AN ENERGY MODEL FOR A LOW INCOME RURAL AFRICAN VILLAGE

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ABSTRACT

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 from ingesting paraffin, and whole villages have burned from fires triggered by paraffin stoves and lamps.

This paper reports on efforts to extend a MARKAL[1] 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. 2002) 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[2], 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 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 account for why earlier studies often over-stated 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

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[1] For an overview of the MARKAL family, please see Goldstein, G.A., L.A. Greening, and the Partners in International Energy Agency – Energy Technology Systems Analysis Programme (IEA-ETSAP), 1999, *Energy Planning and the Development of Carbon Mitigation Strategies: Using the MARKAL Family of Models;* available from the ETSAP website, www.etsap.org. The model is fully described in *User's Guide for MARKAL* (BNL/KFA) Version 2.0," Fishbone, et. al., BNL 51701, July 1, 1983.

[2] 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.

supply from appliances results in understating the services met by the appliance and understating its economic performance.

We report load curves for energy demand activities such as cooking, heating and lighting and identify 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. We also investigate scenarios in which villagers are able to procure electricity (via grid connection, decentralized stand-alone generators and photovoltaics), and we examine the effects on energy choices if household pollution from appliances is internalized as health-related externality costs. Internalisation of pollution costs leads households to select at least a low volume of electricity, for lighting; when grid connections are available the shift to electricity is more extensive and less costly (to households and perhaps also to 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 schemes such as the Kyoto Protocol's Clean Development Mechanism (CDM).

INTRODUCTION

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 2003).

Apart from lack of funding, one of the main obstacles to facilitating this energy "transition" away from traditional fuels towards modern fuels is the lack of knowledge by policy makers about that factors that determine energy choices by rural consumers. This population group has been given priority in South African energy planning only recently, and thus time series data on energy choices is 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 in electrified areas (McFadzean 2002). This apparent sub-optimal allocation of resources has also probably led to over-estimates of the total system cost of an optimal electrification policy, which in turn may exacerbate the political difficulty in sustaining support for the economic viability of low-income electrification programs. A better understanding of the energy requirements and choices in low-income villages is needed.

This paper presents a new model of energy system dynamics of a low-income rural community in South Africa. We identify deficiencies in earlier efforts to model energy choices in rural villages, present this new model, and summarize a new survey of a non-electrified village (Nkweletsheni) that we use for calibration. We compute a baseline scenario for future consumption of energy services in the village, and we 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 modeling 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, with direct severe implications on health (IEA 2002, UN DESA 2001).

Most rural villagers have a low and sporadic income, which affects how they select energy services in at least three ways. First, and most simply, households with low levels of income will be 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 households have been given access to electricity through the subsidized electrification programme, only to be disconnected at a later stage because 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 institutions for financing and collective savings—such as "microfinance"—the barriers to entry 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. 2003). 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 the second choice for quick-start and small batch cooking (e.g., afternoon tea). (Even in other villages where electricity is available, expensive electrons are 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—but they are given the freedom to switch to other devices, such as efficient pressurized ("primus") devices for lighting. 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 and van Hooren, 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. Electricity is widely viewed as the cleanest fuel for households (Howells et al. 2002), 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 that are affordable at scale to limit airborne emissions. 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 for the lack of appropriate models and for limited availability of hard data. Modeling 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 in 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 for lack of appropriate modeling detail but also for 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 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 and Victor 2003), but they rarely quantify energy consumption to the level required by energy modelers.

THE MODELING FRAMEWORK

Building on previous work (Howells et. al., 2002), we develop a model 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 we are 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[3] (SHT);
- 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 1: List of 'end-use' appliances) satisfy these services, and 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 2. 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 1 & 2). Table 1 also notes which energy service each appliance can serve.

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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, and thus in the next section we focus briefly on those aspects of the modelling framework that are novel. First we 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, we examine the problems associated with multiple services supplied by single appliances. Having thus outlined this model and its novelties, we then turn to calibration and finally to presentation of results. Third, we 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.

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[3] 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.

Inclusion of Load Curves

Usually analyses of low-income villages are 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. We will examine prospects for both through in all scenarios considered in this study. Of particular interested 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 because 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, we rely on a new energy survey[4] that offers load curves with hourly resolution; for computational simplicity we average and adopt six 4-hour time-slices (2am-6am, 6am-10am and so forth) for each day; we 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.

In outlining our approach to modeling load curves we focus on electricity since electricity systems are sized for the peak during the load curve. Although we aim in this paper to build a model for a non-electrified village, we also explore scenarios that involve electrification and therefore we have 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 we

[4] Developed in previous work (Howells et al. 2002), may be downloaded, as an annex from http://ldml.stanford.edu/cesp/pdf/rural_energy_modeling.pdf

derive through calibrating our model against a rural energy survey (a subject we address in the next section). However, that alone 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 all devices being used for cooking will do so for that hour[5]. 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).[6]

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, we 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 TIIMES is driven by the amounts and profile of the projected useful energy demand, and the model must be able to operate in both pre-electrification and post-electrification environments, we address this shift to a more peaky load profile by adding availability constraints to the usage patterns for electrical appliances. In addition, we 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 smooth demand for cooking in the survey but, at the same time, have a more peaky electrical consumption.

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[5] 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.

[6] 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 is used to inform the shape of the load profiles of electrical devices used in this study.

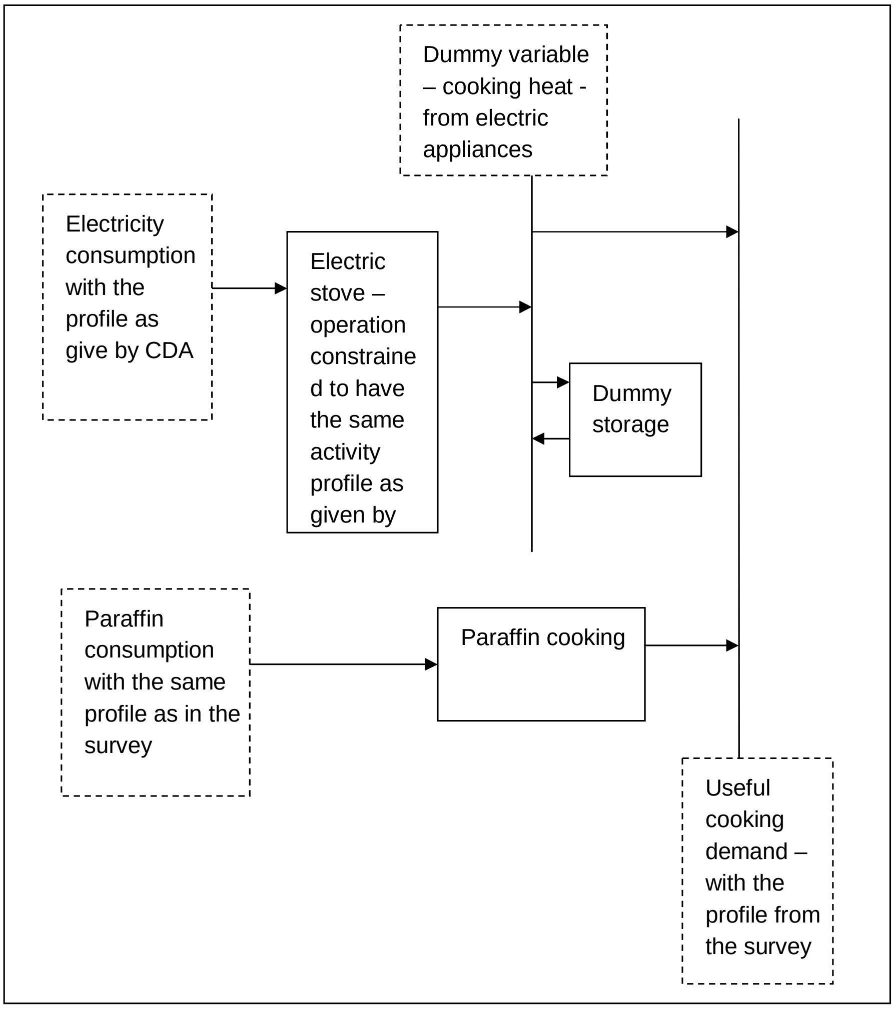

Figure 3: Modelling a device specific profile in TIMES

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

Modeling 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 thus 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[7] Such actions do indeed change the shape of the load curve by smoothing the peaks and valleys.

By capturing these effects we can estimate the load curves for individual appliance 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 4 below.

[7] 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.

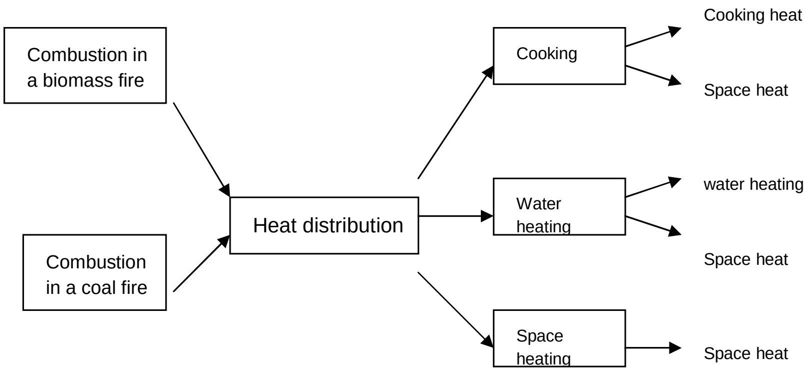

Figure 4: Modeling flexible appliances

In the approach employed, flexibility is ensured by letting the model choose the mix of energy forms (inputs) as well as and the output splits in satisfying the total demand for energy services. However, as shown on the right set of boxes in figure 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.

This approach contrasts with most other studies, which have focused on strategies for estimating total fuel consumption rather than disaggregating services, appliance 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). 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. An 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 we 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 appliance 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 the 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. Our model uses standard emission factors for appliances (Howells & de Villiers, 1998) 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 we present later illustrates this approach, with particular attention 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, which is examined cursory 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 and de Villiers (1999), summarized in table 3. These costs are then added to the objective function (total discounted costs) and are included in the least cost optimization.

CALIBRATION AND VILLAGE SURVEYS

Before presenting the model we must outline the method used for calibration, which requires surveys or some other method for measuring actual energy use data. Given the state of knowledge about energy choices and the myriad of 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 electric 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 we 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:

- 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 modeling (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. 2002) 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[8]. 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

In order to carry out meaningful modeling, it was necessary to select a typical village, which is not a trivial exercise as villages vary in many attributes and no single village is "typical." Nkweletsheni, the village selected by the survey team, is situated on the banks of the Umkomaas River in the foothills of Kwa-Zulu Natal. It lies between the Drakensberg mountains and the East Coast and the closest towns to the community are Highflats and Ixopo which are approximately 40km and 50km away respectively. The ongoing Housing Energisation project, funded by USAID and administered by Parallax (Lloyd et. al. 2002), proposes to measure the impact on greenhouse gas emissions from a rural community through the introduction of cleaner, more efficient energy sources, specifically solar photovoltaic (PV) stand-alone systems and liquid petroleum gas (LPG). The community of Nkweletsheni was included in this project, and a survey on energy use was conducted prior to initiation of the technology diffusion

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

programme. Data was gathered through interviews of 150 households. The factors underlying Nkwetetsheni's selection included the following (Lloyd et. al. 2002):

- It appeared typical of rural communities in large areas of Kwa Zulu Natal, with a low population density (less than 50 households per square kilometre) and an as yet undeveloped infrastructure.
- It would not receive grid electrification for the foreseeable future regardless of whether or not there is a transmission power line in the vicinity. (In fact there is a power line approximately 10 km away.) It is presumed that it is not cost effective for the national utility to electrify low population rural communities, such as Nkwetetsheni.
- Its selection as an experimental site had the support of the community and local authorities.
- Limited, but significant, resources of wood are available. (No attempt was made to quantify the reserves or maximum 'sustainable' yield.)
- The survey that was used for data gathering for this site was designed with the described model in mind. The questionnaire structure was proposed in a previous study.

These characteristics are similar to those suitable for this study and the survey data was therefore used as the basis for this work.

As is typical 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, services 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 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 use 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, and LPG is 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 (about 1:9) 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.

SCENARIO ANALYSIS

Characterization of the scenarios

With the calibrated model, we develop a reference Base case and several alternative scenarios. All scenarios begin with the simplified assumptions that 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): We assume that electricity is not available to 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, but not connecting to the national grid.

Grid electrification (GE): For this scenario, the model is allowed access to the national grid from 2005 onwards, 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)[9]: While all the scenarios include the availability of demand side management measures, this scenario also includes a time dependant 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 (willing to pay 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 we envision the application of time of use generation costs in order to evaluate the potential of DSM measures to accompany grid electrification.

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 3, and phased in over a 3-year period. We also assumed a cost of one US cent per kilogram for wood collection (Lloyd et al. 2002). This is based on a market cost for rural wood supply, which is marginally cheaper than local coal prices (Lloyd et al. 2002) – 1.4$/GJ (or 34$/ton). The various scenarios are summarized in Table 4 below.

Table 4: 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

9 Marginal grid electricity costs – increasing with national grid power station expansion.

Model Results

This section focuses on a few key implications of each scenario. As we are working within the MARKAL/TIMES optimization framework, the results indicate economically optimal conditions 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 the figure below, wood dominates the final energy picture because there are few substitution possibilities.

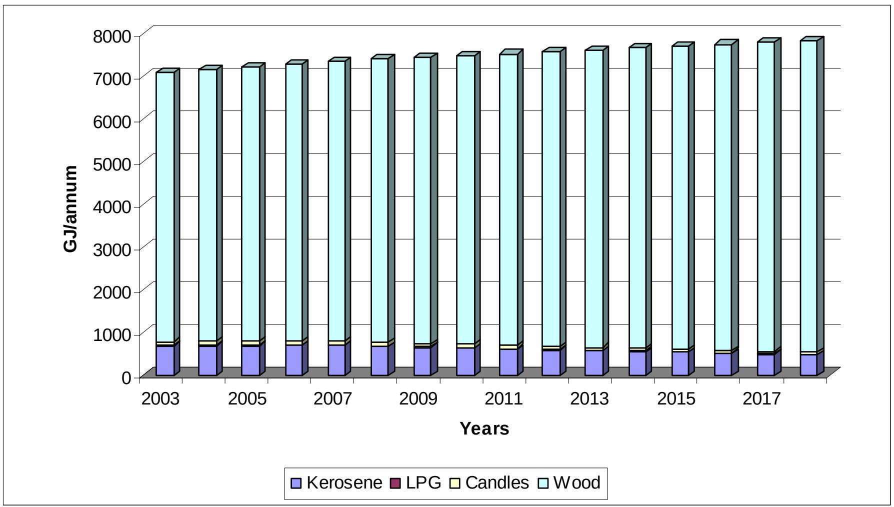


Figure 6: Final energy demand by fuel

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.

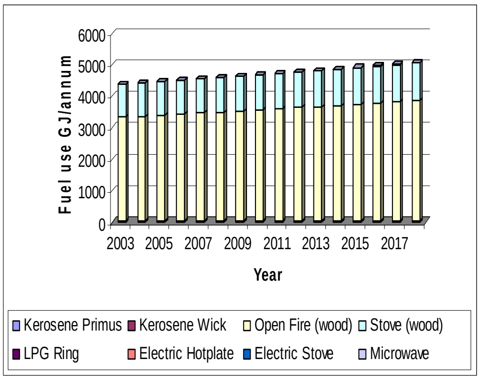
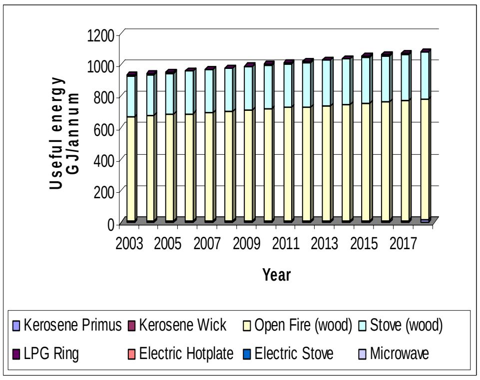
Final energy used for cooking	Useful energy required for cooking
	

Figure 7: Cooking devices used

Water heating demand is met in much the same way as cooking, with biomass being the dominant fuel paraffin playing a minor role, mainly in a backup role. 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%.

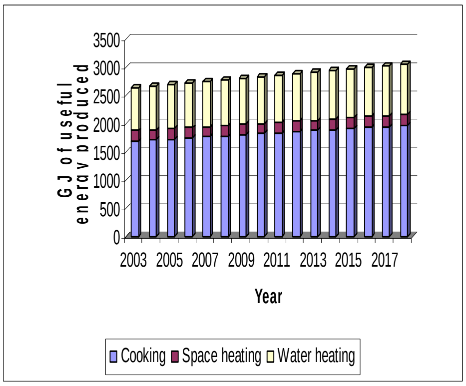
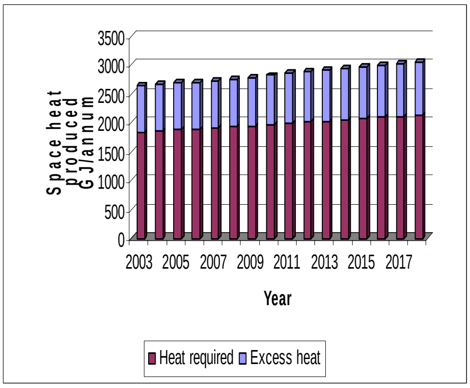
Space heating as a function of activity	Requirements and over production of space heat
	

Figure 8: Space heating

Over the modeling 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. 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[10].

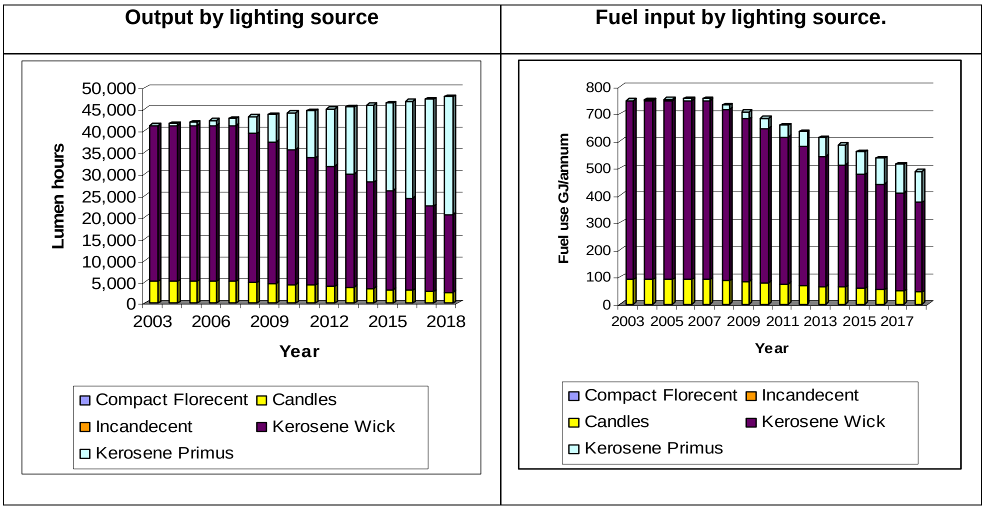


Figure 9: Lighting and fuel consumption in the base case

Energy supply to other demand devices (TVs and radios) is exclusively from batteries, 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 displaced paraffin, and ‘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

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

electricity from these sources is generally high[11].

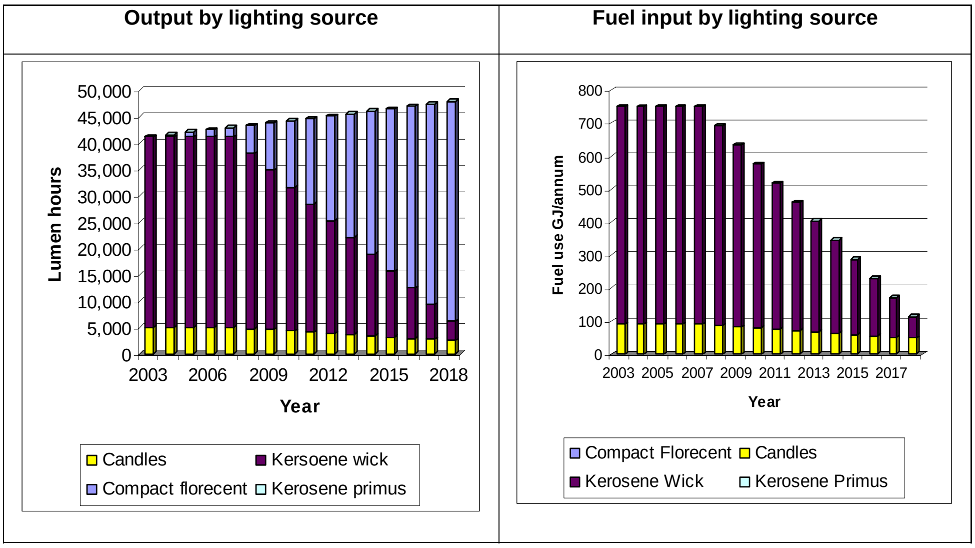


Figure 10: Lighting and fuel consumption in the stand-alone generation only scenario

Cooking and space heating are still supplied mostly with wood. Thus the conventional fuels and multi-service devices prevent the distributed generation technologies 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 10, where the substitution of appliances is even more dramatic than in pattern in the base case. The availability of electricity means that households shift to CFLs rather than investing in Kerosene primus stoves—the CFLs have extremely high light output and yet are extremely efficient. Total fuel use for lighting is one-fifth the level in the base case.

Grid electrification (GE)

In the GE scenario the model is given the option to invest in both distributed generation and connection to the national electricity grid. Contrary to the assumption that electrification would not be economic for Nkweletsheni, mentioned in the village description, the model chooses grid electrification[12]. It should however again be noted that the model chooses electricity only at low consumption levels for activities where electrons have special value—

[11] Estimated at 20-30c/kWhr vs. about 15c/kWhr from a diesel genset. Please 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.

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

such as for lighting and entertainment devices. (Indeed the energy cost of electricity could be increased six-fold and the electricity consumption from the grid would not vary from these specialized applications.) The model calculates that supplying these low volumes of electricity from a new grid connection would be less costly than purchasing or charging of batteries for radios etc., or the use of inefficiently burned 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 later, 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. It is the ability of this model to account for the multi-use wood devices that enable the correct relative economic value of the older technology to be properly captured, and thereby retain its market share. This as opposed to other studies (McFadzean 2002, Gaunt 2003) where higher penetration and use of electric appliances post-electrification were expected.

Electrification with cost reflective electricity prices[13] (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) national electric power system[14]. This scenario also varies the marginal cost by time of day and season in a manner consistent with an electric system that allows for real-time pricing. The principal consequence of this approach to costing electricity is a shift in electricity consumption from peak to off-peak times; much of that shift occurs through batteries that are charged during off-peak periods and used in entertainment devices during peak. The overall effect, however, is an 8% increase in total consumption due to the losses from the storage process.

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13 Marginal grid electricity costs – increasing with national grid power station expansion.

14 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 15.

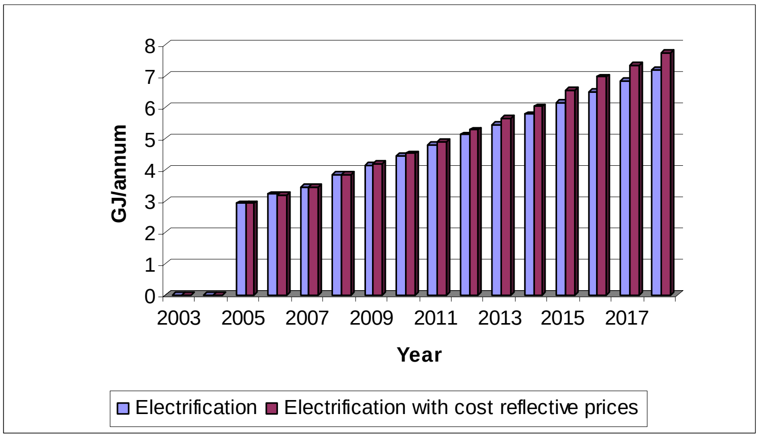


Figure 11: Comparison between the grid electrification and the EREP Scenarios: increased total consumption due to greater reliance on storage.

In the EREP scenario demand side measures become cost-effective. Figure 12 displays the electricity consumption during a summer day for the GE and EREP scenario and the effects of including accounting for a time dependant grid electricity cost. The figure, used for illustration, is for a summer day near the end of the modeling period. While in this illustration total consumption is lower in the EREP case, it is useful as it shows a clear reversal of the shape of the demand curve can be seen, 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. Thus was electrification to take place without accounting for varying electricity cost, the profile of electricity drawn from the grid would add to the overall ‘peakyness’ of current national demand and increase the system costs. The change in shape is accounted for by the model increasing the share of DSM over the Base case.

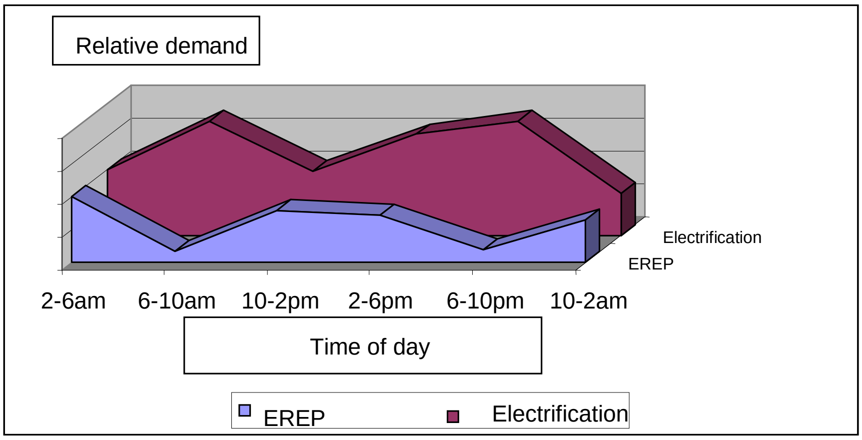
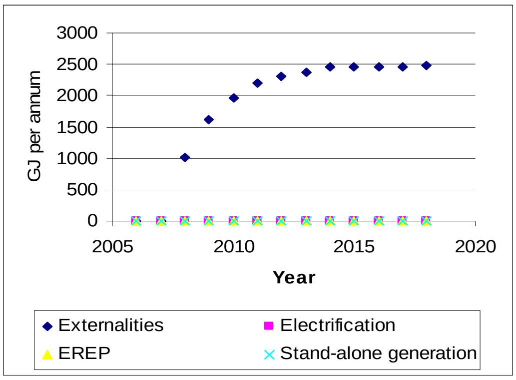
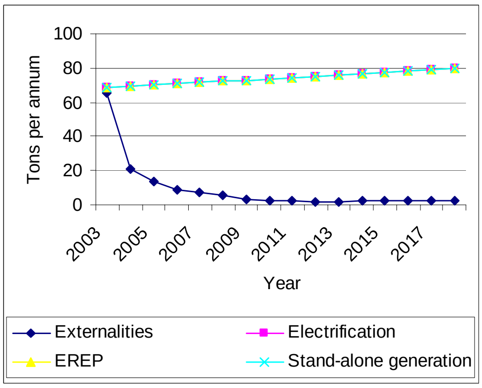
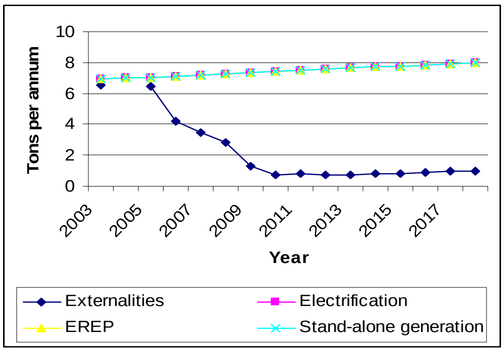


Figure 12: Summer electricity consumption by appliances in the EREP case versus the electrification (GE) scenario

Externalities (EX)

The externalities scenario builds on the grid electrification (GE) scenario but includes the cost to health and other externalities from local combustion emissions; Table 3 summarizes the assumptions that we used for these externalities. For this exercise we used just the point estimates reported in Table 3, but we are mindful of the large uncertainties and the need to explore sensitivity in future formulations and scenarios. The net effect, as shown in figure 13, is a shift to greater use of electricity and thus a sharp reduction in local pollution.

<table>
<tr><th>Electricity consumption per scenario</th><th>CO emissions per scenario</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>NMVOC emissions per scenario</td><td>Particulate emissions per scenario</td></tr>
</table>



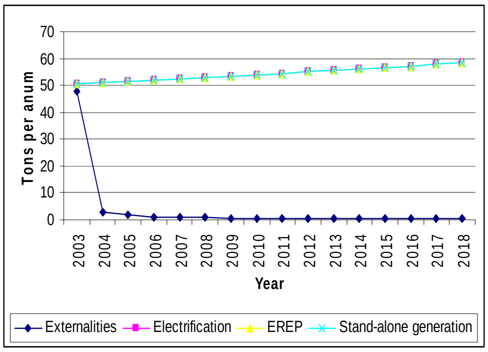


Figure 13: Electricity consumption and emissions

We also run a special case of this scenario in an attempt to reflect the cost of carbon emissions—a sub-scenario we call EX-Carbon. In this sub-scenario we assume that the cost of CO_2 emissions is 5$/ton CO_2. The principal effect of this scenario, when compared with the EX scenario, is to dampen the shift to electricity. The high CO_2 emissions due to coal-fired power plants increases the net cost of electricity Normally the model would shift back to wood-fired devices for some of the energy services supplied by electricity in the EX scenario. However, if we assume that firewood is harvested in an unsustainable manner (as is the case in many areas) and apply the $5/ton tax accordingly, the model selects LPG devices and solar hot water heaters to avert carbon-releasing deforestation. These results suggest that real attempts to control greenhouse gas emissions in developing countries—such as through 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 and prodigious 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). Such a result would not be obvious without the modeling.

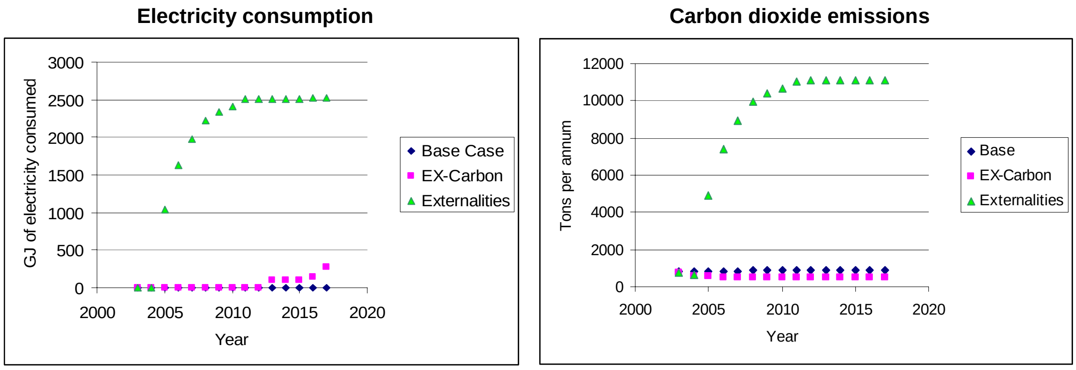


Figure 13. Electricity consumption and CO_2 production for the base case and the externality scenarios

Total Energy Consumption

Finally, we briefly compare the total energy consumption in each of the scenarios. As shown in the following figure, when compared with the base case each scenario envisions a reduction in total consumption, which 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—appliances that, 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—as villagers attempt to avoid the cost of pollution externalities—with the result that total energy consumption is the lowest when externalities are included the calculation.

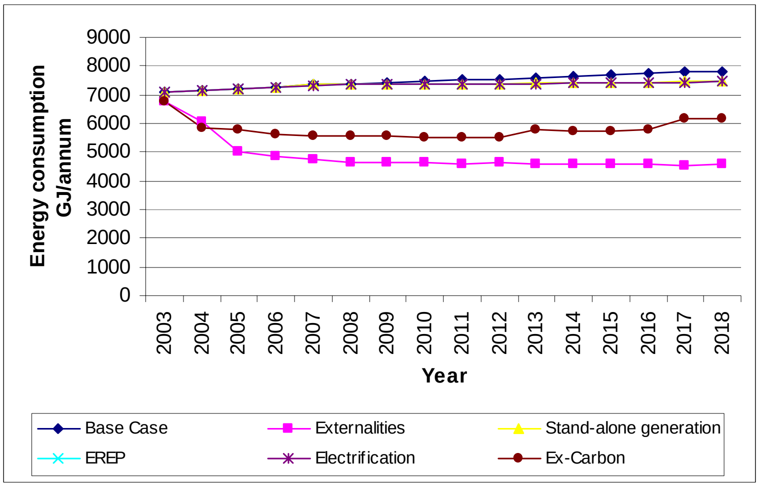


Figure 14: Total energy consumption: comparison of base case with the five main scenarios

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 paper we have illustrated ways to apply the tools of modern energy modeling to a rural village in Africa. We have argued that appropriate survey as well as advanced modeling techniques are needed for this task, and we offer a framework within the MARKAL optimization family of models for further work. In particular, we have focused on improving the MARKAL system through the TIMES computational system, which has allowed us to increase the time resolution to reflect daily load curves and has allowed us 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 modeling 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), at least 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 massive 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, and 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 and 2003).

One of the major factors that limits the uptake of commercial energy—such as paraffin, LPG and electricity—is the very low cost of wood fuel that is gathered locally. Field research also confirms that local fuel wood squeezes the new entrants and slows their diffusion (Williams et al. 1994 and 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 of needed 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.

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 then more than one can read at night. More generally, it is clear that factors beyond economics and simple externalities affect household patterns of energy use (Qase 1999). Among the other improvements to the modeling 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 modeling frameworks such as agent-based models and equilibrium models—to investigate such multiplier and rebound effects.

More work is also needed to integrate surveys with the model uses of survey data. At present this model can't be tested and refined with data from survey data from villages beyond the one we use for calibration, and thus we do not have a good test of the robustness of the model framework. Improved surveys may also make it possible to compute appliance-specific elasticities in a way that would allow future models to estimate village behavior by income level (which surveys suggest is an important determinant of energy choices) rather than as an aggregation of all incomes.

Finally, as we have shown, the inclusion of externalities and of time-of-day pricing of electric services can have a large effect on the optimal energy system. More progress is needed in modeling both. For externalities much work is needed to identify (as uncertain ranges, not simply point estimates) the valuation 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 many implications for policy is the particularly important role for electricity and fossil fuels in developing village economies. Notably, electricity appears to play a particularly robust role, especially when attempts are made to "price" non-electric energy carriers in ways that reflect their full costs.

Charts and figures

Figure 1: Reference energy system for non-electrified community

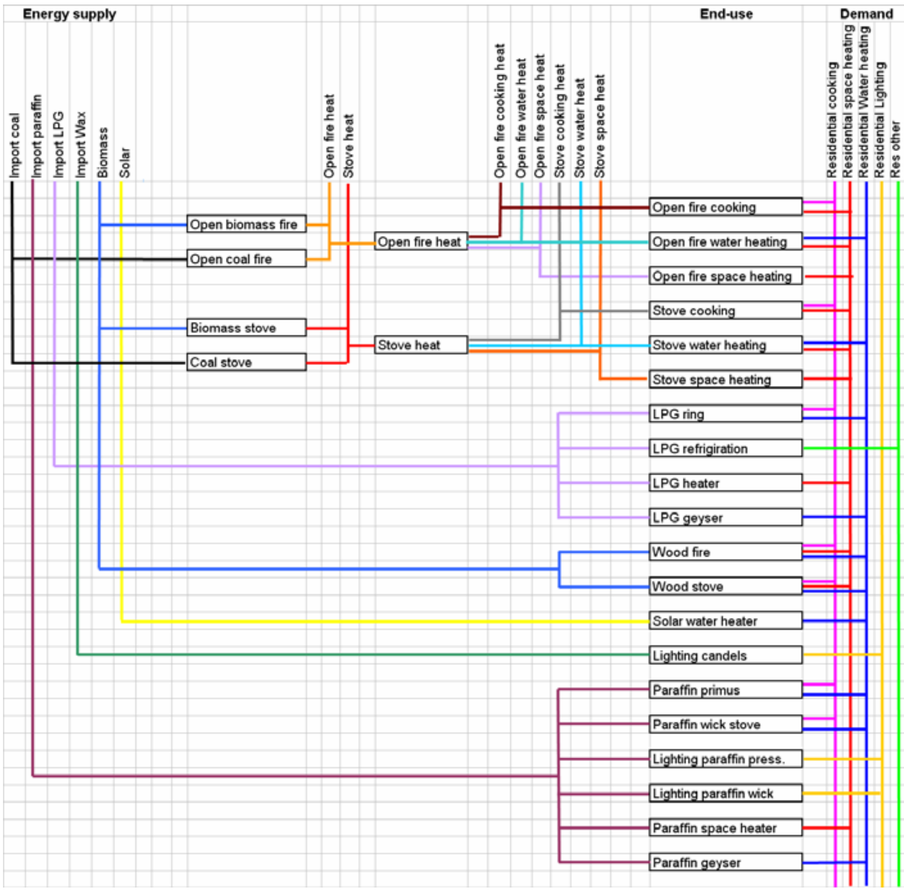


Figure 2: Reference energy system for electrification options

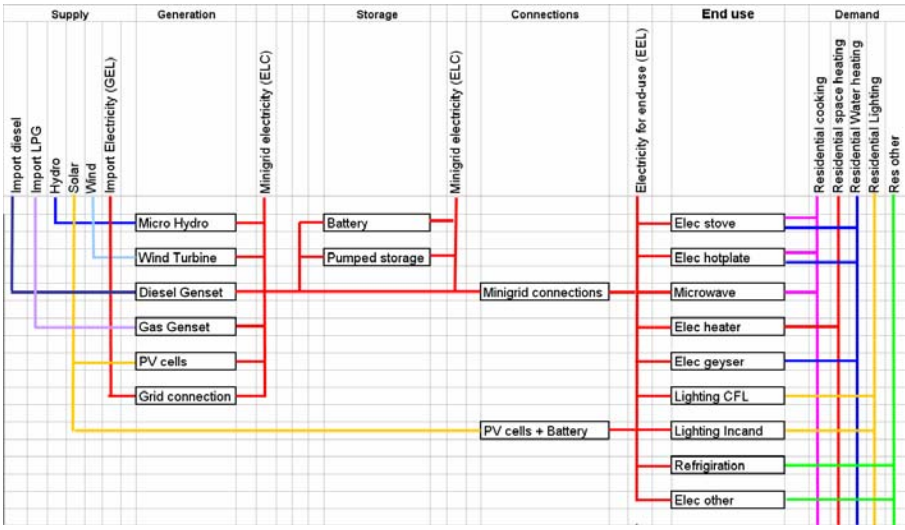


Figure 15: Electricity assumed electricity cost profile for 2018

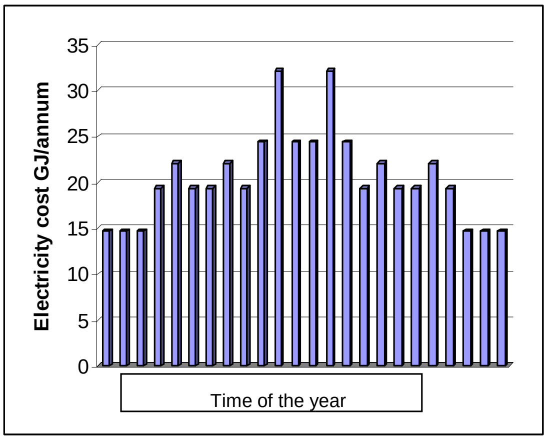


Table 1: List of 'end-use' appliances

	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 2: Energy supply technologies

Deleted: 3

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 3: Externality costs[15]

Deleted: 4

$/ton	US range[a]	UK[b]	Van Horen (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

a Sarkar and Wolter (1998)(40), and Sorensen (1992)(41). No distinction is made between low-level and high-level emissions. Those externality costs calculated on the basis of cost of control are excluded.

b The Royal Society (1995)(42), 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 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.

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

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