasticities) endogenously in the model as well as (cross elasticity) effects with other sectors.

GP-MARKAL Modelling

In order to carry out the optimization, and account for the attributes of the energy system, I develop a partial equilibrium GP-MARKAL energy model. Two special aspects of this study are that it is the first detailed application of the new goal programming formulation of this tool, and that I have set the tool up to take account of changes of energy demand as a function of investments and the changes in money flows in the economy that they represent. I add ability to account for changes in jobs in the system.)

By accounting for changes in electricity demand from the energy efficiency and renewable energy investments, I can use GP-MARKAL to calculate the required investment in new

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[272] This does not include mining.

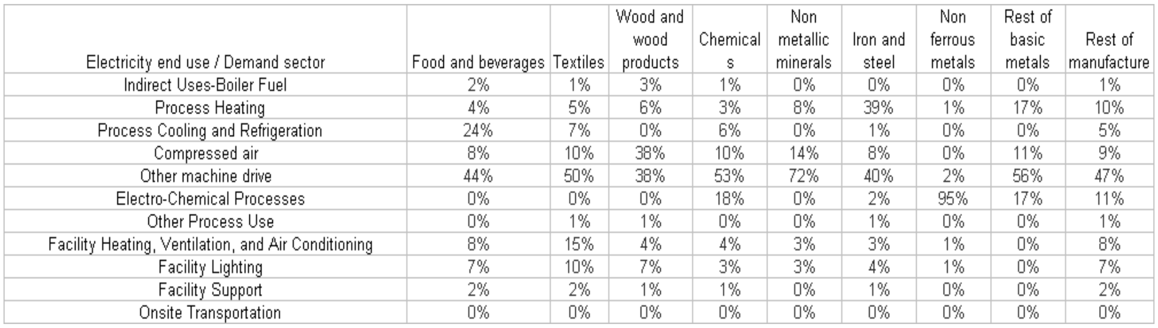
power stations. A novel structure is defined for the standard MARKAL reference energy system (RES) in order to include the input output dynamics (see Appendix B.9).

We calibrate the model using detailed sector-by-sector demand projections (Howells 2004a) and identify a limited set of power investments based on recent electricity sector planning (NER 2004). I consider coal, open-cycle gas peaking plant and wind. Natural gas investments are not considered due to limited local reserves and limited gas infrastructure and relatively inexpensive alternatives.

In order to calculate the attributes of the system, coefficients gathered from various sources are used to relate energy use with the attribute considered. Gaseous emissions per unit of power station fuel consumed are taken from the IPCC (1996) and van Horen (1996), water emissions data from van Horen (1996), and indicators for the 'difficulty of implementation' and industry 'un-profitability' from Howells and Laitner (2003). Job creation and the effects of other sector growth are calculated using the national SAM (TIPS 2001). A first order estimate is made of emissions from non-electricity fuel use. This is done by assuming that fuel use patterns (apart from the uptake of electrical energy efficiency measures modeled here) do not change significantly over national expectations over the scenario period (DME 2003a). The model is then run and the attributes of the system calculated.

The effect and potential penetration of the energy efficiency measures were determined by considering growth in individual industry sectors (NER 2004) and then the use to which this electricity is put (considering several studies[273]), as shown in Table B.1 below.

Table B.1: Electricity end use by industry



Electricity end use / Demand sector	Food and beverages	Textiles	Wood and wood products	Chemicals	Non metallic minerals	Iron and steel	Non ferrous metals	Rest of basic metals	Rest of manufacture
Indirect Uses-Boiler Fuel	2%	1%	3%	1%	0%	0%	0%	0%	1%
Process Heating	4%	5%	6%	3%	8%	39%	1%	17%	10%
Process Cooling and Refrigeration	24%	7%	0%	6%	0%	1%	0%	0%	5%
Compressed air	8%	10%	38%	10%	14%	8%	0%	11%	9%
Other machine drive	44%	50%	38%	53%	72%	40%	2%	56%	47%
Electro-Chemical Processes	0%	0%	0%	18%	0%	2%	95%	17%	11%
Other Process Use	0%	1%	1%	0%	0%	1%	0%	0%	1%
Facility Heating, Ventilation, and Air Conditioning	8%	15%	4%	4%	3%	3%	1%	0%	8%
Facility Lighting	7%	10%	7%	3%	3%	4%	1%	0%	7%
Facility Support	2%	2%	1%	1%	0%	1%	0%	0%	2%
Onsite Transportation	0%	0%	0%	0%	0%	0%	0%	0%	0%

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[273] US Department of Energy's Energy Information Administration (EIA 2004) and the British Department of Trade and Industry (DTI 2004), and for mining the South African Department of Energy's Integrated Energy Plan (Howells et al 2002)

We assume low[274] penetrations for each of the energy efficiency measures, with a maximum of about seven percent total saving in consumption allowed[275]. The saving assumed per measure by industrial sector for each end use is given in the appendix.

A special feature of GP-MARKAL is its ability to solve for various goals. The model employs a technique known as non-preemptive programming[276]. In this model, I weight the important minimizing attributes of model runs. In standard MARKAL, minimizing total system costs only, is the goal.

In this application, technology-specific discount rates are considered – or 'hurdle rates' – associated with the uptake of specific measures or technologies. (This is apart from a global discount rate of 10%). In the case of industry, I shall describe the low penetration in terms of a high hurdle rate. Little energy efficient practice in South Africa is taken up for various reasons (Fletcher et al. 2003).

B.6 Scenarios

We develop scenarios in terms of different weightings of the development goals, the effect of reducing the hurdle rates of energy efficient technologies and the role of technology transfer on job creation. In some scenarios, defined by different weightings of development goals, I shall attach a zero weighting to the goal of greenhouse gas mitigation, as in many cases this is not a consideration in national level decision making. In summary, I define the following families of scenarios:

Scenarios with different hurdle rates for energy efficient technologies

In these scenarios I shall reduce the hurdle rate from one that is reflective of current practice (which I shall refer to as the Base Case) to one that is economically efficient (which I shall call the Least Cost case) and report the effects in terms of the system attributes.

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[274] This data is based on local energy auditing work (see Howells et al. 1999)

[275] Future studies should consider an increased number of measure and potential savings.

[276] See Goldstein and Hobbs (2003) for a detailed description,

Development scenarios

In these scenarios, I wish to determine optimal levels of new technologies in the energy-economy by solving the system for different weightings of the defined development goals. I consider three scenarios with the same weighting structure defined by earlier work (Howells and Laitner 2003):

7. *Government goals*, based on current government spending that is skewed heavily toward job creation. This does not include policy to reduce greenhouse emissions.
8. *Industry goals*, is a scenario in which development is driven by industry and weights improving profitability and improving the ease of implementing any changes (or in the model construct: decreasing un-profitability and difficulty of implementation). Again, greenhouse gas mitigation is not considered as a goal in itself.
9. The *Green goals* scenario is a case that increases the weighting of environmental improvement, including greenhouse gas mitigation.

Sensitivity scenario

In the sensitivity study I investigate the effects of decreasing job losses from the set of interventions that I have considered. In particular I consider the relative proportions of local to foreign content involved in the interventions.

B.7 Results

We report selected results from the hurdle rate, development and sensitivity scenario families.

In the hurdle rate scenarios, I report the effects of using a range of technology specific discount rate (or hurdle rate) energy efficient technologies and wind generators. The effect of having a high discount/hurdle rate for new technology is to reduce the penetration of the new investments. This represents in economic terms the reluctance of the market to adopt the new technology. A high technology specific discount rate (close to 500%!) is reflects the attitude of several leading industries in South Africa (see ERI 2000). I report levels of energy efficient technology penetration, changes in job losses, industry profitability, system cost, CO_2 emissions and water savings. (We compare all values relative to the least cost solution with all discount rates set at 10%).

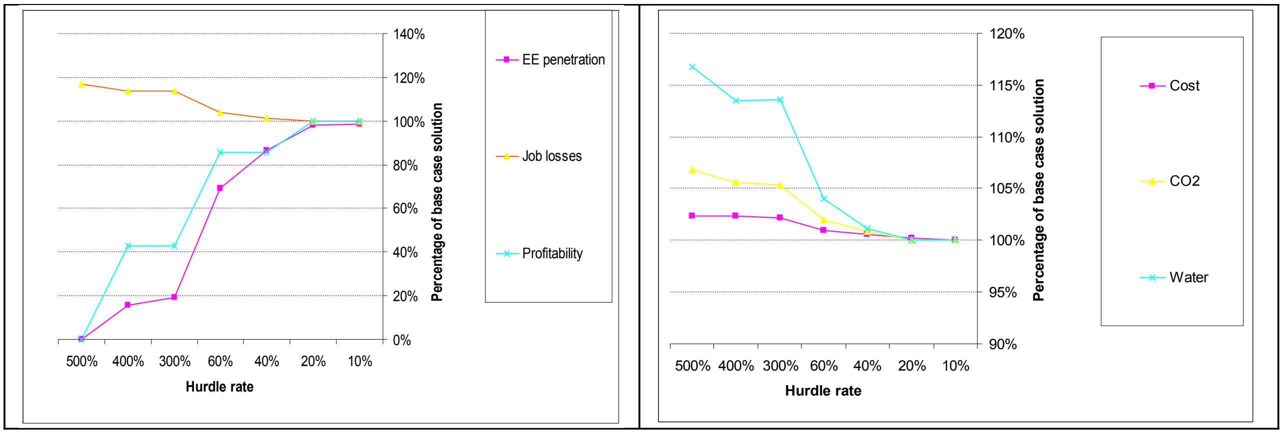

Figure B.3: Reducing the hurdle rate for EE and RE technologies to an efficient 12% discount rate

In all cases, all attributes move towards levels desirable for increased development. The reason for this is an uptake of various energy efficient technologies. At lower discount rates wind generated electricity becomes a desirable solution. However, the discount rates required for wind to become an economic option would not be economic. These results show that there are benefits to developing the market for energy efficient technologies such that investment decisions are made in an economically efficient manner.

Next I consider the effect of the meeting the multiple goals of the development scenarios rather than simply changing parameters within a cost minimizing model. The aim is to determine what the energy system would look like if the goals (and the weighting) of the development scenarios were modeled. This approach is particularly powerful as it takes advantage of potential synergies within the system in such a way that parts of the system that meet more than one goal may now be selected. These would not have been selected if only one goal were being optimized. It also allows different goals to be traded off against each other in a single framework, and it identifies type of investment and gives its timing. I report the three different development cases and the Least Cost case against the base case. Figure B.4 shows the attribute levels of the scenarios modeled as a percentage of the Base Case values.

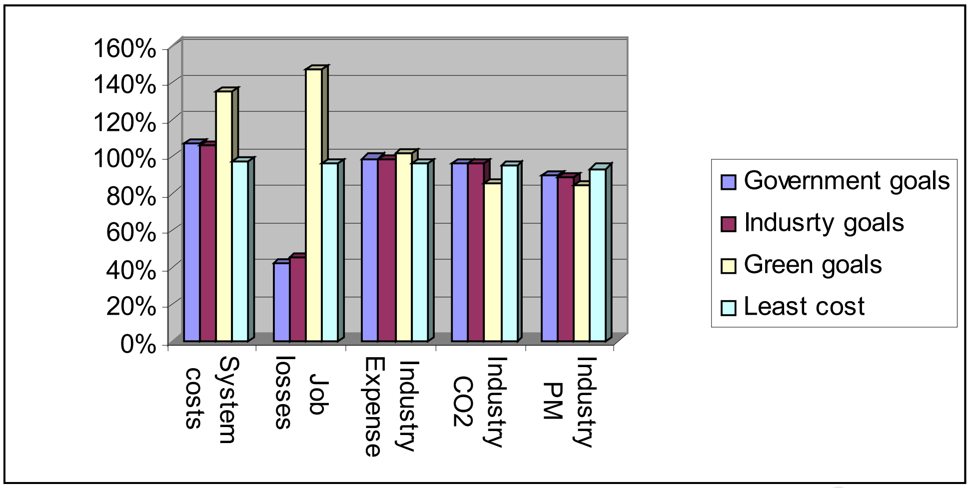

Figure B.4: Attributes of different development futures relative to business as usual

In all cases CO_2 is mitigated. This is due to adoption of renewable energy (wind) and energy efficiency technologies. In the least cost solution, renewable energy is not included in the solution. This implies that there are technologies that co-incidentally mitigate greenhouse gas emissions that are needed for all optimal 'development' scenarios. Conversely if these mitigation measures were to be implemented in an energy system with the purpose of reducing greenhouse gas emissions, these would 'drive' development.

Finally I report the results of a sensitivity study in which I examine the role that technology transfer could play on job creation. In order to do this, I set the model to meet various levels of job creation at lowest cost to the system, and report the relative quantities of local to foreign content of the new energy efficiency investments made. (A low percentage of local content is taken to be indicative of a high level of technology transfer.) I graph local content versus job creation in Figure B.5. The figure shows a trough below 100% figure for local content and it is clear (given our start assumptions in Figure B.5.) that there is a role for technology transfer to play in the system defined.

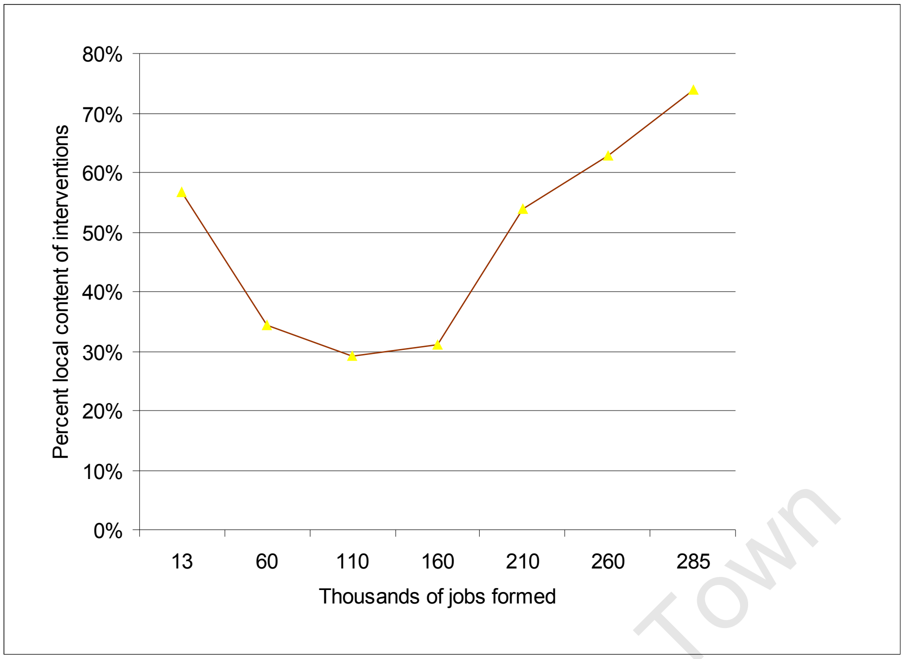

Figure B.5: Local content of EE technology to meet the constraint of increased job formation

In a similar manner, other parametric sensitivity studies may be undertaken. In itself that should be a valuable exercise as data used is uncertain.

B.8 Conclusion

This paper reports the development and application of a model that optimizes the energy system of a developing country to meet goals of development. The modeling technique chosen is a partial equilibrium, energy systems model that accounts for various attributes of the energy and economic system of South Africa. Also integrated into this model are aspects of an economic Input-Output model. I use the GP-MARKAL[277] framework, which allows us to minimize several attributes of the system and these are reported as 'development goals'. I examine a limited set of potential interventions to a business as usual energy future, their effect on the energy-economy and the role that they may play in different development scenarios. This analysis allows the specific investments required and their effects to be identified.

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[277] The tool used is a variant of the MARKAL family of models of the International Energy Agency's Energy Technology and Systems Analysis Program (ETSAP).

A key finding is that certain energy investments both drive development, and co-incidentally reduce emissions. Were these investments to be implemented for greenhouse gas reduction reasons, they would in effect drive development. Because of the transparent modeling techniques chosen, these measures and their effects can be clearly tracked.

This conclusion has a potentially profound effect in terms of the international climate change debate. This moves the pro-mitigation lobby's anecdotal arguments for clean development to arguments that are quantifiable. It also weakens the position that GHG emissions are necessarily synonymous with development. The implication is that developing countries can focus their attention on meeting urgent development imperatives under a climate friendly future.

We also deliberately consider the short to medium term (with a scenario period from 2004 to 2022) and do not consider induced structural changes to the economy as a mitigation measure. This allows us to consider a limited set of measures that may be influenced by policy in a short period of time.

Mechanisms such as the Clean Development Mechanism (CDM) have an important role to play funding measures (such as in this case centralized wind electricity generation) which would otherwise slow down economic development. There are, however, a range of measures currently not being[278] investigated, which meet development and GHG mitigation goals at a profit to our case study economy, compared to a business as usual 'Base Case'. An example from the South African case study is improved industrial electrical energy efficiency. Programs should be developed to reduce the hurdle rate to optimize their adoption, both for the sake of national development in poor countries and reduction of global greenhouse gas emissions.

Acknowledgements

The author very gratefully acknowledges both the intellectual and financial support of the EPA and its senior economist John'Skip' Laitner.

B.9 Appendix Key parameters for coal and wind generation plant considered in the I/O and GP-MARKAL models

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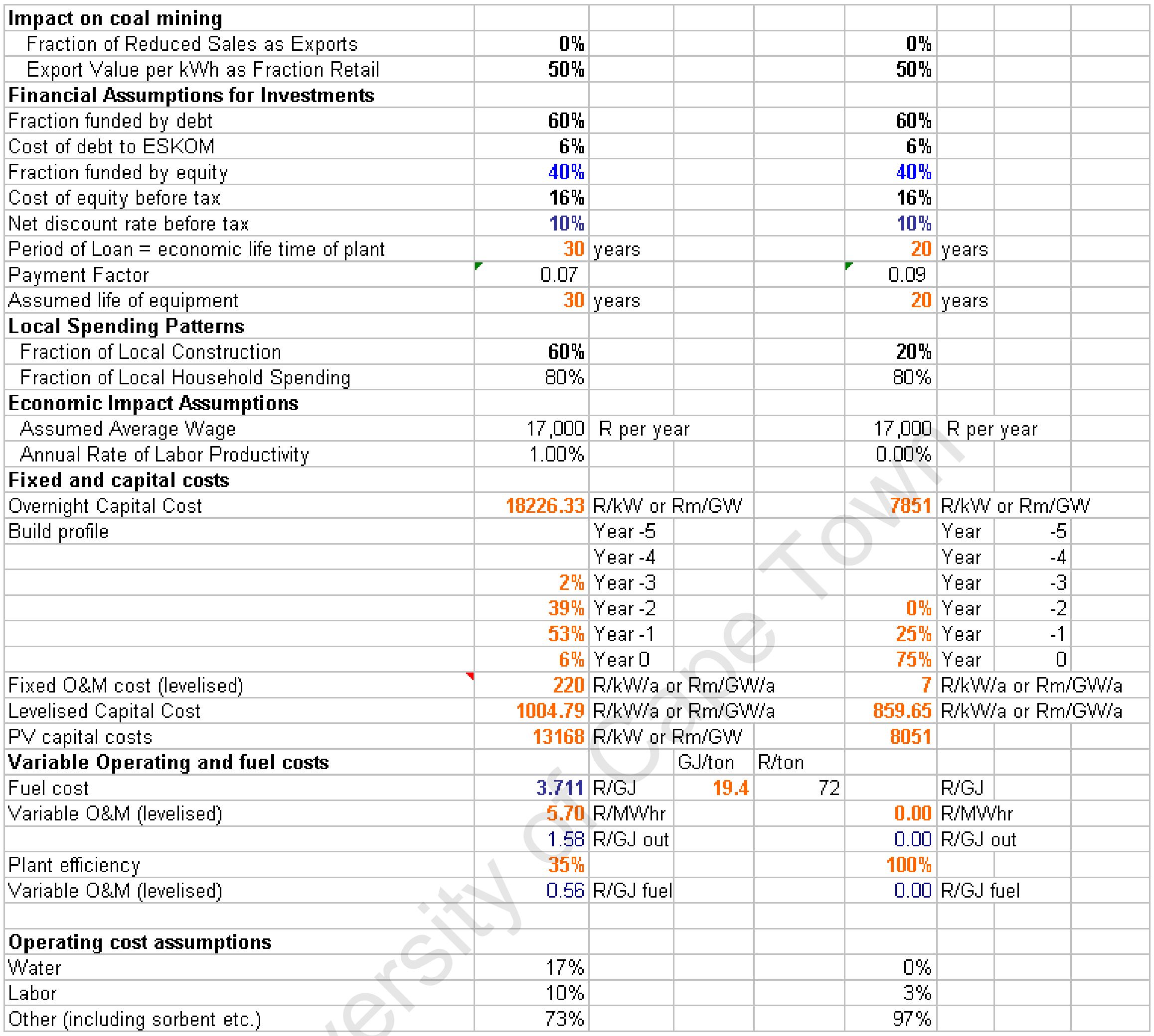
[278] Or being invested in at a slower than optimal rate.

Table B.2: Parameters used in I/O and GP MARKAL runs



Impact on coal mining								
Fraction of Reduced Sales as Exports	**0%**				**0%**			
Export Value per kWh as Fraction Retail	**50%**				**50%**			
Financial Assumptions for Investments								
Fraction funded by debt	**60%**				**60%**			
Cost of debt to ESKOM	**6%**				**6%**			
Fraction funded by equity	**40%**				**40%**			
Cost of equity before tax	**16%**				**16%**			
Net discount rate before tax	**10%**				**10%**			
Period of Loan = economic life time of plant	30	years			20	years		
Payment Factor	0.07				0.09			
Assumed life of equipment	30	years			20	years		
Local Spending Patterns								
Fraction of Local Construction	**60%**				**20%**			
Fraction of Local Household Spending	80%				80%			
Economic Impact Assumptions								
Assumed Average Wage	17,000	R per year			17,000	R per year		
Annual Rate of Labor Productivity	1.00%				0.00%			
Fixed and capital costs								
Overnight Capital Cost	18226.33	R/kW or Rm/GW			7851	R/kW or Rm/GW		
Build profile		Year -5				Year	-5	
		Year -4				Year	-4	
	2%	Year -3				Year	-3	
	39%	Year -2			0%	Year	-2	
	53%	Year -1			25%	Year	-1	
	6%	Year 0			75%	Year	0	
Fixed O&M cost (levelised)	220	R/kW/a or Rm/GW/a			7	R/kW/a or Rm/GW/a		
Levelised Capital Cost	1004.79	R/kW/a or Rm/GW/a			859.65	R/kW/a or Rm/GW/a		
PV capital costs	13168	R/kW or Rm/GW			8051			
Variable Operating and fuel costs			GJ/ton	R/ton				
Fuel cost	3.711	R/GJ	19.4	72		R/GJ		
Variable O&M (levelised)	5.70	R/MWhr			0.00	R/MWhr		
	1.58	R/GJ out			0.00	R/GJ out		
Plant efficiency	35%				100%			
Variable O&M (levelised)	0.56	R/GJ fuel			0.00	R/GJ fuel		
Operating cost assumptions								
Water	17%				0%			
Labor	10%				3%			
Other (including sorbent etc.)	73%				97%			

Changes in the electricity sector (assuming least cost operation) due to investment in renewable wind electricity generation.

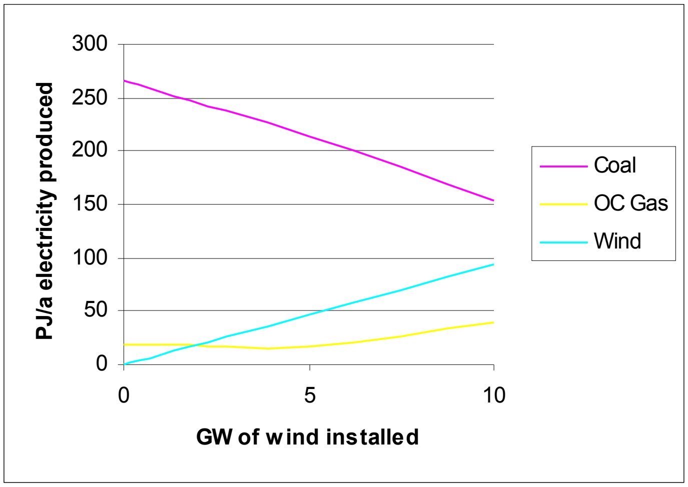


Figure B.6: Changes in electricity production as a result of an investment in wind capacity

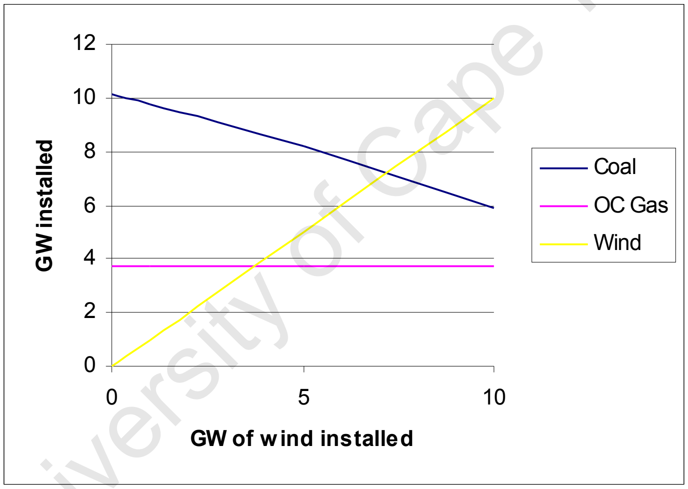
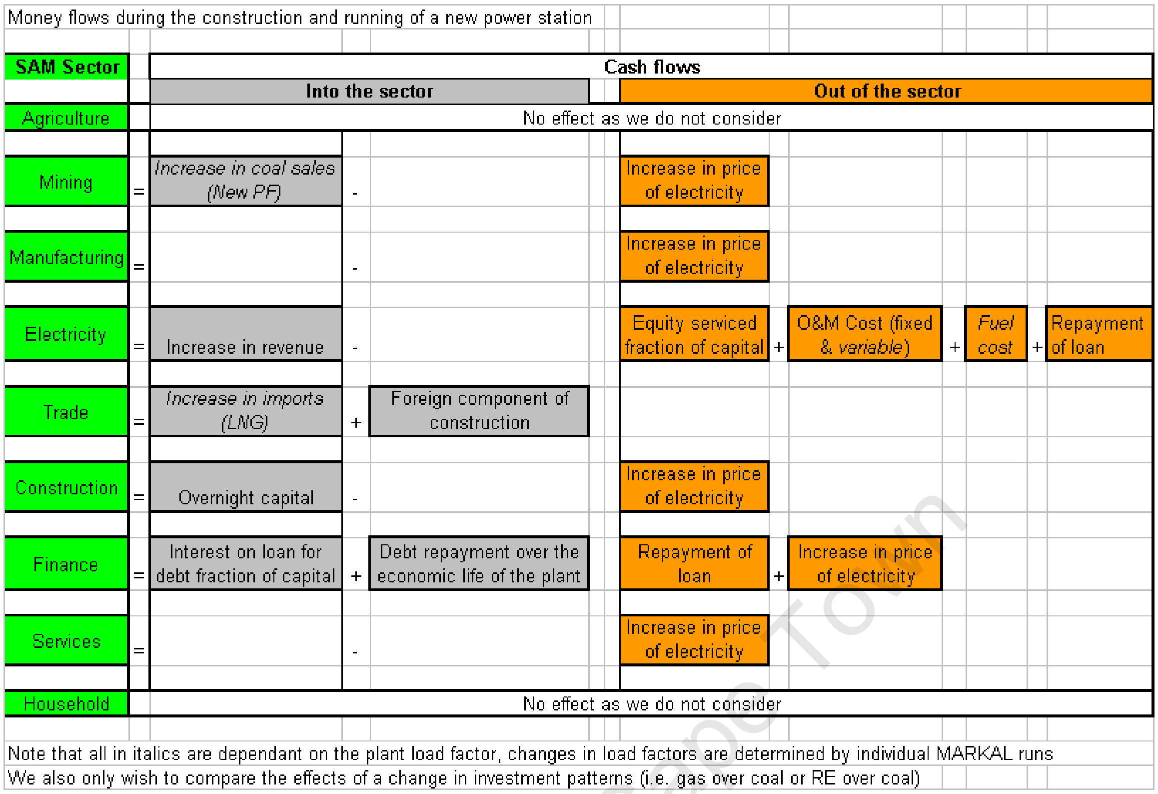


Figure B.7: Changes in electricity production capacity as a result of an investment in wind capacity



Money flows during the construction and running of a new power station

SAM Sector		**Cash flows**									
		Into the sector			**Out of the sector**						
Agriculture		No effect as we do not consider									
Mining	=	*Increase in coal sales (New PF)*	-		Increase in price of electricity						
Manufacturing	=		-		Increase in price of electricity						
Electricity	=	Increase in revenue	-		Equity serviced fraction of capital	+	O&M Cost (fixed & *variable*)	+	*Fuel cost*	+	Repayment of loan
Trade	=	*Increase in imports (LNG)*	+	Foreign component of construction							
Construction	=	Overnight capital	-		Increase in price of electricity						
Finance	=	Interest on loan for debt fraction of capital	+	Debt repayment over the economic life of the plant	Repayment of loan	+	Increase in price of electricity				
Services	=		-		Increase in price of electricity						
Household		No effect as we do not consider									

Note that all in italics are dependant on the plant load factor, changes in load factors are determined by individual MARKAL runs

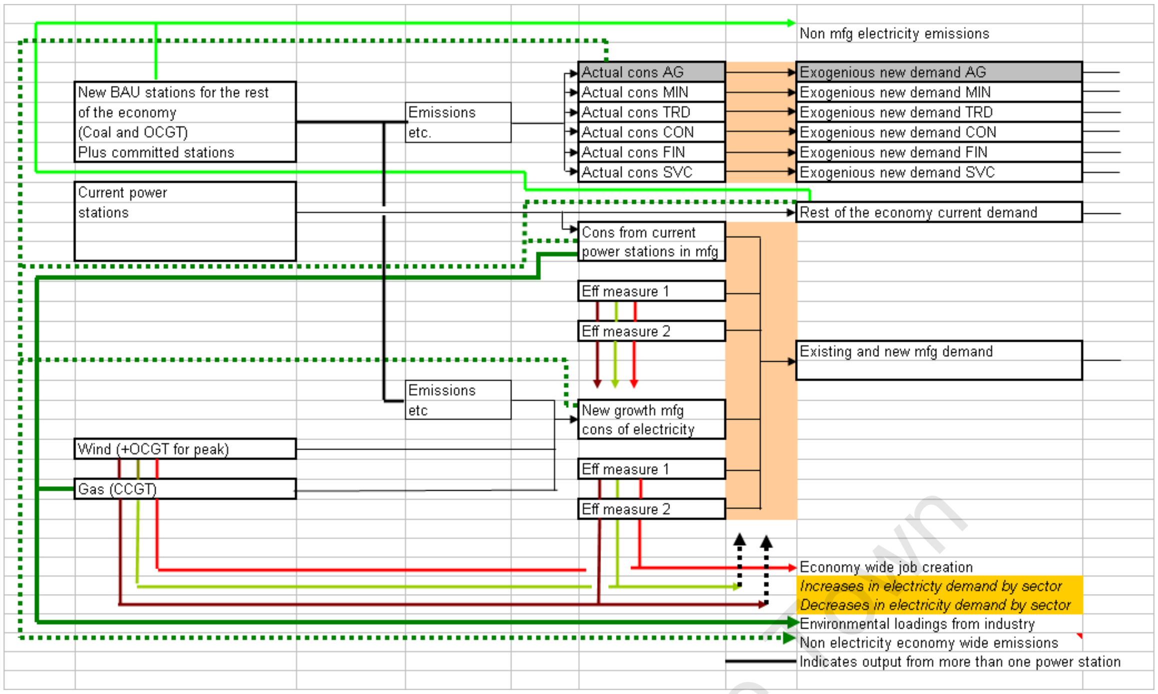
We also only wish to compare the effects of a change in investment patterns (i.e. gas over coal or RE over coal)

Figure B.8: Graphic illustration of cash flows through the economy for investment in new power generation options.

0-41 Table B.3: Energy efficiency assumptions

	Compressed Air	*HVAC*	*Lighting*	*Motors*	*Other thermal saving*	*Refrig-eration*	*Steam system*	*VSDs*
Rising index of 'Difficulty of implementation' (Howells and Laitner 2003)	1.0	2.0	3.0	3.0	1.0	2.0	1.0	3.0
Un-Profitability (Payback) (Howells and Laitner 2003)	1	1	3	5	0.5	1.0	0.5	4
Life (Howells and Laitner 2003)	4	5	5	8	2	5	3	8
Cost difference between local and foreign (assumed for this study)	0.9	1.1	1.2	1.4	0.9	1.4	1.3	1.4

Dummy
storage
Electric
stove –
operation



46 Figure B.9: RES for incorporating I/O components to the GP-MARKAL structure

0-42 Table1 B.4: Energy savings by measure for each end use considering a case where all measures[279] are applied.

All measures applied	Steam system	Other th	Efficient mot	VSDs	Efficient lig	Compresse	HVAC	Refrigeratic	Load shifting
Indirect Uses-Boiler Fuel	14%	4%	0%	0%	0%	0%	0%	0%	0%
Process Heating	0%	5%	0%	0%	0%	0%	0%	0%	0%
Process Cooling and Refrigeration	0%	0%	0%	9%	0%	0%	0%	9%	10%
Compressed air machine drive	0%	0%	2%	2%	0%	19%	0%	0%	0%
Other machine drive	0%	0%	3%	2%	0%	0%	0%	0%	0%
Electro-Chemical Processes	0%	0%	0%	0%	0%	0%	0%	0%	0%
Other Process Use	0%	0%	0%	0%	0%	0%	0%	0%	0%
Facility Heating, Ventilation, and Air Conditioning	0%	0%	4%	8%	0%	0%	13%	0%	10%
Facility Lighting	0%	0%	0%	0%	30%	0%	0%	0%	0%
Facility Support	0%	0%	0%	0%	0%	0%	0%	0%	0%
Onsite Transportation	0%	0%	0%	0%	0%	0%	0%	0%	0%

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[279] As some measures reduce the potential savings of others, when implemented in parallel. Reduction in compressed air demand, for example, will in turn reduce the possible savings that would be accrued if a compressor were fitted with a more efficient motor. In keeping with the theme of representing lower end potentials for the effect of energy efficiency we adopt these potentials.