DISSERTATION

ON THE ENERGY SOURCES OF MOZAMBICAN HOUSEHOLDS AND THE DEMAND-SUPPLY CURVES FOR DOMESTIC ELECTRICITY IN THE NORTHERN ELECTRICAL GRID IN MOZAMBIQUE

Submitted by

Maria de Fatima Serra Ribeiro Arthur

Department of Mechanical Engineering

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY MARIA DE FATIMA SERRA RIBEIRO ARTHUR ENTITLED ON THE ENERGY SOURCES OF MOZAMBICAN HOUSEHOLDS AND THE DEMAND-SUPPLY CURVES FOR DOMESTIC ELECTRICITY IN THE NORTHERN ELECTRICAL GRID IN MOZAMBIQUE BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

Committee on Graduate work

William S. Duff

Wade O. Troxell

Robert W. Kling

Advisor: Bryan D. Willson

Co-Advisor: Craig A. Bond

Department Head: Allan T. Kirkpatrick

ABSTRACT OF DISSERTATION

ON THE ENERGY SOURCES OF MOZAMBICAN HOUSEHOLDS AND THE DEMAND-SUPPLY CURVES FOR DOMESTIC ELECTRICITY IN THE NORTHERN ELECTRICAL GRID IN MOZAMBIQUE

The development of electrical infrastructure to supply rural households is considered economically unfeasible because of the high cost of capital investment required to expand the distribution grids. Although domestic electricity consumption in many developing regions is small when compared to the requirements of some emerging agro-industries, the social benefits are significant, such that many donor agencies agree to finance grid extensions based on poorly projected social benefits of electrification. However, there is evidence that households with electrical connections do not increase their electricity consumption above the bare minimum, allegedly because electricity is more expensive and possibly because of insufficient funds to invest in electrical appliances. The controversy is then whether or not electrification can support household development (and poverty alleviation) and vice-versa, can domestic consumption support the costs of electrification investments.

The current work is composed of a theoretical model and two empirical models, developed in order to answer the following specific questions: 1) To what extent the ownership of assets is determinant to the adoption of high-grade energy sources in the domestic settings of poor families? 2) What is the price of electricity that sustains the supply costs and still promotes increased energy consumption in Mozambican households?

To answer these questions the study formulated an inter-temporal utility maximization problem by which households can determine the limits of investment for energy consumption and for income generation that is required to evolve out of poverty in a sustainable manner. Next, the study calculated the elasticities of demand for the various domestic sources used by Mozambican households, surveyed in 2002/3 at the national level, enabling the construction of demand curves for these sources. The study also derived empirical loss equations for the northern transmission electrical grid (Linha Centro-Norte, LCN) in Mozambique, and constructed the supply curves for the distribution networks connected to the substations of the system. Based on the household data, the likelihood of adopting electricity as a domestic source was analyzed and results show that wealth is a major determining factor, confirming the findings of the theoretical and empirical household models. Finally, the study constructed the supply and demand plots, from which the sustainable price of electricity supplied to domestic consumers can be estimated and welfare evaluations made.

Results indicate that households can evolve consuming electricity if credit for investment is made available and the income base is enlarged. Furthermore, it is demonstrated that current electricity prices are within budget of households and that electricity is competitive with biomass sources and kerosene in the domestic setting.

Maria de Fatima Serra Ribeiro Arthur
Department of Mechanical Engineering
Colorado State University
Fort Collins, CO 80523
Summer 2009

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PREFACE

"Each old person is a living library". Anonymous, Mozambique

The extent of human knowledge, experiences and intuitions are infinite when compared with our ability to acknowledge, understand and process them. This research intends to shed some light in aspects of human behavior that may help improve policies targeting a better access and higher affordability of electricity as a domestic source. In recent years, the basic-needs bundle extended to include water and sanitation, and development policies finally established that infrastructure access is essential to poverty alleviation. However, these improvements are still insufficient as the infrastructure listing is quite bare: energy supply, as a means to improve life quality and the productivity of households, is still missing from the basic-needs bundle. The poor, fed and clean, are left to fend for themselves on finding external energy sources to maximize their potential as productive human beings. They still struggle to find new ways of generating income, to be educated and to witness, if not participate, in the public debate through television and radio, and to benefit of a good lighting source that will make their lives easier, safer, more productive. In summary, the poor still struggle alone to evolve out of poverty for lack of an external efficient domestic energy source I dream of the day when electricity supply is listed as a human right and as such must be provided for everyone. The economic viability of electricity supply to households has been at the center of its limited access in developing regions. This research intends to clarify the energy supply-demand characteristics for the Mozambican households, thus helping to pave the way for a wider the use of electricity as a domestic energy source.

"If the poor just knew that their life can be partly described by mathematical equations…"

Gösta Werner, Sweden.

To my father for his dreams, to my mother for her strength. To all my family for their love.

To my daughter Michelle because she is everything and more. I love you all.

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CHAPTER I: INTRODUCTION

THE RESEARCH QUESTION

In Mozambique, the development of electrical infrastructure to supply rural households is considered economically unfeasible because of the high cost of capital investment required to expand the distribution grids. Often, electrification projects anchor their economic viability in major industrial or mining enterprises that ensure cost recovery at the destination-sites, leaving the benefits to the domestic sector only as secondary considerations to the project viability. Domestic energy consumption in many Mozambican districts is small when compared to the energy requirements of some emerging agro-industries. However, the social benefits of electrification are significant such so that many donor or public finance agencies agree to finance grid extensions based on poorly projected social benefits of electrification, see Gaunt (2005) for a good presentation on the South African approach to mass-electrification, and Sida's policy (2005) on sustainable energy services.

Can electrification projects positively contribute to poverty alleviation and social development? In other words, can electrification support household development, and vice versa, can households support investments on the expansion of the electrical grid through their electricity consumption? The research question, on whether electrification can be an effective poverty alleviation tool, needs evaluation in its five components, schematically shown in Figure I.1 and discussed in the following subsections.

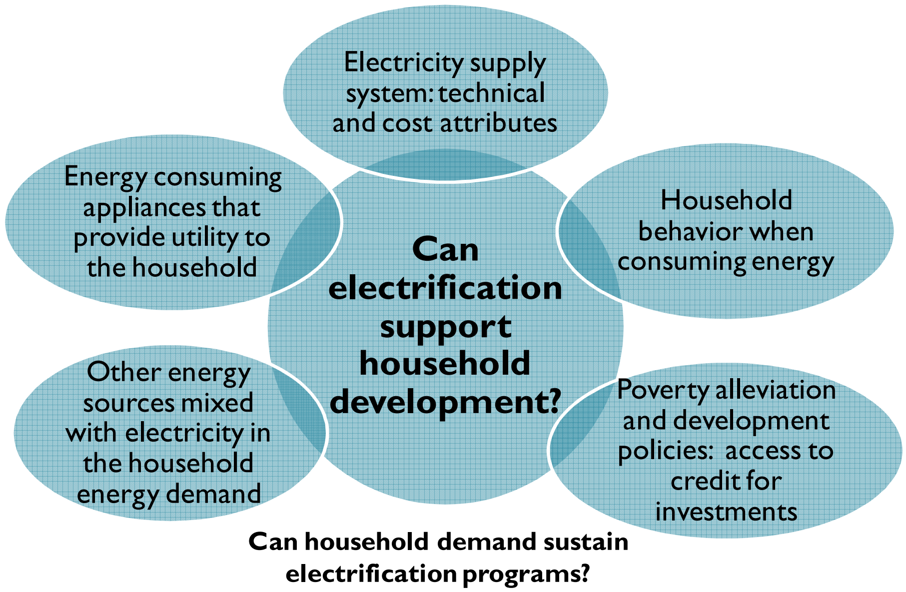

Figure I.1 – The component-aspects of the main question

ENERGY CONSUMING BEHAVIORS OF HOUSEHOLDS

Mozambican households consume primarily biomass sources (firewood and charcoal) for cooking, and kerosene for lighting (Falcão 1999; Brouwer and Falcao 2004). Although the national public electricity company (Electricidade de Moçambique - EDM) has invested heavily in electrification programs in the past 30 years[1], electricity consumption only benefited 8.2% of the population in 2006, and the average consumption recorded at 89 kWh/household (EDM 2007), is only about a third of the current US domestic energy consumption (EIA 2001).

A household's choice of energy sources for (domestic) consumption, assumed rational, is based on factors such as price, accessibility, convenience and safety of use, cleanness and others that the household may perceive as important (Hughes-Cromwick 1985; Green and Erskine 1999; Gupta and Kohlin 2006). Taste and cultural preferences are also deemed to

[1] In the US, government also intervened to expand residential electricity in the late 40s-50s (Morton 2002)

play a role in the domestic energy mix (Reddy 1995; Masera, Saatkamp et al. 2000; Brouwer and Falcao 2004). Electricity will be used by the household to the extent that it satisfies its preferences. In other words, households will consume electricity by different shares in the domestic mix and in different end-uses. For example, households may opt to consume electricity for lighting but maintain charcoal and firewood for cooking, or may complement electrical consumption with LPG or kerosene for cooking (Brouwer and Falcao 2004; Madubansi and Shackleton 2007).

The factors determining the households' preferences on energy sources for the various domestic uses, including access and affordability of the sources' consumption, will establish the demand levels for domestic electricity and the returns it may provide to its supplier. The use of electricity as a domestic source by the poor depends on how it meets with the household's preference criteria for energy use.

POVERTY ALLEVIATION AND DEVELOPMENT POLICIES

Demand growth projections are often inaccurate and based in national trends or, at most, are aggregated by consumer classes. These forecasts are not sensitive to demand variations at the (individual) household level, nor do they incorporate preference factors in the household consumption behavior. Households may react differently in response to the availability of more than one energy source at varying prices, and as such contribute to an accelerated (or slower) growth-rate of demand in the electricity supply area.

The evaluation of "affordability" (price versus income) of the poor is often unrealistic, in some cases well below measured figures. The poor earn in the form of cash and directly in 'species' from self-production, and sometimes just don't declare their real earnings to avoid taxation (Simler, Mukherjee et al. 2004; Zacarias, Chipembe et al. 2004). Studies indicate that the poor spend in low-grade sources almost as much, and sometimes even more, than they would if consuming high-grade energy sources (Bose and Shukla 2001; Cockburn and Low 2005; Raineri and Giaconi 2005; Kebede 2006). Consequently, electricity may wrongly be considered a source only for macro developments (industries and services), rather than a source that is affordable by the poor and that can be planned within the scope of poverty alleviation strategies. The Mozambican PARPA[2] (Mozambique 2001) and the findings of the Committee for Poverty Reduction of the United Nations (Sarkar 2007; United-Nations 2007) still list electricity as only an input to economic development and do not include any source of domestic energy in the basic-needs bundle, even though humans require energy for lighting and cooking at the very least.

The importance of electrification in development and in poverty alleviation is better established through the study of domestic energy evolution (transition behaviors) and of energy intensification (increased consumption per household). Energy transition in households is not fully understood, nor is domestic energy adequately forecasted. Detailed forecasts per source specifically for domestic consumers will allow the design of optimal and possibly sustainable development strategies and electrification plans, conforming to economic, social and environmental needs. The design of policies that cheapen and facilitate access to electricity use will allow it to become a domestic source of the poor.

OTHER ENERGY SOURCES IN THE HOUSEHOLD MIX

In Mozambique, the national statistics indicate that the main sources of domestic energy are firewood, charcoal, kerosene, Liquefied Petroleum Gas (LPG) and electricity. In the years 2002/3 the following composition of lighting energy was recorded: electricity (6.9%), kerosene/gas (53.8%), firewood (31.7%), candles (2.2%) and other sources (4.7%), see (INE 2005). On the other hand, domestic cooking uses the following composition of energy

[2] Poverty Alleviation Program 2001-2005

sources, in 2004 in Maputo: firewood only (2.1%), charcoal only (11.7%), kerosene only (10%), LPG only (3.8%) and electricity only (4.6%), see (Brouwer and Falcao 2004). Most of the households use charcoal for cooking, alone or in combination with other sources (71.7%). Diesel and gasoline are primarily used in transport systems (EarthTrends 1999), animal traction has an incidence of barely 8% in farming activities - only 2.5% of farmers own and use animal traction in the farms (Toro and Nhantumbo 1999), and finally the use of renewable sources such as micro-hydro, wind and solar is as yet negligible.

Energy sources compete with specific strengths and weaknesses in the Mozambican domestic markets. For example, firewood suffers from scarcity cycles that may be severe around urban areas (Pereira, Brouwer et al. 2001) although it does not require investment in any specific appliance for cooking. It burns with low technical efficiency, nevertheless may be the preferred source of rural families that can collect it with no cash expenditures. Charcoal on contrary is produced through a semi-industrial process (kilns) and is mostly used in urban areas, far from forest residues. Charcoal is subjected to (market) price variations, influenced by the proximity of forest resources, transport prices and consumption levels (Mangue 2000). It is more efficient than firewood, but it requires a charcoal stove to burn i.e. a small investment in an 'energy-consuming asset'. Kerosene is imported and subjected to price regulation for bulk-sales, but market driven prices at the retail levels. Exhibits good efficiency, but with versatility limited by the cost of the appliances. In Mozambique, about half of the population uses it mostly for lighting, which requires only cheap kerosene lamps to use (Brouwer and Falcao 2004; INE 2007). Electricity consumption can only occur in the presence of supply infrastructure (access to the electrical grid[3]), but it exhibits good efficiency and high versatility. However, its use also

[3] Private generators are significantly more expensive per unit energy (as they consume imported diesel) and require high initial investment.

requires an electrical connection and the ownership of electricity-consuming assets (appliances) that may be too expensive for low-income families to invest-in (Campbell, Vermeulen et al. 2003).

The accessibility, the price (affordability) of the sources and the cost of the appliances required for their consumption, relative to electricity, determine the domestic mix and consequently, the possible returns in investment for electricity supply. Electricity needs to be competitive in relation to the other sources, in terms of unit price, and the investment in electrical appliances must be affordable, so the poor may transition to the consumption of electricity in the domestic setting.

ENERGY CONSUMING APPLIANCES

The “universe of appliances” (appliances available for acquisition in the local markets) for household use is vast and diverse, containing devices that consume one or other source of energy (biomass, kerosene, electricity, etc) and satisfy one or other household need (lighting, cooking, etc). Some appliances serve more than one need (cooking and heating for example), others serve the same need but at different prices and efficiencies.

What makes a household select one appliance rather than another, as the next investment, thus selecting which energy source to consume and which need to satisfy next? For example, a household owns a charcoal stove; it has some money for investment and wants to choose which appliance (need) it will acquire (serve) next… Will it buy an electrical stove to replace its charcoal’s, thus reducing cooking time and the pollution in the kitchen? Or rather, it will acquire a kerosene fridge, thus increasing its capabilities for food conservation to refrigeration, which it did not have before, allowing the family to eat fresh produce and leftovers that do not rotten in the kitchen counter?

What makes a household choose a particular appliance for acquisition (investment)? The household preferences may depend on the market conditions and on the technical characteristics of the "universe of appliances". If the electricity costs increase twofold, will the acquisition of an electrical stove be as attractive as before? If kerosene lamps become available at cheap prices in the local market, will the household choose to buy and use them instead of candles, as main sources of light? If income increases considerably, due to payoffs from previous income generating investments, will the household prefer to acquire an electrical refrigerator, rather than a kerosene one? Alternatively, if the household already owns an electrical stove, will it not be more attractive to acquire an appliance that it does not possess instead of another electrical stove?

Consumers are as diverse in their choices as their number, from each other and overtime. However, commonalities exist that allow for behavioral generalization, particularly when consumers are living in the limits of poverty. Most households' requirements for energy consuming devices correspond to the satisfaction of basic-needs as follows:

a) Every family needs some sort of cooking device
b) Every family needs a lighting system
c) Every family needs to keep warm in the cold
d) Every family needs to conserve food for leaner times, etc.

The difference between need and want is subtle and varied: where for some, running water is a necessity, for others it is luxury. The perception of Need *versus* Want is also varying in time, as the household conditions and its environment change. Needs, affordability of the energy sources and their appliances, and the availability of supply (access) are determinant factors in the household choice of domestic energy. Electricity supply must geographically expand (access) and have competitive prices (affordability) in order to be a poor's source.

Furthermore, households must invest in electrical appliances (in a sustainable manner) in order to become electricity consumers.

THE PRICE OF ELECTRICITY SUPPLY

In Mozambique, electricity supplied from the national grid is primarily generated by hydropower stations, located in the centre west of the country (Manica and Tete provinces), Charcoal and natural gas generation are also planned in future developments in these same provinces (EDM 2005; Bucuane and Mulder 2007; EDM 2007; Nunes 2008). Private and municipal small generators (mostly diesel engines) and few installations of renewable energy account for less than 1% of the total electrical supply (Mulder 2007). Diesel generation is more expensive (only on fuel costs) than the actual national grid tariff (EDM 2007), however off-grid schemes are becoming more competitive with the grid electricity supply when solar and other renewable technologies are used (WB 2008). Still, it is cheaper for electrical consumers to plan for connections to the national grid, wherever it exists, and budget their costs based on the rates of the national electrical company (EDM) that operates it by public mandate (Mozambique 1977).

EDM's tariff system, reviewed and approved, by decree of the Council of Ministers, in 2003, is based in the findings of KPMG's Tariff Study that identifies the average cost basis of the company and recommends a three-component tariff rate: the energy rate, the capacity rate and the connection fee[4,5]. The first recovers the variable costs of operation and maintenance (O&M), the second recovers the investment in new capacity, and the third covers the local costs of the electrical connection. The so-called "unique tariff" was introduced at the

[4] In 23 June 2003, the rule concerning Tariff Setting for EdM (the national public utility) was reviewed by the Council of Ministers, and approved by Decree 29/2003. This revision revokes the previous Decrees 32/91 from 30 December, 2/97 from 11 February and 59/99 from 21 September. It also reconfirms the applicability of the Decree 10/85 that creates a National Tariff for Electricity, the "unique tariff".

[5] Final Report for EDM tariff study, KPMG, 14 February 2001

creation of the national public utility in 1977, and is maintained on the argument that remote areas should be subsidized to facilitate their economic development (decree 10/85, see note 4). The transmission system pricing thus contain a cross-subsidy to the more remote areas, and all consumers are charged for the electrification efforts at the national level, regardless of their own location. The only costing difference between geographical areas is related with the transmission and distribution losses, factors that are, to some extent only, under the scope of the local management teams.

The economic viability of an electric infrastructure (supply) system requires that the sales generate enough revenue to maintain the system in operation, i.e. to pay for the power taken and for all the operation, maintenance, environmental, tax and financial costs of the infrastructure. Capital (investment) costs are of different types (soft loans, commercial investments, etc), nevertheless must also be paid for. The higher the volume of electricity delivered to the customers, the lower the price that ensures viability, the breakeven price, and vice versa. The existing and future generating stations are not close to the consumer networks, making the transport costs significant in the retail electricity price.

The estimation of transmission and network distribution losses along the LCN allows a differentiation of the sustainable cost-recovery average price of electricity supply and may thus guide the tariff reviewing processes and the establishment of the social tariff (poverty alleviation) rate.

THE CHALLENGE

The above sections described the various aspects of the question on whether electrification can support poverty alleviation, and vice-versa, on whether domestic consumption can provide viable returns to the investments and operations of the electrical grid.

The brief discussion on the five main aspects show the vastness of this question and the impossibility of fully answer it in the present research. Furthermore, the above discussion clarifies the differences between the demand-side and the supplier-side of the problem. Poor consumers may not be able to afford electricity at a price that is sustainable to the supplier, and suppliers may not be able to provide access to domestic consumers at an affordable price, i.e. competitive with other sources' currently used by the domestic poor.

This research study focused on two specific aspects of the main problem, namely:

1) What is the average price in each community supplied from an electrical grid that ensures the recovery of costs by the supplier and encourages the consumption of electricity by poor households?
2) What is the rationale of energy transition as explained by the progression of ownership of energy consuming appliances by evolving households?

In other words, the Challenge is to find the electricity price that ensures cost recovery (by the supplier) but also allows poor households to consume it. This match is sought under the assumption that the affordability of electricity depends not only on the price at retail level but also on the availability of investment funds for the acquisition of electrical appliances, i.e. even if the electrical price is competitive (and access is ensured), without appliances households will not adopt electricity in the domestic setting.

This study is based on the assumption that although poverty may take different forms in different communities and regions, its root causes and solutions are the same, regardless of the geographic location and culture specificity. The lack of food still results in hunger, whether the main staple is corn or cassava. The lack of credit for productive investments still result in household stagnation or regression into poverty, and the use of low-grade energy sources is a commonality of the poor, whether they use cow-dung or firewood (van der Plas and Abdel-Hamid 2005). Similarly, the rationale of energy transition that depends on the technical and market characteristics of the energy supply systems, will be the same, regardless of the particular sources and the particular market prices. This generalization allows the use of published material for various developing countries, necessary because there is not much on the Mozambican domestic energy consumption.

The combination of household economics with technical modeling for electricity supply gives a unique opportunity to understand the impact of infrastructure development in human development, and to quantify the critical combinations of price versus demand that may constitute thresholds of development versus stagnation for households.

THEORETICAL CONCEPTUALIZATION

The current study developed a household model and a grid model, interfaced to generate Demand-Supply functions for domestic electricity. These demand-supply functions describe the viable price of the infrastructure (for which the electrical supplier faces normal profit) and at the same time, the affordable price for an evolving household, i.e. the threshold of sustainability, at which the household can increase its consumption in a sustainable manner for itself and the industry.

For an electrical distribution grid in the northern Mozambique (Linha Centro-Norte) empirical analysis calculated the electricity prices that ensure cost recovery and respond to a changing demand pattern of household consumption (the supply functions). On the demand-side, empirical estimations of demand elasticities to price and income allowed the calculation of the demand functions. The elasticities' estimations are theoretically conforming with a mathematical model of inter-temporal utility maximization, which formulates for the first time the concept of an "asset ladder rule".

The household energy transition behavior results from an “asset ladder rule” that contains income, consumption and investment funds as the explanatory variables. The “asset ladder rule” establishes the optimal path of investment that ensures a continuing increase in consumption, in energy and in other goods, in a sustainable manner.

THE HOUSEHOLD THEORETICAL MODEL - DEMAND FOR DOMESTIC ENERGY

A household is simultaneously a consumer (of goods and services), a producer (farm or fishing produce, handcrafts, saleable goods, energy generation, etc) and a supplier (of labor)[6]. As consumers, households act rationally, and constantly seek to maximize their utility. As producers, households tend to perform at the threshold of sustainability, for several reasons varying from knowledge base and asset productivity to behavioral factors[7]. As suppliers, households tend to optimize their usage of labor[8].

Households that experience no growth of their income nor increase their consumption basis are stagnant. Most poor households experience this condition, i.e. they are able to maintain their expenditure as long as no extra (new) cost is charged, or as long as their health is good and their asset base is in operative condition. As such, they are quite vulnerable to any occurrence or out-of-the-ordinary expense[9].

These households operate at each time in an equilibrium, by which the household’s income equals the household expenditures, hereafter called the “sustenance cycle”, represented in

[6] The multiplicity of roles is well discussed in Barnum and Squire (1979)

[7] The access to information and the lack of credit to achieve the highest productivity are limitations in the exploitation of the household’s own resources

[8] Labor maximization is extensively discussed in household models developed in the farming context (Barnum and Squire 1979). A household may hire cheaper labor and sell its own, if it will earn extra income, or vice versa choose to use its own labor for household activities, if labor for hire is too expensive.

[9] There is a whole body of research on poverty and vulnerability, see for example The Institute of Development Studies research on ‘Vulnerability and Poverty Reduction’ (http://www.ids.ac.uk), and the Millennium Development Goals recognize vulnerability factors in their strategies to reduce poverty (World-Bank 2007).

Figure I.2. The household consumes inputs and produces outputs for sale (to finance the consumption of goods and services). Inputs are its own labor force, and hired labor, capital base for income generation (land, tools, and interest-earning investments), education and access to information sources, energy consumption, and others. This inputs are consumed either by the persons of the household or by the assets from where the household obtains utility or produces output for sale. From the consumption of the inputs, the household is able to generate outputs (labor force, goods and services for sale) from where it will obtain income to cover its costs.

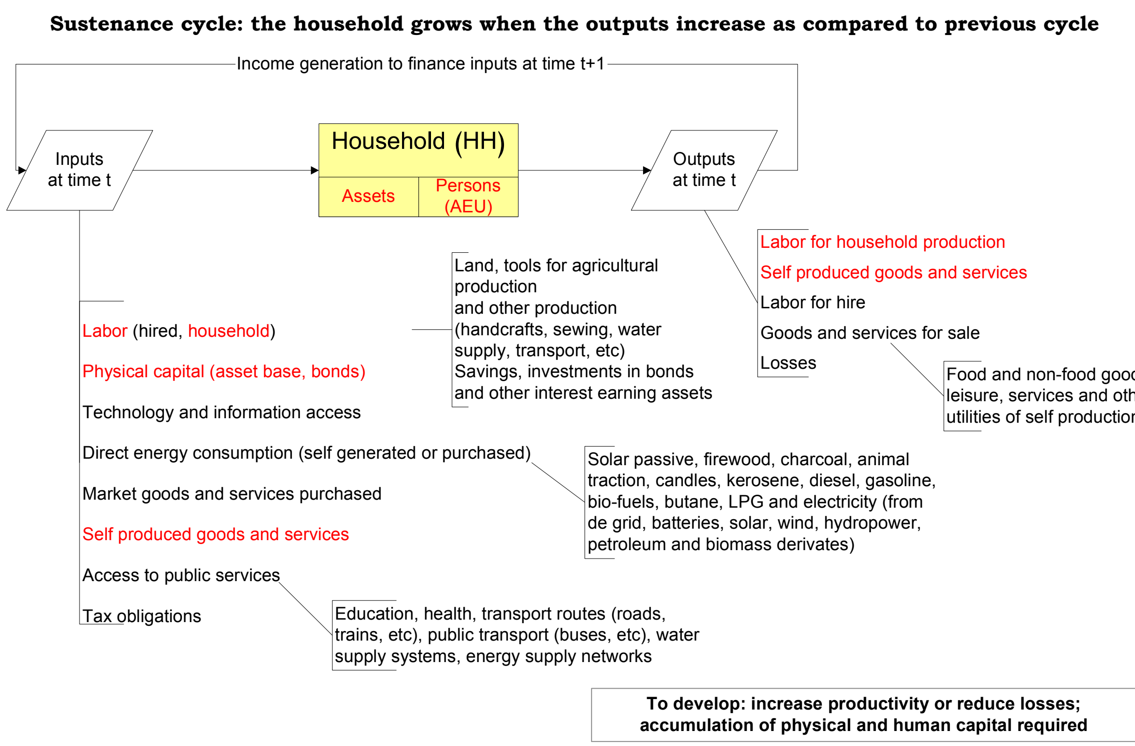

Figure I.2 – Household at the "stagnation" stage: no growth

By the sustenance cycle, the household experiences no growth, however manages to earn enough to maintain its (current) consumption for goods and services. The local markets (where prices are not fixed) influence the household economics, by creating a dynamic mechanism through which they progress or wilt, pending on their ability to earn income above or below their consumption needs. Poor households that consume barely enough for survival, are particularly vulnerable to price variations, and may plunge very rapidly into deprivation[10].

Household development occurs by increasing the household net income that in turn increases the consumption of goods and services or the household capital base (Figure I.3). The capital base in turn is composed of investments for income generation (increase the household earnings) and of acquisitions of energy consuming assets (appliances) that increase the household utility serving (and increase the household "operating" costs).

Household cycles: characteristic of each class of household. Interaction with the community markets for labor, goods and services, public services, financial and energy supply markets

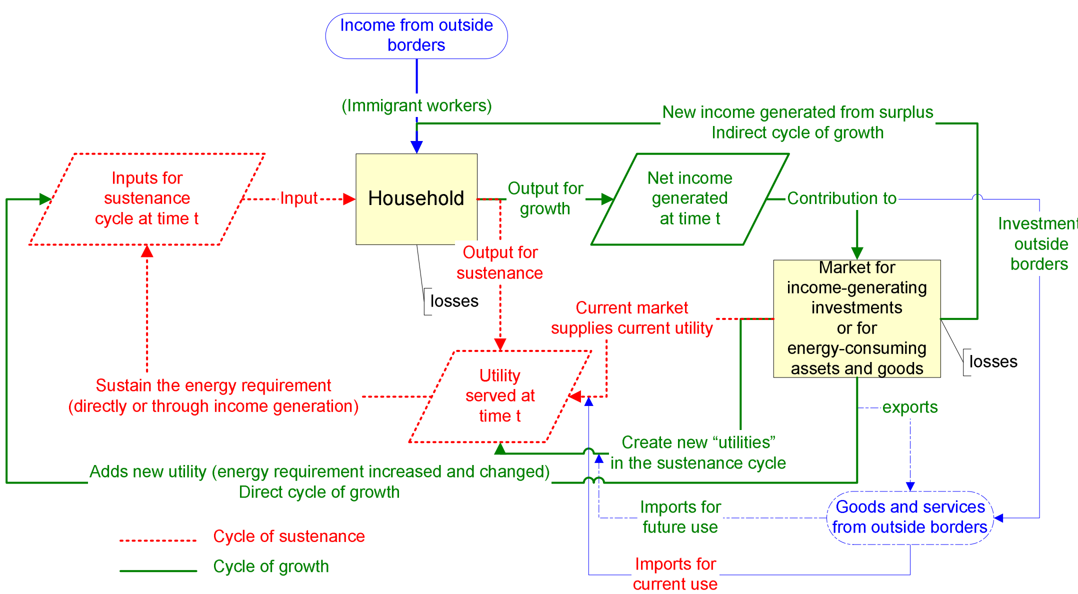

Figure I.3 – Interaction household versus the local market

Growth can only occur when the household net income is positive. Extrapolating, a household can only evolve out of its current development level (be it at the poverty line or above) if it generates excess "cash" (net income) to invest for more income-earning

[10] Vulnerability to market changes or disaster is discussed, in the aftermath of a flood in Bangladesh, as a characteristic of poverty ridden households (Khandker 2007)

activities which in turn will allow the extra consumption of goods and services or the investment in assets that provide extra utility. The goal of development should then be the increase in the net incomes of the average (poor) households, as successfully demonstrated by the experiments carried out by Grameen Bank in Bangladesh (Haque 2000).

The net income can increase by reducing expenditure in goods and services (by reducing consumption, or by reduced prices) although this is at most a temporary measure. To achieve a trend of an increasing income, the household will have to either invest in its human capital (increase wages by increasing educational base[11]) or invest in income generating / interest earning assets. In the horizon of viability of an infrastructure project, no household has time to evolve its human capital (education base) and earn higher wages. Although causality of education to economic growth exists, long time lags exist between rise in education levels and overall economic growth (Self and Grabowski 2004). The number of adults per household that sell labor for income generation and possibly the number of households in a community may also show little variation in this period. The timeframe of a study is thus important to determine if there will be alterations in the income generated from labor sales or if income can only be generated from new investments in "productive" capital, generating returns for the household[12].

Most population studies use income as an indication of the household development stage. However, in poor areas not all income is declared (for tax purposes) making its measure inadequate to describe the development paths of these households. As the household evolves, it increases its consumption of goods and services, i.e. consumption levels are a

[11] In the USA the returns in education investments are increasing, as compared to the interest earning investments (Chanda 2007)

[12] Statistics for Mozambique show that, as a result of Aids and poverty related deaths, the population growth rate is currently of 1.8% per year (CIA 2007)

more appropriate measure of the household income or poverty level (Simler, Mukherjee et al. 2004).

The consumption of energy sources require appliances, ranging from the simple cheap three-stone stove that burns firewood, to the sophisticated expensive microwave stove in richer families. A measure of the family wealth in energy-consuming assets is consequently also a measure of the family's stage of development[13].

Rather than just using the demand level and the type of energy source to indicate the household development stage, as postulated in the "energy ladder" concept, it is also necessary to consider the cost of acquiring the energy-consuming appliances (Reddy 1995) and the cost (and disbursement schedules) of the energy sources themselves (Masera, Saatkamp et al. 2000). A household energy demand per source evolves based on the household's ability to pay for the appliance and to maintain the expense of consuming that particular source. The transition between sources occurs at different paces for different household activities that consume energy (Kidane 1991). For example, a family may retain charcoal as the main cooking energy source, but evolve from candles directly to electricity for lighting, without even experiencing kerosene as an intermediate source.

These choices are based on various preference factors such as source and appliance costs, availability, safety and cleanness, facility of use, security of use, multiplicity of uses, social desirability, and other factors[14]. The household continuously ranks the appliances by its

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[13] This idea has its origins in the assumption that the consumption of energy is an input into a production function of utility by the household, through its appliances, exemplified in the model of the domestic demand for energy sources by Willett and Naghshpour (1987). The ownership of appliances is furthermore equated with a measure of household development stage (McKenzie 2005).

[14] The quantification of ranking criteria for domestic energy is sparsely documented (Hughes-Cromwick 1985; Gupta and Kohlin 2006)

perception of their cost and benefit ratio. On the assumption of rationality, it selects the appliance and energy source that will serve the highest utility[15].

Figure I.4 shows the choices the household must make when considering its future investment and the fundamental concept behind the theoretical household model.

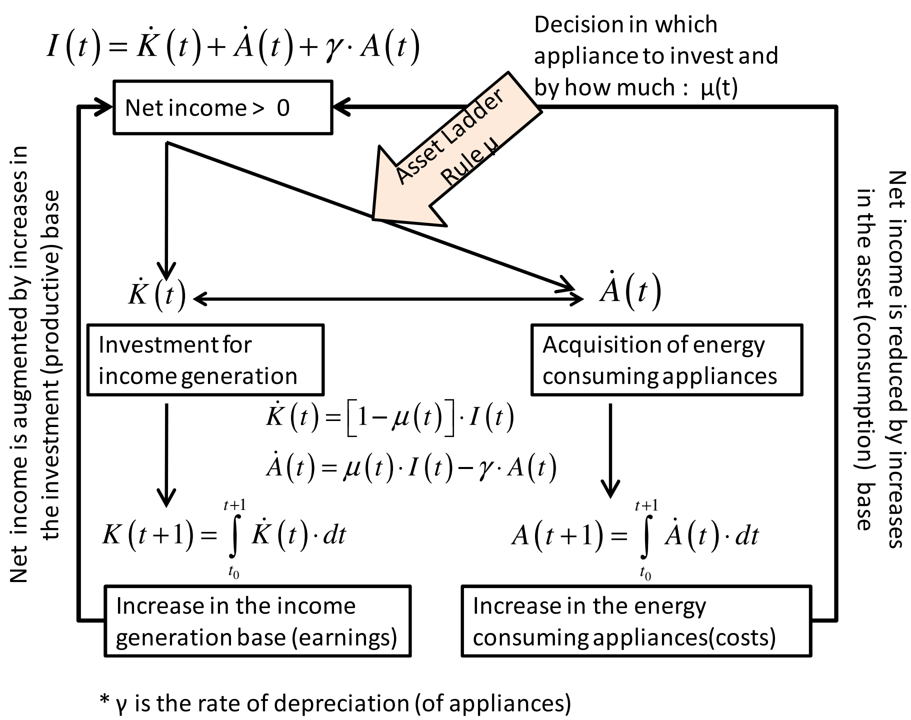

Figure I.4 – Components of the investment decisions

The cost of the appliance, its efficiency of energy consumption and other technical characteristics and the burden it will impose in the family's budget (cost of the energy source) are important factors. The household will consider them when evaluating the adequacy of a particular appliance to satisfy its need. The household's "path" of investment in energy-consuming appliances may alter as a response to prices, ownership levels and technology changes. The household, faced with a positive net income at any moment in

[15] The subjectivity of the definition and the nature "need" are well discussed in Pachauri, Mueller et al. (2004) In his paper atypically energy is rightly recognized as being part of the basic need "package" though no quantification has yet been done.

time, will have then to decide what amount to allocate to the acquisition of appliances (the enlargement of its asset base) and the remaining amount for income generation.

This path of acquisition of energy-consuming appliances, called *asset ladder rule*, is also a path of energy transition and a path of household development. The formulation of a rule to guide the investment decision in energy consuming appliances is then the formulation of a rule to describe how the household evolves from the low-grade energy sources such as fuelwood to the consumption of electricity.

THE GRID MODEL – SUPPLY OF DOMESTIC ELECTRICITY

The link between the household energy demand and the infrastructure viability is through the energy prices that stimulate household growth up the "asset ladder" and at the same time ensure project economic viability. The energy prices, if responsive to demand variations, should lower in response to increases in the source's demand. Thus if households increase their income base (partly to be invested in more energy consuming appliances), the ultimate effect will be the reduction of the energy price, without compromising project viability, and at the same time promote better quality of life.

Electricity prices depend on several factors such as the primary source availability pattern (hydropower availability follow the seasonality of rainfall) and the financial markets, and the demand variations of the power flows in an interconnected grid.

Figure I.5 shows the transmission lines, the substations and the distribution feeders of the Linha Centro-Norte (LCN), owned and operated by Electricidade de Mozambique (Fernando 2006), highlighted in red the system-components this study will model.

The electricity price in the northern electrical grid is comprised of:

- The energy cost at the source or Generation cost. The national grid in the northern provinces transports and distributes power generated in the Cahora Bassa hydrostation, measured and billed at the delivery substation of Matambo. Thus, wherever this energy is delivered, the cost of acquisition is the same. In other words, the generation cost of energy does not vary anywhere along the transmission and distribution system.

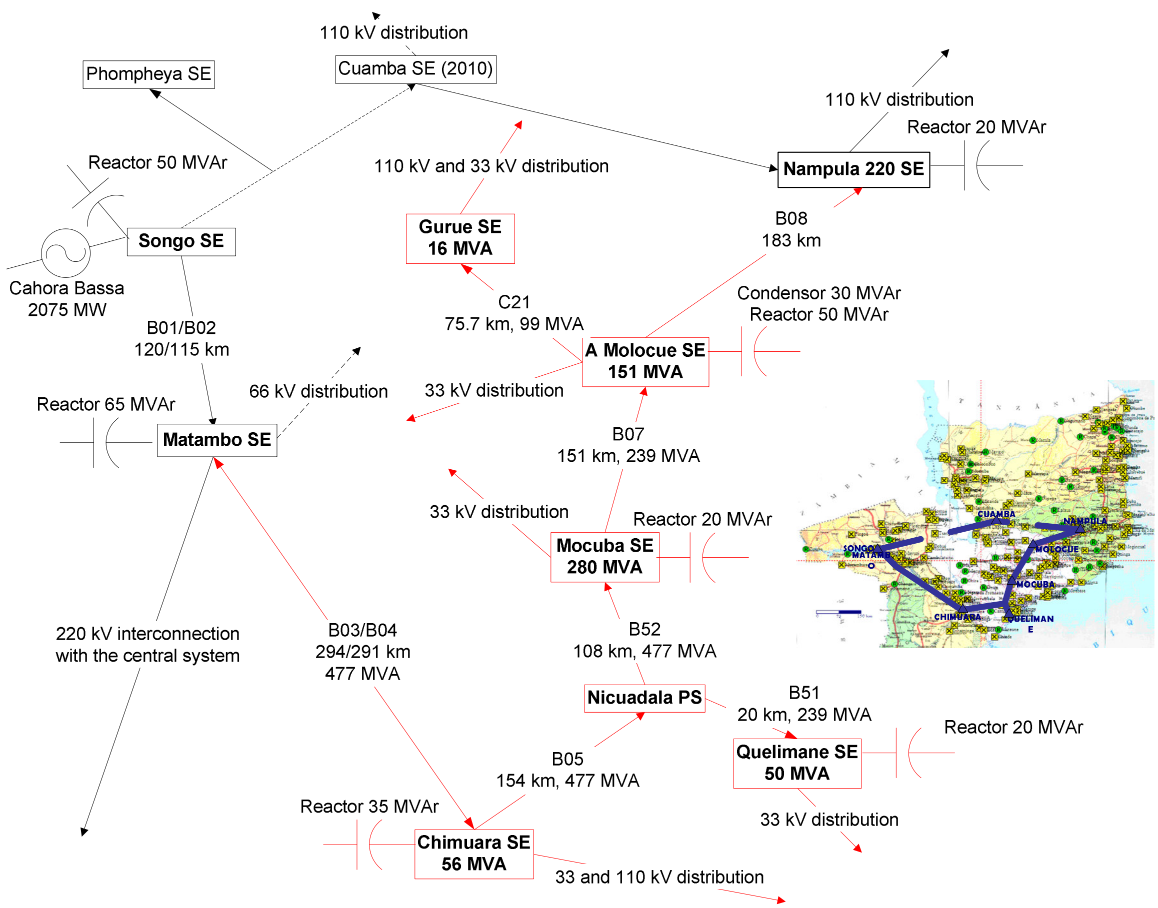

Figure I.5 – Schematic representation of the linha centro-norte (LCN)

- Transportation and Distribution costs[16], respectively at the regional level and within the local area. Transportation and Distribution (T&D) costs contain a relatively

[16] In Mozambique, Transport includes all high-voltage power flows equal or higher than 66000 Volts, and Distribution includes all the medium voltage flows, between 1000 and 66000 Volts.

constant cost of investment, of labor[17] and administrative costs, which reduces on a per unit basis as the power flowing in the system increases. These systems also register costs varying directly with the power flows, i.e. unit costs increasing with the power flows, due to transmission and distribution losses.

- The commercialization costs (costs of retail for final supply to the customers) are in general high and reduce per unit of power delivered, though not linearly[18].
- The financial costs associated with the capital investment, during the payback period, zeroed afterwards, reduce with increases in power flows.

Thus, all partial unit costs tend to reduce with increases in the power flows, excepting the costs of losses. This study will fix the Generation, the Transmission, the Distribution, the Commercialization and the financial costs to the 2007 levels, and only vary the costs of T&D losses as functions of demand, to calculate and draw the electricity supply curves for the northern system. Losses in transmission and distribution will thus be the differentiating factor in the cost of electricity supply along the grid.[19]

The sparseness of reliable and detailed data in electrical supply systems, particularly in the low voltage distribution grids, calls for statistical methods to establish approximate relational equations for supply losses and associated costs, in a spatial distribution.

DATA AND METHODS

The study of household behaviors is based on data from a household survey conducted in 2002/3 by the National Institute of Statistics (INE 2007), of public access. This data set

[17] The staffing of the transmission and distribution substations and networks depend more on the size and technical characteristics of the systems, than on the power flowing through.

[18] The increases of consumer populations do not immediately increase labor or administrative costs if productivity investments are made, but eventually it will.

[19] No repartition of costs was available. The 2006 EDM statistics report an average cost for Cahora Bassa power at 4.2 c$/kWh and an average price at 28 c$/kWh in the whole grid (EDM 2007).

recorded 8700 households in their consumption, earnings and demographic characteristics. The dataset was processed with regression methods, namely Angus Deaton's econometric approach to estimate own- and cross- elasticities (Deaton 1987; Deaton 1988; Deaton 1990; Kedir 2005) and logistic regression to estimate the likelihood of households adopting electricity as a domestic source. Calculations were programmed in MATLAB as shown in Annex. The elasticities thus estimated were compared with published energy price- and income-elasticities of other developing countries and show reasonable results.

The study of the electrical northern grid (LCN) was based on operating data recorded for power flows in the system during the year 2007 and associated financial data, obtained from the records of the national electric company (EDM). Hourly records on active power, flowing in and out of transmission lines and distribution feeders were used to estimate, through quadratic regression, the power loss equations for each substation and each transmission line. The loss equations thus formulated were validated by their use in a simple forecasting exercise of acceptable accuracy. Loss allocation to the distribution networks is proposed by simple weights of yearly energy flows in the system. Financial data was directly processed to calculate the average selling price in the northern grid (including generation, transmission, distribution, commercialization and financial costs), thus allowing the draw of the supply curves for the electricity supply.

The theoretical model was formulated using the optimal control approach and numerically solved for a simple example using dynamic programming techniques, developed from the Comp-Econ MATLAB library for numerical optimization (Miranda and Fackler 2002).

REPORT STRUCTURE

The dissertation contains eight Chapters and appendices. Chapter 1 poses the main research question and discusses the study approach. Chapter 2 presents a literature review and the background information for the current study. An econometric method calculates in Chapter 3 the elasticities of demand for various domestic energy sources based on a sample of Mozambican households surveyed in 2002/3. Chapter 4 calculates by logistic regression the likelihood of Mozambican households adopting electricity as a domestic source, and demonstrates that prices per-useful-energy-unit invert the order of the domestic energy ladder. A quadratic regression model in Chapter 5 estimates the loss equations for the distribution networks supplied from the northern electrical transmission grid (Linha Centro-Norte) in Mozambique, based on data collected from operational records for the year 2007. The theoretical model in Chapter 6 is an inter-temporal utility maximization mathematical model that establishes the determinant factors in a household's choice of domestic sources and the conditions for it to evolve sustainably out of poverty. The loss equations of Chapter 5 combine with the price elasticities of Chapter 3, in Chapter 7, to calculate the demand - average cost curves in 2007, for the distribution networks in the northern grid. Chapter 7 also discusses the role of current tariff design in facilitating new electrical connections and consumption of electricity. Chapter 8 discusses the results and projects future work to clarify further the issues here raised, as well some policy implications. The Annex presents instructions for calling the functions programmed in MATLAB and is complemented with a CD containing the MATLAB code files.

As agreed with the committee, Chapters 3 and 5 have been submitted for publication in professional journals (respectively Energy Economics and IEEE Transactions on Power Systems), and Chapter 6 will be submitted for publication after the work is completed.

Furthermore, Chapter 4 of the dissertation is also to be submitted for publication in a professional journal (Energy Policy). Data and analyses that could not be incorporated in the articles are presented in the appendices of the respective Chapters.

CONTRIBUTIONS

The initial research question is so vast and multidimensional that this study could not answer it in full. However, it contributes to the current knowledge on the Mozambican scene and for the theoretical understanding of domestic energy transition by quantifying, using known statistical methods, the following:

- A reasonably accurate estimation of price and income elasticities of demand for domestic energy sources used in Mozambique, namely firewood, charcoal, kerosene and electricity (Chapter 3). These elasticities have not been previously estimated for the Mozambican domestic energy scene.
- The establishment that prices per units of useful-energy are inverted in the order of the energy ladder in Mozambique (Chapter 4). The evidence on cheaper expenditures per unit of useful-energy basis for electricity clearly demonstrates that poor households are currently paying more for low-grade sources than would if consuming electricity. This is indicative of potential for electricity to become a domestic source of the poor.
- The calculation of the likelihood of Mozambican households adopting electricity as a domestic source, that confirmed that wealth rather than income level is the more important determining factor (Chapter 4). The ownership of wealth indicates the capability to acquire energy-consuming appliances, thus confirming the importance of investment funds in the household energy transition behavior.

The theoretical inter-temporal utility maximization problem, formulated on the assumption that energy consumption can only evolve with wealth acquisition, defines for the first time the concept of an *asset ladder rule* as explanatory of currently observed deviations from the original energy ladder concept in the domestic energy transition behavior (Chapter 6). This optimization model, although applying mathematical methods well known in the optimal control economic theory, is innovative in its use to study energy-consuming behaviors of households[20]. The model includes energy appliances in the utility function, keeping the energy sources themselves as inputs into the operation of these devices[21], and divides investment in two possible choices, investment for income-generation or investment for energy consuming capability, thus allowing the formulation of the *asset ladder rule*. The *asset ladder rule* is a new concept that describes the optimal path for the share of investment in appliances *versus* in income-generating stocks that allows a household to evolve by increasing its consumption of leisure, non-energy goods and domestic sources in a sustainable manner.

To establish the dependency of the cost-recovery price of electricity in the northern grid empirical equations of transmission and distribution losses were developed (Chapter 5). These equations allow for a better loss allocation between the distribution networks and can be used to forecast of power taking at the source with satisfactory accuracy. This forecasting approach can be used instead of more sophisticated commercial forecasts (for example, software PSS/E for load flow calculations), whenever accuracy must be sacrificed in the name of expediency.

[20] Traditionally these optimization models have been applied to the consumption of food and to capital investment behaviors only, see for example Barnum and Squire (1979) and Singh, Squire et al. (1986)

[21] First suggested by Dubin and McFadden (1984) and then expanded by Willett and Naghshpour (1987)

The loss equations are then combined with cost data and points of the average cost curve for domestic electricity in the Mozambican northern provinces are drawn (Chapter 7). The demand-average cost graphs for domestic electricity in northern Mozambique are plotted and the viable-sustainable electricity price is calculated as a function of demand levels. These results may guide the design of policies (Chapter 8) for domestic electricity access and affordability levels.

CHAPTER II: LITERATURE REVIEW

The literature review does not distinguish the geography of the studies in their general discussions, i.e. a citation to a study in India may well be beside a citation to another in Europe. The assumption of this study is that different communities may use different energy sources, and show different characteristics in consumption levels and investment portfolios. However, the basic human needs and solutions, portrayed in the various studies, are still comparable.

ENERGY IN MOZAMBIQUE: HISTORY AND PERSPECTIVES

HISTORICAL INTRODUCTION

In June 25 1975, Mozambique won its independence from the Portuguese colonial government, after about 20 years of armed struggle. By Independence, there was no integrated plan for electricity supply, and no goal to widen access to electricity in all the territory. Most of the population lived in rural areas (only 9% urban in 1970[22]), dependent on the use of wood derivates and kerosene[23], and electrification was then confined to the

[22] Urbanization levels vary from province to Province. The rush for urbanization, which resulted in urbanization levels of the order of 50% by 1992, was a result of the war that made the urbanized areas safer; even after the restoration of peace, the displaced population (estimated about 2 million people) did not return to the war ravaged infrastructure-destroyed rural areas (Ferraz and Munslow 1999).

[23] The World Bank report (World-Bank 1987) refers to a wood fuels consumption of about 90%, in 1986. Ferraz and Munslow (1999) places 90% wood-fuels consumption in 1970 and 80% in 1994. Brouwer (2004), argues that the reduction registered in the 80’s was the result of war, which made the countryside inaccessible – where the raw materials – forests are, despite the growing populations of the urbanized areas. Currently, the estimated levels are of 70-80% in Maputo, in various combinations of use with other fuel sources, such as kerosene and electricity (Brouwer and Falcao 2004). This number is based on a small sample and varies across households based on income and other factors the authors well explain. The authors also discuss a trend of substitution of wood-based fires by other energy sources; they also refer to the deforestation

boundaries of the provincial towns and the capital city of Lourenço Marques (currently Maputo). At this time, the electricity sector was composed mostly of:

- Small municipal diesel generators
- Few micro hydro generators in the Tea plantations and the upper land districts, run either by private companies or by the municipalities
- One coal fired power station, in Maputo, burning imported coal from SA mines, soon to be replaced by transmitted power from the South African grid
- Two hydropower stations in the Revue River (built by SHER - Sociedade Hidroeléctrica do Revué, and named Chicamba and Mavuzi), in the central region supplying Beira, Chimoio and Zimbabwe
- One major hydropower enterprise, Cahora Bassa, which started operations in 1972 and was completed in 1974, whose main consumer was the SA market; electrical energy was supplied to Lourenço Marques, capital city, through the South African AC transmission system.[24]

As part of the agreement for Independence, signed by the transition government of Mozambique in 1975 (Mozambique 1975), Cahora Bassa was transformed into an "Anonymous Society of Limited Powers" (SARL), named HCB, 82% of which owned by the Portuguese government in representation of the investors (Zamco[25]) and 18% owned by the Mozambican government. The agreement gave the right to exploit the enterprise,

resulting from increased production of charcoal, which placed at about 50-60 km of Maputo, and briefly inferred to stand at least at 100 km radius of Maputo (Ferraz and Munslow 1999).

[24] Cabora Bassa (or Cahora Bassa in the local language), started construction in 1969 and was completed in 1974. Capacity of 2075 MW (5 x 408 MW generators), 18 GWh per year, 137 m high dam, reservoir with capacity to store 57 millions m3 of water (250 km long lake), total construction cost $517.7 million. The dam also supplies water for irrigation in small areas of the Mozambican northwest and the Zambian border (Azevedo, NNadozie et al. 2003). The power is transmitted through a 1400 km HVDC power line to SA, which interconnects with the SA HVAC transmission system in the converter station Apollo, in the SA territory.

[25] Zambezi Consorcio Hidroelectrico, Ltd (Mozambique 1971)

produce and export power primarily to South Africa[26]. This agreement was later amended (1984, 1988) for new levels of power tariffs, without however provisioning for tariff review based in economic indicators such as inflation rates[27]. Consequently, a "battle" for fair tariffs ensued, years later, and was not really ever resolved to the satisfaction of the Portuguese investors. Cahora Bassa (HCB) kept its role as an energy exporter with little impact in the supply to the rest of the country, paying small dividends to the Mozambican state (Isaacman and Sneddon 2003).

The hydro stations belonging to SHER had an associated transmission system, with 60 kV AC lines supplying Chimoio and Beira, and 110 kV lines to Zimbabwe. Already by colonial time it was recognized the profitability of enlarging of the transmission network to interconnect with Beira and Cahora Bassa, consequent to the fast growing rate of the area. In the South a transmission line 275 kV between South Africa and Maputo transported power from Cahora Bassa to the capital at an increased price of wheeling through the South African system. Apart from these two small "systems", the country had isolated distribution grids, small, old in some cases, of different voltage levels and unprepared for interconnection.

[26] Mozambique's economy it's always been closely linked with South Africa's (Newitt 1995). By the late nineteen century coal was discovered in northern Natal and northeast Cape, of which 15% was consumed in the gold mines, 24% in the railways and also exported, busting thus the SA economy (Konczacki, Parpart et al. 1991). The mines absorbed Mozambican (forced) labor, which became an important source of financing of the colonial apparatus (Konczacki, Parpart et al. 1991). As the industry in South Africa grew and more and more power was needed, the price of coal started to rise making the development of Cahora Bassa dam a profitable investment for both the Portuguese and the SA governments.

[27] In 1984, during the civil war in Mozambique supported by the apartheid regime, both the Mozambican and the South African government recognized their mutual interest in maintaining operational Cahora Bassa dam, within the spirit of the Nkomati Accord. Consequently, both countries agreed in joint actions to protect the HVDC transmission line, which was a usual target of the guerrilla forces, and also agreed in new tariffs for the power supplied to the South African market. Still this move was not enough to prevent the sabotage conducted by Renamo in 1981 (Isaacman and Sneddon 2003), which destroyed about 400 pylons in the Mozambican territory, and continuously harassed the teams trying to repair them. The supply to South Africa was interrupted and the station generated (between 1982 and 1997 about 0.5% of its installed capacity, supplying the north of Mozambique, through the recently constructed "Linha Centro Norte". In 1992, the construction of a 400 kV line to Zimbabwe started, and from 1998, HCB has been supplying Zimbabwe with about 500 MW peak. Currently ongoing is a project to build a 220 kV line to Malawi (Phompeya). Swaziland is benefiting through an interlink with SA.

The first Mozambican government established, as priority, the regular and reliable supply of electricity to the whole country and stated its importance in the development of a fair society[28]. Consequently, the Mozambican government constituted the Electricity State Company, EDM in August 27, 1977, giving it exclusive rights to operate and expand existing electrical infrastructure on generation, transmission and distribution, and to supply electricity to consumers at the national level (Mozambique 1977). Cahora Bassa was still a separate entity and separately run and accounted for at the governmental level.

In response to the goals set by the government and with a lot of support from donors such as Sweden and Norway, the national monopoly set out to expand the infrastructure of electricity supply. This is still a goal of the company's investment program, notwithstanding all the changes in the country, the sector and in the company itself since 1977.[29] See the graphic representation of the changes in the transmission infrastructure of Figure II.6:

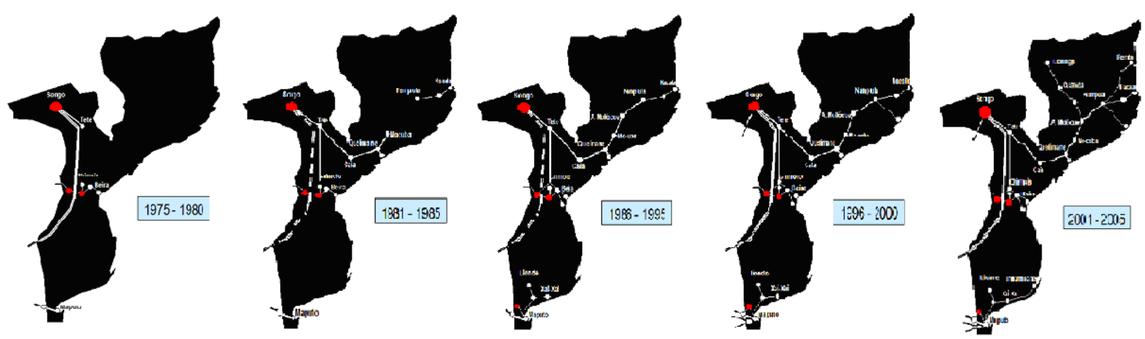

Figure II.6: Evolution of Transmission Grid 1975-2000 (Fernando 2006)

[28] The Constitution Bill of 1975 (Mozambique 1975) sets individual rights and obligations which are still valid, and establishes that "work is the main criteria for the distribution of the national riches" ("*O trabalho (…) constitui criterio para a distribuição da riqueza nacional*"). The constitution law was reviewed in 1990 transforming Mozambique into a "republic" and eliminating wordings such as the one presented above. Mozambique was (still is) transforming into a state where economic requirements sometimes overpass social development objectives.

[29] Fernando (2006) presents a comprehensive chronology of the development of the transmission system, that in Mozambique incorporates lines of 110 kV and above (see Figure II.6).

In 1995, EDM was transformed into a Public Company, with administrative and financial autonomy, still fully owned by the state and mandated to manage and expand the electrical infrastructure in the country (Mozambique 1995). The role as a primary agent of electrification is still maintained. To ensure the viability of the electrification programs the government allowed the cross subsidy at the national level, through what is known as "tarifa unica": one electricity tariff, differentiated across the consumer population but not geographically. In practical terms, it means that those areas, where infrastructure is already paid for and electricity could be cheaper than current rates, finance recently interconnected economically unviable rural areas still being electrified.

South Africa's apartheid regime fell in 1994 opening the way for a full integration of the Southern Africa Development Community (SADC) countries and more intense economic and political ties. Changes in the political scene of Southern Africa have thus resulted in a bigger cooperation between electrical utilities, which constituted, in 1994, the SAPP – Southern Africa Power Pool (Musaba, Naidoo et al. 2004). Through this institution, electricity trade is being carried out both with long to medium term supply contracts and through the STEM – short-term energy market – located in Harare. Mozambique is exporting energy to STEM and earning additional revenue, mostly on the hydro-generated surplus in the center of the country. Recent shortages in peaking power, resulting from an accelerated growth and the non-construction of new generation capacity have increased the prices of trading in STEM, and reduced the power availability particularly at peak - see estimations of load scarcity by Musaba, Naidoo et al. (2006).

In 1997, the Mozambican Parliament approved the Electricity Act 21/97 of October 1, which opens the electricity market to private operators, from generation to distribution and supply. By this law, the operation of the transmission grid will still be public responsibility, and the National Electricity Council is established as an advising body only, to support the government in exercising regulatory and supervisory powers that it retains.

Although the framework was delineated in the Electricity Act, many regulations were lacking which, associated with a small market of apparent small profits and an unfavorable risk assessment resulted that very little private investment occurred in the energy sector.[30] EDM continued to be, not only, the government's tool to carry out its development programs and extend basic infrastructure for electricity supply, but also the main generator and distributor in the country.

Regulations drafted and approved by the Council of Ministers establish the procedures to grant and supervise private or public enterprises in the electricity sector, thus reducing the investment risk. Some private enterprises (mostly of foreign capital sources) have initiated the move to control and develop the energy sources in Mozambique. As a response, EDM is changing towards a more commercially viable enterprise and increasingly competing with the private sector to develop the significant energy resources, yet unexploited, to supply the growing internal demand and the Southern African market – see (Graeber, Spalding-Fecher et al. (2005) for a good presentation on the joint expansion of the Southern Africa Power Pool (SAPP).

INFRASTRUCTURE DEVELOPMENT

In the past 28 years, EDM has built more than 3000 km of 66 kV lines and above, rehabilitated, upgraded and expanded distribution systems. Demand for electrical power

[30] ENMO is a private investment in generation, distribution and supply, small scale, the first since independence, to manage the Vilanculos and Nova Mambone area. This experience allowed the identification of regulatory "holes", particularly in the sensitive area of tariff setting and enforcement: the consumers opposed the raise of tariffs and called for arbitration, that was carried out by the government itself. This of course raised issues of incompatibly and double standards which are not, so far, resolved.

has grown from a mere 200 MWh/year in 1960 to about 1600 MWh/year in 2005[31] (Fernando 2006), bringing the hydropower from Cahora Bassa to all provincial capitals (Sebitosi and da Graça 2009).

In Figure II.7, it is clear that for the time of non-operational HCB, due to war ravages, South Africa's power company (ESKOM) supplied the growing demand in Mozambique. Meanwhile, as the interconnection to the national grid progressed (also suffering huge losses and delays due to sabotage in transmission lines) the diesel and coal generators were progressively shut down. Only hydro generation remains today as EDM's source of power, together with HCB's share for EDM[32].

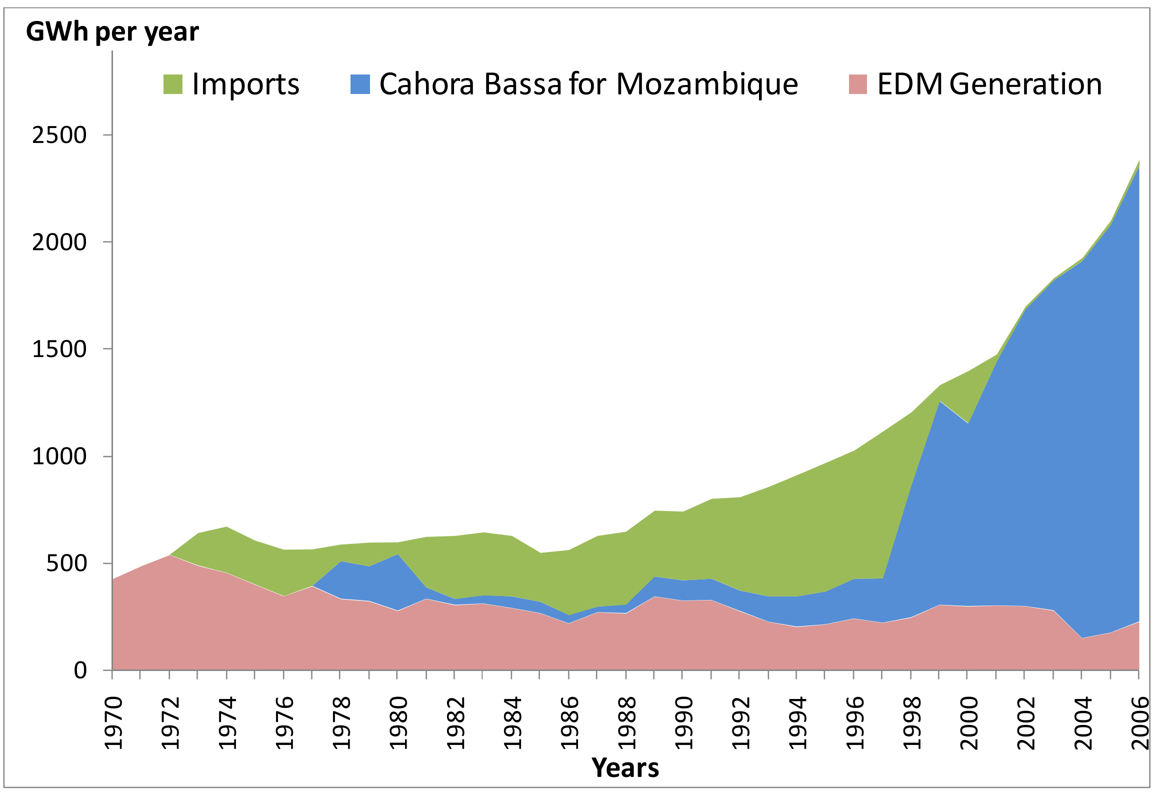

Figure II.7: Energy balance (Based on EDM's data)

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[31] Excluding small district generators and private generation, of whatever source.

[32] Currently EDM is entitled to acquire 300 MW of power from HCB at 16.72 cR/kWh (2.4 c$/kWh), and 100 MW non-firm at 20.97 cR/kWh (3.0 c$/kWh), 2008 prices. Good management practices allowed EDM to cover peak power with its own hydro stations, and avoid the high costs of importing power from ESKOM-SA.

The expansion of the transmission and distribution systems was laid out, for the next 15 years, in the Electricity Master Plan (EDM 2005). The electrification of district towns will raise the overall access from 4.6% to 14.5%, a demand increase from 250 MW in 2002 to 876 MW in 2020, and a corresponding investment in transmission and distribution of about 390 million USD. New generation is also planned, both hydro (Mepanda-Nkwa 1600 MW) and thermal (Temane, natural gas, 500 MW and Moatize, coal, 1000 MW).

The Mozambican government bought Cabora Bassa, becoming for the first time 85% Mozambican owned, 15% Portuguese. Mozambique has also agreed that of its share will only retain 80%, and sell the remaining 5% to an interested third party. The deal will be completed upon the payment of 950 million USD.[33]

By 2014, if all the planned power generation and transmission interconnections are completed, the existing generating capacity will feed the growing demand in the Southern Africa grid (SAPP 2006). This makes any power generation potential worth to look at and possibly viable for development at some stage in the region. Mozambique has the privileged location of bordering with 7 of the total 12 signatories of SAPP, thus strengthening transmission interconnections and developing new power generation are viable, potentially profitable investments.

It is fortunate that Portuguese occupation retained all the rugged terrain that, only by the 20th century, became of economic value with the development of hydropower in big scale. Until then energy was mostly equated with fossil fuels, and Mozambique consequently classified as not very rich in energy resources - the gas fields were not discovered until mid 20th century (World-Bank 1996). In SAPP, most of the current power generation is thermal

[33] Newspaper "Noticias" (First Page), Maputo, Tuesday, October 27, 2006. News Africa (www.iol.co.za), "Mozambique assumes control of Cahora Bassa", November 26, 2007.

(73%) and the call for environmentally friendly technologies makes hydropower projects much more attractive (Fernando 2006).

Although Mozambique has an estimated 12.5 Gigawatts of hydropower potential, only in the Zambezi northwest areas (Mulder and Tembe 2008), electricity only benefited 8.2% of the population in 2006, and the average monthly domestic consumption is only 89 kWh/month per household (EDM 2007), about a third of the current US domestic energy consumption (EIA 2001). In other words, the currently developed generation and transmission infrastructure does not benefit the majority of the population.

The expansion of electrical grids supports future economic and social development, see analysis by Mulder and Tembe (2006), and remains a priority in the company's agenda. However, the low connection and consumption rates of domestic energy raises doubts on the validity of accelerated electrification as a poverty alleviation strategy targeting households and rural communities. A study on domestic energy must necessarily include biomass sources and kerosene, as these are used by approximately 80% and 50% of the population (Brouwer and Falcao 2004).

Domestic energy in Mozambique is primarily composed of firewood, charcoal, candles, kerosene, LPG and electricity (from the grid, from batteries or from private diesel generators). Renewable energy installations such as solar and wind are few. Energy consumption levels are small and energy mixes are present in most of the Mozambican households as recorded in the IAF 2002/3 household survey (INE 2007), typical of poverty-ridden families.

POVERTY AND PRIMARY ENERGY SUPPLY

Poverty is plaguing the world of today with a rate as high as 41.1% of people in sub-Saharan Africa, living with as little as no more than one dollar (PPP) a day (United-Nations 2007). Efforts are being made to reduce poverty around the world (an overall reduction of 270 million people moving out of this extreme poverty limit, between 1990 and 2004); however, it is still a global catastrophe that needs solving. In the scope of the Millennium Development Goals (MDG, established in the UN Millennium Summit in September 2000 in South Africa), monitoring data indicate that although the Mozambican population has not effectively grown more than 2.1% on average, between 1990 and 2004, extreme poverty levels have sharply increased to about 32%.

The recognition that there can be no development if basic infrastructure and access to other services (telephones, internet, etc) is not provided, is evident in the progress chart for 2007 (United-Nations 2007), and in the overall programs for the MDG. Unfortunately, as sub-Saharan African is not progressing well in these goals, mechanisms to accelerate infrastructure development, to support health care and educational systems, need to be put in place (Africa 2007).

Electricity in particular, and energy supply in general, are rarely cited as essential “goods” for household development (Pachauri, Mueller et al. 2004), which is surprising as not only families consume energy in every aspect of their lives but they also consume it indirectly, in the use of goods and services whose production processes use energy as a major input. Fortunately, the Action Plan for the Reduction of Absolute Poverty (PARPA 2001-2005) recognizes the need for reliable energy services and aggregates “energy services” with “water supply” and “road extension”, as basic infrastructure. The lack of basic infrastructure in poorly developed in rural areas constitutes a determinant factor of poverty (Mozambique 2001). The approach of the World Bank's ERAP (Mozambique Energy Reform and Access Program) in Mozambique, set to support the energy supply to the development needs in health, education and water supply in rural areas, for poverty alleviation (Mozambique and World-Bank 2002), still relies heavily on central planning for the extension of energy services. It mostly consists in the expansion of generation and distribution systems, centrally planned and managed, rather than in promoting local individual initiatives for energy transition. Other transitional sources such as kerosene, batteries and Liquefied Petroleum Gas (LPG), are thus, effectively barred from the integrated planning process. Even the Ministry of Energy, created in 2005, is mostly concerned with the national systems of electricity and oil derivates. The market and the demand for charcoal is not specifically within its scope (might peripherally fall into the scope of "renewable sources"), though it constitutes the primary source for about 80% of the Mozambican population.

In Mozambique, the national statistics indicate that the main sources of domestic energy are firewood, charcoal, kerosene, LPG and electricity. In the years 2002/3 it is recorded the following composition of lighting energy: electricity (6.9%), kerosene/gas (53.8%), firewood (31.7%), candles (2.2%) and other sources (4.7%), see (INE 2005). On the other hand, domestic cooking uses the following composition of energy sources, in 2004 in Maputo: firewood only (2.1%), charcoal only (11.7%), kerosene only (10%), LPG only (3.8%) and electricity only (4.6%), see (Brouwer and Falcao 2004). Most of the households use charcoal for cooking, alone or in combination with other sources (71.7%). Diesel and gasoline are primarily used in transport systems (EarthTrends 1999), animal traction has an incidence of barely 8% in farming activities - only 2.5% of farmers own and use animal traction in the farms (Toro and Nhantumbo 1999), and finally renewable sources such as micro-hydro, wind and solar are as yet negligible.

The transition from low-grade sources[34], such as firewood and charcoal, to electricity, not only serves the policy of household development and poverty alleviation, but also satisfies concerns that an increasing urbanization, in African countries, will result in irreparable deforestation and its all the environmental, social and economic consequences (Mwampamba 2007). Although the extent of the impact of household energy, in deforestation trends, is uncertain[35], it is still accepted that household demand for wood-fuels will significantly reduce the forest cover, not only because forests constitute the poorest energy source, but also because it provides a source of income for farming families (Heltberg, Arndt et al. 2000).

The use of a more efficient energy source, and of diverse applicability, can benefit the household with regards to time saving for other productive activities, can support educational activities and finally allows for the diversification of income generating activities that will take it out of poverty (Ellis 1998; Abdulai and CroleRees 2001). The substitution of charcoal as the main energy source by any other of higher grade, will also

[34] Low-grade sources, by the concept of the energy ladder, can have several definitions. Hosier and Dowd (1987) were the first to describe an “energy ladder” in the context of Zimbabwean communities, and the first differentiation used is whether the sources are non-commercial (fuelwood, charcoal) or commercial (oil, electricity). The authors also make reference to “high quality carriers” which can be interpreted in many ways:

- In terms of energy content per volume of solid fuel: fuelwood (15.1 MJ/kg) at the lowest, passing through kerosene (43.12 MJ/kg) up to LPG (45.84 MJ/kg), see (Kadian, Dahiya et al. 2007)
- In terms of ease of use: at the worse, charcoal and fuelwood with the lowest ranks, and electricity with the highest, passing through kerosene and LPG, see (Gupta and Kohlin 2006)
- In terms particulate emissions: dung cake the biggest pollutant, with 0.1879 g/MJ, followed by charcoal (0.0923 g/MJ) and wood (0.687 g/MJ), and at the lowest pollutant, kerosene (0.0163 g/MJ) and electricity (no particulate emissions), see (Kadian, Dahiya et al. 2007)
- In terms of the source’s energy price and payments modalities, fuelwood cheaper and small (daily) payments, electricity more expensive and lumpy payments – see Table 2 in (Leach 1992)

All these classifications can be used to establish low-grade or high-grade sources, and it is the author’s choice the one to apply. In this study an important factor is the multiplicity of use of the source in a domestic setup. The energy ladder in Mozambique will be assumed to be: fuelwood, charcoal, kerosene, LPG, electricity. This configuration is verified in the results of Chapter 4.

[35] UN data indicates that forestry cover has changed from 25.5% in 1990 to 24.9% in 2000, of the total area of the Mozambique (United-Nations 2007) Other reports indicate that although overall the deforestation rate is only of 0.26% per year, individual urbanized (corridor) areas can register rates above 1% (Mangue 2000).

impact significantly in the health of family, by reducing particulate and other emissions in the household environment (van Horen, Eberhard et al. 1993; Smith, Apte et al. 1994). Efforts are being made to reduce household emissions, in the form of the numerous "improved stoves" projects and monitoring of domestic energy alternatives (Ramakrishna, Durgaprasad et al. 1989; Ellegard 1993). However, ultimately, the only effective way of improving the families' health is the adoption of electricity as the main source.

Electrification increases the household's choice for energy sources by introducing electricity in the range of options, at a possibly competitive price. The adoption of electricity as one of the sources in the household mix, allows it to diversify its income, by doing productive work with electricity (for example, mechanical work, sewing, etc). It also allows the access and the participation in public awareness and education programs, through the media (TV, radio). Electrification thus abolishes some causes of poverty in developing regions[36].

END-USES AND FORECASTING

Domestic consumption in poor households does not go beyond cooking and lighting (Campbell, Vermeulen et al. 2003), while in richer households it can be very diverse, to include space heating and cooling, dish washing and other uses. Not many records of consumption per end-use are available, particularly for the electricity users that have many end-uses in the household. Most of the studies on electricity supply patterns do not adequately characterize domestic energy, see Hondroyiannis (2004). Even sparser, is data from developing countries, on consumption levels and the end-uses of domestic energy. The lack of energy consumption data is more critical in these countries, because electricity statistics from the public databases are also not always reliable.

[36] Some authors (Foley 1992; Howells, Victor et al. 2006), argue against electrification programs as a means to reduce poverty, mostly because of the recourse to subsidized electrical supplies, they clearly state that electricity brings a significant improvement in the lives of the poor.

The types of energy end-use of households show variations for different income levels, both in the end-uses and in the preferred energy sources for household consumption. For example, the preferred lighting energy is electricity. However, budget constraints may force poor communities to consume more in less efficient lighting energy such as kerosene (van der Plas 1988). On the other hand, the preferred cooking source in most of southern Africa is charcoal even when electricity is available (Madubansi and Shackleton 2007). Several studies indicate that candles and kerosene are the more common transitional sources for lighting while charcoal remains the main source for cooking in southern African countries. Factors such as the energy source availability and costs may shift this pattern. For example, in Tanzania and in South Africa, kerosene is a main cooking energy in urban areas, and in Mozambique the main cooking source, in urban areas, is still charcoal (Hosier and Kipondya 1993; Davis 1998; Brouwer and Falcao 2004).

Parti and Parti (1980) pioneered the estimation of electricity consumption shares per household appliance, by using the conditional demand analysis (CDA model) that calculates regression coefficients for each type of energy consumption in the household. Their approach was later developed (Bartels and Fiebig 1996; Larsen and Nesbakken 2004), mostly for households consuming electricity in European settings.

Larsen and Nesbakken (2004) present two models to estimate the electricity consumption per end-use in the Norwegian environment, of which the econometric Conditional Demand Analysis (CDA model) is the less data intensive and requires relatively simple household surveys. Direct metering is expensive and usually not done, reason for which researchers have developed ways to optimally sampling for regression analysis of energy end-uses (Bartels and Fiebig 1996).

By this approach the ownership of certain types of appliances, indicate the probable electricity consumption through each of the appliances, based on which forecasts for demand growth can be made. Easier than measuring electricity consumption in each household's appliance, is to count the ownership of those and estimate the associated electricity demand. Most of the CDA models concern households with varied electrical appliances, in Norway, Australia and other developed societies. Still, the method is valid for different classes of household demand and for different energy sources[37].

The quest to quantify the energy consumption per end-use comes from the recognition that load curves change when the energy source change, because the household also changes its schedule of use, and the appliances for different sources have different efficiencies of energy use. Furthermore the multiple-use nature of some sources (for example charcoal for cooking also heats water and space) alters their substitutability for other sources (Howells, Alfstad et al. 2005), which can account for having charcoal for cooking "co-existing" with electricity for lighting.

The identification of the composition of the energy consumption in households is of particular interest in the design of strategies to reduce carbon emissions associated with domestic energy consumption. A study conducted in Portugal (Almeida, Lopes et al. 2004) show that, despite allegations that the use of natural gas for space heating would result in lower emissions than electrical heaters, electricity can, over the life cycle, generate lower emissions if appropriate technology and a combination of sources is used. Thus, the "cleanness" of electricity, or any other source for that matter, depends on its main fuel-source and on the efficiency of the electrical appliances used by the end-use consumers.

[37] The South African electrical utility, ESKOM used similar approach to determine the lifeline tariff for electricity supply (Louw, Conradie et al. 2008)

Mozambique is fortunate in that its main electricity source is hydropower, although there are also significant reserves of natural gas. Increasing carbon and environmental taxes are making these sources more competitive in the southern African region[38]. Hydropower has a lifecycle emission estimate considerably lower than any other renewable technology at the small scale (Pehnt 2006). A study on Greenhouse Gas (GHG) emission lifecycle analysis (Weisser 2007) shows that, at the large scale, hydropower emits on average 50 times less CO_2^{eq} gas per kWh generated than natural gas, and 100 less emissions than coal-burning generated electricity. It is thus fair to state that in Mozambique the consumption of electricity will not increase the GHG emissions, and in a "long shot" might even result in its reduction, a double dividend, by means of reducing emissions from charcoal burning and increasing carbon storage by reducing deforestation.

Poor households consume most of their energy in the form of direct energy (cooking, heating, lighting, transportation) while richer households tend to increase their share of indirect energy (in the form of goods and services) in the total demand. Vringer and Blok (2000) established that energy intensity levels (energy per income) for household consumption goods and services do not vary much across income classes, for any reduction in direct energy due to efficiency gains is compensated by an increase in indirect energy consumption. Although very far apart from Holland, their results are confirmed by studies in India (Pachauri and Spreng 2002). These findings are important for the forecasting approaches, in the sense that they imply a substitution mechanism in the energy choice that is independent of cultural and geographical factors.

[38] Under the scope of the Southern African Power Pool (SAPP) and its regional integrated resource planning approach (Graeber, Spalding-Fecher et al. 2005), Mozambique's energy sources are very attractive for regional finance and development.

Data from Brazilian household direct energy consumption (Cohen, Lenzen et al. 2005), indicate that there is convergence in the budget share of energy consumption, on the household's income[39]. The national energy dematerialization[40] trend is restated by Bashmakov (2007) in his first law of energy transition, *The law of stable long-term energy costs to income ratio*, that states that "stability of energy costs to income ratio results from the existence of energy affordability thresholds and behavioral constants". At the household level, this law has the following interpretations:

- As the household earns more (increases its income) it will be able to afford greater volumes of energy, and more expensive appliances and energy sources. It will also be more willing to pay for more expensive energy sources. In contrary, an increase in the energy costs will reduce the household's ability to pay for its current consumption forcing it to reduce demand.
- Price increases reduce the competitiveness of the source in comparison with other energy sources.
- There is so much energy that a household can consume. Although the higher the income, the higher the expenditures in energy, households tend to converge to a relatively constant level of energy intensity per end use

The variations in household energy intensity are more related to the variety of energy uses *rather than variations in the total consumption of each end-use*. For example, cooking with kerosene, LPG or dung cake is estimated to consume an average of 6.0 to 6.8 GJ per household; cooking with electricity consumes about 3.7 GJ. Significant increases in a

[39] The correlation is extraordinarily good, however the lack of the base data doesn't allow the use of these results as a definite proof of convergence.

[40] The authors' definition: Dematerialization can be defined as "the reduction in the raw material (energy and material) intensity of economic activities, measured as the ratio of energy consumption in physical terms to the gross domestic product (GDP) in deflated constant terms" (Vringer and Blok 2000).

household demand for electricity will probably result from the acquisition a new ventilating fan, for example, rather than an increase in the total hours of cooking per day. If however, one member of the household starts studying in nocturnal school, it makes sense to expect increases in the total energy consumption. Lighting energy intensity shows the highest variation between sources (Kadian, Dahiya et al. 2007).

In Europe, a comparison of direct and indirect energy expenditures as share of income for an average household places the first varying between 5.4% and 11.5% (or 34% - 64% on total energy requirement) - such variation is mostly attributable to climate effects, consumption for heating and cooling (Reinders, Vringer et al. 2003).[41]

Energy sources vary in their applications (multiplicity of use), efficiency of use, and economic characteristics (price and typical schedules). At both ends of the scale, firewood and electricity are sources for cooking, heating and lighting with very different efficiencies, cleanness and safety factors, and costs. Firewood is bought in small bunches at a time, enough for each meal, commonly on a daily basis, very much in line with the "retail economy" of a typical poor household: daily (small) expenditures for daily (small) earnings. In contrary, traditionally, electricity is usually bought in bigger quantities, and poor households face monthly big bills that they cannot possibly save for, which makes electricity an unaffordable source. The onset of prepaid metering (called Credelec in Mozambique) and of load-cap technologies (called Quadrolec in Mozambique), for domestic energy in poor communities, has reduced this disadvantage and transformed electricity in an "almost" retail-economy source, see experience of the South-African pre-payment scheme for electricity domestic consumers (Tewari and Shah 2003).

[41] This study will concentrate in the study of direct energy consumption in households, and treat the indirect energy as incorporated in the other "non-energy" goods consumed by the household.

The forecasting methods of electricity demand of the residential sector, consist of the study of trends, with or without time lags, at the national, regional or even consumer-class levels (Pouris 1987; Whittaker and Barr 1989; Holtedahl and Joutz 2004; Yang and Yu 2004). The ownership of assets, as an indication of electricity consumption for forecasting purposes, has been to some extent abandoned, due to lack of reliable data in most cases (Kamerschen and Porter 2004). Empirical methods, some of which evaluate the interrelations between sources in the energy market through cross-price elasticities, or alternatively estimate future consumption based on detailed characteristics of households (size, location and others), such as Bernard, Bolduc et al. (1996) and Haas, Biermayr et al. (1998), are popular. The later developed the notion of Laspeyres structural and intensity indexes, to account for efficiency variations as well as time trends. However, the rationale of the energy mix at the household level is still elusive.

FUEL MIX AND ENERGY TRANSITION

The concept of the "energy ladder" links the choice of energy source with income, and postulates that increased income calls for more efficient sources, also more costly and less polluting (Masera, Saatkamp et al. 2000). The association of efficiency, cost and pollution rate is somewhat dubious[42], as studies have shown that in some cases the sources in the lower level of the energy ladder, such as wood fuels, may in fact be more costly, in real terms, per unit energy than, for example, kerosene (Gupta and Ravindranath 1997). This author shows that kerosene can be quite inexpensive through viable subsidies, even competing with fuelwood, as consequence of being a more efficient source. Kebede (2006) confirms this view by showing, from empirical data for Ethiopian households, that even the

[42] Smoky coal combustion, which is more efficient than fuelwoods burning and, as such, of a higher grade in the energy ladder, is significantly more hazardous for human health than fuel wood (Mumford, Chapman et al. 1989)

poor can afford the consumption of kerosene if their capital costs are met with subsidies, and even without subsidies poor families are very close to the affordability level if consuming kerosene. Kebede (2006) presents electricity as an extremely expensive source, well beyond the reach of households, including the non-poor, by equaling the non-subsidized electricity cost to its LRMC (long run marginal cost). On contrary, Cockburn and Low (2005) indicate that non-electrified households in Mozambique may be spending as much as 4 times more per kWh than those with electricity.

Nevertheless, the affordability level of electricity may be altered by creating financing resources of capital lending and tax benefit packages, specific for development projects that will cheapen the viable price of the electricity supply, and by introducing price schedules (tariffs) that are compatible with the poor's economic power. Bose and Shukla (2001) have shown that poor consumers may have the ability to pay more for electricity consumption and that tariffs may be raised (reducing the subsidies) for most of the residential consumers, the farmers and the industrial consumers, though the very poor may still need a cheap electricity rate. In their study, consumers were paying more for liquid fuels used in productive activities, than the current electrical tariff would require them to. The affordability of an energy source is thus dependent on the price design (Raineri and Giaconi 2005) and on the required returns for the capital investment: without soft loans and donor financing for electrification, Mozambique could not have developed its electrical grid as fast nor maintained the current (affordable?) domestic tariffs.

The energy ladder concept appeals to our intuition and our desire for simplicity. However, it is not as straightforward as one would wish, for it is a transitional bi-directional process, rather than a clear cut predetermined (ascending) path of energy evolution.

Poor households are vulnerable to varying prices and the availability of energy sources, and respond by combining several energy sources with the objective of minimizing costs for a particular (sought) level of utility. Madubansi and Shackleton (2006) even suggest that investing for environmentally sustainable markets of fuelwood would be the way to reduce household's share-of-energy in income, and make it less vulnerable to energy price variations and poverty-inducing factors. Their recommendations are validated by later surveys (Madubansi and Shackleton 2007) showing the prevalence of fuelwoods for cooking in electrified households and a consistently larger fuelwood market, possibly as a result of price increases for the other sources. Although evidence points to the existence of a trend concordant with the concept of the energy ladder, other factors play a part, and while some energy sources are substitutes to each other, others are complements (Kidane 1991).

A question that Hosier and Dowd (1987) tried to address is whether the households are free to choose between fuels based solely on their income levels. Factors such as the cost of the appliances for the specific energy source (Reddy 1995), and the compatibility of the cost schedule with the household earnings have shown strong correlations with household choices of fuel (Masera, Saatkamp et al. 2000). Preferences are also based in the environmental characteristics, for example, rural households may prefer to continue consuming fuel-wood, gathered at very little cost, and reserve the cash earned to other utility serving purposes (Hosier and Dowd 1987), as opposed to urban households for whom fuelwoods are bought in the commercial market.

In the urban markets, wood fuels compete with other sources for their share of the income, with preferences leaning for cheaper sources. It's been shown from surveys that the cost of appliances make "modern" energy sources such as kerosene more expensive than the fuelwood that does not require an imported stove for cooking (Elkan 1988). In other words, whenever appliances' costs are subsidized, directly or through low interest rates, "modern" energy sources become more affordable to the poor (Gupta and Ravindranath 1997).

Dube (2003) presents data that show the comparability of the energy costs for households in the consumption of electricity-only and of fuelwood-plus-kerosene. Statistics can show that they actually pay more for energy when consuming kerosene and LPG, than when consuming electricity. Anozie, Bakare et al. (2007) calculated that the cost of cooking 500 g of yams in Nigeria 2004 was of 2.34 naira for electricity, i.e. 1.5 times more expensive than fuelwood, but 4.8 times cheaper than kerosene[43].

Households are willing to pay for higher forms of energy that are as costly as the electricity prices without subsidies, which raises the question of "what factors determine the household preferences in the choice of the energy source(s)?

FACTORS OF CHOICE IN THE ENERGY TRANSITION

On the assumption of rationality[44], households choose to obtain the maximum utility from their labor and capital earnings and are very adaptable to a changing environment if it serves their interest. Some authors (Reddy 1995; Masera, Saatkamp et al. 2000; Brouwer and Falcao 2004) recur to taste and tradition to explain behaviors that are discordant with the energy ladder expectation. However, it is important to recognize that, notwithstanding the uniqueness of the individual's preferences in choice, if self-interest is served the household will adopt progressively the higher-grade source[45,46]. Thus, new energy sources

[43] At 0.05 $/N official 1994 exchange rate (Dept of State 1994), it corresponded respectively to 11.7 c$ for fuelwood, 17.6c$ for electricity and 56.2c$ for kerosene, average cooking price.

[44] Instrumental rationality (Tomer 2008).

[45] Jenkins and Scott (2007) show that were self interest is served, together with accessibility and affordability of the technology, it is adopted by the household.

[46] Again, this assumes that the household members know what is best for themselves, refer to Tomer (2008) for an interesting discussion on the concept of rationality.

will be adopted if the households can access and afford them and if they are adequately informed of the benefits and the opportunity costs are not too high; were it not so, the developed world would still be cooking with coal and dung[47,48].

The problem of fuel substitution is really of importance for households transitioning from inefficient energy sources towards electricity, as above a certain income level (or consumption level) most of the energy consumed usually comes from electricity supply. Electricity, because of its cleanness and diversity in use, is the source of choice for the wealthier families and "the ultimate goal of an energy progression"[49]. In most households, as income earning increases, the tendency is to opt for a mix of energy sources that serve the specific utilities in the household, as well as to increase the overall energy consumption (Campbell, Vermeulen et al. 2003).

The nature of the mix, varying between the "lower" extreme of the wood fuels, passing through the transitional kerosene and ending in the "upper" extreme of electricity consumption, depends on the household and on specific environmental factors. The energy mix is also dependent on the end-use of the energy consumption: for example, most households make the switch from fuelwood to kerosene for lighting purposes, but retain the use of fuelwood for cooking, or use electricity mostly for lighting and other sources (fuelwood, LPG) for cooking, as shown by Hughes-Cromwick (1985).

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[47] Wood and Newborough (2003) tested 44 UK households in the adoption of energy-saving behaviors for electricity consumption, and found that households respond positively under a regime of information-feedback. Although relying mostly on electricity, households in developed-countries still show behavioral choices, discordant with the progression of an "energy consumption ladder", that would contain energy saving at the very top of the ladder.

[48] Not all technology transfer programs are successful, and many times the poorer (target) population is missed and the benefits of subsidized "new" technologies stays in the richer classes, as well reported by Troncoso, Castillo et al. (2007) for the Mexican cooking-stoves program. This case demonstrates the difficulty of incorporating all factors of choice in a development program, for some of them are unknown or non-quantified.

[49] Typically a progression of acquisition of electrical appliances, starts with lights, followed by entertainment, food refrigeration and space cooling/heating (Tyler 1996) – see Appendix VI.2 for a typical progression list.

All energy sources require some sort of technology to be used: even the most basic burn of fuelwood for cooking makes use of the three stone stove or similar, the basic oil or liquid paraffin lamp requires a container and a wick, and so forth, up to the sophisticated electricity consumption in modern homes' computers and kitchen appliances. Tiwari (2000) recognized this relation by creating an "appliance index" to quantify the household capacity to consume electricity[50].

How does the household select which appliance to invest in? What factors determine the fuel switching in a household? Hughes-Cromwick (1985) has surveyed the reasons behind the selection of primary fuel in Kenya, and economics is most important for poor households, while factors such as convenience and availability play an important role for more favored households. Similarly, Gupta and Kohlin (2006) ranked sources for cooking activities based on price, availability, ease of use, capital cost of appliance (oven) and pollution level, and asked the households to rank the cooking sources based on these criteria. Not surprisingly, most of the households ranked electricity as the most expensive and the cleanest, and fuelwood as the dirtiest and the cheapest.

Green and Erskine (1999) on the other hand surveyed the inconvenience ranks for several sources, derived from the time taken or the distance travelled to secure a specific source. Surprisingly, households perceive fuelwood as much inconvenient as energy from a petrol generator, from a gas generator and from a car battery. Green's result indicate that when sources are not readily available at the household location they may be undesirable, no matter their relative position in the energy ladder. The household values time, required in securing the source, more than any classification of grade that has no practical meaning for itself.

[50] This index consists of a weighted average of ownership in electricity consuming appliances as compared with the maximum possible number of appliances, weighted by the per appliance maximum electricity demand.

Although there are differences, between regions, on which energy source is more common (availability, price), the factors that determine the choice of fuel for domestic use and the intensity of consumption are very similar, and poverty is the major determinant of household preferences. For example, in Maputo, the majority of the (sampled) population burns charcoal for cooking and firewood is in a descending trend (Brouwer and Falcao 2004), as opposed to Ouagadougou, where firewood is the most common source (Ouedraogo 2006). However, the household size and educational levels are, in both cases, significant in the choice of fuel for cooking.

Brouwer and Falcao (2004) show that a significant proportion of bakeries in Maputo city rely on firewood for their production, contributing to the resource depletion, although domestic consumption is still predominant in the overall fuelwood consumption, particularly by the poorer population. Small enterprises lack the capital resource to invest in higher efficiency and compete with households for the few available funds from development agencies. Nevertheless, the study shows the number of gas, electric and paraffin stoves increased, from 1992 to 2000, indicating increased availability and possibly an increased purchasing power. Again a trend of reduced firewood consumption, with increased income, is present and indicative of correlations between the energy choices and the access to energy appliances, although the charcoal consumption is fairly even across time and household categories.

MODELING FUEL SWITCHING

Researchers have modeled fuel switching and studied the influence of factors such as household size, location, income level, energy prices, household employment, education and others (vulnerability to market changes and to natural disasters may also be a factor of preference), with varied results not always consistent with each other. Reasons for the disparities are, among others, the simplifications required to model the fuel switching, the representativeness of the empirical database and the linearization of consumption behavior through linear regression methods.

Ouedraogo (2006) developed a multinomial logit model to establish the dependency of the choice for energy sources on several household characteristics, which interestingly include not only demographics and educational characteristics but also religion and a quantification of wealth. For the author, characteristics such as the ownership of the dwelling, whether cooking occurs inside and/or outside the dwelling, and the existence of the electrical connection, are important determinants in the choice of fuel. Again, the capital element is a key factor for household development.

Models for energy consumption vary between direct derivations of functional relations from survey data (Dubin and McFadden 1984) to general equilibrium models that use empirical data for estimation of demands from utility maximization problems (Halvorsen and Larsen 2001; Gundimeda and Kohlin 2006).[51]

Other authors simply study the distribution of energy consuming appliances and energy sources used in households in a population (Pongsapich and Wongsekiarttirat 1994; Mirza, Ahmad et al. 2007), and sometimes calculate elasticities of substitution between sources, from the household perspective (Hughes-Cromwick 1985), or at a national level (Holtedahl and Joutz 2004; Kamerschen and Porter 2004).

Statistical methods are creatively used to establish credible equations that describe the mechanisms of energy adoption and switching (Hausman 1979; Terza 1986; Burt and Taylor 1989; Iniyan and Sumathy 2003). Static input-output models are also developed to

[51] The author has only seen one model of energy expenditure minimization in the literature (Rushdi 1986)

study the sectoral interrelationships and how policies can impact economic development (Wu and Chen 1990; Hawdon and Pearson 1995), however of limited applicability in the study of households' consumption behavior.

In general, all models for household energy consumption behavior agree that households use a mix of sources, based on factors of price, availability and access, and on the characteristics of the household (income, size, location, etc) that determine its perception of benefit in evaluating the sources. Whether households consume electricity or low-grade sources, or a mixture of both, the process of choice is still hard to explain. Consequently, authors rely on empirical evidence to find patterns in the household consumption behavior that will facilitate the prediction of future behavior and the forecast of energy demand for one or all sources.

The ability to predict future demand accurately will facilitate the adoption of policies that promote development and will ensure a good planning of energy availability and the economic health of the sector.

THE ENERGY ECONOMICS OF POVERTY

In developing countries, poverty is usually higher in rural areas than in cities and the patterns and types of energy consumption are very different. Urban households, even the poorer ones, have a greater choice of energy source (not always at a lower price) as both biomass and the "higher" forms of energy (electricity for example) compete for their share in the household income (Kebede, Bekele et al. 2002). Analyses should thus differentiate rural and urban households. Furthermore, households vary from poor (rural and urban) to non-poor (rural and urban) with different levels and patterns of energy demand and sources.

The differences in level and schedule of consumption are income-based, although factors such as household resources, for example land ownership, need to be included in the analysis. Kebede, Bekele et al. (2002) showed that even among the poor there is a differential in the energy purchasing power, indicating the non-homogeneity of poor communities in their energy consumption patterns, and the need for flexible policies capable of accommodating varying behaviors among the poor.

Several energy sources coexist at one time in the same local market, with prices not necessarily correlated, as not all energy sectors regulate by the same mechanisms. For example, electricity and petroleum usually run as economies of scale, with an element of price control, while family or industrially produced charcoal competes in an almost perfect market environment. On the other hand, petroleum derivates and electricity differ in that the first make use of a transportation system (roads, bridges) whose cost is not totally inputted into the energy source, while the second requires a specific transportation system (electrical transmission network), whose cost fully falls in the electricity tariff. The prices of these sources are linked with the international, or at least the regional, energy markets.

Some energy sources show seasonal or a trend of scarcity that will ultimately result either in reductions of energy consumption or in the substitution of the scarce source by an alternative (Arnold, Kohlin et al. 2006). The scarcity of fuelwood around urban centers is pushing urban households to switch from firewood to charcoal, and in some cases even adopt other sources, as kerosene and LPG.

Families with little human or physical capital, for whom adaptation is not possible, will suffer welfare losses with decreased availability of fuel woods. In addition, Arnold, Kohlin et al. (2006) rightly notes that a switch to “higher grade” fuels would reduce demand in wood fuels and create unemployment to the poor, whose income depends on charcoal production.

For these households, income-generating alternatives are needed, so they evolve out of poverty.

Development of a household (out of poverty), i.e. an increase in its income over time, can only occur with an increase in the household capital base, both physical (assets) and human (education) (Ahluwalia, Carter et al. 1979). Income is not always measurable because it may be in the form of goods for the household consumption (like food, water), or even may be from not fully legalized practices (tax evasion), and as such undeclared[52]. It seems thus logical to measure household development by its capital base, rather than by its income[53].

Willett and Naghshpour (1987) stated that energy sources "do not yield utility in and of them, but are demanded as inputs in the provision of other goods or services directly yielding utility". He has formulated a household model where energy inputs appear in household production functions of goods that generate utility. Note that he has recognized that some investments yield direct utility (appliances) while others are generators of goods that serve utility.

Poverty alleviation depends not only on the average income levels in any given region, but also on the distribution of its growth. This distribution is unequal across rich and poor, due to differences in the ownership of capital (Ahluwalia, Carter et al. 1979), among others: better educated households have a better chance to earn more from the sale of labor, owners of land can produce at lower costs, etc. The inequality of income generation across the population is often targeted in development programs for poverty alleviation, through the creation new opportunities for income generation by the poor.

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[52] This argument was used by Simler, Mukherjee et al. (2004) to justify the use of consumption rather than income to quantify poverty levels in Mozambique.

[53] McKenzie (2005) uses the ownership of durable goods (capital) by households to study and estimate inequality in living conditions.

In general, the poor grow their income much slower than the national rates. Ahluwalia, Carter et al. (1979) argue that an increase in domestic savings and in the efficiency of resource use, can lead to an accelerated growth. In other words, if the poor can increase their income generation, access energy from more efficient sources, they will be better prepared to fight poverty. Increased efficiency of energy consumption will also save women's time for other household or productive tasks, overall benefiting the household development (Hendricks and Green 1999).

CAPITAL RESOURCES FOR THE POOR

The link between the lack of capital resource and poverty is well established by several authors. Abdulai and CroleRees (2001) stress the lack of access for capital investment by households as one of the main reasons for their inability to diversify their income generation and evolve out of poverty. It is thus crucial, when evaluating the path of development of a household, to analyze its path of capital investment and ownership.

The electric connection is sometimes an unaffordable capital investment, forcing the household to consume kerosene and other less reliable sources for lighting. Once installed, the household will mostly rely on electricity for lighting, even if using other sources for cooking and other activities. Karekezi and Majoro (2002) note an increased number in illegal connections to the grid in suburban neighborhoods as an indication of a demand that could be satisfied by current income levels, were the electrical installation available.

There are studies showing that a large investment in public infrastructure may result in an increase in real interest rates and consequently have negative influences in the economy (Feltenstein and Ha 1999). However, without infrastructure, rural households cannot sell their produce and labor in the (urban) markets, and they cannot access more efficient energy sources for their own production and consumption. Without infrastructure development, the poor will more likely remain poor for a longer time, see the Grameen experience for telephone access (Bayes 2001).

ENERGY PRODUCTION AS AN INCOME GENERATING ACTIVITY

Karekezi and Majoro (2002) discuss the insufficiency of statistical data on electrification of African populations, of which the top beneficiary are the urban rich, followed by the urban poor and the rural populations. They also suggest that the informal sector role as employment agency in most African countries may serve the purpose of disseminating clean technologies. Although the authors do not elaborate much, this idea as applied to the dissemination of renewable sources, in a distributed generation structure, is already in implementation through some developing initiatives (Biswas, Bryce et al. 2001; Biswas, Diesendorf et al. 2004).

Taylor and Adelman (2003) describe the dichotomy that own-price elasticity represents for the food goods in a farm household, based on the classic model first presented by Singh, Squire et al. (1986), for which food production occurs simultaneously with food consumption. Were a household to consume energy and be its producer, situation that often occurs with charcoal producers in developing regions, the same dichotomy could apply. Own-price elasticities for the particular source would be positive when the benefits of selling would exceed the costs of acquisition, i.e. whenever own generation could compete with the interconnected grid supply.

Higher productivity of small, distributed generation can shift the balance between producing for own consumption to producing to supply a competitive market. In this regard, Barnes, Plas et al. (1997) suggest to rethink the traditional rural electrification programs, intended to supply grid electricity to rural areas, and to introduce solar and wind power as alternatives to domestic supply. Already in developed countries the concepts of distributed generation are being tested, and interestingly show that grid supply becomes complementary rather than the principal source (Entchev, Gusdorf et al. 2004).

Experiences on renewable sources as income generating enterprises in Bangladesh is briefly discussed by Islam, Islam et al. (2006). It is important to highlight the adequacy of multi, micro-generation systems (particularly in rural areas where demand is small) for microfinance schemes, associated with poverty alleviation programs. The author refers to the success of a program targeting rural women as energy (micro) generators for income earning purposes.

The access to modern energy sources also allows a greater diversification of income earning activities, for which an average of 5.7% capital returns was estimated for the Sri Lanka's urban poor (Woodruff, McKenzie et al. 2007).

The institution of credits for rural energy could pave the way for poverty alleviation and increased access to modern sources. Finance packages such as those of Clean Development Mechanism (CDM) and Carbon Credits, and other micro credit initiatives, will be needed to support capital investment programs in developing regions[54].

ELECTRICITY AS A POVERTY ALLEVIATION RESOURCE

TRADITIONAL APPROACH TO ELECTRIFICATION

In countries like Mozambique, the challenges electrification poses to the sector are enormous. From a starting point in which only 8.2% of the population (in 2006) has access

[54] Anderson, Locker et al. (2002) confirm that microcredit has beneficial impacts in household income earnings and production, and may also be a way to promote environmental conservation behaviors.

to electricity (EDM 2007), in a country of about 800,000 km^2 and an average population density of 24.3 persons/km^2 in 2005 (INE 2005), electrification programs need to accommodate the geographical, social and economic differences throughout the territory. Electrification not only satisfies an identified need for electricity, for those with the economic power to pay for it, but also constitutes the basis of all socio-economic development, and is required to achieve the human development goals agreed for the Millennium (Mozambique and World-Bank 2002; Africa 2007).

Targeted consumer populations for electrification programs are not, in general, homogeneous:

- there are differences between the provinces and the districts, depending on their social and economic level of development and the types of natural resources they possess;
- there are different expectations across consumers, in terms of quality and price, that contain historic elements to it;
- and finally, there are differences in the use of electricity in the consumer population, varying from industrial extraction and processing to domestic loads.

The tariff (price) structures try to address some of the differences, by establishing several consumer categories, for example domestic, agricultural, commercial and industrial. In each of these categories, there may be classes of consumption and the option of contracting in a time-of-use setup. Sometimes tariffs show limited geographical differentiation, to give developmental opportunities to currently non-electrified or recently electrified districts, by spreading the cost of infrastructure expansion through all consumers, regardless of where they live (cross subsidy).

Cross subsidies also appear across consumer categories, “confounding” the statistics and the evaluation of the willingness to pay from each type and location of consumer. Bose and Shukla (2001) present the results of a survey in India, showing that consumers can pay higher electricity tariffs than currently in practice, which is a positive result for the substitution of polluting, cheaper, technologies for power generation by renewable sources.

Ideally, electrical tariffs should meet the consumer’s needs and ability to pay. Realistically, tariffs need to reflect the cost and the losses of energy transportation, increasing with distance from the source: closer sources reduce the cost of supply. Consumers closer to power generation sources benefit thus from lower transportation costs and losses, yet one more argument for distributed generation, composed of spread out generating units. However, the capital cost of installations is still high and an impediment to the widespread adoption of electricity generation from renewable[55].

Losses in electricity supply systems are a result of the technical characteristics of the transportation system, the energy volume transferred and environmental variables such as temperature. Losses also show seasonal and daily variations. In Southern Africa the recorded system losses can be as high as 39% for Uganda, and of the order of 18% for the Mozambican supply system (Nhete 2007). Billing and collection losses, sometimes dubbed “commercial losses” are in turn a result of social factors, such as income levels, neighborhood poverty levels (Francisco and Fagundes 2006) and the share of electricity in the household energy mix. These can be as high as 20% of the total energy availability (EDM 2007). On the other hand, the metering system can be very expensive, so accuracy (hence loss reduction) is, sometimes, sacrificed to affordability (Rao and Deekshit 2006).

[55] Jacobson (2007) goes as far as calling solar PV as a “middle class consumer good” given that it is mostly used for TV viewing; the author however indicated benefits in production in rural Kenya.

Metering accuracy is always an issue. For most forecasting exercises the load averaging over half-an-hour is considered accurate, although authors such as Wright and Firth (2007) would argue that in domestic consumption here are load spikes of shorter duration that do not get registered in 30 minute meter-integrators. These authors recommend a "logging of 5 minutes" to obtain data sufficiently accurate for a good planning of "on-site generation": as distributed generation becomes an alternative for domestic supply, given the smaller sizes of the generating systems, it becomes more critical the accuracy of the peak load forecast and energy utilization rates.

Normally electrical markets forecast future demand based on monthly consumption figures, differentiated by general categories of consumers (domestic, industrial, commercial, farming, etc.). One reason for this approach is the unavailability of more detailed data, as for the management of electrical companies this level of detail is sufficient for reporting and for short to medium term management planning; the other reason is the simplicity of only analyzing time series for trends.

The use of prices as variables to forecast consumer demand is contested by Whittaker and Barr (1989), in the context of the South African electricity grid. They argue that the domestic demand response to price was so slow in the period under analysis (they calculated 8 years lag) as to be insignificant. Nevertheless, this study assumes that demand determines price and vice versa, i.e. even in the context of developing countries, the assumption of competitive effects in the energy supply markets is made. The multiplicity of sources for consumer supply, studied for various purposes, make the correlation between the prices of sources difficult to formulate. The cross-elasticities found, for example by Rushdi (1986), are too specific of time and location and insufficiently explained by quantitative factors.

While for consumers the more significant cost of electricity consumption is the average cost[56], the pricing structure of suppliers depend on the nature of the market and the characteristics of the power system.

If pricing was solely directed to recover the utility's cost and did not reflect the need for efficiency in supply, and fairness to consumer's demand requirements, the application of the traditional Ramsey pricing scheme would be advised. However, components of the electrical supply increasingly operate in a competitive market, for which the Ramsey Price is not adequate (Shepherd 1992)[57].

Economic theory shows that monopolies operate at the average cost pricing, while perfect competitive markets require marginal cost pricing schemes. Electricity supply, though increasingly open to competition, still retains characteristics of "natural monopoly" (Cave and Doyle 1994), and as a consequence, the transition to a marginal cost pricing is not straight forward. The transition is usually made in steps, with some level of regulation to protect vulnerable customers and a competitive tariff at the retail end of the supply: a two part tariff is still commonly composed of an access fee and the short-run marginal cost pricing (Friedmail and Weare 1993). The access fee, however, was too simplistic to reflect the full costs of the company, including investment costs in infrastructure expansion, and

[56] "Consumers estimate the current price of electricity by comparing their bill in the previous month with the total kWh consumed that month", i.e. they evaluate the average price and not the marginal price, George as cited by Rushdi (1986)

[57] Ramsey pricing, also called second-best pricing method, is very useful for traditional monopolistic utilities that cannot charge the marginal cost (lower than the average cost), and that supply a set of heterogeneous products (or consumers) whose demands are not necessarily related (Scott 1986). The method weights pricing per consumer class by the rule of inverse elasticity, i.e. the more elastic demand, the lower the price weight applicable. In this way, utilities can make good profit out of the so-called captive consumers, i.e. those of fewer (or none) alternative supply options. Ramsey pricing consequently needs to impose a profit constraint in the utility, with the goal of minimizing consumer costs. There are some issues associated with this pricing methodology, not the least of which is achieving fairness in the allocation of revenue requirements per consumer class, or the enforcement of constant profits.

created inequalities in the consumer's affordability levels. The tariff scheme required consumer differentiation and the fair apportion of the capital investment. Hunt and Shuttleworth (1993) proposed that the adoption of the marginal cost pricing should still ensure the incentive to invest in the system expansion and a full cost recovery rate that recognized that

- the transmission system constituted a highway for power flow, and as such could be valued in terms of "right of use" in addition to the actual power flow. This component of the price, the opportunity cost, would ensure the recovery of the investment cost and the incentive to continued investment;
- the transmission system has power losses that need to be apportioned fairly to the end consumers. On this regard, the authors propose that consumers nearer the power source would incur into lower transmission losses and as such benefit from lower prices.

The question is what tariff structure is best to use and how to allocate the investment costs, fairly to the various consumer classes. Billinton and Chu (1992) discussed the methods in use, favoring the probabilistic method of Loss of Energy Expectation (LOEE). There are however several methods in use, some without much precision in the calculation as a result of being based in monthly or annual averages, rather than in daily load profiles of varying time intervals.

The flow of energy along a transmission path is a result of an instantaneous balance between demand and supply in each delivery point, and is determined by the physical characteristics of the transmission system. There are no storage devices in transmission systems, so generation adjusts in time to demand variations. Different time lags in the electrical response of the various components (generation units, transmission lines, switchgear and transformers) are actually the cause for grid instabilities and generate losses and sometimes even interruptions to supply. Because of this, pricing mechanisms not only contain cost recovery components but are also subjected to contractual penalties to discourage generators and users of exploiting the network's vulnerabilities: for example, generators may be limited to generate up to a certain capacity, consumers may be required to install compensators to reduce their reactive power demand. Furthermore, pricing must distinguish between contracted (committed) power and dispatched power[58].

Depending on the transmission grid formation (ring, radial or both) and the characteristics of the power flow, for each distribution community (node) a price function, incorporating all the cost elements of electricity supply and sensitive to demand, can be developed. If reliability indices are part of the tariff system, these must also be part of the cost equation for electricity supply.

Hsu (1997) discusses spot electricity pricing with a location component. By this author, the "marginal loss" between two nodes constitute the actual marginal cost of transmission and as such the appropriate wheeling tariff. This pricing methodology is not used, in most cases, in developing countries, where utilities retain in large a monopolistic structure. In most developing countries the process of unbundling and privatization has not reduced energy prices, and in some cases has even increased them (Nagayama 2007). A balance is thus needed in applying competitive pricing and maintaining low investment risk, to ensure the continuation of infrastructure expansion.

Mozambique retains a monopolistic structure in the transmission system. Even though private entities are participating in the market, they are still heavily regulated, due to the

[58] See Schweppe, Caramanis et al. (1988), for a comprehensive presentation of the physics of power transmission and spot pricing mechanisms.

sparsely developed network to supply electricity consumers. The change was facilitated by the regional integration of electrical utilities, through the loose power pool, SAPP, however infrastructure expansion is still slow. Transmission lines of regional interested are either linked to new hydropower generation (Mepanda Nkwa is the more attractive project) or to interconnection with neighboring countries (Bowen, Sparrow et al. 1999; Musaba, Naidoo et al. 2004). Prices are regulated by bilateral contracts, and only 3% of electricity generated in the country's hydropower stations is sold in the short-run energy market (STEM) in the SAPP region (EDM 2007). In the whole, only about 5% of the total energy traded in the region is so done through STEM[59]. The transition from monopoly to competitive structure will take many years, while the infrastructure is expanded and the regulatory and legal framework evolve to allow for appropriate consideration of the transition costs[60].

EDM's tariff system[61], reviewed and approved, by decree of the Council of Ministers, in 2003[62], is based in the findings of KPMG's Tariff Study[63] that identifies the average cost basis of the company and recommends a three-component tariff rate: the energy rate, the capacity rate and the connection fee. The first recovers the variable costs of operation and maintenance (O&M), the second recovers the investment in new capacity, and the third covers the local costs of electrical connection.

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[59] Remarks by Hon. Minister of Mines and Energy Namibia, Erkki Nghimtina, during the Signing of the Revised Southern African Power Pool Inter Governmental Memorandum of Understanding in Gaborone Botswana on 23rd February 2006, http://www.sadc.int/news/news_details.php?news_id=634

[60] See Hadley, Hirst et al. (1997) for a good discussion on the complexity of the monopoly sunken costs and how they may affect the success of privatization of utilities.

[61] Electricidade de Moçambique, E.P. (EDM), is the national public utility for electricity generation, transmission, distribution and supply, and is charged, by the government, with the electrification of rural Mozambique

[62] In 23 June 2003, the rule concerning Tariff Setting for EDM (the national public utility) was reviewed by the Council of Ministers, and approved by Decree 29/2003. This revision revokes the previous Decrees 32/91 from 30 December, 2/97 from 11 February and 59/99 from 21 September. It also reconfirms the applicability of the Decree 10/85 that creates a National Tariff for Electricity, the "unique tariff".

[63] Final Report for EDM tariff study, KPMG, 14 February 2001

In Mozambique, the commercial and residential consumer population is subjected to one tariff scheme, across the country. The so-called "unique tariff" was introduced at the creation of the national public utility in 1977, and is maintained on the argument that remote areas should be subsidized to facilitate their economic development (Mozambique 1985). The transmission system pricing thus contain a cross-subsidy to the more remote areas, and all consumers are charged for the electrification efforts at the national level, regardless of their own location. The only costing difference between geographical areas is related with the transmission and distribution losses, factors that are, to some extent only, under the scope of the local management teams.

It is common the recourse to a unified tariff (one tariff for all supplying bus bars), particularly when the electrical utility covers a vast geographic area and is charged with electrification pro-development. Bernard and Guertin (2000) show, for the Hydro-Quebec Electrical Utility, three types of price rating that are applicable to a similar case. These rates differ in their treatment to transmission losses that, as the author rightly mentions, have been understudied by the utilities, possibly because they are small as compared with commercial and distribution losses and with the costs of energy generation in general. The introduction of competition in the electrical sector incentives the move to more efficient and profitable operations and a better understanding of the origins of the loss burden.

Dismukes, Cope et al. (1998) present a transmission cost empirical quadratic function that contains capacity, power flows and wage rates as explanatory variables, in a trans-log modeling exercise. Their approach is convenient when accounting data is not readily available to researchers, though other explanatory variables should be incorporated, namely:

- Technical losses in the transmission and distribution networks, based in simple energy and power metering (Rao and Deekshit 2006)[64].
- Losses of unserved energy that are caused by power interruptions in the supply system[65]. The calculation of unserved energy is based in the concept of "cost of unserved energy", which requires the quantification of the impact of interruptions to supply in the several consumer categories, and some level of weighted averaging to obtain an easy to use figure. This calculation also incorporates the penalties for non-supply, were applicable. Ghajar and Billinton (2006) loss allocation method is used in the context of an annular supply grid, and takes power flow characteristics (load factors, peak loads, distances between nodes/buses) to calculate the weights for loss allocation.
- The characteristics of the consumer population and their dispersion in the supply area (Filippini and Wild 2001)[66].
- Finally, temperature and humidity condition the thermal losses, particularly in long distance transmission lines.

Losses are cumulative and hard to measure, necessary to allocate in the various supply nodes of a transmission network. Kristiansen and Wangensteen (2006), Ding and Abur (2007) and other authors developed methods of loss allocation, fitting to the correspondent data availability. Mozambique's transmission and distribution systems lack a detailed metering of electrical parameters and the composition of the consumer population. The

[64] Voltage levels of the distribution system and age of the installed equipment are also technical factors determining the level of thermal losses. Other important factor of loss is the composition of reactive load in the distribution network, which tends to increase in small industrial installations.

[65] See Wijayatunga and Jayalath (2004) for a discussion on the impact of interruptions in the profitability of an electrical supply system, and their impact also in the productivity of the country's industrial park.

[66] More compact consumer population, in urbanized areas, record lower O&M costs per consumer than more sparse installations.

tariff system is also relatively simple and its application simply monitored. Under these conditions, the loss function can only be simply estimated, from readily available supply and demand data.

When the cost function has the geographical dimension of the loss function, the pricing scheme, intended to recover the full supply cost and based on the average cost of supply, will also have an equivalent geographical dimension.

DISTRIBUTED GENERATION IN THE ELECTRIFICATION EFFORTS

Electricity is the “cleanest and more versatile source to the end-user” and as such, once the household takes it as the main source it will not return to other sources; “(its) unique characteristics shake the foundations of substitutability” (Pouris 1987). This view is confirmed by Rushdi (1986) findings, in domestic energy in South Australia, where electricity is a substitute for household oil and gas consumption, but not the reverse.

The use of electricity and other “higher” forms of energy, not only contain gains in efficiency and time, but also reduce the health hazards that cooking with wood fuels imposes (Kanagawa and Nakata 2007). Electricity consumption stands at the top of the energy ladder and as such is considered the ultimate goal of any energy development path. The traditional electrification project consists primarily of the extension of transmission and distribution lines that carry power from centralized large sized power stations to the end consumers (Barnes, Plas et al. 1997).

Access levels and affordability levels vary significantly across country and population, making electrification programs unviable in a purely economic basis, and as such eligible to finance from cheap loans and donations. Conventionally, by “electrification” one means the construction or strengthening of transmission and distribution (T&D) networks. Rarely electrification contains an element of power generation, generally classified and treated as profitable investments for both public and private entities. Nevertheless, the expansion of T&D grids results in an increased demand for power, which can raise the price of power supply (due to scarcity) if new generation is not properly planned for[67].

Distributed generation is an alternative for domestic and communal energy supply, and for public utility (centrally) managed (scattered) units. When one talks of distributed generation, to mind comes the image of a dense network of distribution lines and generating units of varying sizes scattered about, publicly or privately owned, feeding into the network the excess power produced after supplying its own main load. The concept of Distributed Generation is applicable mostly in interconnected networks, sufficiently dense and stable to accommodate varying flows of energy at different periods and with different characteristics - see Alanne and Saari (2006) for a good discussion on the origins and particulars of distributed generation system.

There are two main reasons to consider distributed generation in developing countries' electrical future, from a supply side view. First, traditional electrical infrastructure is costly and takes time to expand. The planning of grid expansion to include distributed generation units can result in efficiency gains and greater coverage, at possibly lower cost than the conventional approach. It can also ensure that any investment made can still (upon interconnection) earn return for its owners: the isolated generators evolved out of the need to ensure electricity supply to remote areas, not interconnected to the main grid, being the only alternative to electrical supply. In summary, distributed generation can accelerate the pace of electrification of rural communities.

[67] SAPP countries are currently suffering from peak demand shortage, due to the mismatch between demand (domestic and industrial) growth and the expansion of the supply systems.

Second, though there are no agreed size limitations, the nature of distributed generation makes it mostly of the order of micro to small sizes, and possibly of medium sized power capacity. Consequently, distributed generation requires multiple "smaller" packages for capital investment (in smaller generating units), which associated with the geographical distribution, inherent to the concept, favors the development of the micro and small renewable power potentials existing in the country. Environmental concerns and a worldwide promotion of the use of renewable energy sources to contain pollution (Granovskii, Dincer et al. 2007), make it essential to plan for the development of the country's renewable potential, at whatever scale, in the pursue of development.

Distributed generation can improve the reliability of supply in local areas, reducing the number of interruptions to end consumers and voltage fluctuations in the network. Furthermore, given its small size, it is better fit to respond to peak load variations in demand, faster and cheaper (Borges and Falcao 2006; Dudhani, Sinha et al. 2006).

From the consumer side, the recourse to distributed generation constitutes yet one more alternative toward a full electrification of the household, in complement or substitution of car batteries and small diesel generators (van der Vleuten, Stam et al. 2007). Furthermore, the generation of electricity may also constitute a source of income for the domestic consumer. However, the adoption of renewable energies requires an active transition from being solely a consumer to being also a producer of electricity. This dual-role is already true for biomass producers, or collectors, that are also consumers. For renewable technologies, the change in consumer behavior will require financial adequacy, and technical/social acceptance of the new technology:

- In the context of UK, Sauter and Watson (2007) identified good information on the technologies, lower capital investments and shorter pay-back periods as the possible incentives to mobilize individual consumers to become co-generators of their own power (the authors also elaborate on regulatory and institutional mechanisms to bring about these incentives).

- In South Africa, a survey showed that though solar home technology was desirable to the interviewed households, economic restrictions, theft incidence and access to technologic know-how made it not the first choice of source (Green and Erskine 1999).

Electricity consumption levels in developing countries are much lower than in developed countries, particularly because most of the population consumes a mix of sources and have relatively few utilities in the households. The access to cheap and efficient electrical appliances can really improve the life quality of the poor, by reducing the electricity bill and increasing the affordability of the source. For example, Van Buskirk, Ben Hagan et al. (2007) indicate a gap of about 3.1 kWh/day or more, in the electrical consumption of food refrigerators, between African countries and the US. However, not many developing countries can set the minimum efficiency standards and reinforce them, which results in an appliance market of expensive, obsolete and often inefficient items. The high costs of new (efficient) technology makes it unaffordable by the poor, effectively forcing those of lesser purchasing power to consume more for the same utility. A good example is the non-use of efficient lamp bulbs, also known to last longer (Balachandra and Shekar 2001).

The role of government and public institutions, to make renewable energy sources and efficient technologies accessible and affordable to the neediest, is crucial, as both contain commonalities in their financial sustainability setups, and in aspects of social acceptance and information dissemination. Both are initiatives of technology penetration that will promote development and better quality of life. The adoption of electricity as the main source can occur, not just by increasing the income base, but also by adopting efficient appliances and consuming less. The objectives of energy conservation can also be served by this dual-approach.

Greenhouse gas emissions tend to rise as a country treads economic development, particularly in sectors such as construction, mineral industries, manufacturing and transportation. This effect was observed by Murthy, Panda et al. (1997) in a 15 year period in India. Power generation has increased emissions mostly whenever generation is from burning fossil fuels. At the domestic energy level, emissions per capita tend to increase as households move from rural to urban, from poor to richer, through their increased consumption of luxury goods.

Although wood-fuels are more polluting for the household itself (Barnes, Plas et al. 1997; Masera, Saatkamp et al. 2000) and present higher levels of particulates than any other source[68], if regarded in the overall cycle of harvesting production and consumption, oil derivates have greater and more damaging contributions to the environment as a whole (Weisser 2007). For example levels of NOx emissions have been reported (Anozie, Bakare et al. 2007) to be significantly higher for kerosene and LPG than for firewood. Even at the level of large scale production, if incorporated all the costs associated with pollution and other externalities, for the duration of the generating plant's life cycle, renewable sources have costs comparable to the fossil fuels' (Roth and Ambs 2004).

The risk increasingly recognized of global warming is pushing emission control into the policy agendas, making electrical generation object of scrutiny and tax for environmental protection. Nagurney, Liu et al. (2006) developed a model for three policy approaches on carbon taxing of an "electric power supply chain network", which may be adapted to

[68] "10-100 times more than the modern fuels (…)" (Parikh, Balakrishnan et al. 2001)

distributed generation power expansion and to the inter-relations between several energy sources' markets.

The approach of capping emissions in each generating unit may be useful when dealing with separate utilities. However, the approach of capping the full system, from generation to retail distribution, may be more adequate for centralized management and financial packages. Whichever the case, appropriate demand forecast could make a difference between sustainability and bankruptcy of an infrastructure project, as costs are increasing and financing becoming scarcer.

Distributed generation using renewable sources can offset the trend for growing emissions in developing countries, substitute conventional electrification in the short-term planning speeding the access to electricity in rural areas, and constitute a source of income and a technology dissemination vehicle for the poor. Although distributed generation is not the object of this research, it is complementary of electricity supply programs and too important to ignore.

FINAL COMMENTS

Electricity supply can ease the lives of poor households and as such should be included in poverty alleviation strategies. However, behavioral, economic and technological constrains may prevent the fast expansion of electrical networks and the intensification of electricity use. It is important to understand the factors determining the adoption of domestic sources and the requirements of the suppliers, so that a better demand-supply fit may be sought.

CHAPTER III: ESTIMATION OF ELASTICITIES FOR DOMESTIC ENERGY DEMAND IN MOZAMBIQUE

ABSTRACT[69]

In Mozambique, households consume a mix of energy sources to satisfy primarily their needs for lighting and cooking and, for the wealthier households, other domestic necessities such as refrigeration. The domestic energy mix depends on the prices of the sources and on the capability of the household to invest in the energy-consuming appliances, required to satisfy those needs. Based on data from a household survey carried out in Mozambique during 2002/3 (IAF), this paper calculates the price and the income elasticities of demand for domestic energy, using an econometric method developed by Angus Deaton. In this formulation, proxies for asset ownership are used as demographic characteristics of the households under study, allowing for a simple evaluation of the effects of asset ownership in the demand for each particular energy source. Own- and cross-price elasticities for six individual domestic sources are obtained: low-grade sources such as firewood and charcoal are less elastic (elasticities of -0.37) than kerosene and electricity (respectively -0.67 and -0.51). Results for candle and LPG (Liquefied Petroleum Gas) consumptions are suspicious. Income elasticities are of the same order for all sources, in the range of 0.5.

[69] Submitted for publication in the Journal of Energy Economics

INTRODUCTION

In Mozambique, households consume mostly biomass for cooking and kerosene for lighting. In most households, domestic energy is comprised of a composition of sources, each with different end-uses and prices. Factors determining the energy mix are unknown, however previous studies indicate that households will most likely choose the sources that are affordable and for which they own the respective appliances. Previous research, e.g. from Karekezi and Majoro (2002) and from Pachauri et al. (2004), argues that the ownership of assets for consumption of energy sources is a prerequisite to transitioning from low-grade to high grade sources up the "energy ladder"[70]. In other words, demands for sources are conditional on asset ownership. The formulation of energy demand equations should thus include prices, income and the ownership of energy-consuming assets, in order to describe the behavior of energy transition across households.

Biomass sources are at risk of depletion, particularly around urban areas. Biomass does not support a wide range of uses in the domestic setting nor do they support income-earning activities. The access to affordable higher-grade sources, as substitutes to biomass consumption, can benefit poor households in terms of time saving, cleanness and efficiency, and allows a greater variety of end-uses (including the expansion of the income generation basis). Thus the domestic energy responses to price and income variations (the price and income elasticities of demand) needs to be better understood in order to design energy pricing schemes for higher-grade sources that will effectively support poverty alleviation programs. In other words, price and income elasticities of demand are important inputs in the policies for expanding and strengthening energy supply systems.

[70] The concept of the "energy ladder" links the choice of energy source with income, and postulates that increased income calls for more efficient sources, also more costly and less polluting (Masera, Saatkamp et al. 2000).

The current study will calculate the elasticities of demand for domestic energy sources, using data collected in a household survey, carried out in the years 2002/3 in Mozambique. The survey, called IAF 2002/3, recorded data from 8700 households, located in 857 clusters in the 10 provinces and in Maputo City (INE 2007). We will derive the cross- and own price and income elasticities for the individual energy sources in the domestic mix, using an econometric method which was developed to estimate price elasticities of multiple consumer goods when their market prices are not observable (Deaton 1987; 1990). The price and income elasticities estimated using Deaton's method are then compared with those obtained from directly regressing quantities by their unit values (expenditure divided by quantity consumed) as if they represented the true market prices of energy untainted by measurement errors or individual perceptions of quality. This derivation is for comparison purposes only, to show how the presence of measurement errors and quality effects in the original dataset can change and/or bias the estimated price elasticities of demand for domestic energy.

So far, no estimations of domestic energy consumption responses to energy price variations have been made for the Mozambican households. The present study calculates the own and cross price elasticities as well as the income elasticities for several domestic energy sources in Mozambique, which can be useful in setting policies that target domestic energy consumption and poverty-related issues. The study makes use of a reasonably known econometric method (Deaton's), for which a detailed appendix on the calculation steps and the corresponding code in MATLAB is available from the authors. To our knowledge, this method has only recently been applied to the study of the mix of energy sources in the domestic setting (Olivia and Gibson 2008). Finally, the regression derivations of this method use proxies for asset ownership as independent variables that determine the household consumption and expenditure behavior on the various domestic energy sources, from which inferences on the importance of assets' ownership can be made.

A REVIEW OF THE ENERGY SOURCES IN THE DOMESTIC ENERGY MIX

The particularities of use of each energy source and the characteristics of the households are determinant for the elasticities of demand of these sources. Most households will select a mix of energy sources based on their perceptions of costs, convenience, safety and other variables (Hughes-Cromwick 1985; Gupta and Kohlin 2006). Households select the mix of sources for their domestic needs taking into consideration the end-uses that are served, the quality of the service provided by each source and the affordability of the source; taste and cultural preferences may also be factors of choice.

Developing countries show differences in the characteristic sources that are commonly used for domestic applications. The energy ladder usually places biomass sources at the bottom (low-grade) and electricity at the top (high-grade) and the differences between countries are mostly on the transitioning sources such as kerosene or LPG. Intermediate sources such as charcoal and kerosene, with specific technical and price characteristics, are consequently the differentiating elements in the diverse paths that domestic energy transitions can take across regions, see Heltberg (2004).

The presumption that higher efficiency and lower pollution rates are typical of higher-grade sources in the energy ladder is somewhat dubious: for example, smoky coal combustion, which is more efficient in burning than fuelwoods and, as such, of a higher grade in the energy ladder, is significantly more hazardous for human health than fuelwood (Mumford, Chapman et al. 1989). Studies have also shown that in some cases the sources in the lower level of the energy ladder, such as wood fuels, may in fact be more costly, in real terms, per unit energy than, for example, kerosene (Gupta and Ravindranath 1997). Gupta and

Ravindranath (1997) show that kerosene can be quite inexpensive (through sustainable subsidies) on a per unit basis as consequence of being a more efficient source. Kebede (2006) confirms this view by showing, using empirical data from Ethiopian households, that the poor can afford to consume kerosene if their capital costs are met with subsidies, and that even without subsidies poor families are very close to the affordability level for consuming kerosene. He presents electricity as an extremely expensive source, well beyond the reach of most households including the non-poor[71]. On contrary, Cockburn and Low (2005) indicate that non-electrified households in Mozambique may be spending as much as 4 times more per kWh of energy bought than those connected to the electricity grid, making thus electrification a good strategy to alleviate poverty.

The grading associated with the energy ladder is, consequently not the whole story when choosing the optimal domestic energy mix. Factors such as the end uses of the energy sources and how essential are the needs they satisfy, can determine the responses of the household to price variations. For example, firewood and charcoal are used mostly for cooking, while kerosene and candles are mostly used for lighting. Electricity is more versatile allowing for lighting cooking, refrigeration and so forth, though in poor households it serves mostly lighting purposes. Liquefied Petroleum Gas (LPG) is mostly used for cooking and water heating, though some applications in lighting were recorded in the household survey (IAF 2002/3). Some sources serve 'complementary needs'[72] of the household, for example charcoal for cooking and kerosene for lighting. Other sources are substitutes, for example kerosene and electricity that are mostly used for lighting purposes and as such compete with each other. Often LPG stovetops combine with electrical

[71] The author equaled the non-subsidized electricity cost to its long run marginal cost (LRMC), which of course contains the costs of investment for grid expansion. High LRMC are typical of developing countries.

[72] All households need energy for cooking and for lighting, whatever the source used: these are consequently 'complementary needs' to be satisfied in parallel, not one or the other.

stovetops, potentiating the combination of these two sources in the household cooking – see data on LPG and electric consumption for cooking in Brouwer and Falcao (2004).

These relative characteristics of 'complementarity' and substitutability may help to explain the cross price elasticities of demand between the various domestic sources. For more detail on the energy mix, see Madubansi and Shackleton (2006; 2007) who elaborate on the nature of the energy mix in South African villages, not dissimilar to that in Mozambique, although in Mozambique cooking relies mostly on charcoal while in South Africa the common source is kerosene. Howells et al. (2005) also present the varied typical uses of domestic sources in African rural households, and their findings can be generalized for developing countries such as Mozambique.

A REVIEW ON THE PRICE ELASTICITIES OF ENERGY DEMAND

The study of the affordability of various energy sources and the reasons why one source and not other is used for a particular domestic need as well as their consumption levels in the domestic energy mix, require the understanding of their price mechanisms. For example, while firewood and charcoal have their prices regulated by the market (when not in self-production), electricity has its prices regulated by contract with the supplier company[73]. Some sources can be easily indexed to one another (for example charcoal and firewood), while others have more complex price interactions, for example kerosene and hydro generated electricity.

Electric pricing schemes vary across consumer categories: industrial or bulk consumers often require (and negotiate) customized pricing[74], while residential and other small-scale

[73] The design of electricity rates is constrained by the need to support domestic and industrial development

[74] Many times the viability of the enterprise is determined by the electricity rate

consumers are price-takers, on a rate designed for simplicity of use, for equal opportunity[75], and for lower billing and collection costs. As an example of regulatory constraints, the liberalization of the electricity retail market in Europe was completed only in 2000 and, even so, covered only bigger consumers (Nagayama 2007): for small residential consumers in Europe, electrical suppliers are not yet free to rate only by market rules[76]. In Mozambique, the domestic rates are geographically undifferentiated and only vary by the principle of 'pays more who consumes more', in consumption levels. Electricity pricing is thus "contaminated" with regulatory considerations (contrary to biomass prices that are fully retail-market regulated) and is shaped by the nature of the industry, and regulators and policy makers need to understand better the effect of price variations in the consumers' domestic energy mix. Kerosene on the other hand is partly regulated (price cap at the bulk sales and in the formal retail market) and partly market-driven (retail price in the domestic informal market), in Mozambique.

Although the pricing structures of suppliers depend on policy choices, on the nature of the electricity consumers, and on the characteristics of the power system, consumers typically evaluate the cost of electricity consumption based on average price of the last transaction (Rushdi 1986). Consumers of electricity have shown to be sensitive to the prices of other sources that compete with electricity in providing household utility, particularly those that satisfy the consumer's "thermal needs" (Madubansi and Shackleton 2006), i.e. sources used mostly for cooking and heating like charcoal. The extent of this sensitivity, represented by the respective cross-price elasticities, is yet to be determined for the Mozambican domestic market.

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75 "(…) typically, high-cost geographically remote customers pay the same retail prices as low-cost urban customers" (Cave and Doyle 1994)

76 Regulators often use price caps and pace the timing of rate-reviews to "stabilize" the affordability of domestic energy

The use of prices as variables to forecast domestic consumer demand of electricity in the short-run is contested by Whittaker and Barr (1989), for the South African electric grid: they indicate a negligible response to price variations of the quantity (of electricity) demanded, in the period under analysis (8 years lag). Furthermore, Louw, Conradie et al. (2008) calculated price elasticities for electricity consumption in the South African domestic market, and found it to be quite inelastic to its own price, arguably because electricity is unmatched by other sources for the satisfaction of basic domestic needs[77]. Ubogu (1985) observed very small own-price elasticities for the consumption of electricity in the Nigerian households, and Koshal et al. (1999) for the consumption of kerosene in the Indonesian households. Koshal et al. (1999) also indicates the poor substitutability of kerosene by electricity, because of prevailing poverty in the Indonesian sample. Other authors calculated the price and income elasticities of domestic energy sources, by different methods and in different countries:

- Abdel-Khalek (1988) used logarithmic regression with average 'official' prices for the aggregated source, weighted on their respective consumption share, to estimate price and income elasticities of energy demand for Egyptian households
- Filippini and Pachauri (2004) used logarithmic regression using the unit-values as prices for each source consumed, to estimate price and income elasticities of demand for Indian households.

The results of these authors will be used to evaluate the reasonability of the estimations of price and income elasticities in the current study, as no Mozambican domestic energy elasticities are so far calculated.

[77] Electrical lighting is of better quality and safer, even if it is more expensive. A user of electrical lighting will not change (back) to kerosene lighting if it can be avoided

THE METHOD

Deaton (1987; 1988; 1990) developed a method to estimate own- and cross-price elasticities of consumption goods from household surveys when prices are not available in the data. Typical explanatory variables of the regression derivation for demand functions are the good's own price, the prices of related goods, the household income level and some demographic variables characteristic of the household. However, in most of the household surveys, prices are not observable, only quantities and expenditures. Some studies, see Deaton (1988), use the unit values, calculated by dividing the recorded expenditure by the correspondent quantity, as if they represent the market prices of these goods, and derive demand equations and price elasticities directly from regression calculations. The author, however, argues that this approach will bias the estimated elasticities with measurement errors and with effects associated with income levels and demographic characteristics, and develops a method to eliminate these effects to obtain the true (unbiased) price elasticities of the consumption goods.

It is important to emphasize that the unit values are not the actual market prices of goods for each of the cluster areas, but rather an expression of these prices and of the household's purchasing power (income level, demographics) as well as the quality of the goods consumed. As households increase their income, the prices of the goods they consume are expected to increase (higher quality goods) and the quantity consumed is also expected to increase (higher consumption intensity). These effects, called *quality effects*, will be isolated and eliminated from the estimated elasticities. Errors in the data are frequent and affect the estimated quantities and unit values of the goods under study. Deaton's method also eliminates these errors from the estimated elasticities.

By interpretation, the method is based on the following assumptions:

- Households are organized in many clusters of few households, within which no significant price variations are expected; consequently, for each cluster, the estimation of the average budget-share per good consumed and the average unit value of the good(s) are representative of the cluster's households (average) behavior.
- The average values in each cluster are uncontaminated by price variations and are true representations of the income and quality effects. The average values represent the cluster's behavior without any measurement errors, present in the residual values of the within-cluster regression estimation.
- Clusters are spatially distributed. Inter-cluster data is assumed to contain price variations associated with the level of urbanization, geographic location and other factors such as proximity of the goods' source that impact on the consumption levels of the studied goods.
- Goods within the same group are of comparable measurement units (or converted for comparability) and interchangeable with each other. The income variable in the regression corresponds to the income portion allocated only to the group of goods (for example, the energy group), thus limiting the analysis to the set of preferences determining the household choice for the goods' group.
- The unit values, calculated by dividing expenditure by quantity consumed, represent the market prices multiplied by a "measure of quality" by which households of higher income will seek goods of higher quality, thus distorting the demand response to price variations.

Deaton (1988; 1990) proposes that the budget-share of the goods under study and their unit-values of purchasing can be described as linear regression functions of income, prices and demographic effects:

$$
\begin{aligned}
w_f^i &= \alpha_0^i + \beta_0^i \cdot \ln x_f + \sum_j \theta_0^{i,j} \cdot \ln p_j + \sum_h \gamma_{h0}^i \cdot z_f^h + \xi_{f0}^i \\
\ln v_f^i &= \alpha_1^i + \beta_1^i \cdot \ln x_f + \sum_j \theta_1^{i,j} \cdot \ln p_j + \sum_h \gamma_{h1}^i \cdot z_f^h + \xi_{f1}^i
\end{aligned}
\qquad (1)
$$

where, as applicable to the group of domestic energy sources [78]:

$i \equiv$ index for the good i (varying between 1 and n)

$j \equiv$ index for the good j (varying between 1 and n)

$f \equiv$ index for household (HH) f

$h \equiv$ index to distinguish between the demographic variables used as explanatory

$w_f^i \equiv$ budget-share of consumption for the energy source i by the HH f, MTn/MTn (response)

such that $w_f^i = \dfrac{X_f^i}{\sum_j X_f^j}$ where $X_f^i \equiv$ expenditure in energy source i by the HH f, in MTn

$v_f^i = \dfrac{X_f^i}{q_f^i} \equiv$ unit-value of energy source consumed i by the HH f, in MTn/kWh-equiv. (response)

$q_f^i \equiv$ quantity consumed for the energy source i by the HH f, kWh-equivalent

$x_f \equiv$ portion of income of HH f allocated to energy goods, MTn (predictor)

$p_j \equiv$ market price of energy source consumed j, in MTn/kWh-equivalent (predictor)

$z_f^h \equiv$ household demographic characteristic of type h by the HH f (predictor)

$\alpha_0^i, \alpha_1^i \equiv$ intersects of the budget-shares' and unit-values' regression for source i

$\beta_0^i, \beta_1^i \equiv$ income elasticities of budget-shares and unit-values, for energy source i

$\theta_0^{i,j}, \theta_1^{i,j} \equiv$ price elasticities of budget-shares and unit-values, for energy source i (by price j)

$\gamma_{h0}^i, \gamma_{h1}^i \equiv$ coefficients of response of budget-shares and unit-values, for energy source i, to the demographic variable h

$\xi_{f0}^i, \xi_{f1}^i \equiv$ fixed & random deviations in budget-share and unit-values, for source i by the HH f

Because prices are not observable and on the assumption that there is no price variation within clusters, any deviation of the budget share and the unit values from the cluster's mean is assumed to be measurement error. As such, estimating equations are defined for variations within cluster by subtracting off the cluster means:

$$
\begin{aligned}
w_{fc}^i - w_{\bullet c}^i &= \alpha_0^i + \beta_0^i \cdot \left(\ln x_{fc} - \ln x_{\bullet c}\right) + \sum_h \gamma_{h0}^i \cdot \left(z_{fc}^h - z_{\bullet c}^h\right) + \left(u_{fc0}^i - u_{\bullet c0}^i\right) \\
\ln v_{fc}^i - \ln v_{\bullet c}^i &= \alpha_1^i + \beta_1^i \cdot \left(\ln x_{fc} - \ln x_{\bullet c}\right) + \sum_h \gamma_{h1}^i \cdot \left(z_{fc}^h - z_{\bullet c}^h\right) + \left(u_{fc1}^i - u_{\bullet c1}^i\right)
\end{aligned}
\qquad (2)
$$

[78] "MTn" is the Mozambican currency

where:

$fc \equiv$ index for household f from cluster c

$\bullet c \equiv$ index for average (of logs where aplicable) of variables within cluster c

$u^i_{fc0} - u^i_{\bullet c0} \equiv$ residuals obtained from the budget-share regression, per household f for source i

$u^i_{fc1} - u^i_{\bullet c1} \equiv$ residuals obtained from the unit-value regression, per household f for source i

The income regressors obtained for these two equations (β^i_0 , β^i_1) represent the effects of the income level in the household choice of budget to allocate (quantity to consume, first equation) and of quality of the good to consume (second equation). A positive regressor in the first equation β^i_0 corresponds to an increase in the budget allocation to the particular source *i*, whenever the household's income increases. A positive regressor in the second equation β^i_1 corresponds to choosing valuing the particular source *I* as of better quality (the household pays a higher unit value), when income increases.

The residuals are then used to calculate the effect of measurement errors in the final estimation of elasticities. For each cluster, the budget-share and the unit values of the consumption-good (energy source) can be "corrected" by weighting the original means with the regression coefficients, through the following relations:

$$\left.\begin{aligned} \tilde{y}^i_{0\bullet c} &= w^i_{\bullet c} - \beta^i_0 \cdot \ln x_{\bullet c} - \sum_h \gamma^i_{h0} \cdot z^h_{\bullet c} \\ \tilde{y}^i_{1\bullet c} &= \ln v^i_{\bullet c} - \beta^i_1 \cdot \ln x_{\bullet c} - \sum_h \gamma^i_{h1} \cdot z^h_{\bullet c} \end{aligned}\right\} \text{ to write as } \left\{\begin{aligned} \tilde{y}^i_{0\bullet c} &= \alpha^i_0 + \sum_j \theta^{i,j}_0 \cdot \ln p_j + \xi^i_{\bullet c0} \\ \tilde{y}^i_{1\bullet c} &= \alpha^i_1 + \sum_j \theta^{i,j}_1 \cdot \ln p_j + \xi^i_{\bullet c1} \end{aligned}\right. \tag{3}$$

The right side relations are derived directly from equation (1) and by these, the variances and covariances of the corrected variables, $\tilde{y}^i_{0\bullet c}$ and $\tilde{y}^i_{1\bullet c}$ are representations of the inter-cluster income and demographic effects on the "uncontaminated" price response of the household ($\theta^{i,j}_0$, $\theta^{i,j}_1$) for each source under study. The coefficients for the unobservable prices ($\theta_0^{i,j}$, $\theta_1^{i,j}$) are then calculated and used to estimate the price and income elasticities of demand, uncontaminated by measurement errors or quality effects, as follows:

$$\begin{aligned} &\text{The price j elasticity of demand for source i:} && \varepsilon_p^{\,i,j} = \frac{\theta_0^{\,i,j}}{w^i} - \theta_1^{\,i,j} \\ &\text{The total expenditure elasticity of demand for source i:} && \varepsilon_x^{\,i} = \frac{\beta_0^{\,i}}{w^i} + 1 - \beta_1^{\,i} \end{aligned} \tag{4}$$

where:

$\varepsilon_p^{i,j} \equiv$ price elasticity of demand for energy source i (by price j)

$\varepsilon_x^{i} \equiv$ income elasticity of demand for energy source i

$w^i \equiv$ budget-share for energy source i

Deaton (1988; 1990) and Kedir (2005) applied this method with reasonable success to calculate price and income elasticities for the food group, using data from household surveys in the Ivory Coast in 1979 (for 1920 households), in Indonesia in 1981 (for 14487 households) and in Ethiopia in 1994 (for 1500 households). Olivia and Gibson (2008) used this method for 29000 households in Indonesia, for a group of five energy sources.

Often data in these surveys is missing or inconsistent with the procedural approach of the survey. It is important to discuss the treatment given to this data in this application. In the sample often the following situations occur:

- Households for which there is no record of energy expenditure of any type: These are considered invalid for the study, and are eliminated from the sample, on the basis that every household consumes at least one type (source) of energy, even if it is in very small quantities.
- Households for which there were records of quantities consumed (in kWh-equivalent) but no records of expenditure, or vice-versa, for an energy source (or more) are considered zero-purchasers for the particular source, and are included in

the regression of the budget-share, but excluded from the regression of the unit-value[79].

The estimation of the own- and cross-price and income elasticities for the individual sources was made after filtering the sample for valid data (see next section) and then compared with own-price elasticities derived from direct regression formulations, using unit values as if they were the same as market prices. The next section discusses the data and the approximations made in order to solve the problem.

THE DATA

The National Institute of Statistics (INE) of Mozambique conducted the household survey (IAF 2002/3), for one year (2002 to 2003) in 856 clusters located in all the national territory. Data for a total of 8700 households was collected. In each cluster, 12 or 9 households were interviewed and data was recorded on daily, monthly and annual expenditures and earnings. The ownership of assets[80] (in monetary value) and several demographic variables, such as household sizes and composition, were also recorded. Altogether, about 450 product codes were registered in expenses, generating more than 400 thousand records. Revenues were registered in more than 25 thousand records, and the asset ownership in more than 21.8 thousand records.

This study considered only the following domestic energy sources: firewood and charcoal, candles, kerosene, Liquefied Petroleum Gas (LPG) and electricity. The study did not include Diesel and Gasoline, as they are important mostly as inputs for transport. Other sources of

[79] This approach is valid on the assumption that all self-produced biofuels were given a monetary valuation (survey's standard procedure), and those who have recorded consumption but zero expenditures constitute data errors rather than self-consumption.

[80] The asset ownership records do not contain the values of land and housing, even if they are owned by the household

biomass, such as wood residues and animal dung, were incorporated in the overall "firewood" consumption, for the sake of simplicity. There is not enough data on expenditures and on energy consumption from batteries, to include it in the domestic mix. Of the original sample, the authors selected 8147 valid households[81], corresponding to those that recorded the quantity consumed and the expenditure in at least one source, as well as a positive income.

Table III.1 presents the summary statistics on the survey data. Mean income in the sample is 104.820 MTn/day-HH, which converted to $PPP[82] corresponds to 18.49 $PPP/day-HH, with a median of 4.79 $PPP/day-HH, indicating the incidence of low-income families in the sample[83]. The analysis of the income data shows that of the 8454 households for which income was recorded, about 8206 (94.3% of the sample) recorded incomes within one standard deviation of the mean, i.e. less than 533,775.68 MTn/day (94.15 $PPP/day-HH)[84].

Of the households that registered incomes higher than one standard deviation from the mean, 15.3% recorded consumption of electricity, 5.8% recorded charcoal consumption, 1.53% recorded the use of kerosene as an energy source, and 34% were LPG users. Although these incomes are far above the average, and represent only 5.4% of the total sample, they were kept in the estimation because they represent the few but considerably wealthier classes in the Mozambican communities.

[81] The cleanup of the invalid data and the zero-purchasers reduced the number of households in the sample by 553 households, as described in the next section

[82] Conversion to Dollar-Power-Purchasing-Parity of 5669.1 MTn/$PPP, corresponding to the year 2003 (United-Nations 2007)

[83] The income earnings (in the sample designated also by revenue) include cash incomes and income in species. The difference between mean and median establishes the presence of many low-income and few very high-income families.

[84] US statistics indicate 40.12% of households earning incomes within one standard deviation of the mean, in 2006. Source: http://pubdb3.census.gov/macro/032007/hhinc/new06_000.htm

Table III.1 – Statistics on the household survey data

Values in $PPP/day-HH	Income earnings	Expenditures per source (non-zero purchasing households)					
		Firewood	Charcoal	Candles	Kerosene	LPG	Electricity
Max	3,653.6	21.17	28.53	3.53	14.97	5.80	23.46
Mean	**18.5**	**0.87**	**1.86**	**0.43**	**0.44**	**1.36**	**2.17**
Std	78.7	0.87	3.17	0.55	0.75	0.70	2.39
Median	4.8	0.65	0.82	0.21	0.18	1.02	1.45
Count	8147	6301	1727	601	4154	213	987
% of households recording consumption		75%	21%	7%	50%	3%	12%
National statistics		70-80%[85]	17.3%[86]		2.4%[87]		5.3%[88]

The daily expenditures on energy sources are on average small, and the total daily expenditure on the aggregated domestic energy registers a mean of 1.59 $PPP /day-HH, with a standard deviation of 2.3 $PPP /day-HH and a maximum of 30.3 $PPP /day-HH[89]. Although small, this daily expenditure corresponds to about 10% of the mean income, i.e. significant for these poor households. The average daily expenditure on firewood, among users, is of 0.87 $PPP /day-HH, smaller than charcoal (1.86 $PPP /day-HH) and electricity (2.17 $PPP /day-HH) expenditures. The daily expenditure on kerosene is the smallest, making it an accessible and affordable source (50% of the sample). It is important to note that although charcoal (mostly used for cooking) is cheaper than electricity, see prices for

[85] The World Bank report (WB, 1987) refers to a wood fuels consumption of about 90%, in 1986. Ferraz, 2000, places 90% wood-fuels consumption in 1970 and 80% in 1994 (Brouwer, 2004, argues that the reduction registered in the 80's was the result of war, which made the countryside inaccessible – where the raw materials – forests are, despite the growing populations of the urbanized areas). Currently, the estimated levels are of 70-80% in Maputo, in various combinations of use with other fuel sources, such as kerosene and electricity (Brouwer, 2004). Woodfuels is a combination of firewood and charcoal

[86] Informal Maputo recorded 17.3% of households consuming charcoal, while only 1.6% households of Maputo Cement recorded consumption of charcoal in 1990 (Mangue 2000)

[87] Kerosene consumption in Informal Maputo in 1990, higher than 0.6% recorded for the Maputo Cement (Mangue 2000)

[88] National statistics for 2003, source: Statistics of Electricidade de Mozambique (EDM 2007)

[89] In the Midwest of the US, west-north-central, the total domestic energy expenditure in 2002 was recorded with and average of 4.3 $/day-HH. Source: http://www.eia.doe.gov/emeu/recs/recs2001/detailcetbls.html

firewood, charcoal and kerosene in (Falcão 1999) and for electricity in (EDM 2007), because of its low efficiency its daily expenditure is quite close to the electrical expenditure indicating potential for energy transition.

Energy expenditures and the recorded quantities, converted into equivalent kWh, were used to estimate the price and income elasticities of consumption. In this calculation, the total expenditure in energy sources was used as the income measure, for the estimation of elasticities for the individual sources.

The survey collected data on the ownership of assets, but it does not seem sufficiently reliable to be used as explanatory variable for the elasticity estimations, because of the misalignment with the recorded expenditures and national statistics. For example, charcoal expenditures were recorded for 72.4% households (when national statistics place it at around 80% including firewood, or 17.3% in Maputo Informal, see Table III.1), but asset ownership of charcoal stoves and other appliances is only recorded for 0.6% households. Similarly, expenditures of electricity were recorded for 11.3% of households, for a national statistic of 5.3%, while assets for electricity consumption were recorded for 59.6% households of the survey. Clearly, the asset ownership is not properly reported, and is not usable for the current estimation. However, the survey also recorded which energy sources are used by the sampled households for cooking and for lighting. The representation of these sources in the sample through expenditure and quantities (see Table III.2) is closer to the national statistics presented in Table III.1 and these variables will be used as proxies for asset ownership.

For explanatory variables, the authors selected one income variable and eight others representing the household usage of the various sources (see Table III.2), directly obtained from the household sample. Other demographic characteristics were tested for their explanatory power in the regression equations, for example the household size, the type of dwelling or the source of drinking water, and showed insignificant contributions, being consequently excluded from the derivations.

Table III.2 – Explanatory variables in the regression derivation

Symbol in appendix	Nature	Description	Share (8147 HHs)
x_{ic}^{k}	Income	Total expenses in energy sources	-
$z_{ic}^{h=1}$	Proxies to Asset Ownership	Main cooking source: charcoal	17.6%
$z_{ic}^{h=2}$		Main cooking source: kerosene	1.2%
$z_{ic}^{h=3}$		Main cooking source: LPG	1.3%
$z_{ic}^{h=4}$		Main cooking source: electricity	0.8%
$z_{ic}^{h=5}$		Main lighting source: firewood and other	28.6%
$z_{ic}^{h=6}$		Main lighting source: candles	4.9%
$z_{ic}^{h=7}$		Main lighting source: kerosene	56.1%
$z_{ic}^{h=8}$		Main lighting source: electricity, solar/diesel generator	10.3%

The count of energy consuming households in the sample show that all use firewood for cooking and only 17.6% use charcoal as a main source. It is not surprising that charcoal users are present in a lower percentage than that reported by Brouwer and Falcao (2004) for Maputo City, as most of the households surveyed are located in rural areas (53% of total households are rural, located in 61% of the clusters). Note that only 78 (23%) of the 335 clusters recorded as urban are located in Maputo. Most of the other urban areas are closer to the biomass sources and are significantly smaller than Maputo city, thus it is expected that they report lower usage of charcoal and higher usage of firewood.

The percentage of households using kerosene for lighting is within range of published predictions. The percentage of households using electrical lighting is, however, above the national average for 2003 which indicates a coverage of 5.3% of the total population[90] consuming electricity (EDM 2007) . This discrepancy is unlikely to result from electrical supply of private (isolated) generators, as they are estimated to cover only between 0.18% and 0.34% of the population (Mulder 2007), and will be taken as representing a bias in the sample. Considering that the sample contains mostly poor households (of low-income levels) the electricity consumers recorded are expected to be of low consumption levels and more sensitive to high electricity prices, i.e. the bias is expected to increase the estimated own-price elasticity of electricity demand.

THE RESULTS

PRICE ELASTICITIES FOR THE INDIVIDUAL SOURCES IN THE DOMESTIC MIX

The application of Deaton's method to estimate the individual elasticities of the six energy sources, using the total energy expenditure as the income variable, resulted in the regressors and the elasticities presented respectively in Table III.3 and Table III.4. The intermediate calculations of budget-share and unit-value price elasticities are presented in Table III.5.

QUALITY EFFECTS IN THE INTERMEDIATE CALCULATIONS

The price elasticities of the budget-shares φ_0 for the various energy sources are quite small when compared to the response of the unit values φ_1 (Table III.5). In other words, energy price variations affect primarily the household unit expenditures rather than the allocation of budget to energy expenditures. Households' budget-shares for energy consumption seem not to have a great variation between clusters, possibly because poor households consume energy at a proportion of their budgets that is independent of price variations, even if some

[90] Data for 2003, based on an average family size of 4.2 persons

pay more and others less for each energy unit. The quality effects evident in the variation of the unit values differentiate, between clusters, the households' willingness to pay for a sources' unit of energy.

The quality effects in the unit values (φ_1) are positive in own-price terms, and in general insignificant in cross-price terms, though the signs of the cross-price elasticities may be indicative of choice-behavior:

- Charcoal consumers will accept an increase in their unit expenditures when firewood prices increase (and vice-versa), but will require lower charcoal (firewood) unit expenditures with increases in the prices of other sources. The link between firewood and charcoal price responses makes sense, as firewood and charcoal are price correlated. Charcoal is mostly used for cooking while candles, kerosene and electricity are mostly used for lighting, thus when the price of lighting sources increase the household reduces the unit expenditure in cooking sources.
- Charcoal consumers will accept an increase in their unit expenditures when firewood prices increase (and vice-versa), but will require lower charcoal (firewood) unit expenditures with increases in the prices of other sources. The link between firewood and charcoal price responses makes sense, as firewood and charcoal are price correlated. Charcoal is mostly used for cooking while candles, kerosene and electricity are mostly used for lighting, thus when the price of lighting sources increase the household reduces the unit expenditure in cooking sources.
- Kerosene unit expenditures do not respond to price variations of other sources, and the response of electricity consumption is very small. These two sources, mostly used for lighting serve too essential a need to be very responsive to other sources' prices.

Table III.3 – Regression results for the estimation on the individual energy sources – national

	Sample Clusters – Mean						Sample Clusters - Std Deviation					
Dependents: Budget-share (W) and Unit-value (V)	**Firew.**	**Charc.**	**Cand.**	**Keros.**	**LPG**	**Electr.**	**Firew.**	**Charc.**	**Cand.**	**Keros.**	**LPG**	**Electr.**
W: energy expenditure per source divided by total energy expenditure	0.63	0.12	0.02	0.16	0.01	0.07	0.41	0.26	0.09	0.25	0.067	0.212
V: energy expenditure divided by kWh consumption per source (non-zero only)	8.61	7.62	6.58	5.63	3.97	6.05	0.80	1.07	1.69	1.762	0.528	2.45
Statistics of regression	**Firew.**	**Charc.**	**Cand.**	**Keros.**	**LPG**	**Electr.**	**Firew.**	**Charc.**	**Cand.**	**Keros.**	**LPG**	**Electr.**
R square	0.38	0.40	0.33	0.31	0.55	0.66	0.53	0.50	0.11	0.04	0.03	0.04
F-test	554.0	601.2	436.9	395.6	1119.4	1745.0	773.4	187.5	7.9	20.4	1.3	4.1
p value for F-test	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	26%	0%
error variance	0.03	0.02	0.004	0.03	0.001	0.01	0.07	0.27	0.37	0.64	0.005	2.45
	Regression coefficients for Budget share						**Regression coefficients for Budget share**					
Independents:	**Firew.**	**Charc.**	**Cand.**	**Keros.**	**LPG**	**Electr.**	**Firew.**	**Charc.**	**Cand.**	**Keros.**	**LPG**	**Electr.**
ln of Income variable:												
Total expenses in energy sources	0.02	0.03	-0.01	-0.03	-0.004	-0.001	0.65	0.78	0.20	0.26	-0.01	0.47
Demographic variables (dummies):												
Main cooking source: charcoal	-0.50	0.45	0.01	0.03	0.003	0.01	-0.31	0.41	0.01	-0.18	0	0.08
Main cooking source: kerosene	-0.54	0.03	-0.01	0.53	0.001	-0.02	-0.09	0.13	0.42	0.08	0	-0.31
Main cooking source: LPG	-0.49	0.06	-0.004	0.005	0.36	0.07	-0.50	-0.22	-0.63	0.29	-0.02	-0.09
Main cooking source: electricity	-0.47	0.08	-0.02	-0.01	0.02	0.40	-0.67	0.17	-0.48	-0.54	-0.02	0.11
Main lighting source: firewood and other	0.21	0.10	-0.003	-0.23	-0.003	-0.08	0.10	0.02	0.39	0.06	0	3.85
Main lighting source: candles	0.001	0.09	0.23	-0.25	-0.002	-0.07	-0.08	0.19	0	0.51	0	0.22
Main lighting source: kerosene	-0.004	0.10	-0.002	-0.01	-0.002	-0.08	-0.05	0.20	0	0	0	-2
Main lighting source: electricity, etc	-0.11	-0.001	-0.016	-0.28	0.002	0.40	-0.25	0.004	-0.79	-0.27	0	-0.13

Table III.4 – Household price elasticities (urban + rural) - national

E_P - Deaton's own- and cross-price elasticities of energy consumption						
	Firewood	**Charcoal**	**Candles**	**Kerosene**	**LPG**	**Electricity**
Firewood	**-0.3674**	0	-0.0001	-0.0001	0	-0.0001
Charcoal	0.0003	**-0.3721**	-0.0004	-0.0007	-0.0004	-0.0004
Candles	0	0.0013	**-0.6490**	0.0031	0.0039	0.0006
Kerosene	0	0	-0.0002	**-0.6729**	0	0
LPG	0.0024	0.0121	0.0275	0.0240	**-0.9117**	0.0113
Electricity	-0.0002	-0.0001	0.0003	0.0005	0.0004	**-0.5156**

Table III.5 – Measurement errors and quality effects in the household - Intermediate steps in the calculation of Deaton's elasticities for all households, equation (1)

Φ_0 – Price elasticities of the budget-share variable						
	Firewood	**Charcoal**	**Candles**	**Kerosene**	**LPG**	**Electricity**
Firewood	**0.0006**	0.0001	-0.0001	-0.0001	0	-0.0001
Charcoal	0.0001	**0.0002**	0	-0.0001	-0.0001	-0.0001
Candles	-0.0001	-0.0001	**0.0003**	0.0001	0.0001	0.0001
Kerosene	0	0	0	**0.0002**	0	0
LPG	-0.0008	-0.0005	0.0004	0.0004	**0.0009**	0.0005
Electricity	0	0	0	0	0	**0**
Φ_1 – Price elasticities of the unit-value variable (standard deviations in brackets)						
	Firewood	**Charcoal**	**Candles**	**Kerosene**	**LPG**	**Electricity**
Firewood	**0.3683** (0.45)	0.0001	0	0	0	-0.0001
Charcoal	0.0002	**0.3734** (2.33)	-0.0001	-0.0002	0	-0.0002
Candles	-0.0034	-0.0066	**0.6663** (1.51)	0.0025	0	0.0021
Kerosene	0	0	0	**0.674** (2.30)	0	0
LPG	-0.0848	-0.0685	0.0139	0.0188	**1.0084** (1.02)	0.0389
Electricity	-0.0002	-0.0003	0.0001	0.0002	0	**0.5161** (18.02)

The standard deviations in these “quality effects” are large for electricity, indicating that households widely vary in their perception of value of this source and establishing greater imprecision in the respective estimations of elasticities.

ESTIMATED PRICE ELASTICITIES

Although the R^2 values of the regression equations are not very high (see Table III.3), the F-statistic in the regressors indicate a significance level below 1%, with exception of the coefficients of regression for the LPG unit-values, that are at a significance level of 26%. The own and cross-price elasticities calculated for the various sources are presented in Table III.4.

The consumption of firewood will reduce by 0.37% for every 1% price increase, and will increase with increases in the charcoal price, indicating some level of substitutability though small. The negative cross-elasticities of firewood consumption with the prices of commercial sources such as candles, kerosene and electricity may indicate that when lighting sources prices are higher the constrained budget forces the household to reduce consumption of the source for cooking (firewood). The same argument is valid for the consumption of charcoal. Firewood and charcoal show very close elasticities, which make sense given their common origin (forestry resource) and their condition as low-grade energy sources.

Candles and kerosene, primarily lighting sources, show similar own-price elasticities, -0.65 and -0.67 respectively, and very small cross-price elasticities; candles show only a small substitutability effect with kerosene, LPG and electricity. The kerosene own-price elasticity is higher than those calculated by other authors, namely Abdel-Khalek for Egypt (Abdel-Khalek 1988) (-0.23 and -0.41), by Koshal, Koshal et al. (1999) for Indonesia (-0.06 and -

0.17), and by Pindyck for Brazil and Mexico (Koshal, Koshal et al. 1999) (-0.13 and -0.20), respectively for the short and long term.

The result for LPG is suspicious as the original sample is very small (2.4% of expenditure records only) and its consumption is, in this particular sample, complementary to that of low-grade sources, i.e. uncharacteristic.

The own-price elasticity for electricity consumption, of -0.51 is smaller than the results of Pouris (Pouris 1987), calculated as -0.9 and corrected to -1.01 by Whittaker (Whittaker and Barr 1989), for the South African domestic market. These authors calculated their elasticities with time lags of 12 and 8 years respectively, and confirm a very slow response in the short term, i.e. small own-price elasticities in the short term. A better match is found with Filippini and Pachauri (2004) results, which show a price elasticity for electricity consumption of -0.42 for winter, -0.29 for summer and -0.51 for the monsoon months. The almost zero cross-price elasticities are not surprising in that they indicate that the choice of energy sources for the household consumption does not really depend on other sources prices, rather it depends in factors such as accessibility, ownership of assets to consume the source and, in some cases, the affordability of the source itself.

COMPARISON WITH PRICE ELASTICITIES OBTAINED BY DIRECT REGRESSION

The calculation by direct regression of the own-price elasticities of the energy sources gave different results than those obtained through applying Deaton's method, for all sources with exception of kerosene (see Table III.6). The comparison indicates that the quality effects tend to decrease the own-price elasticities for the lower grade sources, and increase them for the higher-grade sources (excepting LPG, dismissed due to its poor representation in the households' sample). This result makes sense in that the consumption of lower-grade sources is indicative of a condition of poverty and occurs at a much lower consumption level and as such, the household is less able to respond to price changes. The poor are already consuming the minimum (basic) quantity of energy, and cannot live without it. On the other hand, the wealthier households, consuming higher-grade sources, support not only their basic energy needs but also energy consumption for more leisurely or comfort-oriented activities, and as such respond more widely to price variations.

Table III.6 –Deaton's and Direct regression own-price elasticities

	Firewood	**Charcoal**	**Candles**	**Kerosene**	**LPG**	**Electricity**
Deaton's	-0.37	-0.37	-0.65	-0.67	-0.91	-0.52
p-value of F test for regression W , V	*0 , 0*	*0 , 0*	*0 , 0*	*0 , 0*	*0 , 0. 26*	*0 , 0*
Direct	-0.17	-0.28	-0.43	-0.68	-0.76	-0.97
p-value of F test for direct regression	*0*	*0*	*0*	*0*	*0*	*0*

INCOME ELASTICITIES FOR THE ENERGY SOURCES IN THE DOMESTIC MIX

Table III.7 presents the income elasticities of the separate sources, calculated by Deaton's method and by direct regression. The income elasticities estimated by Deaton's method for the various energy sources are within the same range, -0.37 for firewood and charcoal, -0.65 and -0.67 for candles and kerosene, and -0.52 for electricity, with exception of LPG's estimated to -0.91. The elasticities obtained from direct regression, assumed to still contain the quality effects and measurement error effects, are lower for all sources excepting electricity consumption. In other words, these effects depress the household energy consumption response to income variations, with exception of electricity, possibly because households view the later as an expensive though useful source and as such the first to reduce when budget is tightened, and the first to increase when more money is available.

Other authors found income elasticity for kerosene consumption to be 0.26 / 0.47 (Abdel-Khalek 1988) for the short and long term in Egypt, 0.29 / 0.79 in Indonesia (Koshal, Koshal et al. 1999) and 0.10 / 0.15 in Brasil/Mexico (Koshal, Koshal et al. 1999). The income elasticity of kerosene consumption, here calculated for the Mozambican households, is of 0.54, within the range of those authors' elasticities.

Table III.7 –Deaton's and Direct regression income elasticities

	Firewood	Charcoal	Candles	Kerosene	LPG	Electricity
Deaton's	0.38	0.47	0.38	0.54	0.57	0.51
p-value of F test for regression W , V	*0 , 0*	*0 , 0*	*0 , 0*	*0 , 0*	*0, 0.26*	*0 , 0*
Direct	0.17	0.30	0.30	0.51	0.30	0.66
p-value of F test for direct regression	*0*	*0*	*0*	*0*	*0*	*0*

Louw et al. (2008) indicate that the electricity price is insignificant (in their analysis) because other factors determine the level of electrical consumption. These authors also indicate that electricity is income inelastic, i.e. the level of consumption is not really determined by changes in income, contradicting the obtained result of +0.51 for income elasticity of electrical consumption. However, the income elasticity of electricity here calculated (+0.51) makes good sense given that this sample is composed of many poor households (refer to previous discussion on income levels).

COMMENTS ON THE REGRESSORS FOR THE 'ASSET OWNERSHIP' PROXIES

The regressors representing the effects of the ownership of assets in the budget-share and unit expenditure equations (see Table III.3) give some indication of the correlations between sources in the choice-behavior of the household, as follows:

- Firewood budget-shares and unit-values reduce in the presence of assets to consume other cooking sources (charcoal, kerosene and electricity) and assets to light with electricity, but increase when lighting with firewood itself.
- Charcoal budget-shares and unit-values increase with 'ownership' of other sources for cooking and for lighting. The ownership of electric lighting does not influence charcoal's budget-shares and unit-values.
- Kerosene budget-shares and unit values increase with ownership of kerosene assets for cooking but reduce for lighting[91]. Cooking and lighting with electricity on the other hand will reduce the budget-shares and unit values of kerosene consumption. The ownership of other sources' assets for cooking and lighting affects kerosene consumption for increase of budget-shares and decrease of unit-values (cooking with charcoal) and vice-versa (lighting with firewood and candles).
- Electricity budget-shares and unit values increase with cooking with charcoal and electricity, and reduce with cooking and lighting with kerosene. Lighting with firewood and electricity affects budgets-shares and unit-values of electricity consumption in contrary ways.
- Candles and LPG are not analyzed, given the suspected imprecision of their records.

The effects of the asset ownership proxies in the estimation of the budget-shares and unit values of the individual sources are all positive in the 'self' effect (ownership of the respective assets for lighting and cooking), which conforms to expectations: the household will consume more of a source if it owns assets for its consumption. The exception found is the effect of owning electrical lights in the households' unit values: the effect is negative indicating that the household's increasing ownership of electrical lights makes it unwilling

[91] It may be that kerosene, as the cheaper source, will represent lower budget-shares and unit expenditures when it is used for lighting. Kerosene effectively is at the bottom of the ladder for lighting purposes only: candles are under- represented and electricity is more expensive.

to pay more for electricity consumption, although it tends to increase the source's budget-shares. These effects only make sense, given the structure of the electric tariff (pays more per unit who takes more, for domestic consumers), if the higher budget-shares correspond to a smaller budget, i.e. to poor families consuming less electricity at lower prices[92]. The cross-effects are harder to discuss with exception of the following:

- Firewood consumption is replaced by other (higher-grade) sources when the household owns assets to consume them.
- Charcoal is the cooking source of choice and its expenditure will always increase with the ownership of assets for consuming other sources. In words, when the household evolves and acquires assets to consume other sources, it will also increase its charcoal consumption: Brouwer and Falcao (2004) refer to taste preference to explain the adoption of charcoal even in higher income families. It also may be a result of charcoal being the primary cooking source while electricity and kerosene are primarily lighting sources, for the sampled households.
- When the household own assets for cooking and lighting with kerosene, it will not consume electricity as much, the same way that households owning electrical assets for cooking and lighting will not consume kerosene as much.
- The ownership of electrical lights decreases the unit-values of electrical consumption, but increases its budget-shares; in words, the household is willing to pay lower values per unit electricity because its budget allocation (to electricity expenditure) is higher (lower budget).

[92] Can this be a direct effect of the subsidized electrification programs for poor communities?

This discussion is based on the sign of the regressors derived for the asset ownership proxy-variables. The mater should be further investigated with specific surveys on domestic energy use.

CONCLUDING REMARKS

Energy is a special domestic consumption good, with characteristics of substitutability and complementary between sources that muddle the individual choice. This study shows that the individual sources in the households' sample behave as normal goods, and all have negative own-price elasticities of demand and positive income elasticities of demand.

The derivation of own-price elasticities per source was made for data for which the energy prices were unobservable, using Deaton's econometric method. The results conform reasonably with expectations on household energy consumption and preferences, low-grade sources being in general less elastic *(-0.37 for firewood and charcoal)* than high-grade sources, and the cross elasticities between sources being negligible. This not surprising, because most of the households surveyed are at the edge of poverty and their energy consumption constitutes a basic unavoidable need. Electricity and kerosene registered, respectively, own-price elasticities of -0.52 and -0.67 at the national level. Income elasticities were estimated in the range of +0.50 for the separate sources (respectively 0.38 for firewood, 0.47 for charcoal, 0.54 for kerosene and 0.51 for electricity, at the national level). The sample used did not characterize the consumption of candles and LPG sufficiently to trust the own- and cross-effects of these sources in the other sources' elasticities of demand. Consequently, the results for these sources elasticities should be used with great caution. To a lesser extent, the same applies to the estimated elasticities of electricity demand.

The analysis of the demographic regressors confirms that ownership of energy-consuming assets is inductive of increasing the demand for the respective source. It also indicates the presence of cross-effects, resulting from the substitutability of the sources, which need further investigation.

In conclusion, this study calculated price- and income elasticities of domestic energy sources for the Mozambican households, at a national scale, and demonstrated that the ownership or energy consuming assets is a determinant in the household choice of the domestic energy mix.

APPENDIX III.1: ECONOMETRIC DERIVATION OF ELASTICITIES OF DOMESTIC ENERGY DEMAND

The following exposition intends to clarify the steps of estimation of demand elasticities, as formulated by Deaton (1987; 1988; 1990), and as applied to the group of energy sources used for domestic consumption. Ideally the empirical equation for demand for good *i* would take the following form:

$$\ln q_f^i = \alpha^i + \varepsilon_x^i \cdot \ln x_f + \sum_j \varepsilon_p^{i,j} \cdot \ln p_j + \sum_h \gamma_h^i \cdot z_f^h + \xi_f^i \tag{5}$$

where the variables and indices represent[93]:

i ≡ index for the good i (varying between 1 and n)
j ≡ index for the good j (varying between 1 and n)
f ≡ index for household f
h ≡ index to distinguish between the demographic variables used as explanatory
q_f^i ≡ quantity consumed for the energy source i by the household f, kWh-equivalent
x_f ≡ variable representative of income of household f, MTn
p_j ≡ market price of energy source consumed j, in MTn/kWh-equivalent
z_f^h ≡ household demographic characteristic of type h by the household f
ε_x^i ≡ income elasticity of demand for energy source i
$\varepsilon_p^{i,j}$ ≡ price elasticity of demand for energy source i (by price j)
γ_h^i ≡ coefficient of demand response, for energy source i, to the demographic variable h
ξ_f^i ≡ fixed and random variations in quantity demanded, for source i by the household f

93 "MTn" is the Mozambican currency

However, the market prices of the energy sources p_j are not observable, and it is only possible to formulate the empirical relations for the budget-share of energy consumption and their unit-values (calculated by dividing expenditure to quantity consumed), as follows:

$$\begin{aligned} w_f^i &= \alpha_0^i + \beta_0^i \cdot \ln x_f + \sum_j \theta_0^{i,j} \cdot \ln p_j + \sum_h \gamma_{h0}^i \cdot z_f^h + \xi_{f0}^i \\ \ln v_f^i &= \alpha_1^i + \beta_1^i \cdot \ln x_f + \sum_j \theta_1^{i,j} \cdot \ln p_j + \sum_h \gamma_{h1}^i \cdot z_f^h + \xi_{f1}^i \end{aligned} \tag{6}$$

where the variables and indices represent:

$0 \equiv$ index for the regressors in equation of budget-share

$1 \equiv$ index for the regressors in equation of unit-value

$w_f^i \equiv$ budget-share of consumption for the energy source i by the household f, MTn/MTn

$$w_f^i = \frac{X_f^i}{\sum_j X_f^j} \quad \text{where } X_f^i \equiv \text{expenditure in energy source } i \text{ by the household } f\text{, in MTn}$$

$v_f^i = \dfrac{X_f^i}{q_f^i} \equiv$ unit-value of energy source consumed i by the household f, in MTn/kWh-equivalent

The coefficients α, β, θ and γ are regressors obtained from solving the equations, and represent the respective effects of the independent variables in the energy budget-shares[94] and in the unit-values recorded for each household. Households are surveyed per geographic areas named clusters. By assuming, that within each cluster there are no true price variations, we can eliminate price as an explanatory variable and for each household *f*, within cluster *c*, for energy source *i*, we have:

$$\underbrace{w_{fc}^i - w_{\bullet c}^i}_{\text{from HH survey}} = \underbrace{\alpha_0^i}_{\text{intersect}} + \underbrace{\beta_0^i}_{\text{coeff of income}} \cdot \underbrace{\left(\ln x_{fc} - \ln x_{\bullet c}\right)}_{\text{from HH survey}} + \sum_h \underbrace{\gamma_{h0}^i}_{\text{coeff of demographics}} \cdot \underbrace{\left(z_{fc}^h - z_{\bullet c}^h\right)}_{\text{from HH survey}} + \underbrace{\left(u_{fc0}^i - u_{\bullet c0}^i\right)}_{\text{regression residuals}}$$

$$\underbrace{\ln v_{fc}^i - \ln v_{\bullet c}^i}_{\text{from HH survey}} = \underbrace{\alpha_1^i}_{\text{intersect}} + \underbrace{\beta_1^i}_{\text{coeff of income}} \cdot \underbrace{\left(\ln x_{fc} - \ln x_{\bullet c}\right)}_{\text{from HH survey}} + \sum_h \underbrace{\gamma_{h1}^i}_{\text{coeff of demographics}} \cdot \underbrace{\left(z_{fc}^h - z_{\bullet c}^h\right)}_{\text{from HH survey}} + \underbrace{\left(u_{fc1}^i - u_{\bullet c1}^i\right)}_{\text{regression residuals}}$$

[94] The method initially used quantity and unit value, as the variables to regress (Deaton 1987); in later papers (Deaton 1988; Deaton 1990; Kedir 2005), it uses the budget-share instead of the quantity. No evidence of better accuracy for using quantity or budget-shares is found in these papers.

where the variables and indices represent:

$fc \equiv$ index for household f from cluster c

$\bullet c \equiv$ index for average (of logs where aplicable) of variables within cluster c

$u^i_{fc0} - u^i_{\bullet c0} \equiv$ residuals obtained from the budget-share regression, per household f for source i

$u^i_{fc1} - u^i_{\bullet c1} \equiv$ residuals obtained from the unit-value regression, per household f for source i

$\alpha^i_0 \equiv$ intersect of the budget-share regression for source i

$\beta^i_0 \equiv$ coefficient of income, calculated in the budget-share regression for source i

$\gamma^i_{h0} \equiv$ coefficient of demographic h, calculated in the budget-share regression for source i

$\alpha^i_1 \equiv$ intersect of the unit-value regression for source i

$\beta^i_1 \equiv$ coefficient of income, calculated in the unit-value regression for source i

$\gamma^i_{h1} \equiv$ coefficient of demographic h, calculated in the unit-value regression for source i

The residuals of these equations represent the variations due to measurement errors, and are used to calculate the measurement errors' effects. Regressors β and γ represent the quality effects without any measurement errors, in other words, income and demographics that determine the cluster's perception of quality for the consumption good. In this application, the quantity x_{fc} represents the level of income of household *fc*, and corresponds to the "total household expenditure in energy" when all sources are studied in separate (number of sources (goods): $n > 1$), and to the "total household income" when all sources are studied in aggregate form (only one good, $n = 1$). The vector of household characteristics of size h represents the household demographic effects in the purchasing behavior for energy. Note that the budget share is not regressed in the logarithmic form. When explanatory variables take a binary form, their means correspond to the proportion of households for whom the demographic variables were recorded as one.

Deducting from the clusters' means the quality effects, due to the income levels and demographics of each cluster, we obtain the "corrected" cluster variables $\tilde{y}^i_{0\bullet c}$ and $\tilde{y}^i_{1\bullet c}$, which, from equation (6), also correspond to the "real" price term in regression (plus the intersect and the deviations per cluster):

$$\tilde{y}^i_{0\bullet c} = w^i_{\bullet c} - \beta^i_0 \cdot \ln x_{\bullet c} - \sum_h \gamma^i_{h0} \cdot z^h_{\bullet c} = \alpha^i_0 + \sum_j \theta^{i,j}_0 \cdot \ln p_j + \xi^i_{\bullet c0}$$
$$\tilde{y}^i_{1\bullet c} = \ln v^i_{\bullet c} - \beta^i_1 \cdot \ln x_{\bullet c} - \sum_h \gamma^i_{h1} \cdot z^h_{\bullet c} = \alpha^i_1 + \sum_j \theta^{i,j}_1 \cdot \ln p_j + \xi^i_{\bullet c1}$$

The corrected quantities are only intermediate steps in the calculation and represent the clusters' price effects isolated from the error measurements and from the quality effects. Their variances can then be used to calculate the "true" price-elasticities and their variances, by the following steps:

1. Calculate the price and expenditure elasticities for *n* goods as follows:

The own- and cross-price elasticities of the budget-share are (nxn):

$$\tilde{\Theta}_0 = \tilde{B} \cdot \left(D_0 + W - \tilde{B} \cdot D_1\right)^{-1} \cdot \left(D_0 + W \cdot \left(I - D_1\right)\right) = \left\{\theta_0^{\,i,j}\right\}$$

where:

I = identity matrix (nxn matrix)

$W = \text{diagonal}\left\{w^i\right\}$ (nxn matrix)

D_0 = $\text{diagonal}\left\{\beta^i_0\right\}$ (nxn matrix)

D_1 = $\text{diagonal}\left\{\beta^i_1\right\}$ (nxn matrix)

The own- and cross-price elasticity of the unit-value are (nxn):

$$\tilde{\Theta}_1 = \tilde{B}^{-1} \cdot \tilde{\Theta}_0 = \left\{\theta_1^{\,i,j}\right\}$$

See the definition of $\tilde{B}$ in the next step. The budget-share per good w^i in the equation is taken as the average budget-share recorded for all households per good *i*. For *n* goods (the energy sources studied in separate), these elasticities intermediate are matrices, and allow the calculation of the price and expenditure elasticities of consumption as:

The own- and cross-price elasticities (nxn): $\left\{\varepsilon_p^{\,i,j}\right\} = W^{-1} \cdot \tilde{\Theta}_0 - \tilde{\Theta}_1$

The total expenditure elasticities (nx1): $\left\{\varepsilon_x^{\,i}\right\} = W^{-1} \cdot D_0 + I - D_1$

The comparison of these results with those obtained from directly regressing quantities with unit values, only for the non-zero purchasing households per good *i*, given by

$$\ln q_f^i = \alpha^i + \rho^i \cdot \ln v_f + \sigma^i \cdot \ln x_f + \sum_h \psi^{ih} \cdot z_f^h + e_f^i$$

Shows differences that can be attributable to both measurement errors and quality effects:

$$\text{compare} \quad \varepsilon_p^{\ i,i} \quad \text{with} \quad \rho^i \quad \text{and} \quad \text{compare} \quad \varepsilon_x^{\ i} \quad \text{with} \quad \sigma^i$$

Note: the direct regression is based on the assumption that the unit prices (expenditure divided by normalized quantity) recorded are true representations of the market prices experienced by the households. Some authors consider the elasticities obtained by direct regression to be sufficiently accurate, although they both contain measurement errors and behavioral deviations.

2. In the above equation, the matrix $\tilde{B}$ corresponds to the ratio of the responses to price variations (elasticities) of the variables budget-share and unit-value, calculated from the ratio of their covariances:

$$\tilde{B} = \left(\tilde{S} - \tau_+^{-1} \cdot \tilde{\Omega}\right)^{-1} \cdot \left(\tilde{R} - \tau^{-1} \cdot \tilde{\Gamma}\right) = \left\{ \frac{\theta_0^{i,j}}{\theta_1^{i,j}} \right\} \qquad \text{is a nxn matrix}$$

$\tilde{B}$is a scalar quantity in the case of one good only (*n = 1*), or a matrix *nxn* for *n* goods. This ratio represents the cluster budget-share variation on cluster "price" (unit value), after eliminating the effects of measurement errors, but still containing the quality effects of each cluster, by the relation:

$$\tilde{B} = \frac{\theta_0^{i,j}}{\theta_1^{i,j}} = \frac{\partial w_f^i \big/ \partial \ln p_j}{\partial \ln v_f^i \big/ \partial \ln p_j}$$

With measurement errors (and with quality effects) the ratio would be $\tilde{B}_{\text{with m.e.}} = \tilde{S}^{-1} \cdot \tilde{R}$.

3. The variables-component of the ratio $\tilde{B}$ are calculated as follows:

   a. For one good only (n = 1), the average size of the clusters is given by $\tau^{-1} = C^{-1} \cdot \sum_{c=1}^{C} (N_c)^{-1}$, a scalar quantity. However, in the case of n goods, the average size of the clusters correspond to the sources sizes calculated only for the non-zero purchasing households in a *nxn* diagonal matrix τ_{+}^{-1}, whose i^{th} diagonal entry is given by $\left(\tau_{+}^{-1}\right)^{\mathrm{i^{th}\ entry}} = \left(C_{+}^{i}\right)^{-1} \cdot \sum_{c=1}^{C_{+}^{i}} \left(N_{c+}^{i}\right)^{-1}$.

   b. The variances and covariances of the original budget-shares and unit values are calculated from the residuals obtained from regression per household per cluster, with i and j as indexes for goods:

$$\tilde{\Omega} = \mathrm{cov}(v^i, v^j) = \left\{ \frac{\sum_{c=1}^{C_{+}^{i,j}} \sum_{f=1}^{N_{+}^{i,j}} \left(u_{fc1}^{i} - u_{\bullet c1}^{i}\right) \cdot \left(u_{fc1}^{j} - u_{\bullet c1}^{j}\right)}{N_{+}^{i,j} - C_{+}^{i,j} - V} \right\}$$

$$\tilde{\Gamma} = \mathrm{cov}(w^i, v^j) = \left\{ \frac{\sum_{c=1}^{C_{+}^{i,j}} \sum_{f=1}^{N_{+}^{i,j}} \left(u_{fc0}^{i} - u_{\bullet c0}^{i}\right) \cdot \left(u_{fc1}^{j} - u_{\bullet c1}^{j}\right)}{N_{+}^{i,j} - C_{+}^{i,j} - V} \right\}$$

   These variances and covariances represent the effect of measurement errors in the original data; for only one good (case of the aggregated sources), each quadrant will be a scalar, or for n goods, the quadrants will be *nxn* matrices of values (case of n sources studied in separate).

When calculating variances and co-variances, as well as the average cluster size, this application considers the possibility of clusters for which all households are zero-purchasers; i.e. it differentiates between the total number of clusters in the valid sample,

C, and the number of clusters with non-zero purchasing households for goods i and j, $C_+^{i,j}$. Similarly differentiated are the total number of valid households N and the number of non-zero purchasing households for goods i and j, $N_+^{i,j}$. V is the number of independent variables used in regression.

4. The covariance matrices of the corrected variables, as representations of the income and quality effects inter-cluster, as *nxn* matrices whose elements, for each combination of goods i and j, are also necessary for the derivation of the price and income elasticities of demand:

$$\tilde{S} = \text{cov}(\tilde{y}^i_{1\bullet c}, \tilde{y}^j_{1\bullet c}) = \left\{ \frac{\sum_c \left[\tilde{y}^i_{1\bullet c} - mean\left(\tilde{y}^i_{1\bullet c}\right)\right] \cdot \left[\tilde{y}^j_{1\bullet c} - mean\left(\tilde{y}^j_{1\bullet c}\right)\right]}{C_+^{i,j}} \right\}$$

$$\tilde{R} = \text{cov}(\tilde{y}^i_{1\bullet c}, \tilde{y}^j_{0\bullet c}) = \left\{ \frac{\sum_c \left[\tilde{y}^i_{1\bullet c} - mean\left(\tilde{y}^i_{1\bullet c}\right)\right] \cdot \left[\tilde{y}^j_{0\bullet c} - mean\left(\tilde{y}^j_{0\bullet c}\right)\right]}{C_+^{i}} \right\}$$

$$\tilde{Q} = \text{cov}(\tilde{y}^i_{0\bullet c}, \tilde{y}^j_{0\bullet c}) = \left\{ \frac{\sum_c \left[\tilde{y}^i_{0\bullet c} - mean\left(\tilde{y}^i_{0\bullet c}\right)\right] \cdot \left[\tilde{y}^j_{0\bullet c} - mean\left(\tilde{y}^j_{0\bullet c}\right)\right]}{C} \right\}$$

where C_+^i is the number of clusters with non-zero purchasing households for goods i. These covariances represent the inter-cluster range of the corrected values, for each combination of sources $i, j = 1 \ldots n$, i.e. the covariances of the clusters' price effects in the measured variables.

5. Finally, the accuracy of the estimated elasticities is determined by the scale of the variances of the responses to price variations of the variables budget-share and unit values (Deaton 1988):

$$\mathrm{var}\left(\tilde{B}\right)=\left(\tilde{S}-\tau^{-1}\cdot\tilde{\Omega}\right)^{-2}\cdot\frac{\left(\tilde{Q}-2\cdot\tilde{R}\cdot\tilde{B}+\tilde{S}\cdot\tilde{B}^{2}\right)\cdot\tilde{S}+\left(\tilde{R}-\tilde{B}\cdot\tilde{S}\right)^{2}}{C-1}$$

$$\mathrm{var}\left(\theta_0^{\,i,j}\right)=\frac{\sum_c\left[\theta_0^{\,i,j}-mean\left(\theta_0^{\,i,j}\right)\right]^2}{C}$$

$$\mathrm{var}\left(\theta_1^{\,i,j}\right)=\frac{\sum_c\left[\theta_1^{\,i,j}-mean\left(\theta_1^{\,i,j}\right)\right]^2}{C}$$

where the quality elasticities are functions of the household budget-share of good *i*, namely w_{hous}^{i}:

$$\theta_0^{\,i,j}=\frac{\tilde{B}^{i,j}\cdot\left(\beta_0^{i}+w_{hous}^{i}\cdot\left(1-\beta_1^{i}\right)\right)}{\beta_0^{i}+w_{hous}^{i}-\tilde{B}^{i,j}\cdot\beta_1^{i}}\qquad\text{and}\qquad\theta_1^{\,i,j}=\left(\tilde{B}^{i,j}\right)^{-1}\cdot\theta_0^{\,i,j}$$

Final note: This method is approximate and laborious; however, it provides a reasonably accurate estimation of own and cross-price elasticities of consumption goods.

APPENDIX III.2: FURTHER STUDIES OF ENERGY ELASTICITIES

THE SELECTION OF THE EXPLANATORY VARIABLES

The estimation of demand elasticities for the group of energy sources used by Mozambican households was made in several runs, to test its sensitivity to the inclusion of demographic variables other than the eight initially selected as proxies for asset ownership (see Table 2 in the main text). The variables tested were the Size of the household (in Adult Equivalent Units), three characteristics of the Dwelling (namely whether its walls are made of concrete, the number of rooms and whether its drinking water is piped), and two characteristics of the Head of the household, namely its gender and its age. The results and its variability with reference to the estimations using only assets' ownership as explanatory demographic variables are presented in Table III.8.

Although the inclusion of size (AEU) as a demographic explanatory variable in the regression equation can give estimations of elasticity up to 7% smaller than the reference (for electricity), the scale difference is still not very big. The other demographic variables generated estimations up to 2% difference than the reference estimations. Because the introduction of these other demographic variables did not significantly change the results, the authors chose to keep the minimal number of demographics and use only the original eight explanatory variables.

Table III.8 - Own price elasticities per source: demographic effects

Price Elasticity	assets only	+ size (AEU)		+ dwelling char		+ gender/age	
Firewood	-0.3674	-0.3856	5%	-0.3686	0%	-0.3685	0%
Charcoal	-0.3721	-0.3781	2%	-0.3704	0%	-0.3731	0%
Kerosene	-0.6729	-0.654	-3%	-0.6629	-1%	-0.6689	-1%
Electricity	-0.5156	-0.4815	-7%	-0.5107	-1%	-0.5043	-2%
Aggregate	-0.9512	-0.9504	0%	-0.9591	1%	-0.9542	0%
Income elasticity	**assets only**	**+ size (AEU)**		**+ dwelling char**		**+ gender/age**	
Firewood	0.3772	0.3958	5%	0.3788	0%	0.3785	0%
Charcoal	0.4658	0.4782	3%	0.463	-1%	0.4675	0%
Kerosene	0.5371	0.5209	-3%	0.5286	-2%	0.5323	-1%
Electricity	0.5060	0.4724	-7%	0.5015	-1%	0.4948	-2%
Aggregate	-0.4977	-0.5623	13%	-0.5115	3%	-0.5027	1%

ELASTICITIES AT THE NATIONAL LEVEL *VERSUS* PER STRATA

COMPARISON WITH PRICE ELASTICITIES PER CAPITA

Deaton's method was also run for the sample in which the household expenditures were converted into per capita expenditures, through the AEU (Adult Equivalent Unit) conversion, seeking to obtain a more accurate result, see Table III.9.

There is a significant difference in own-price elasticities for the individual sources between those calculated for households and those calculated for on a "per capita" basis. It is difficult to determine whether the estimation per household or the estimation per AEU is more accurate, also because the records of household sizes (in AEU) may themselves be full of errors. However, the coefficients of determination for the regression calculation of 'per household' records are higher than those of the 'per AEU' records; consequently in this study 'per household' elasticities will be taken as the more accurate.

Table III.9 – Comparison of own-price and income elasticities

Own-price elasticities	All Households	All / Capita	Urban Households	Rural Households
Firewood	-0.3674	-0.8040	-0.4552	-0.2901
Charcoal	-0.3716	-0.5616	-0.3274	-0.5178
Candles	-0.6493	-0.8222	-0.6820	-0.7624
Kerosene	-0.6728	-0.7638	-0.6632	-0.7255
LPG	-0.9099	-0.9202	-0.8961	-
Electricity	-0.5143	-0.6085	-0.5108	-0.0715
Income elasticity	**All Households**	**All / Capita**	**Urban Households**	**Rural Households**
Firewood	0.3772	0.8189	0.4887	0.2897
Charcoal	0.4658	0.6641	0.3854	1.1336
Kerosene	0.5371	0.6673	0.4966	0.7473
Electricity	0.5060	0.5969	0.5020	1.8491

COMPARISON WITH PRICE ELASTICITIES PER URBAN AND RURAL STRATA

The study of the strata, 'only urban households' and 'only rural households', was also made and the results are shown in Table III.9. Urban households show elasticities aligned with the national figures, except for firewood that records an own price elasticity of -0.46 for urban only, versus -0.37 countrywide. Rural households however show lower own-price elasticity for firewood (-0.29) than the national figure, which can be explained with the proximity of the production sites and the prevalence of self-produced firewood. In contrary, charcoal, candles and kerosene show higher own price elasticities, respectively -0.52, -0.76 and -0.73, than their national figures, respectively -0.37, -0.65 and -0.67. The elasticities for LPG and electricity in rural households are suspicious, possibly because the sample is quite small (only 5 rural households consume LPG, and only 11 consume electricity, constituting respectively 0.12% and 0.25% of the sample). There are 128 households consuming candles and 57 consuming charcoal, in the rural areas, and the elasticities calculated for rural households are consequently unreliable for all sources with exception of firewood.

Income elasticities for urban households compare to the countrywide statistics (see Table III.9), though a bit lower for charcoal (+0.39 versus +0.47 countrywide) and a bit higher for firewood (+0.49 versus +0.38 countrywide), which is consistent with a greater dependency on charcoal than on firewood. In contrary, rural households show comparatively much higher income elasticity for charcoal and electricity consumption (+1.14 versus +0.47 and +1.85 versus +0.51 countrywide), a higher elasticity for kerosene (+0.75 versus +0.54 countrywide) and a lower for firewood (+0.29 versus 0.38 countrywide), again consistent with a greater dependency on firewood usage by the households.

ESTIMATION OF PRICE & INCOME ELASTICITIES FOR THE NORTHERN PROVINCES

By filtering records only from the Northern provinces of Mozambique (Niassa, Cabo Delgado, Nampula, Zambezia and Tete) and using the same estimation procedure for firewood, charcoal, kerosene and electricity[95], we obtained the regression results (see Table III.13 at the end) and the price elasticities shown in Table III.10.

Table III.10 –Price elasticities for the northern provinces

E_P - Deaton's own- and cross-price elasticities of energy consumption				
	Firewood	**Charcoal**	**Kerosene**	**Electricity**
Firewood	-0.2618	0.0001	-0.0004	-0.0002
Charcoal	-0.0002	-0.5062	-0.0019	0.0027
Kerosene	0	0	-0.6014	0.0001
Electricity	-0.0001	-0.0002	0.0005	-0.4250

The own-price elasticity for firewood demand is below the national figure at -0.26, for charcoal above the national figure at -0.51, for kerosene and electricity below, respectively

[95] As the records for candles and LPG are insufficient to represent accurately the demand for these sources

at -0.60 and -0.43. In words, northern households are less responsive to own-price variations for firewood, kerosene and electricity (though not by much for the last two), and more responsive for charcoal own-price variations, as compared to the national estimates. The cross-price elasticities are very small for all domestic sources.

Income elasticities for firewood are smaller, and for charcoal higher than their national counterparts (respectively +0.27 versus +0.38 and +0.74 versus +0.47 countrywide), consistent with rural households' behavior. However, the northern households register income elasticities that are lower than national figures for kerosene and electricity consumption (respectively +0.46 versus +0.54 and +0.39 versus +0.51 countrywide), possible an effect resulting from the urban areas in the north.

COEFFICIENTS OF REGRESSION FOR DEMOGRAPHIC VARIABLES IN THE NORTHERN PROVINCES

The coefficients of regression for the demographic variables in the budget-shares' equation indicate the effect of the ownership of each particular asset in the allocation of the household energy budget, regressors in the unit-values' equation indicate their effect on the price the household is willing to pay for the particular source. The comparison of the results for the northern provinces with the national results, see Table III.14 at the end, shows significant differences:

- The ownership of charcoal cooking assets only affects differently the north in that the households are willing to pay a higher price for consuming electricity (0.46 in the north, 0.08 nationwide). This makes sense if charcoal is considered an expensive source, to be consumed by wealthier households; this also explains the high income elasticity of charcoal consumption.

- The response of firewood budget-share to the presence of kerosene cooking facilities is actually positive (0.16), which only makes sense if cooking with kerosene actually represents a higher income and an increase in the expenditures with firewood. This possibility is supported by having the unit-values for firewood increase with the ownership kerosene's assets, namely 0.20 and 0.08 for cooking and lighting respectively. Firewood budget-shares and unit-values still reduce with the presence of assets for cooking with charcoal (-0.51 and -0.36) and with electricity (-0.05 and -0.10), indicating a measure of substitutability with these sources, and again placing charcoal at the side of the higher-grade sources such as electricity.
- Charcoal consumption show substitutability with cooking with kerosene and LPG (budget-shares reduce in the presence of assets for these sources, -0.02 and -0.04), however it increases in the presence of assets for lighting of any other source. The effects of demographics in the budget-shares and unit-values if charcoal consumption are more accentuated in the north. A noteworthy effect is that of reducing charcoals' unit-value (-0.51) when firewood is a main energy source (for lighting, and presumably for cooking, as all households in the sample cook); in words, households are willing to pay less for charcoal when they are poor (charcoal's budget-share is increased by 0.23) and consume firewood for lighting.
- The budget-share of kerosene will reduce when other sources are used for lighting (-0.18 for firewood, -0.23 for candles and -0.21 for electricity), however it will increase when cooking with other sources (0.02 with charcoal, 0.016 with LPG and 0.07 with electricity). Kerosene's unit-values are highly (negatively) responsive to cooking with electricity (-1.80) and to lighting with firewood (-0.21) and its own price (-0.21). When mainly consuming candles for lighting, the household is willing

to pay more for kerosene consumption. In the north kerosene's unit-values are not affected by the presence of assets for lighting with electricity.

- The budget-shares of electricity consumption will reduce in the presence of assets to cook and light with other sources, in much more accentuated effects in the north than nationwide. The presence of cooking and lighting electrical assets will increase the household's budget-shares of energy consumption. The willingness to pay for electricity consumption will only reduce in the presence of assets to light with kerosene and electricity itself, indicating substitutability with kerosene and small budgets (poverty) on the electricity consumers.

These effects need to be further investigated with surveys and more data on energy consumption.

THE ELASTICITIES OF DEMAND FOR AGGREGATED DOMESTIC ENERGY

THE ESTIMATION OF PRICE AND INCOME ELASTICITIES BY DIRECT REGRESSION

All energy sources coexist in the household in a mix here designated 'aggregated domestic energy', which will respond to income levels and to variations in prices of the individual sources.

Although directly regressing quantities consumed on unit-values is theoretically questionable by the argument that unit values are not true representations of the market prices, the authors applied this approach to estimate elasticities of the aggregated source, obtaining an own (aggregated) 'price' elasticity of -0.63 and an income elasticity of 0.15, with a coefficient of determination of 0.82. Published works indicate inflated price elasticity and deflated income elasticity for the aggregated source:

- Own-price elasticities for the aggregated energy were found to be -0.27 and -0.15 respectively by Dhal and McDonald (1998) and Abdel-Khalek (1988), in the short term, and -0.38 and -0.52 in the long term, below the estimated -0.63 by direct regression, respectively for developing countries and for Egyptian households.
- The income elasticity obtained by direct regression +0.15, is well below the estimations of Dahl and McDonald (1998), that calculated an aggregated income elasticity of 0.91/1.20 for developing countries, in the short and long terms respectively. However, these results are not far from Abdel-Khalek's (1988), who found the income elasticity for the aggregated energy consumption in the order of 0.26/0.88 for Egyptian households. Filippini and Pachauri (2004) calculated, for Indian households, the income elasticity of the aggregate consumption of domestic energy in the range of 0.60 to 0.64, again quite high.

In summary, 1% income increases will result in an increase of domestic energy consumption by 0.15%, and price increases for the various sources, mixed to generate 1% aggregated price increase, will result in an average decrease of consumption by 0.63%.

THE DERIVATION OF THE AGGREGATED DEMAND ELASTICITIES

The price elasticity for the aggregated domestic energy is determined by the nature of the energy mix, i.e. by the weights of the sources in the overall consumption of energy and by their individual own- and cross-price elasticities. What is the response of the aggregated demand to individual price variations? The total domestic consumption of energy is the sum of the individual consumptions of the sources in the mix $q = \sum_i q_i$ and the price elasticity of the aggregated consumption, when price of source *j* changes, is thus calculated as a weighted sum of the individual sources elasticities to price *j*:

$$\varepsilon_j = \left(\frac{\partial q}{\partial P_j}\right)\cdot\left(\frac{P_j}{q}\right) = \left(\frac{\partial}{\partial P_j}\sum_i q_i\right)\cdot\left(\frac{P_j}{q}\right) = \left(\sum_i \frac{\partial q_i}{\partial P_j}\right)\cdot\left(\frac{P_j}{q}\right) = \left(\sum_i \varepsilon_{ij}\cdot\frac{q_i}{P_j}\right)\cdot\left(\frac{P_j}{q}\right) \tag{7}$$

The price elasticity of aggregated demand: $\varepsilon_j = \sum_i \left(\varepsilon_{ij}\cdot\omega_i\right)$

where the weights are: $\omega_i = \frac{q_i}{q} = \frac{q_i}{\sum_i q_i}$

Although most of the households (72.4% of the total) record consumption in firewood, the equivalent energy constitutes a lower share (41.8% of the total) in the overall energy consumption in the sample. Rather than using the mean-weights, the source elasticities are calculated per household and then the means taken, only on the non-zero energy-consuming households, and then used with the calculated Deaton's price elasticities (see Table III.11) per source to obtain the price of the aggregated demand per source, whose mean values are (see Table III.12):

$$\left\{\varepsilon_j\right\} = \left\{-0.234 \quad -0.043 \quad -0.017 \quad -0.194 \quad -0.0004 \quad -0.036\right\} \tag{8}$$

These results indicate that the **aggregated demand** for domestic energy is very inelastic for prices of charcoal, candles, LPG and electricity, and shows small elasticities to firewood and kerosene prices, i.e. higher price elasticities of demand for those sources of higher weights in the household overall consumption.

If all the sources' prices are indexed to the electricity price such that:

$$P_j = \left(P_{elect}\right)^{\lambda_j} \quad \Rightarrow \quad \frac{\partial \ln P_j}{\partial \ln P_{elect}} = \frac{\partial P_j}{\partial P_{elect}}\cdot\frac{P_{elect}}{P_j} = \lambda_j \tag{9}$$

then the demand for (aggregated) domestic energy will respond to variations in the electricity price, i.e. to all sources prices, with an elasticity of

$$\varepsilon = \sum_j \varepsilon_j = \sum_j \sum_i \left(\varepsilon_{ij} \cdot \omega_i\right) = \sum_j \sum_i \left(\varepsilon_{elect-i} \cdot \frac{\omega_i}{\lambda_j}\right) = \sum_j \frac{\varepsilon_{elect}}{\lambda_j} \qquad (10)$$

Table III.11 – Price and income elasticities for individual sources

Price elasticities	Firewood	Charcoal	Candles	Kerosene	LPG	Electricity
Firewood	-0.3674	0	-0.0001	-0.0001	0	-0.0001
Charcoal	0.0003	-0.3721	-0.0004	-0.0007	-0.0004	-0.0004
Candles	0	0.0013	-0.6490	0.0031	0.0039	0.0006
Kerosene	0	0	-0.0002	-0.6729	0	0
LPG	0.0024	0.0121	0.0275	0.0240	-0.9117	0.0113
Electricity	-0.0002	-0.0001	0.0003	0.0005	0.0004	-0.5156

Table III.12 - Price elasticities for the aggregated energy demand

Calculated Price elasticities	Firewood	Charcoal	Candles	Kerosene	LPG	Electricity
Mean	**-0.2336**	**-0.0431**	**-0.0167**	**-0.1937**	**-0.0004**	**-0.036**
std dev	0.1504	0.0951	0.0726	0.1863	0.0612	0.1092
Media	-0.3103	0.0001	0.0008	-0.1346	0.0053	-0.0002

For an elasticity-of-price vector calculated from the mean unit values of purchasing households, respectively for firewood, charcoal, candles, kerosene, LPG and electricity, as follows

$$\{\lambda_j\} = \{\ 1.424 \quad 1.260 \quad 1.088 \quad 0.932 \quad 0.657 \quad 1\} \qquad (11)$$

The calculated price elasticity of the aggregated demand was -0.22, smaller though not too far from the (inflated) price elasticity of -0.63, estimated by direct regression.

Testing for an energy mix that contains 20% charcoal and firewood and electricity in 80% share, it is evident that the higher the share of a source in the mix, the higher the aggregated demand response to that source's price variation. The higher the proportion of electricity in the household, the higher the aggregated demand response to a price variation including the effects of price index λ in the other sources' prices, Figure III.8.

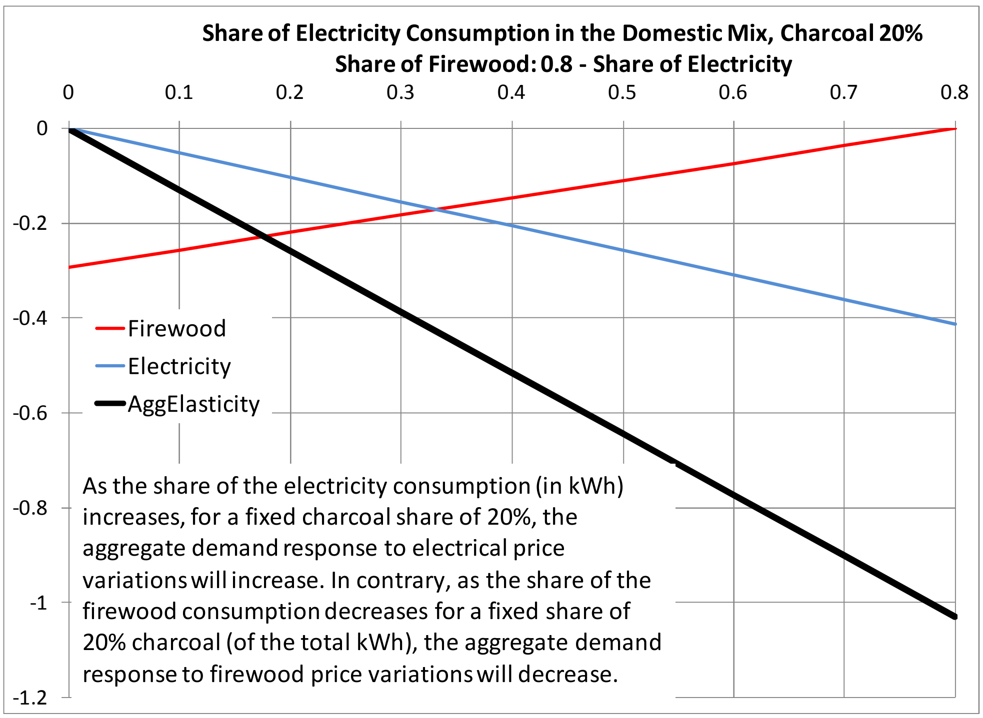

Figure III.8 –Elasticities for a varying share in the energy mix

HOW TO PAIR THE EMPIRICAL AND THE THEORETICAL MODEL

In the empirical model the own price elasticities of demand are

$$\varepsilon_{X_i}^{own} = \frac{\partial \ln X_i}{\partial \ln P_i} \quad \text{where} \quad X_i = E_i \cdot A_i \tag{12}$$

In the above equation X_i is the consumption of energy source "*i*", P_i is the price of the energy source, E_i is the (constant) average consumption of energy per dollar of capital investment in the appliance A_i that consumes energy source "*i*". The elasticity of investment in assets, consuming energy source "*i*", on its own price, is $\varepsilon_{A_i}^{own} = \dfrac{\partial \ln A_i}{\partial \ln P_i}$, which combined with the previous equation results in:

$$\varepsilon_{X_i}^{own} = \frac{\partial \ln (E_i \cdot A_i)}{\partial \ln P_i} = \frac{\partial \ln E_i + \partial \ln A_i}{\partial \ln P_i} = \frac{\partial \ln E_i}{\partial \ln A_i} \cdot \frac{\partial \ln A_i}{\partial \ln P_i} + \varepsilon_{A_i}^{own} = \left(1 + \frac{\partial \ln E_i}{\partial \ln A_i}\right) \cdot \varepsilon_{A_i}^{own}$$

$$\Rightarrow \qquad \varepsilon_{A_i}^{own} = \frac{\varepsilon_{X_i}^{own}}{1 + \dfrac{\partial \ln E_i}{\partial \ln A_i}} \tag{13}$$

The elasticity of the investment in energy consuming assets $\varepsilon_{A_i}^{own}$, for energy source "*i*", on its own price, depends on how the energy consumption (E_i) varies with the value invested capital (A_i) and how the energy consumption responds to its own-price variation $\varepsilon_{X_i}^{own}$:

$$\begin{array}{lll} \text{if} \quad E_i = \text{constant} & \Rightarrow & \varepsilon_{A_i}^{own} = \varepsilon_{X_i}^{own} \\ \text{if} \quad E_i = \dfrac{1}{A_i^{\alpha}} \quad \text{where} \quad \alpha > 0 & \Rightarrow & \varepsilon_{A_i}^{own} = \dfrac{\varepsilon_{X_i}^{own}}{1-\alpha} \end{array} \tag{14}$$

In words, if the energy consumption per unit capital cost of the appliances is constant, the price elasticity of the investment in assets for demand of source *i* coincides with the own price elasticity of the sources' demand. If on the other hand, the energy consumption per unit capital cost invested in appliance is a function of the appliances' capital cost itself *f(A)*, then the asset elasticity to price of source equals the product of the price elasticity of the source and a factor $\left(1 + \dfrac{\partial \ln E_i}{\partial \ln A_i}\right)^{-1}$. If the energy consumption of source *i* increases with each new unit of capital investment, then the assets' elasticity to price of source *i* will be smaller that the elasticity of demand, and vice versa.

In conclusion, the calculation of own-price elasticity of demand for the individual energy sources is necessary to calculate the own-price elasticity of investment in energy-consuming assets, for the respective energy sources.

Table III.13 - Regression results for the estimation on the energy sources – Northern provinces

	Sample Clusters – Mean				Sample Clusters - Std Deviation			
Dependents: **Budget-share (W) and Unit-value (V)**	**Firewood**	**Charcoal**	**Kerosene**	**Electricity**	**Firewood**	**Charcoal**	**Kerosene**	**Electricity**
W: energy expenditure per source divided by total energy expenditure	0.78	0.06	0.13	0.03	0.34	0.19	0.2266	0.1461
V: energy expenditure divided by kWh consumption per source (non-zero only)	8.51	7.46	5.88	5.38	0.88	1.31	1.8039	1.8924
Statistics of regression	**Firewood**	**Charcoal**	**Kerosene**	**Electricity**	**Firewood**	**Charcoal**	**Kerosene**	**Electricity**
R square	0.36	0.39	0.25	0.64	0.66	0.48	0.05	0.10
F-test	220.2	250.6	128.6	690.2	846.8	40.9	11.4	2.9
p value for F-test	0%	0%	0%	0%	0%	0%	0%	0%
error variance	0.03	0.01	0.02	0.00	0.05	0.22	0.72	1.12
	Regression coefficients for Budget share				**Regression coefficients for Budget share**			
Independents:	**Firewood**	**Charcoal**	**Kerosene**	**Electricity**	**Firewood**	**Charcoal**	**Kerosene**	**Electricity**
ln of Income variable:								
Total expenses in energy sources	0.04	0.03	-0.03	-0.003	0.77	0.71	0.30	0.52
Demographic variables (dummies):								
Main cooking source: charcoal	-0.51	0.46	0.02	0.02	-0.36	0.38	-0.19	0.46
Main cooking source: kerosene	0.16	-0.02	-0.05	-0.14	0.20	0.00	0.00	1.84
Main cooking source: LPG	-0.63	-0.04	0.016	-0.13	0.00	0.00	0.00	1.21
Main cooking source: electricity	-0.47	0.05	0.07	0.42	0.00	0.38	-1.80	0.38
Main lighting source: firewood and other	0.32	0.23	-0.18	-0.34	0.27	-0.51	-0.24	0.00
Main lighting source: candles	0.05	0.22	-0.23	-0.30	0.14	0.45	0.33	0.29
Main lighting source: kerosene	0.09	0.23	0.04	-0.34	0.08	0.41	0	-1
Main lighting source: electricity, etc	-0.05	0.12	-0.21	0.12	-0.10	0.20	0.00	-0.21

Table III.14 –The national versus the northern estimated elasticities and demographic regressors

Estimated elasticities of demand	Firewood		Charcoal		Kerosene		Electricity	
	Country	North	Country	North	Country	North	Country	North
Own-price elasticity	-0.37	-0.26	-0.37	-0.51	-0.67	-0.60	-0.52	-0.43
Income elasticity	0.38	0.27	0.47	0.74	0.54	0.46	0.51	0.39
Regressors for budget-shares equation	**Firewood**		**Charcoal**		**Kerosene**		**Electricity**	
	Country	North	Country	North	Country	North	Country	North
Main cooking source: charcoal	-0.50	-0.51	**0.45**	**0.46**	0.03	0.02	0.01	0.02
Main cooking source: kerosene	-0.54	0.16	0.03	-0.02	**0.53**	**-0.05**	-0.02	-0.14
Main cooking source: LPG	-0.49	-0.63	0.06	-0.04	0.005	0.016	0.07	-0.13
Main cooking source: electricity	-0.47	-0.47	0.08	0.05	-0.01	0.07	**0.40**	**0.42**
Main lighting source: firewood and other	**0.21**	**0.32**	0.10	0.23	-0.23	-0.18	-0.08	-0.34
Main lighting source: candles	0.00	0.05	0.09	0.22	-0.25	-0.23	-0.07	-0.30
Main lighting source: kerosene	0.00	0.09	0.10	0.23	**-0.01**	**0.04**	-0.08	-0.34
Main lighting source: electricity, solar/diesel generator	-0.11	-0.05	-0.001	0.12	-0.28	-0.21	**0.40**	**0.12**
Regressors for unit-values equation	**Firewood**		**Charcoal**		**Kerosene**		**Electricity**	
	Country	North	Country	North	Country	North	Country	North
Main cooking source: charcoal	-0.31	-0.36	**0.41**	**0.38**	-0.18	-0.19	0.08	0.46
Main cooking source: kerosene	-0.09	0.20	0.13	0.00	**0.08**	**0.00**	-0.31	1.84
Main cooking source: LPG	-0.50	0.00	-0.22	0.00	0.287	0.000	-0.09	1.21
Main cooking source: electricity	-0.67	0.00	0.17	0.38	-0.54	-1.80	**0.11**	**0.38**
Main lighting source: firewood and other	**0.10**	**0.27**	0.02	-0.51	0.06	-0.24	3.85	0.00
Main lighting source: candles	-0.081	0.14	0.19	0.45	0.51	0.33	0.22	0.29
Main lighting source: kerosene	-0.053	0.08	0.20	0.41	**0.05**	**-0.21**	-1.68	-1.04
Main lighting source: electricity, solar/diesel generator	-0.25	-0.10	0.004	0.20	-0.27	0.00	**-0.13**	**-0.21**

CHAPTER IV: THE ADOPTION OF ELECTRICITY AS A DOMESTIC SOURCE BY MOZAMBICAN HOUSEHOLDS

ABSTRACT[96]

In Mozambique, domestic energy is often composed of a mix of sources primarily to satisfy needs for lighting and cooking, with biomass and kerosene being the more common sources of the poor. Electrification programs intended to expand the electrical networks and to connect new consumers countrywide, have not significantly contributed neither to the intensification of electricity consumption nor to the reduction of the use of biomass in the domestic settings. The choice of energy sources often depends on their prices and on the capability of the household to invest in energy-consuming appliances, required to consume those sources. Based on data from a household survey carried out in Mozambique during 2002/3, this paper analyses the geographic differences in unit expenditures for domestic energy and finds evidence of an inverted energy ladder by price of useful energy units. The data shows that often biomass sources are more expensive per unit of useful energy than higher-grade sources, which supports the argument favoring electrification as a poverty alleviation strategy. In addition, this study estimates the likelihood of poor households transitioning from biomass to electricity consumption based on various factors. Results indicate that income is not a determining factor in the transition, but wealth and the level of

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the Primary Energy Consumption Share (PECS) are as important factors as the nature of the energy mix.

Keywords: Mozambique, likelihoods in electricity consumption, domestic-energy-ladder

INTRODUCTION

Mozambican households rely mostly on firewood and charcoal as sources of domestic energy (Brouwer and Falcao 2004). Although the national public electricity company (EdM) has invested heavily in electrification programs in the past 30 years[97], the connection rate was only at 8.2% of the population in 2006, and the average monthly domestic consumption at the level of 89 kWh/month per household (EDM 2007), about a third of the current US domestic energy consumption (EIA 2001). The expansion of electrical grids supports future economic and social development, see analysis by Mulder and Tembe (2006), and remains a priority in the company's agenda. However, the low connection and consumption rates of domestic energy raises doubts on the validity of accelerated electrification as a poverty alleviation strategy targeting households and rural communities.

Although the number of connected households in the country has grown at an average rate of 15% per year between 2000 and 2007, connection rates, discounting for population changes, have only increased by 5.4% of the population. It is obvious that increased access, by extension of the electrical networks, is insufficient to transition households from lower grade energy sources such as biomass and kerosene to electricity.

Typically, the price of electricity also constrains its adoption by poor families. For this reason and in the spirit of equal opportunity, the Mozambican Electricity Law (Mozambique 1977) establishes that:

[97] In the US, government also intervened to expand residential electricity in the late 40s-50s (Morton 2002)

a) The electricity rates at the low-voltage distribution level (retail distribution) cannot be geographically differentiated, i.e. electricity prices are the same whether the consumer lives in a northern province (farthest from electrical generating sources) or in the south;

b) There must be a fixed rate called a "social tariff" that is significantly lower than the average rate for domestic consumers, applicable to all households consuming up to 100 kWh per month.

The retail rates of electricity increased by 18% between 2005 and 2007, however the social tariff, specially designed to favor low-income households was kept at the level of 0.14 $PPP/kWh[98]. This (subsidized) rate is much lower than market prices for charcoal recorded at 0.17 $PPP/kWh in 1997 (Falcão 1999), and for kerosene and LPG (Liquefied Petroleum Gas), recorded both at 0.59 $PPP/kWh[99] in 2006 (Mozambique 2007). Less than 1% of the domestic consumers take advantage of the social tariff rate (EDM 2005).

When planning for domestic electricity, three important issues must be resolved to increase the number of electrical consumers and to intensify the electricity consumption per household:

a) Access: the extension of medium and low voltage networks in rural and urbanized areas must continue, so that the grid may reach a larger number of the population;

b) Capital investment: the cost (investment) in an electrical connection to the grid and in electricity consuming appliances must be within reach of potential new electricity consumers;

[98] Conversion rates published by the United Nations (2007)

[99] Cockburn and Low (2005) place domestic kerosene costs at 0.40 $/kWh versus electricity costs at 0.07 $/kWh, though not converted to $PPP.

c) Affordability: the electricity price must be competitive with other sources and affordable by consumers.

The assumption is that households will consume electricity if they may, i.e. electricity is a preferred source when no budget or capital availability constrains the choice of the domestic source[100]. This assumption corresponds to the principle of an energy ladder, which establishes that as a household increases its income it will transition from cheap, low-efficiency biomass sources to more costly, more efficient and more wide-ranging-in-use sources such as kerosene and electricity.

The energy ladder, first postulated by Hosier and Dowd (1987), is a criterion for ranking preferences for domestic energy sources based on the households' incomes, with biomass sources at the bottom and electricity at the top. Conventionally, the energy ladder places the cheapest sources at the bottom (preferred by the low-income families) and the more expensive at the top, also called 'modern fuels' (Kebede, Bekele et al. 2002; Howells, Alfstad et al. 2005) in recognition of their superiority in convenience, cleanness, safety (Masera, Saatkamp et al. 2000) and on the variety of end-uses.

Although electricity is required for economic, technological and social development, it is still a rare commodity for the majority of the African population (Wolde-Rufael 2006). Urbanization is a major factor in electrification (Karekezi and Majoro 2002) as houses are more compact and closer to services and industries. In fact, a secondary benefit of electrification for profit (industry, commercial and services enterprises, public or private) is a lower grid investment per domestic connection.

[100] Previous research indicates that investment in energy appliances and electricity prices are limiting factors in the transition from low-grade sources to electricity by households (Hosier and Dowd 1987; Reddy 1995; Masera, Saatkamp et al. 2000; Tewari and Shah 2003).

Evidence shows that in developing countries higher-income families retain some level of consumption of biomass fuels, even when combined with electricity consumption (Campbell, Vermeulen et al. 2003; Brouwer and Falcao 2004). The energy transition is not a progressive adoption of higher-grade and more expensive fuels, but rather a combination of fuels from the lower and the top levels of the ladder. Biomass is still the preferred energy source for cooking (Madubansi and Shackleton 2007) even if lighting is obtained from candles, batteries, kerosene[101] or electricity (Davis 1998; Howells, Alfstad et al. 2005). The energy ladder concept, in its initial formulation, does not account for the mix of sources in both extremes of price and efficiency ranges: for example, why do wealthy consumers maintain charcoal as a cooking source?

Hughes-Cromwick (1985) has surveyed the reasons behind the selection of primary fuel in Kenya. The survey indicates that economics is the most important decision factor for poor households, while factors such as convenience and availability play an important role in wealthier households. Similarly, Gupta and Kohlin (2006) ranked sources for cooking activities based on price, availability, ease of use, capital cost of appliance (oven) and pollution level, and asked the households to rank the cooking sources based on these criteria. Not surprisingly, most of the households ranked electricity as the most expensive and the cleanest, while fuelwood was classified as the dirtiest and the cheapest source. Green and Erskine (1999) on the other hand surveyed the inconvenience ranking for several sources measured by the time taken or the distance travelled to secure a specific source. Surprisingly, households perceive fuelwood as inconvenient as energy from a petrol generator, a gas generator or from a car battery. Green's results indicate that sources not

[101] Transitional sources such as candles and kerosene are mostly used for lighting (Brouwer and Falcao 2004; Gupta and Kohlin 2006), while the household still maintains biomass as a cooking source. However, some urban communities use kerosene or LPG, rather than firewood, for cooking (Anozie, Bakare et al. 2007; Troncoso, Castillo et al. 2007), so transitional sources may be different for different geographical locations.

readily available at the household location are undesirable, no matter their relative position in the energy ladder. The household values the time required in securing the source more than any classification of grade in a ladder that has no practical meaning in itself, but rather satisfies the researchers need to categorize and isolate causes and effects.

Although there are differences among communities, the factors that determine the choice of fuel for domestic use and the intensity of consumption are very similar, and poverty is the major determinant of household preferences. For example, in Maputo, the majority of the (sampled) population burns charcoal for cooking and firewood is in a descending trend (Brouwer and Falcao 2004), as opposed to Ouagadougou, where firewood is the most common source (Ouedraogo 2006). The household size and educational levels are, in both cases, significant in the choice of fuel for cooking. Some authors (Reddy 1995; Masera, Saatkamp et al. 2000; Brouwer and Falcao 2004) recur to taste (palate) and tradition to explain behaviors that are discordant with the energy ladder expectation. However, notwithstanding the uniqueness of the individual's preferences in choice, self-interest pushes the household to progressively adopt the higher-grade sources[102]. Thus, new energy sources will be adopted if the households can access and afford them, if they are adequately informed of the benefits and gains from this adoption, and if the opportunity costs of the energy transition are not too high.

Factors such as the cost of the appliances for the specific energy source (Reddy 1995), and the compatibility of the cost schedules (tariffs) with the household earnings (income) have shown strong correlations with household choices of fuel (Masera, Saatkamp et al. 2000). The affordability of energy consuming appliances can accelerate household adoption of electricity (Karekezi and Majoro 2002; Pachauri, Mueller et al. 2004). Note that a wealthy

[102] Jenkins and Scott (2007) show that were self interest is served, together with accessibility and affordability of the technology, it is adopted by the household.

status, or simply the ability to invest after paying for the consumption costs, is necessary for the acquisition of energy-consuming appliances. So far, no quantitative assessment has been made to demonstrate that wealth is a determinant factor in adopting electricity as a domestic source. The ownership of appliances as a necessary condition to adopt higher-grade source (Elkan 1988; Reddy 1995; Tyler 1996; Gupta and Ravindranath 1997; Tiwari 2000) is been suggested, with not quantification of possible effects.

This study investigated energy consuming behaviors, recorded in a household survey from 2002/3 collected by the National Statistics Institute in the whole of the Mozambican territory (INE 2007). The goal is to clarify factors that determine choice in the household energy consuming behaviors and what may determine the adoption of electricity as a domestic source. A brief description of the dataset and the transformations made on the data, and a discussion of the districts' characteristics of energy consumption, can be found in the appendix, available by request to the corresponding author.

This work has two specific objectives:

1) To present the current unit expenditures on energy sources in Mozambique and analyze the relative position of charcoal, kerosene and electricity in the Mozambican domestic energy ladder, by price-per-unit-of-useful-energy.

2) To investigate and quantify the likelihood of transitioning from biomass to higher-grade sources such as kerosene and electricity as a function of income levels, wealth ownership and the level of Primary Energy Consumption Share[103] (PECS).

This paper is organized in the following manner: firstly, we analyze the recorded energy consumption per district and discuss how the domestic energy ladder for Mozambique is

[103] This quantity is calculated by dividing the amount of kWh-equivalent consumed of the primary source, over the total kWh-equivalent consumed in the household, during the same period.

inverted in terms of price-per-unit-of-useful-energy. Secondly, we calculate the likelihood of adopting electricity as a domestic source and discuss the results and their implications for policy strategies. Finally, we summarize the findings and discuss some policy implications.

STUDY AREA

Mozambique, located in the southeast Africa at the coordinates 18:15 South and 35:00 East, with an extension of 799.38 km^2, has a population of 20.4 million people of which 51% are women (INE 2007). Although a country of many resources, in agriculture, mining and energy, and with an economic growth rate of 6.2% in 2005, Mozambique still ranks 172 in the Human Development Index, with a GDP of only 1242 $PPP/capita in 2005[104].

The northern part of the country is more densely populated than the south. The north is also where major agricultural, forestry and mining resources exist. In general the south is more developed (better infrastructure and more industry and services) than the north, and has a better-trained workforce because of the traditional migration to South Africa[105]. The population is concentrated mostly in the coast, along which the main national (EN1) road runs. The Maputo province is a route of transport (between the continent and the Maputo seaport), trade, tourism and migration to and from South Africa, and constitutes one of the main development corridors, named 'Maputo Corridor'. The center of the country is on;ly about 100 km wide from East to West, and it constitutes the 'Beira Corridor', with a system of roads (EN6) and railway lines that links the Zimbabwean hinterland with the Beira seaport. Along the Beira corridor there is an oil pipeline to transfer oil into Zimbabwe, there is also a relatively well-developed electrical distribution system (previously known as

[104] Source: UNDP, Human Development Report 2007/2008 at:
http://hdrstats.undp.org/indicators/5.html

[105] The high concentration in the south of families whose head is a woman is a consequence of the migration to work the South African gold mines.

SHER) and several communities that provide services and trade in this route. In the north, we find the 'Nacala Corridor', also a system of roads and rail tracks connecting Malawi and Zambia to the Nacala seaport. In these development corridors, urbanization and higher standards of living are generally observed[106].

In the spirit of the energy ladder concept, the development corridors should record higher energy consumption levels and the use of higher-grade sources (electricity for example) in the domestic settings[107].

THE DOMESTIC ENERGY LADDER: PRICE-INVERTED?

Figure IV.9 shows the households recorded as consumers of kerosene, charcoal and electricity, and those classified as urban. Kerosene consumers, though more widespread than other high-grade source consumers, are clearly present in the development corridors. Households consuming charcoal and electricity visibly correlate with urban status.

Records for electricity, kerosene and charcoal consumption in the districts of the development corridors[108] overlap records of higher energy consumption and higher income levels, indicating that high-grade sources are the preferred by high-income families. The choice of energy source for consumption in the domestic setting aligns with the traditional (expected) order of the energy ladder: firewood, charcoal, kerosene and electricity.

[106] The revitalization of transport networks has the secondary effect of cheapening the trade of agricultural goods and the provision of services (Simler, Mukherjee et al. 2004). See Tarp, Arndt et al. (2002) for an historic overview of the political and economic policies in Mozambique.

[107] Simler, Mukherjee et al. (2004) studied the determinants of poverty in terms of food consumption and nutrition. They calculated lifelines of consumption per household and demonstrated that rural households have significantly lower lifeline consumption levels, particularly on the non-food items (transport, energy, education, health, clothes and other perishable items such as soap).

[108] Electricity shows significant consumption levels along the development corridors of Maputo and Beira. Electricity expenditures are the highest in the south and some coastal northern districts, where it constitutes an alternative source also for poor families. Higher electricity consumption corresponds to higher electricity expenditures, as the price is geographically uniform and only varies by consumption levels. As the consumption increases, the expenditure of the household per electric kWh will increase, pulling electricity up the energy ladder of domestic sources.

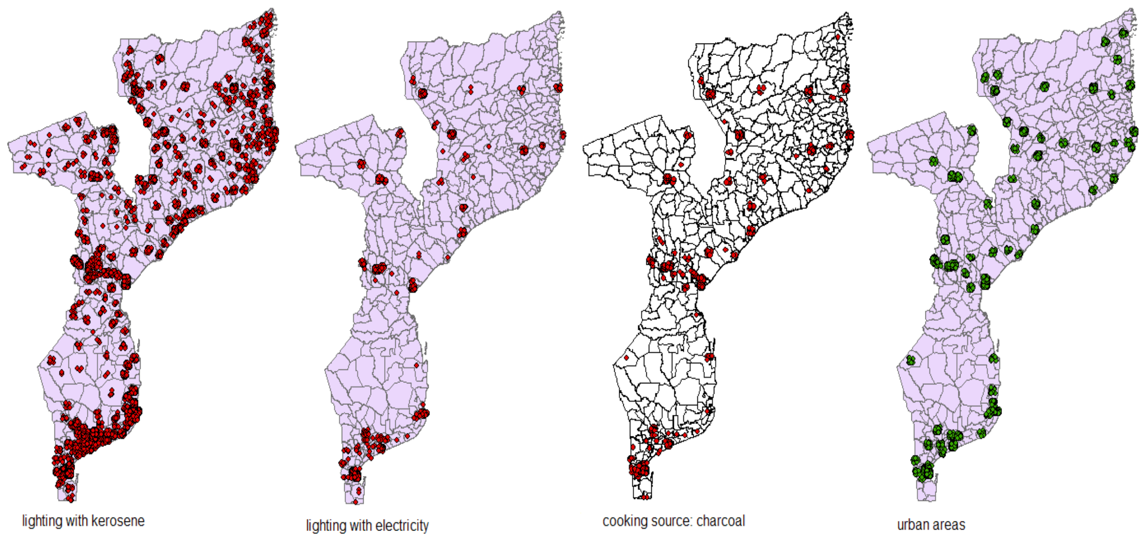

Figure IV.9 – Urbanization and development corridors correlate with higher-grade sources

However, the unit values (prices, recorded per district) do not follow the same pattern as the consumption[109]. The unit values of firewood are higher on the western districts. Charcoal and kerosene's unit values are higher in the central and northern districts. In other words, firewood, charcoal and kerosene unit values seem to be higher in the districts with lower income households and lower in the districts of higher development levels (where retail markets are better developed). So are poor households consuming energy (for their domestic needs) at higher prices than high-income households are? An analysis of the unit values of the total domestic energy consumption (including all sources) shows that households in the poorer districts are spending more per unit of useful energy (Figure IV.10) than those in wealthier districts. If the poor households are willing to pay such high prices for the consumption of biomass energy, they certainly would adopt a cheaper source if they could recognize the gains in this adoption (assuming rational behavior).

[109] The unit values are calculated by dividing the household's expenditure (per source or aggregated for all sources) per day by the equivalent kWh of useful energy consumed, using conversion factors first published by the World Bank (1987), see appendix for more details on the data transformations.

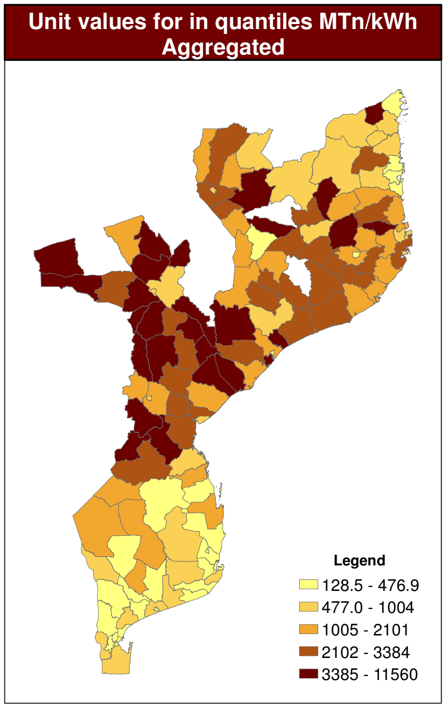

Figure IV.10 – Energy unit values

Countrywide, from the district recorded totals, domestic energy (aggregated) records a mean of 0.41 $PPP/kWh and a standard deviation (SD) of 0.44 $PPP/kWh. This high price is a result of the prevalence of firewood consumption with a unit value of 1.29 $PPP/kWh, SD of 0.69 $PPP/kWh. Higher energy sources show lower prices because of their higher efficiency, respectively 0.30 $PPP/kWh (SD = 0.60 $PPP/kWh) for charcoal, 0.13 $PPP/kWh (SD = 0.23 $PPP/kWh) for kerosene and 0.12 $PPP/kWh (SD = 0.40 $PPP/kWh) for electricity.

The unit values of the individual sources consistently show that firewood is more expensive and electricity less, Figure IV.11. Unit values of electricity consumption do not reflect geographic variation because by law (Mozambique 1977) electricity prices are the same throughout Mozambique. Rather, the unit prices variation between districts show some districts have a larger number of big domestic consumers (high unit-values) than others.

Based on these results, the ordering of sources by their energy price would be first electricity, followed by kerosene, charcoal and firewood. This is an *inverted energy ladder* where the prices are calculated per useful energy unit, i.e. the energy ladder for Mozambican households per price-of-useful-energy-units has the following order: electricity, kerosene, charcoal and firewood (see Figure IV.11).

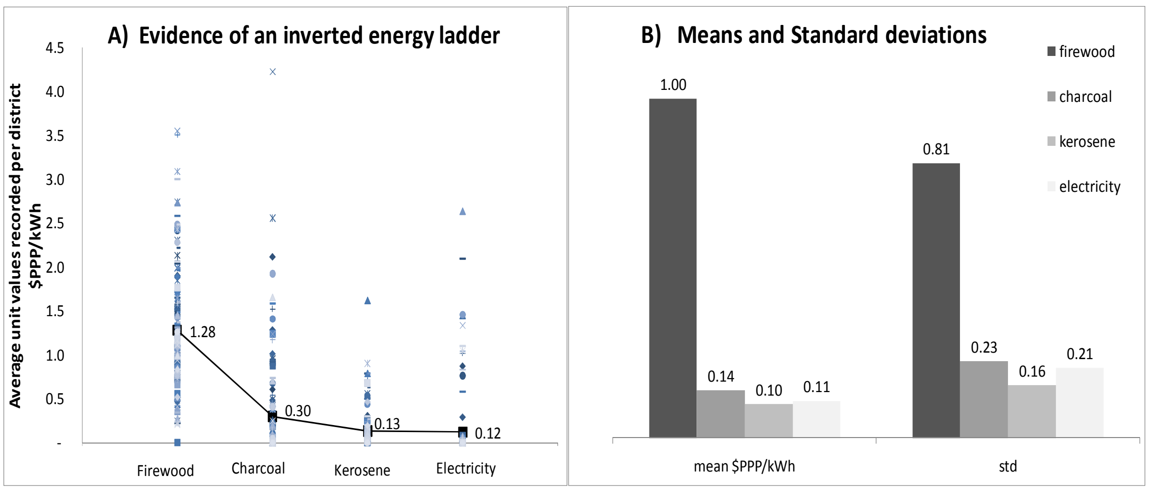

Figure IV.11 – Unit values of domestic sources, a) across districts and b) across the households

The puzzle is then why does the consumption pattern follow the traditional order of the energy ladder when the sources' prices indicate an inverted order? Electricity is cheaper than biomass and in the same price order as kerosene. It is also a more diverse, cleaner and safer source. Why is it then not the choice of the poorer families?

The evidence of an energy ladder inverted by price of useful energy units is strong and encouraging from a policy standpoint, in that the poor need not to be deprived of more efficient, more convenient, more diverse and even cleaner domestic sources. The next section analyses the factors determining the likelihood of Mozambican households adopting electricity as a main domestic energy source.

EXPLANATORY AND RESPONSE VARIABLES

Electricity has cheaper prices than other sources; nevertheless, it remains a source preferred by high-income families. This seemingly irrational behavior may have several possible causes:

1. inadequate access (the grid not reaching poor communities)

2. high capital costs (consumers not having the funds to acquire the electrical connection and the electrical appliances that will allow them to consume electricity)

3. misinformation (consumers not knowing how to use electricity and the cheaper options they have to make it competitive with other sources)

4. mismatched payment schedules (poor consumers living on a day-to-day earnings and unable to accumulate to pay a monthly electricity bill all at once). This problem was addressed with the use of prepaid meters (Credelec) and of load-limiting devices (Quadrolec), increasingly the preferred option even for urban consumers[110].

One reason for poor families not adopting electricity as a main source may be that the electrical networks do not extend to all villages and all districts of Mozambique. Consequently, the evaluation of household choices of domestic source needs to take into account the accessibility of electricity. Other sources use the transportation routes and retail marketers that reach wherever there is demand for the product, so their consumption is not constrained by access. The link between electricity consumption and urban status

[110] Mozambique adopted pre-paid metering after the success of their use in the domestic market of South Africa (Tewari and Shah 2003). In 2004, 26247 connections of new clients in Credelec were connected, against only 5197 new clients with conventional meters. In 2005, 43530 new clients in Credelec were connected, against only 5609 new clients with conventional meters (EDM 2007).

(Figure IV.9) allows using the location of the households (urban or rural) as an indicator of accessibility of electrical supplies.

A second reason relates to the lack of funds to invest in an electrical connection and appliances. In the absence of a rigorous survey of the households' wealth, the study will use the characteristics of the household dwelling as indicators of wealth, namely: whether the dwelling is self-owned, whether it has concrete walls or not, the number of rooms in the dwelling and finally, whether the water for drinking consumed by the household is obtained from a piped system or not. These variables are binary, with exception of the 'number of rooms'.

A third reason may include the unfamiliarity with electricity as a domestic source and the ignorance that it is cheaper per useful unit than other sources. Also, a mismatch between the schedule of earnings and the schedule of electricity costs could influence the preference for a particular energy source. To represent the income and the cultural effects, two variables are used: the recorded daily income per household and the Primary Energy Consumption Share (PECS), the later constructed for this study only.

The PECS variable intends to represent the effect of households being heavily anchored in a predominant domestic source, and as such possibly resisting transition to a new (unknown) source. This variable was calculated by dividing the maximum consumption in any one source (in units of useful kWh/day per household) by the total energy consumption (in units of useful kWh/day per household). Data show that PECS is negatively correlated with electricity consumption.

The following section reports the quantitative evaluation of the likelihood that a household consumes electricity as a function of income, PECS and wealth indicators.

In the sample of 8,377 households that recorded energy consumption, some declare expenses in \$PPP or consumption in kWh of electricity, and some declare electricity to be their main lighting or cooking source. These households are assumed to be consumers of electricity and are given the value 1 for variable 'ElectricYes'. Those that do not record any expense or consumption of electricity, nor declare it to be their main source of cooking or lighting are assumed to be not consumers of electricity and are given the value 0 for variable 'ElectricYes'. Variables 'KeroseneYes' and 'CharcoalYes' are similarly constructed.

The logistic regression is run twice for the response variables 'ElectricYes', 'KeroseneYes' and 'CharcoalYes' and the explanatory variables listed in Table IV.15.

Table IV.15 – Explanatory variables used in logistic regression

Explanatory Variables	Type	Description
Intersect	= 1	To account for a constant effect
Income	Double	The households' daily income \$PPP/day-HH
Urban	Binary	Location: Urban (1) or rural (0)
Self-owned	Binary	Dwelling: Self-owned (1) or rented/borrowed (0)
Concrete walls	Binary	Dwelling: with Concrete walls (1) or otherwise (0)
No of rooms	Double	The number of rooms in the dwelling
Drinking water	Binary	Drinking Water: from a piped system (1) or not (0)
PECS	Double	The % share of kWh on the total consumption, of the predominant domestic energy source

THE FIRST RUN OF A LOGISTIC REGRESSION

The maximum likelihood of being an electricity consumer is estimated using a logistic regression (function *glmfit* of MATLAB in 'binomial mode'[111]) of the variable 'ElectricYes' versus the explanatory variables of income, wealth and PECS. Equation (15) gives the logistic function for the odds of a household being an electric consumer:

[111] The functions used are part of the standard library of MATLAB, http://www.mathworks.com/

$$Odds_{ElectrciConsumer} = \frac{p_{ElectricYes}}{1-p_{ElectricYes}} = e^{\alpha_0+\alpha_I \cdot Income+\alpha_3 \cdot V_3+\alpha_4 \cdot V_4+\alpha_5 \cdot V_5+\alpha_6 \cdot V_6+\alpha_7 \cdot V_7+\alpha_E \cdot PECS} \quad (15)$$

where I is *Income*, V_3 defines the *Urban Status*, V_4 equals one when the *Dweling is SelfOwned*, V_5 indicates the presence of *Concrete Walls*, V_6 is the *Number of Rooms* in the dwelling, V_7 indicates if *Drinking Water* is from a *Piped source* and E stands for *PECS*. The probability of the household adopting electricity as a domestic source is therefore:

$$p_{ElectricYes} = \frac{1}{1+e^{-(\alpha_0+\alpha_I \cdot Income+\alpha_3 \cdot V_3+\alpha_4 \cdot V_4+\alpha_5 \cdot V_5+\alpha_6 \cdot V_6+\alpha_7 \cdot V_7+\alpha_E \cdot PECS)}} \quad (16)$$

The same procedure is applied to the variable 'KeroseneYes' to estimate the maximum likelihood of a household adopting kerosene as an energy source, and to the variable 'CharcoalYes' to estimate the maximum likelihood of a household adopting charcoal as an energy source.

Table IV.16 – Coefficients and odds on being a 'source' consumer

Explanatory	Charcoal		Kerosene		Electricity	
Variables	Coefficient α	Odds	Coefficient α	Odds	Coefficient α	Odds
Intersect	-2.77	0.06	-0.13	0.88	-5.39	0.00
Income	0.000	1.0003	-0.003	0.998	0.011	1.011
Urban	2.85	17.23	1.07	2.92	2.80	16.44
Self-owned	-0.67	0.51	0.08	1.09	0.16	1.17
Concrete walls	1.13	3.11	-0.34	0.71	1.69	5.40
No of rooms	0.00	1.0000	0.00	1.0000	0.00	1.0000
Drinking water	-0.04	0.96	-1.76	0.17	2.23	9.28
PECS	-0.05	0.95	0.23	1.25	-0.50	0.61

The results, shown in Table IV.16, indicate that:

- Income levels have a small effect on the choice of energy source, being slightly positive for charcoal (1.0003) and electricity (1.011) consumption and slightly negative for kerosene (0.998). This result is not surprising as the energy consumption in the sampled households is small and mostly at its lower limits (even poor households need some energy for cooking and lighting).
- Urban households are 16 times more likely to adopt electricity, 17 times more likely to adopt charcoal and 2.9 more likely to adopt kerosene as domestic sources than rural. This confirms that urbanization is an important drive in the transition to more efficient, higher-grade energy sources.
- Interestingly, households living in self-owned dwellings are 0.51 times less likely to adopt charcoal and 1.1 than those living in rented or borrowed dwellings, but 1.2 times more likely to adopt kerosene and electricity as domestic sources, respectively. The majority of self-owning-dwellers (7458 households) are rural (57%), while only 43% are urban. An analysis of the subsamples of only rural and only urban households indicate that rural households are 1.27 times more likely to adopt electricity when they have self-owned dwellings, while in urban settings households are 0.9 times less likely to adopt electricity if they live in self-owned dwellings. This difference may be a result of the self-owned dwellers constituting the wealthier in rural areas, but being the poorest (living in suburbs) in urban areas. In addition, the proximity to firewood sources in rural settings may be the discouraging factor for the adoption of charcoal as a domestic source.
- Households living in dwellings with concrete walls are 5.4 times more likely to adopt electricity, 3.1 times more likely to adopt charcoal and 0.7 times less likely to adopt kerosene as domestic sources. Assuming that having concrete walls in the

dwelling is an expression of wealth, then wealthy households will favor electricity and reject kerosene (out of 2000 recorded households living in dwellings with concrete walls, 87% are urban). In rural settings, concrete walls are more rare. Consequently, having concrete walls in rural areas increases the odds of adopting electricity as a domestic source by 35 times, while in urban areas only by 4.1 times.

- The number of rooms does not seem to have an effect in determining the likelihood of adopting electricity, kerosene or charcoal as domestic sources. However, in urban areas the odds of consuming electricity are increased by 1.4 times with each new room, i.e. larger houses (wealthier) will be more likely to adopt electricity as a domestic source than smaller houses.
- Households with piped drinking water are 9.3 times more likely to consume electricity. However, these households are respectively 0.96 and 0.17 times less likely to consume charcoal and kerosene as domestic sources. Urban households (98.6% of 794 households that have piped drinking water) have their odds increased only by 8.6 times while rural households have their odds increased by 15.2 times (almost doubled).
- Finally, each percentage point of PECS will decrease the consumption of electricity by a factor of 0.61, and only lightly affects the consumption of kerosene (1.3 times more likely) and of charcoal (0.95 times less likely). This result indicates that households will transition to electricity more easily if starting at a lower PECS, i.e. if there are not one but several equally predominant energy sources in the energy mix. On contrary, households with one predominant source will more easily transition to kerosene than those with a more even mix. Rural households have a larger decrease in the odds of consuming electricity, by a factor of 0.44, while urban households are within the national average (0.61).

These results indicate unmistakably that urbanization and infrastructure (drinking water from piped sources) increase the odds of adopting electricity as a domestic source, i.e. infrastructure programs and urbanization favor the adoption higher-grade sources. The results also show that even in urban areas, if the dwelling does not have concrete walls and piped water, the probability of being an electricity consumer drastically reduces to less than 10%.

Comparing probabilities of being a user of a particular source for the cases of being wealthy (the dwelling has concrete walls and piped water) with an income of 2 $PPP/day, a self-owned dwelling with three rooms and an PECS varying between 5% and 100%, we obtain the following outputs at less than 1% standard deviation:

- For wealthy households: 62% probability of being a charcoal user in an urban setting and 9% in a rural setting. For non-wealthy households: 35% probability of being a charcoal user in an urban setting and 3% in a rural setting. Charcoal is therefore an urban source, preferred by wealthier households.

- For wealthy households: 28% probability of being a kerosene user in an urban setting and 12% in a rural setting. For non-wealthy households: 76% probability of being a kerosene user in an urban setting and 52% in a rural setting. Conclusion: kerosene is an urban source, preferred by the poorer.

- For wealthy households: 70% probability of being a electricity user in an urban setting (3% standard deviation) and 53% in a rural setting (5% standard deviation). For non-wealthy households: 6% probability of being a electricity user in an urban setting and 3% in a rural setting. Conclusion: electricity is an urban source, preferred by the wealthier.

Charcoal is confirmed to be above kerosene in the energy ladder, in terms of price and access, although kerosene is of higher efficiency and of more complex production process. Electricity, shown to be cheaper in useful energy units, is still preferred by the wealthier who can afford the acquisition of electric appliances. This study indicates clearly that the wealth of a household is a determining factor in the choice of domestic source.

THE SECOND RUN OF A LOGISTIC REGRESSION

In the above result the higher the PECS level, the lower the odds of being an electricity consumer, which would point to the incentive to a better domestic energy mix as a means to promote the adoption of electricity by the poorer families. To clarify this effect of the energy mix, the logistic regression was run to estimate the likelihood of being an electricity consumer, including the CharcoalYes and KeroseneYes variables to the above explanatory variables, namely:

$$\frac{p_{ElectricYes}}{1-p_{ElectricYes}} = e^{\alpha_0+\alpha_C \cdot CharcoalYes+\alpha_K \cdot KeroseneYes+\alpha_I \cdot Income+\alpha_3 \cdot V_3+\alpha_4 \cdot V_4+\alpha_5 \cdot V_5+\alpha_6 \cdot V_6+\alpha_7 \cdot V_7+\alpha_E \cdot PECS} \tag{17}$$

The results shown in Table IV.17 indicate that being a charcoal consumer reduce the odds of using electricity to 0.68 and being a kerosene user reduces the odds of using electricity to almost zero (0.02). A wealthy 100% charcoal user, with income of 2 $PPP/day in an urban environment has 92% probability of becoming an electricity user, but a 100% kerosene user in the same settings will have only 24% of probability of becoming an electricity user. Moving to a rural setting, the charcoal wealthy user will only have the probability of 19% of transitioning to electricity, while the wealthy kerosene user will have only a 1% probability. Non-wealthy households in urban environments that are 100% charcoal users, have a probability of adopting electricity of only 21%. On the other hand, 100% kerosene users with no wealth, living in urban and rural environments, have a 1% or less probability of becoming electricity users.

Table IV.17 - Logistic regression: coefficients and odds on being an electric consumer

Variables	Electricity	Odds
Intersect	-5.38	0.46%
Consumer of Charcoal?	-0.39	0.68
Consumer of Kerosene?	-4.03	0.02
Income	0.01	1.007
Urban	3.913	50.0
Self-owned	0.03	1.03
Concrete walls	1.61	5.0
No of rooms	0.34	1.4
Drinking water	2.22	9.2
PECS	-0.55	0.58

In conclusion, the consumption of kerosene is not favorable to the adoption of electricity, even for wealthy households. There is evidence that, although electricity is the preferred source for lighting, budget constraints may force poor communities to consume more in less efficient lighting energy such as kerosene (van der Plas 1988). This study shows that kerosene is a source competing with electricity in urban and rural households: both are mostly used for lighting[112], both are in the same price-of-useful-energy-units range (respectively 13 and 12 cents $PPP/kWh, see Figure IV.11-A), and kerosene does not require any appliance (investment, wealth ownership) to be used as a lighting source.

The acquisition of wealth, more specifically the ability to acquire electric appliances is necessary to adopt electricity as a domestic source. Both runs indicate that even urban

[112] In Tanzania and in South Africa, kerosene is a main cooking energy in urban areas. However, in Mozambique, the main cooking source, in urban areas, is still charcoal (Hosier and Kipondya 1993; Davis 1998; Brouwer and Falcao 2004). The preferred cooking source in most of southern Africa is charcoal even when electricity is available (Madubansi and Shackleton 2007).

households will be significantly less likely to adopt electricity as a source, in the absence of wealth.

CONCLUDING REMARKS

This work analyzed the energy consumption patterns in Mozambique, from a sample of 8733 energy-consuming households surveyed during 2002/3 (INE 2007). Results indicate that urban high-income households are the consumers of electricity, while poor rural households rely mostly only on biomass. In other words, the energy ladder concept, associating high incomes to high-grade sources (electricity) and low incomes with low-grade sources (biomass) is applicable. However, the data also shows that expenditures per unit of useful-energy are higher for lower-grade sources than for higher-grade sources, given high efficiencies of use of the latter. Records on energy unit values indicate that electricity, kerosene and charcoal are cheaper by this order than firewood, i.e. the energy ladder is inverted on price-per-useful-energy-units. There is a contradiction in the relation between the income level of the household, the source's price and the source's rank in the traditional energy ladder: high-grade sources, consumed by high-income households are cheaper on price-per-useful-energy-units than low-grade sources, the main choice of low-income households. It is thus possible to conclude that price is not the only determining factor in the adoption of domestic electricity by households.

The likelihood of being and electricity consumer was analyzed by logistic regression in two separate runs, from which we conclude that:

- Income is not a strong determining factor in the adoption of electricity, kerosene or charcoal as domestic sources

- The ownership of wealth[113] favors the consumption of charcoal and electricity, and reduces the probability of being a kerosene user. Charcoal and electricity users are mostly urban.
- High PECS reduces the probability of adopting electricity as a domestic source. However, the use of kerosene for lighting deters the adoption of electricity in the domestic setting, even if it reduces the household PECS.

Data show that charcoal replaces firewood (for cooking) in urban settings and as such is often associated with electricity use (mostly for lighting). Therefore, a policy that facilitates the access to electric appliances will reduce the burden of energy consumption in the budget of poor households and improve their quality of life by allowing them to benefit from a cheaper, more diverse in end-uses, cleaner and safer source. Furthermore, environmental gains are possible by substituting kerosene by hydro-generated electricity. The adoption of kerosene as a transitional source deters the adoption of electricity for lighting.

[113] There sometimes is some confusion between income and wealth. An easy distinction is that Income is a flow and Wealth is a stock. Note however that only households with income surplus may invest by acquiring wealth and those households with productive stocks (wealth) may be able to generate higher incomes. This relationship is mathematically described in Chapter 6 of this document.

APPENDIX IV.1: ON THE HOUSEHOLD SURVEY AND DOMESTIC ENERGY DEMOGRAPHICS

DATASET: THE HOUSEHOLD SURVEY OF 2002/3

THE COMPOSITION AND TRANSFORMATIONS OF THE DATASET

The National Institute of Statistics of Mozambique conducted the household survey of 2002/3 *(INE 2007)*, by selecting randomly 9-12 households per strata, corresponding to 'Localidades' (villages, communities) that are nested in administrative divisions. In total, 8700 households were successfully surveyed. In addition to energy use and expenditure data, the survey collected information on household demographic characteristics such as family size, gender, employment, education and dwelling characteristics. The survey also recorded the sources and levels of income (earnings in cash, in species and government transfers), household expenses (daily, monthly, yearly and in species), and the ownership of a variety of assets (see final report for more detail on survey design and execution, (Zacarias, Chipembe et al. 2004). The survey data was arranged in a matrix 8700x50, from which some columns are described in Table IV.18. These variables were studied using Arc Map and the shape file for territorial division obtained from the 'Centro Nacional de Cartografia e Teledetecção' of Mozambique (Teledetecção 2008).

This study uses the data on income levels and consumption of energy sources to analyze trends and correlations concerning domestic energy behavior. The survey data are cross-sectional and spatially organized, with households classified as urban or rural.

Table IV.18 – Some data used for the ANALYSIS of the households

Column	Field Name / Description	Type
1	Province	Double
2	Cluster	Double
3	Is the household located in an urban environment?	Binary
4	Is the dwelling self-owned?	Binary
5	Are the walls made of concrete or clay blocks?	Binary
6	Number of rooms in dwelling	Double
7	Is the drinking water piped?	Binary
8	Main cooking source: firewood, biomass, dung and others	Binary
9	Main cooking source: charcoal	Binary
10	Main cooking source: kerosene	Binary
11	Main cooking source: LPG	Binary
12	Main cooking source: electricity	Binary
13	Main lighting source: firewood and other	Binary
14	Main lighting source: candles	Binary
15	Main lighting source: batteries	Binary
16	Main lighting source: kerosene	Binary
17	Main lighting source: LPG	Binary
18	Main lighting source: electricity, solar/diesel generator	Binary
30	Household total revenue [MTn per day]	Double
34	Household Expenses in firewood [MTn per day]	Double
35	Household Expenses in charcoal [MTn per day]	Double
36	Household Expenses in candles [MTn per day]	Double
37	Household Expenses in kerosene [MTn per day]	Double
38	Household Expenses in LPG [MTn per day]	Double
39	Household Expenses in electricity [MTn per day]	Double
40	Household consumption in firewood [KWH per day]	Double
41	Household consumption in charcoal [KWH per day]	Double
42	Household consumption in candles [KWH per day]	Double
43	Household consumption in kerosene [KWH per day]	Double
44	Household consumption in LPG [KWH per day]	Double
45	Household consumption in electricity [KWH per day]	Double
46	Household total expenses in energy [MTn per day]	Double
47	Household total consumption in energy [KWH per day]	Double

The variables representing total revenue[114] (income) in MTn/day.HH[115] and total expenses in MTn/day.HH for the 8,700 households interviewed fit lognormal distributions almost perfectly. Altogether, about 450 product codes were registered in expenses, generating more than 400,000 records. Revenues were registered in more than 25,000 records. Monthly valuations (of expenses or earnings) were converted to daily values by multiplying 12 and dividing by 365. Yearly valuations were converted to daily values by division of 365.

Given the variety of products registered in the household expenses, these were reclassified into seven types of energy sources, as described in Table IV.19.

Table IV.19 – Domestic energy in consumption and expenditures

Class	Name	Description
'E1'	'energy sources - firewood and other'	energy sources - firewood and other
'E2'	'energy sources - charcoal'	energy sources – charcoal
'E3'	'energy sources - candles'	energy sources – candles
'E4'	'energy sources - batteries'	energy sources – batteries
'E5'	'energy sources - kerosene'	energy sources – kerosene
'E6'	'energy sources - LPG'	energy sources – LPG
'E7'	'energy sources - electricity'	energy sources – electricity

Revenues were converted into currency units per day per household and summed to obtain a total value of daily earnings per household. For energy source expenditures, energy "prices" (or unit values) were calculated, per household, per day, per kWh; this was done by dividing the recorded expenditure in energy by the standard quantity recorded, and then applying conversion factors detailed in Table IV.20.

114 In the text, revenue, income and earnings will be alternatively used to designate the total amount, in cash or equivalent in species that households earn per day to support their livelihood.

115 MTn is the Mozambican currency; day-HH is 'per day per household'. The value of expenditures and income was converted into $PPP (Dollar-Power-Purchasing-Parity) of 5669.1 MTn/$PPP, corresponding to the year 2003 (United-Nations 2007).

$$\text{Unit\_value}_i \ [\text{MTn/day/kWh-eq}] = \frac{\text{Recorded expenditure}_i \ [\text{MTn/day}]}{\text{Recorded consumption}_i \ [\text{units}] * \text{Net Conversion}_i \ [\text{kWh-eq/unit}]}$$

where

$$\text{Net conversion}_{\text{i to electricity}} \ [\text{kWh-eq/unit}] = \frac{\text{calorific capacity [kWh/unit] * efficiency of burn source i}}{\text{effciency of usage of electricty}}$$

Table IV.20 – Conversion factors for consumption of energy sources

	E1	E2	E3	E4	E5	E6	E7
Source's Unit	Kg	Kg	Un	kWh	L	Kg	kWh
Conversion kWh/Unit	4.07	8.14	9.72[116]	-	9.72	12.55	-
"Burn" efficiency	0.1	0.2	0.1	0.65[117]	0.3	0.45	0.65
"Net" conversion [kWh-eq./Unit]	0.626	2.505	0.449	1	4.486	8.689	1

These conversion factors were used by the World Bank (1987) in the first and more complete energy study ever done for Mozambique, by Hosier and Kipondya (1993) in Tanzania, and by Kebede (2006) for Ethiopia. The net conversion unit applies the "burn" efficiencies to reflect the equivalent kWh consumption (from an electric supply) corresponding to each source's unit of consumption.

OBSERVATIONS ON THE ENERGY DATA

The calculated energy prices (unit values) per source (reflective of the sources' prices per useful energy unit) were plotted by the household consumption (in equivalent kWh units) to demonstrate the typical behavior of the demand curves per individual source, see Figure IV.12. The demand curves in Figure IV.12 indicate that for most energy sources, as the unit value of an energy source increases, the consumption of the energy source decreases.

[116] Assumed the same as kerosene calorific content, at a 0.1 burn efficiency (similar to firewood, an open fire)

[117] Assumed the same as the electrical supply form the grid (in alternate current)

However, cooking energy from LPG and for electricity consumption do not show this behavior; whereas firewood, charcoal and kerosene are sufficiently represented as domestic sources (see Table IV.21) [118,119], the same does not happen with LPG and electricity, for which data are limited.

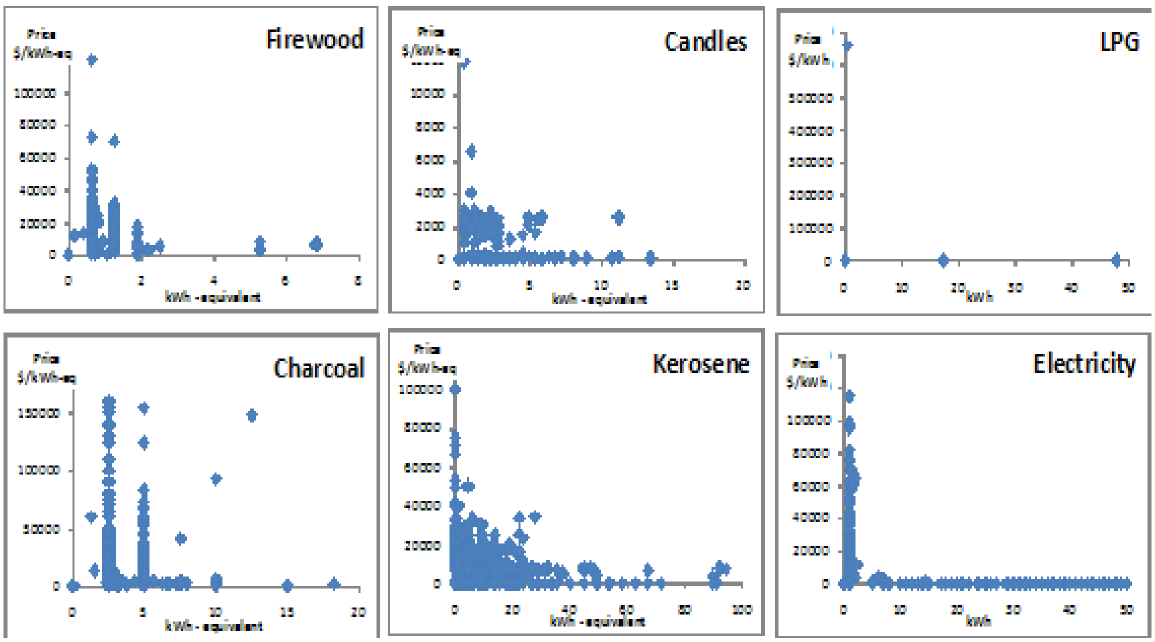

Figure IV.12 –Household expenses IN energy (IAF 2002/3 survey)

In Mozambique, energy sources are used for different purposes, with some sources more restricted in their common usage than others are. For example, firewood and charcoal are used mostly for cooking, while kerosene and candles are typically used for lighting; electricity is more versatile though in poor households it serves mostly lighting purposes; LPG is used in households for cooking and water heating. Some sources are complementary

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118 The quantities of firewood and charcoal, candles and kerosene were recorded in local units and then converted by the surveyors into standard units such as kg and liters.

119 As shown in Table IV.21, 'auto-consumption' is recorded almost entirely for firewood, gathered by poor families on their own or on unsupervised public land. 'Daily expenses' data indicate high usage of low-grade energy sources such as firewood, charcoal and kerosene. To conform with the households' schedule of earnings (retail economy), the electric public utility has installed and expanded the prepaid system for electricity consumers, However, electricity consumption is not recorded as a daily expenditure in the sample; rather, it only shows as a monthly expenditure.

in satisfaction of household needs, for example charcoal in cooking and kerosene in lighting; others are substitutes, for example, kerosene and electricity are both used mostly for lighting. Often LPG stovetops combine with electrical stovetops, making the ownership of stoves for any of these two sources a positive input in the consumption of the other. See Madubansi and Shackleton (2007) for a more detailed elaboration on the nature of the energy mix in South African villages, not dissimilar to that in Mozambique.

Table IV.21 – Number of Records on expenditures surveyed, IAF 2002/3

	Auto-consumption		Daily expenses		Monthly expenses		Total Energy expenses	
Total	22,651		11,625		5,958		40,234	
Firewood	22,626	100%	2,690	23%	973	16%	26,289	65%
Charcoal	21	0%	4,171	36%	755	13%	4,947	12%
Candles			629	5%	346	6%	975	2%
Kerosene	4	0%	4,132	36%	2,685	45%	6,821	17%
LPG					213	4%	213	1%
Electricity			3	0%	986	17%	989	2%

Electricity is of higher import in the 'monthly expenditures', although the recorded percentages (17% of records on monthly expenses, 2% of total number records) do not conform to the company's statistics for 2003 that indicate coverage of 5.3% of the total population (EDM 2007). The recording of the household's ownership in assets for energy consumption do not reflect national statistics: the usage of low-grade sources, which indicate coverage of about 80% for biomass consumption and 17% for kerosene consumption, is unrepresentative (0.6% for charcoal and 0.2% for kerosene, in Table IV.22). On contrary, the percentage count of owners of electricity consuming appliances is surprisingly high when compared with only 2% of households recording expenses with electricity. Discrepancy of the count of owners of electrical assets (59.6%, Table IV.22) with the count of electricity consumers (11.3%, Table IV.23) may be due to recording the possession of electrical appliances even when the household does not consume electricity, which makes the population's asset records unrepresentative of the national average on electricity connection rates.

Table IV.22 – Recorded asset ownership in the sampled households

Sources	MTn total	Average per HH MTn / HH	$PPP / HH	Count HH - % 8700	
Charcoal	9.49E+04	1,899	0.33	50	0.6%
Kerosene	5.78E+04	3,211	0.57	18	0.2%
LPG	6.43E+07	2,297,071	405.2	28	0.3%
Electricity	3.51E+08	67,680	11.94	5188	59.6%

Table IV.23 – Recorded expenditures in energy sources

Sources	MTn total	Average per day.HH MTn/ day.HH	$PPP/day.HH	Count HH % 8700	
Firewood & low-grade	3.10E+07	4922	0.87	6301	72.4%
Charcoal	1.82E+07	10548	1.86	1727	19.9%
Candles	1.47E+06	2443	0.43	601	6.9%
Kerosene	1.04E+07	2498	0.44	4154	47.7%
LPG	1.65E+06	7723	1.36	213	2.4%
Electricity	1.21E+07	12277	2.17	987	11.3%

This discrepancy is unlikely to result from electrical supply of private (isolated) generators, as they are estimated to cover only between 0.18% and 0.34% of the population (Mulder 2007). Brouwer and Falcao (2004) showed that even in Maputo, where access to electricity is the highest in the country, firewood and charcoal are still sources for about 19% and 74% of the population respectively. The expectation is to have higher utilization of these sources in rural areas.

The records for household expenditures in Table IV.23 show the relative importance of the energy sources in the average Mozambican household: at the national level, firewood and other low-grade sources are the most common domestic energy source (72.4%), followed by kerosene (47.7%), charcoal (19.9%) and electricity (11.3%). This ranking differs from the ranking of the unit (daily) cost of the sources, by which firewood is the more expensive, followed by charcoal, electricity and kerosene, see Figure IV.13.

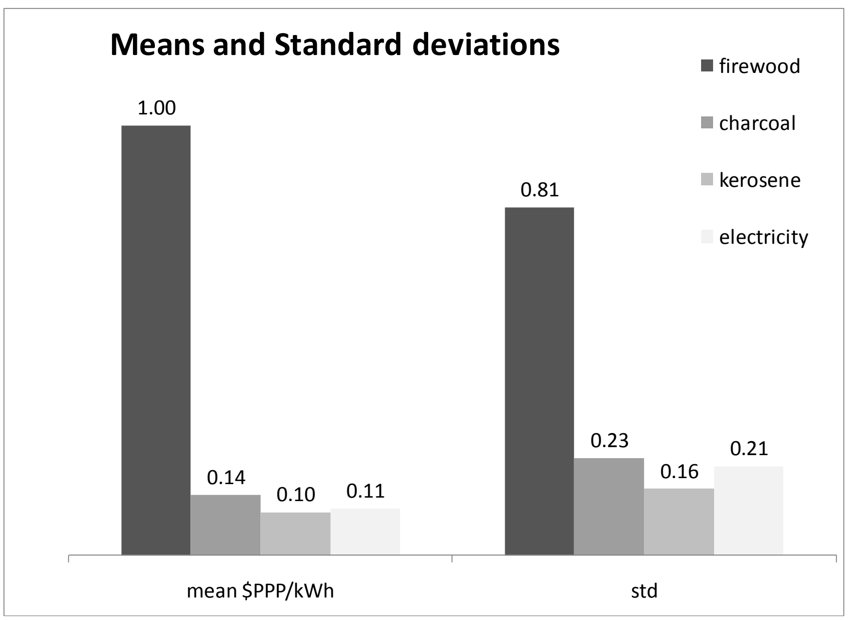

Figure IV.13 – Unit values: from the cheapest to the more expensive

Falcão (1999) has collected average prices for firewood, charcoal and kerosene, and corrected them by the consumer price index as an inflation measure. The data show higher prices for kerosene, per unit consumed. If, however, these prices are converted to a comparable unit of kWh-equivalent, kerosene then is cheaper than charcoal and firewood (see Figure IV.14), because of its higher efficiency of use and calorific content.

The similarity of the sample's unit cost ranking (Figure IV.13) with Falcão's (1999) price ranking (Figure IV.14) provides validation of our results, despite the fact that the unit values shown in Figure IV.12 are a combination of real prices and households' perceptions of the quality of the energy sources and that they are contaminated by measurement errors. Evidence from southern Mozambique (Cockburn and Low 2005) that electricity consumers are actually spending less than charcoal consumers and Falcão's (1999) price ranking, which our results corroborate, show that electricity is cheaper than charcoal. *This suggests an inverted energy ladder for domestic consumption.*

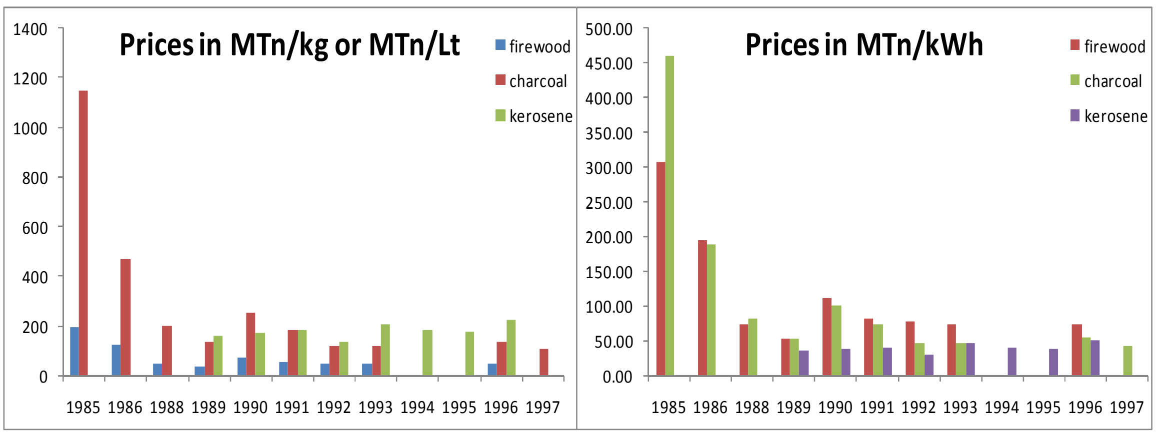

Figure IV.14 – Prices of energy sources in Mozambique, 1985 - 1997

The categorization of the households by wealth and the composition of the domestic energy is important, in that other studies recognize that household wellbeing is linked to acquisition of higher grade sources: see examples in the models of McKenzie (2005), and Larsen and Nesbakken (2004). Location variables per household can also be indicatives of quality of life, as some areas of the country are more developed than others.

Income per day per capita[120], varying in the range of 0.31 to 8.80 $PPP/day-capita, with a mean of 2.39 $PPP/day-capita and a standard deviation of 2.07 $PPP/day-capita, record higher values in Maputo and in the central and some northern districts. A comparison of the income levels with total energy expenditure per household indicate that the higher energy consumers are at the higher levels of income, but that not all high income levels consume more energy. Higher energy expenditures are evident in the development corridors of Maputo, Beira and Nacala. However, energy expenses are not the households' highest priority: the mean energy expenditure is only of 0.24 $PPP/day-capita (0.14 $PPP/day-capita standard deviation), i.e. only 10% of the mean recorded income.

The income-share of expenses in non-energy items (food, clothing, etc) and in leisure tends to be higher in the north while the share of expenses in public services (education, transport, health, etc) tends to be higher in the more urbanized south. Energy expenditure also seems to take higher shares of the income (budget) in the northern districts, though in absolute values higher energy consumption coincide with high incomes, differences being attributable to unit (energy) expenditures[121] (see data at the provincial level, Figure IV.15). Higher budget-shares for energy expenses may signify lower budgets (poorer families) or higher energy prices, which are typical conditions of the northern districts.

The households' statements regarding their main sources for cooking and lighting can be used as proxy for asset ownership. Data conforms with the concept of the energy ladder (higher-grade sources at higher incomes and vice versa). Although firewood is also heavily used in the south for lighting, its higher usage is observed in the center-northern inland

[120] Data per capita was calculated by applying the IAF 2002/3 data on household earnings and expenses to the counting of households and population of the latest 2007 census, (INE 2007)

[121] The consumption of energy, in kWh units, almost perfectly fits the pattern of income in the provinces

districts, where lower income levels are also recorded. The higher-grade sources such as charcoal, kerosene and electricity record higher usage (for cooking and lighting) in the development corridors and urban areas (see Figure IV.9).

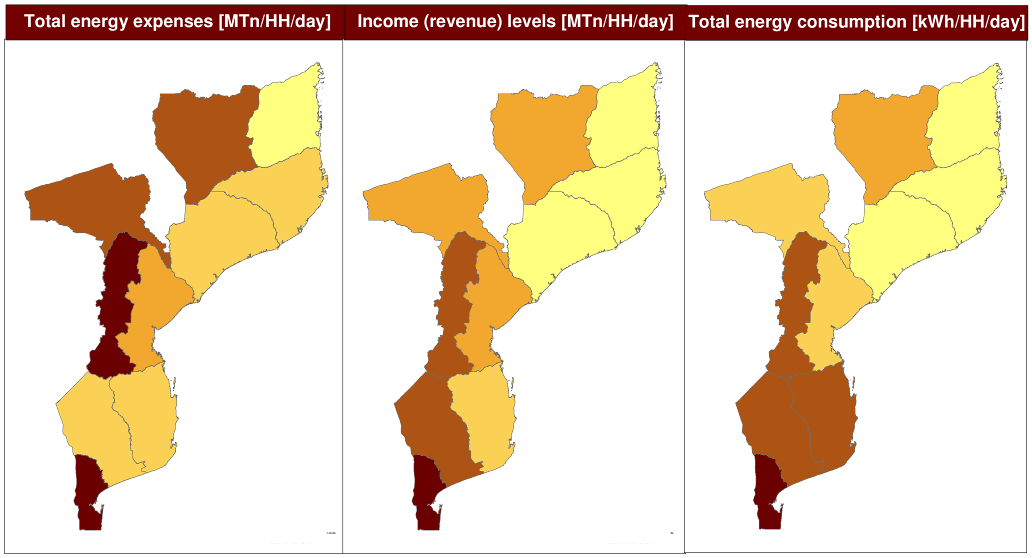

Figure IV.15 – Provincial Energy Expenses, Consumption and income (Scale lighter to darker = smaller to higher values)

The study of the distribution of the sources and their prices and expenditures across the country may clarify the correlation factors between high-income districts and the levels of domestic energy consumption and expenditure recorded, calculated respectively at 0.64 (income x kWh) and 0.55 (income x expense).

ENERGY IN THE DISTRICTS

Districts in the southern provinces of Maputo, Gaza and Inhambane, along the Beira Corridor and in the northwest of Mozambique have higher levels of energy consumption, in kWh per household per day. The consumption of firewood is fairly even across the country, with a countrywide mean of 0.13 kWh/day per capita (0.03 standard deviation), while charcoal, kerosene and electricity are higher at the south, Beira corridor and north-west districts. In words, in Mozambique the consumption of higher-grade domestic sources corresponds to higher energy intensity, and occurs in the south, Beira corridor and north-west districts, coinciding with the use of these sources in cooking and lighting as main sources. Energy expenditure amounts to a mean of 0.24 $PPP/day per capita, about 10% of the mean recorded income. Table IV.24 reports the means and standard deviations of the consumption and expenditures for individual energy sources.

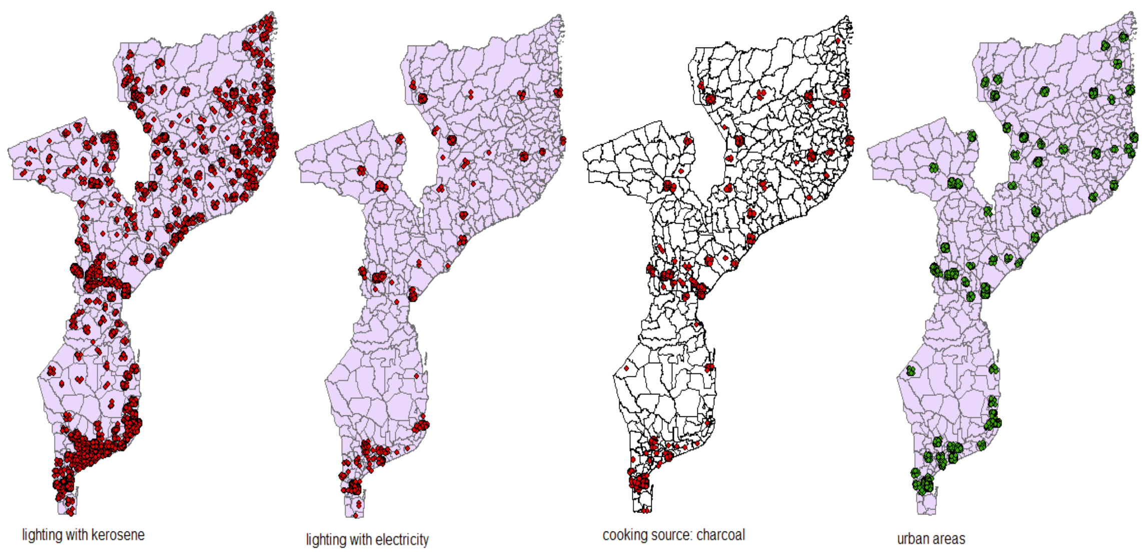

Figure IV.16 – Urbanization & development versus high-grade sources

The sample indicates that the expenditure in energy sources corresponds to a higher share of the household budget in the north, which may only partially be explained by lower incomes in the northern districts. It is important to look at the cost of the more common sources used in the various districts: the calculation of the unit value (expenditure divided by quantity) of energy consumption, in aggregated form, indicates higher unit expenditures in the center-north western districts (Figure IV.10).

Table IV.24 – Energy consumption and expenditures per district

kWh/day-capita	Firewood	Charcoal	kerosene	electricity	aggregate
Mean	0.13	0.05	0.77	0.71	1.78
std deviation	0.03	0.13	0.92	2.03	2.88
Median	0.13	0.00	0.44	0.00	0.71
$PPP/day-capita	Firewood	charcoal	kerosene	electricity	aggregate
Mean	0.16	0.03	0.03	0.01	0.24
std deviation	0.10	0.06	0.03	0.04	0.14
Median	0.15	0.00	0.02	0.00	0.22

CONSIDERATIONS ON THE HOUSEHOLDS' CHOICE OF DOMESTIC SOURCES

Most households consume firewood at a constant energy level, which results in high unit values of firewood for many districts[122]. For charcoal, although the unit values in the south are not among the highest, its consumption is highest. Large expenditures are recorded in the center districts (where the high unit values are also recorded) and in the south (where the highest consumption is recorded).

Although most households in the sample consume firewood, its low energy levels result in a lower share of the total domestic energy consumed. Families where firewood is the only energy source are well represented in this sample, particularly in the center-northern districts. Firewood consumption is predominant as a domestic source in the poorer districts (center-northern), although it is present in households all over the country. By contrast, charcoal consumption occurs mostly in urbanized areas, of higher income, possibly because

[122] This constant level of energy from firewood is a result of standardizing the piles of firewood sold in retail markets and ignoring differences in calorific values of different types of wood and possible varying volumes of woodpiles. This approximation is necessary because data are not available, at the district level, establishing average woodpile volumes and their calorific content.

firewood sources are distant and unavailable, i.e. charcoal consumption substitutes firewood consumption (see Figure IV.18).

For kerosene, although the highest unit values are recorded in the center, the expenditures are at the highest levels in most of the districts, including some of the coastal areas. Kerosene is widely used, with higher consumption shares in the southern districts. Although kerosene may be up in the energy ladder because of its high efficiency and complexity of the production process, it is more affordable and widely accessible than charcoal. Coastal districts reserve a higher share of their budgets for kerosene (lighting) consumption, as well the previously noted south, Beira corridor and northwest.

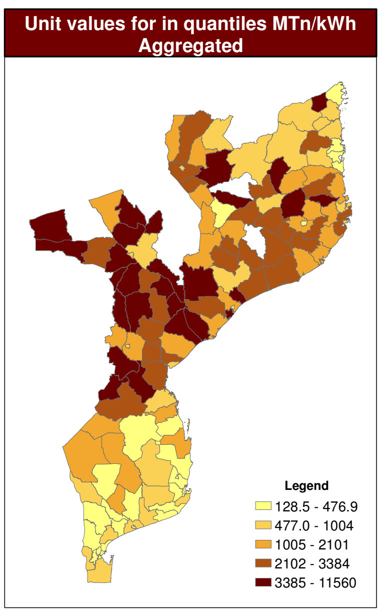

Figure IV.17 – Energy unit values

Electricity shows significant consumption levels along the development corridors of Maputo and Beira. Electricity expenditures are at the highest in the south and some coastal northern districts, where it constitutes an alternative source also for poor families. Higher electricity consumption corresponds to higher electricity expenditures as the price is geographically uniform and only varies by consumption levels. As the consumption increases, the expenditure of the household per electric kWh will increase, pulling electricity up the energy ladder of domestic sources.

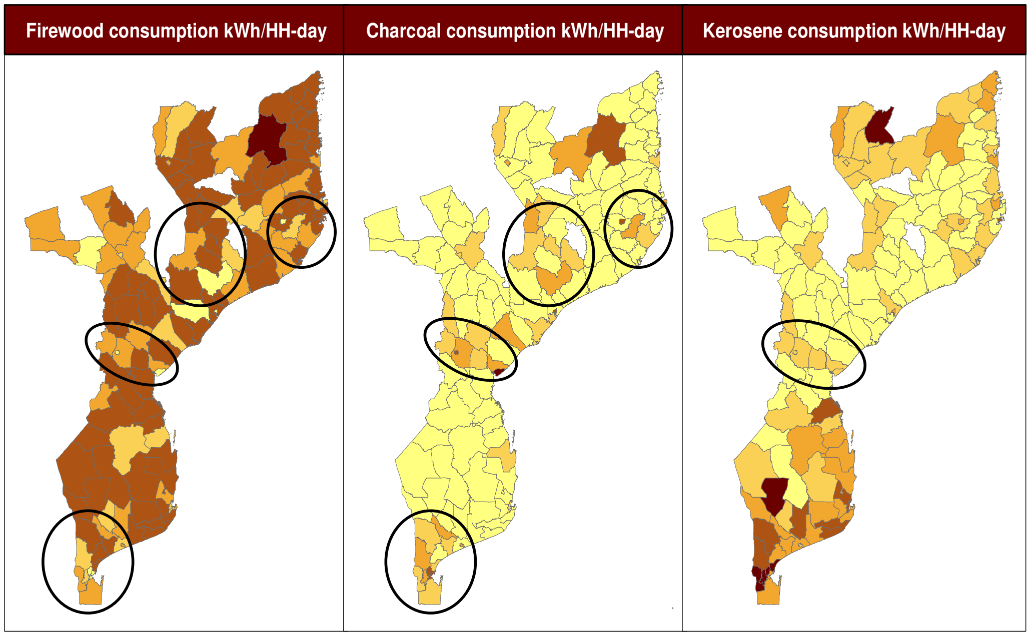

Figure IV.18 – Districts: charcoal replaces firewood consumption

It is important to note that the electrical networks do not extend to all villages and all districts of Mozambique. Consequently, the evaluation of household choices of domestic source needs to take into account the accessibility of electricity. Other sources use the transportation routes and retail marketers that reach wherever there is demand for the product. Still, the evidence of an energy ladder inverted by price of useful energy units is strong and encouraging from a policy standpoint, in that the poor need not to be deprived of more efficient, more convenient, more diverse and even cleaner domestic sources.

CHAPTER V: ENERGY LOSSES IN THE NORTHERN ELECTRICAL SYSTEM IN MOZAMBIQUE

ABSTRACT[123]

Operational records on the electrical supply, in Mozambican transmission and distribution systems are generally unavailable for an accurate calculation of the technical losses of supply. Technical losses in the Mozambican electrical systems have been estimated as high as 20%, mostly originating in the distribution networks. This study collected the operating records of power flows in the northern electrical grid in Mozambique (Linha Centro-Norte) for the year 2007, to derive functions for energy losses using quadratic regression derivations and simple probability estimations. Loss allocation by weight of distributed energy is also formulated for each distribution feeders radiating from the transmission substations.

[123] Submitted for publication in the Transactions of Power Systems, IEEE, reference TPWRS-00010-2009

INTRODUCTION

THE REASONING AND THE CONTENTS

The flow of electric power through transmission and distribution networks is always accompanied by thermal and magnetic losses, respectively originated in the electric resistance of the conductors and in the magnetic fields resulting from the energy flows. Calibration and human (operating and measurement) errors are also contributors to power losses, particularly in installations of analog metering and poor automation. Although technical losses can be calculated analytically, the process requires so many measuring points that it is unpractical. Consequently, researchers and power companies have developed approximate methods to estimate transmission and distribution losses, ranging from the constant percent-rate of the energy flows to the empirically derived linear and quadratic equations.

The estimation of losses as a function of the power flows is important in determining the costs of supply along an electrical grid. In the Mozambican electrical system, the unit costs of generation, transmission and distribution are set at the national level and are spatially unvarying. Only by differentiating electrical losses and charging them accordingly, can unit costs of supply be distinguished between distribution networks. In other words, the costs of supply to each distribution network are differentiated only by their respective loss burdens.

Losses are of a technical nature but also originate in equipment defects, in human intervention and in weather patterns. The use of empirical methods to estimate losses can capture these effects by describing the average losses as functions of energy flows and other significant variables.

For this study, hourly data on the power flows within the Mozambican northern electric grid, named 'Linha Centro-Norte' (LCN), was collected and processed for the year 2007. Empirical equations for transmission losses in the system were established and these losses were then proportionally allocated to the distribution feeders radiating from the transmission substations, by weighting the distributed power in each feeder. Distribution losses were also calculated and respectively allocated to the distribution networks supplied from the system.

The transmission loss equations derived in this study are validated by their use in forecasting 'total power', taken at the source, and the comparison of results with the forecasts from PSS/E software simulations.

IMPORTANCE OF THE WORK

This study is important in that it locates the sources of high transmission losses in the LCN system, prerequisite for any loss reduction program. Transmission losses are then allocated to the distribution networks (supplied by the LCN system), proportionally to the energy flows. Loss allocation is the first step in cost allocation so that the distribution networks be more fairly charged with their share of transmission costs. The marginal losses derived also can be used to estimate the impact of load growth in the variable costs of transmission.

The derivations confirm the presence of calibration defects particularly in the substations of Ceramica, Mocuba and Molocue, and a simple approach to correct these defects in the loss estimation is used with acceptable success.

The study also applies for the first time in the Mozambican distribution networks the hour-equivalent loss factor approach, although the smallness of the distribution dataset does not allow the calibration for the constant χ - see equation (25). For this purpose, future and more detailed studies are recommended, as the results indicate losses lower than the current estimations. Distribution losses due to interruptions, based on yearly records are also calculated, demonstrating the use of indicator SAIDI (Duration Interruption Index) in the estimation of interruption losses. This approach can also be applied to monthly losses or any other period of loss evaluation.

Finally, the transmission loss equations can be reasonably used to forecast power taking from the source (at Matambo substation) in a much simpler procedure than the programming of the PSS/E load-flow models, although the later will still be needed for more accurate final predictions. This estimation should be more accurate than the currently used constant percent-rate, and its use in forecasting exercises can be useful when quick estimations are necessary.

THE ELECTRIC SYSTEM UNDER STUDY

THE TRANSMISSION GRID

The northern electricity transmission system in Mozambique consists of a ring (to be closed with the interconnection Songo-Nampula, via Cuamba) of transmission lines at 220 kV, with a total of 2264 km length and 6 substations (+2 new, Cuamba and Phompheya), with a total (current) transforming capacity of 637 MVA and expanding (Figure V.19). At the substations, 110 kV and 33 kV feeders radiate to smaller substations that in turn feed into the distribution areas at medium and low voltages. Reactors and compensators are installed to reduce the reactive effects resulting from reactive loads for the interconnecting lines and substations.

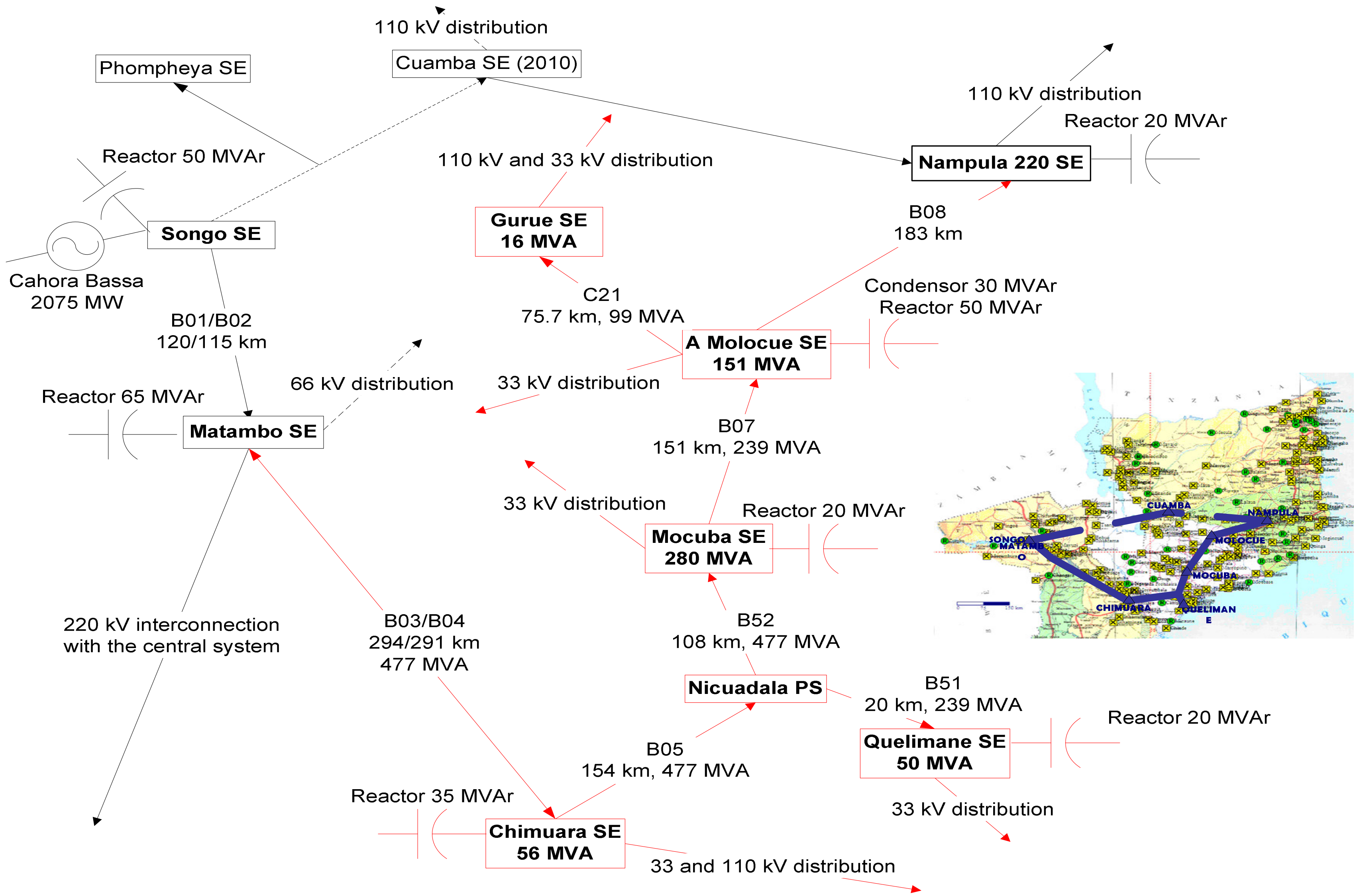

Figure V.19 - Schematic representation of the LCN system

The energy supply originates in Matambo substation and is fed into B03 transmission line, at 220 kV, with a mean (trimmed to 5% of the non-zero observations, to account for outliers and zero records) of 47.5 MW and a standard deviation (STD) of 7.3 MW 'towards' Chimuara. In Chimuara, the energy flow is 'backed' into B04 line to supply Tete (at 110 kV, with a mean load of 6.8 MW and 1.1 STD), feeds the distribution network at 110 kV and 33 kV (0.53 MW, 0.22 STD), and continues 'towards' Ceramica and Mocuba, at 220 kV (38.8 MW, 6.4 STD). In Ceramica, it is transformed down to 33 kV and distributed (6.0 MW, 1.1 STD). In Mocuba, it is transformed down to 33 kV for local distribution (1.4 MW, 0.3 STD) and continues to Molocue at 220 kV (30.4 MW, 5.2 STD). At Molocue, part of the flow continues, at 220 kV to the Nampula substation and the Northern-Eastern districts (26 MW, 4.7 STD), part is transformed down to 110 kV and transferred to Gurue substation and the north-west (3.7 MW, 0.7 STD), and part is transformed down to 33 kV and distributed locally (0.24 MW, 0.1 STD). Finally at Gurue, the energy is transferred to Cuamba and Lichinga at 110 kV (northern-western districts), 2.8 MW, 0.6 STD, and transformed down to 33 kV to supply the nearby distribution networks (0.9 MW, 0.27 STD).

The transmission lines have thermal limits, and the substations have transforming capacity, significantly higher than the current load levels: the sizing of the transmission system planned for larger demand levels that have not yet occurred.

Transmission lines and impedances measured in the substations (EDM 2007) were used to calculate the nominal resistances to power flow, to be used in the calculation of the 'observed' demand (hourly) losses, as per Table V.25.

Table V.25 - Nominal Resistances of the system's components[124]

Component	R_{nom} [Ohms]
B03	11.2
B05	11.5
B07	11.3
C21	7.9
Chimuara	14.8
Ceramica	24.3
Mocuba	23.5
Molocue	35.3
Gurue	16.1

Power forecasts are made from projections of load growth at the consumer level, consequently the loss estimations in this study are made using the power delivered (Power-Out) as an explanatory variable instead of the power received (Power-In).

THE DISTRIBUTION NETWORKS

Of the total 300 GWh of energy transmitted in the LCN during 2007 (68 MW approximate peak load), about 50% was distributed in the northeastern districts of Nampula and Cabo Delgado Provinces, at the far end of the 220 kV transmission system. The larger load centers are Tete, Quelimane and Nampula, and their load profiles determine the load profiles of the power flows through the transmission system (Figure V.20).

Although a slight reduction of electrical loads is recorded in the colder months of June and August, it is not significant across the year. The load profiles are also very similar in all the system's main delivery paths.

[124] The lines' resistances were calculated by multiplying the resistance of the line conductor, in Ohms/km by its length. The substations' resistances were calculated by multiplying the impedances at 220 kV (and 110 kV in Gurue substation) by the cosine of the phase angle. Source: EDM technical database

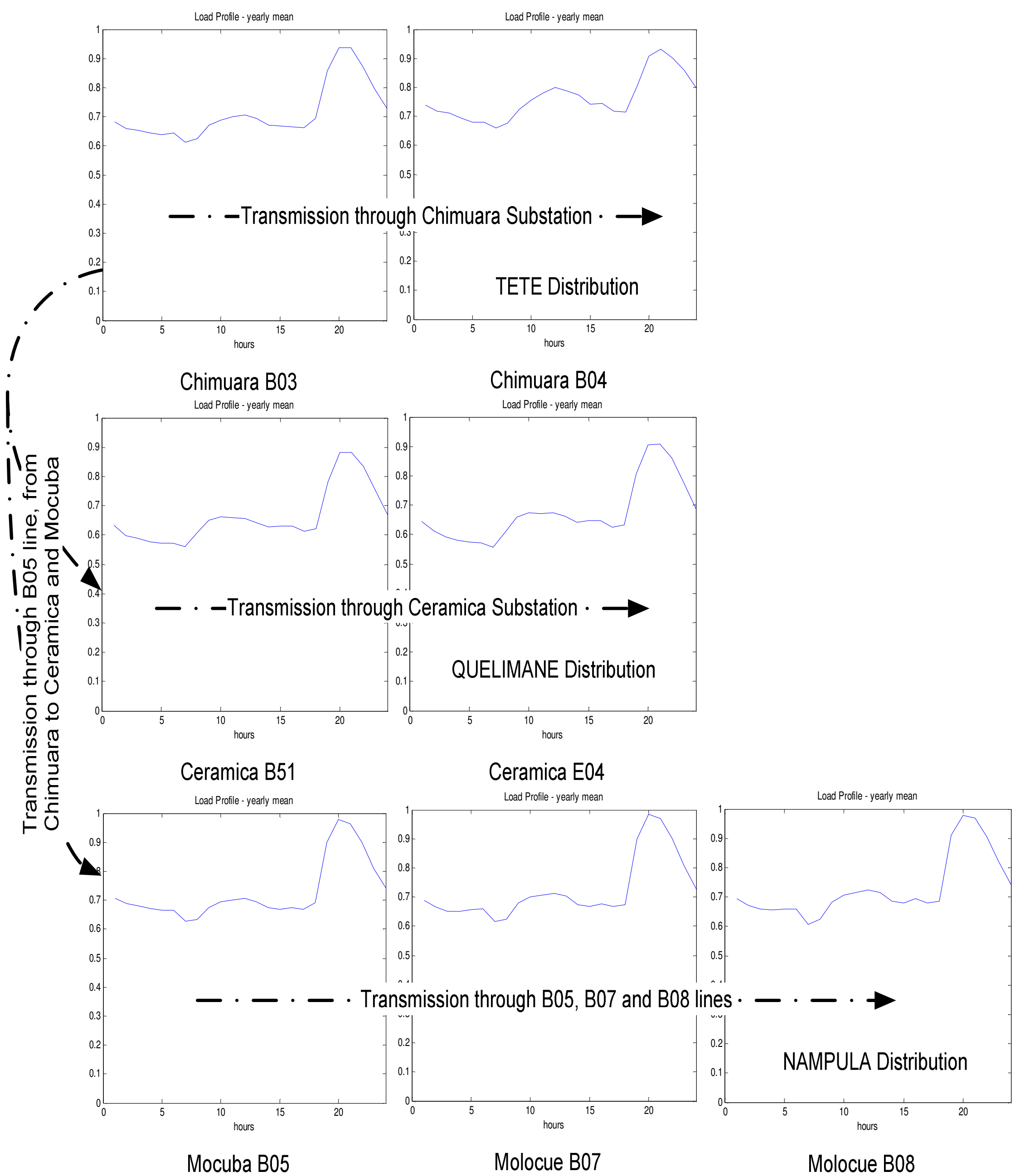

Figure V.20 – Daily load profiles take the shape of major flows

The total energy delivered in the LCN to the distribution networks totaled 293 GWh during 2007, with a load factor of only 0.5 and a total un-synchronized demand of 68.1MW. Of the eight distribution networks, Nampula and the northeast supplied by line B08 radiating from Molocue substation absorbed 52% (151 GWh/year) of the energy flow.

Quelimane-Namacurra-Inhassunge are supplied from Ceramica substation and absorbed 18% (52 GWh/year) of the flow. Tete is the next larger load center, taking 15% (45 GWh/year) of the energy flow. Cuamba and Lichinga is the next larger, with 6.5% (19 GWh/year), followed by Mocuba-Maganja-Pebane (12.5 GWh/year), Gurue (7.9 GWh/year), Morrumbala-Rio-Mopeia (2.7 GWh/year) and Molocue (2.3 GWh/year), see Table V.26.

Table V.26 - Yearly energy and peak loads in the distribution

Substation	Voltage kV	Names of Distribution Areas	Energy MWh/yr	Peak Load MW
Chimuara	220	Tete	44,955	11
	33	Morrumbala, Rio, Mopeia	2,722	1.1
Ceramica	33	Quelimane, Namacurra, Inhassunge	52,049	11.2
Mocuba	33	Mocuba, Maganja, Pebane	12,523	2.4
Molocue	220	Nampula and the northeast	151,391	35
	33	Molocue	2,268	0.6
Gurue	110	Cuamba and Lichinga	19,032	5
	33	Gurue, Tea plantations, Ile, Socone	7,857	1.9

The metering records for hourly power flows and energy distributed in these networks (on the delivery side) concerning 2007 flows are too full of errors to allow a very accurate analysis. Nonetheless, this study estimates losses in each of these networks and recommends on further studies.

PAST METHODOLOGICAL APPROACHES ON TRANSMISSION LOSSES

The formulation of transmission losses using approximate equations goes back quite a while as direct metering and loss calculations are laborious and often unviable. The level of approximation varies between authors, although all express the loss dependency on the squared current and system resistance to the power flows (I^2R). Losses are the differentiating factor in the costs of supply and are used in the formulation of utility supply rates, see for example Bernard and Guertin (2000) work, and have been extensively used in forecasting processes and economic evaluations of power systems.

Chang (1968) establishes that losses in a transmission segment are the sum of losses in the lines and in the transforming equipment reduced by the power injected by the reactors. His main achievement was to reduce the measurement points to only two in the lines (at the start and the end of the transmission lines) complementing the measurement of load levels in the transforming equipment. However, his formulation only contemplates technical losses and assumes no measurement or calibration errors. Gustafson and Baylor (1988; 1989) developed a quadratic regression equation for the transmission losses and reviewed the then existing formulation for distribution losses, recommending adjustments in the coefficients for the distribution loss factors. They also suggest approaching loss allocation per consumer class by weighting consumer loads relative to the system's total. Their work is a precursor of more recent studies on the subject of losses.

Distribution losses are more extensively studied because they comprise the larger part of utility losses, and the mesh-like nature of distribution networks makes the measurement requirements and the loss allocation approaches trickier.

For each line and substation hourly data on voltage levels, active and reactive powers at the incoming and outgoing lines were measured in analog instrumentation and with human intervention. The data thus collected characterizes the operations during year 2007 and is used to calculate the total I^2R power losses in the transmission system, though it contains significant calibration defects and human (measurement) errors.

Before selecting the best formulation of losses, several approaches to calculation of losses and the explanatory variables were tested. Theoretically, the difference between current incoming into a line segment or substation and the current outgoing it should equal the power losses and increase quadratically with the load. However, the presence of calibration defects and measurement errors in the active and reactive power readings, as well as in the reading on line voltages, resulted in 'losses' that reduced with the load and even took negative values in some hours. This method of calculating losses as a response variable was rejected as it misrepresented the loss profiles and over estimated loss factors. Next, rather than estimating losses with regression the authors reasoned that if they estimated 'power-in' as a function of 'power-out' they would be able to actually estimate losses from their difference. This regression showed high coefficients of determination; however, losses were under-estimated as the reactive component of losses was ignored in the estimation. Finally, the authors tested and selected, as more appropriate, the formulation next presented (details on the previous rejected approaches can be obtained from the corresponding author upon request).

For each system's component (line or substation), observed demand (hourly) losses were regressed in MATLAB by the following formulation (see nomenclature section):

$$\frac{\sqrt{P_{in}^2 + Q_{in}^2}}{V_{in}^2} \cdot R_{nom} = \alpha_0 + \alpha_1 \cdot P_{out} + \alpha_2 \cdot P_{out}^2 + \dots \\ + \sum_{h=1}^{23} \alpha_{3h} \cdot H_h + \sum_{m=1}^{3} \alpha_{4m} \cdot M_m + \varepsilon \tag{18}$$

The left-hand side represents the observations for year 2007 and the right hand-side represents the regression derivation, by ordinary least squares. The variable H, introduced to account for the co-linearity between hourly readings, was constructed as a 1x23 vector of 22 zeros and one value '1' for all possible the hours between 01:00 AM and 11:00 PM, or as a 1x23 vector of -1 when the hour of the reading corresponds to the 12:00 AM hour. Similarly, the variable M representing the season of the respective hourly reading, is a 1x3 vector of two zeros and one '1', or a vector of -1 for the summer. The classification in seasons was made based on the temperature variation recorded for the years between 1971 and 2000, for the city of Quelimane, by the National Institute of Meteorology of Mozambique (source: www.inam.gov.moz). Further detail on the classification in seasons and the construction of these variables can be requested to the corresponding author.

Table V.27 - Coefficients of determination for the regression

Component	R^2
B03	84%
B05	80%
B07	89%
C21	51%
Chimuara	91%
Ceramica	95%
Mocuba	89%
Molocue	80%
Gurue	81%

The coefficients of determination obtained indicate good correlations, as listed in Table V.27 (above) with exception of line C21 between Molocue and Gurue, for which the correlation is only of 51% fit.

The fit through this equation conforms with the expected behavior of loss, as shown in Figure V.21 and Figure V.22, where the blue dots represent the observed losses and the red crosses represent the predicted losses.

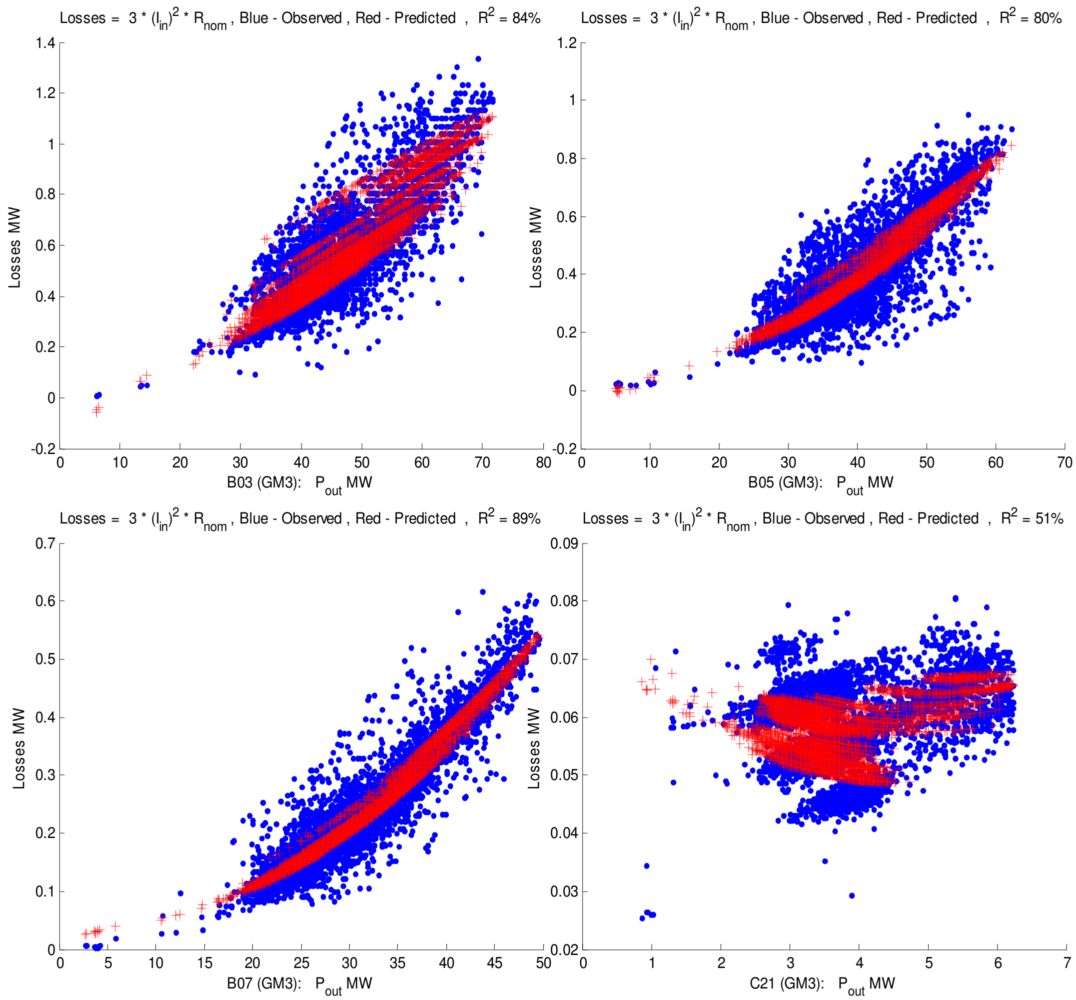

Figure V.21 - I^2R losses in MW observed and predicted in the system's transmission lines, as a function of P_{out} in MW

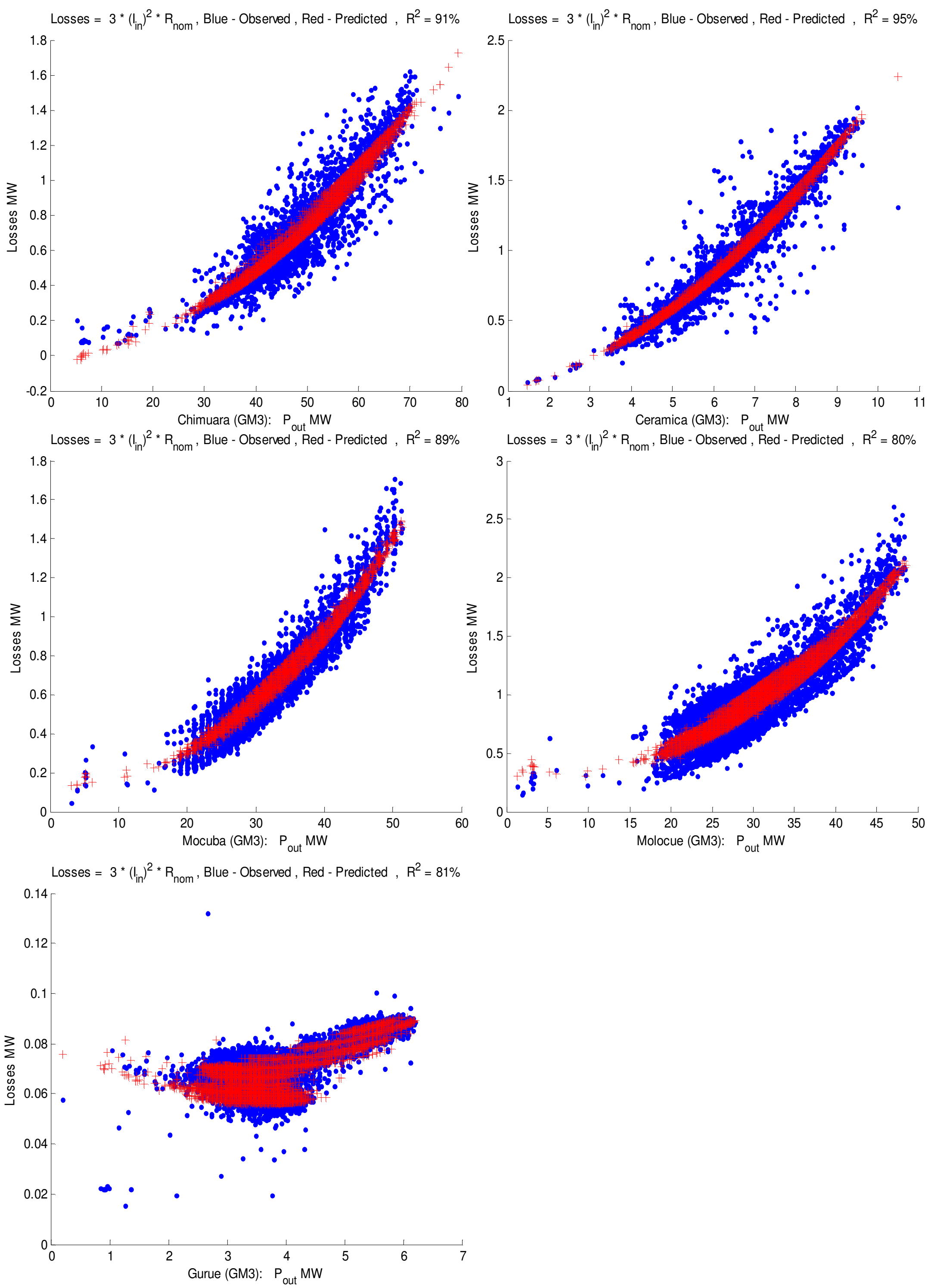

Figure V.22 - I^2R losses in MW observed and predicted in the system's substations, as a function of P_{out} in MW

The statistics and the coefficients of regression are presented in Table V.31 and Table V.32 at the end. The small number of lines (four) and of substations (five) under analysis makes unviable a second-level regression derivation, to explain constant losses as functions of the lines and substations technical characteristics.

The marginal losses, representing the variation of losses in MW per each MW of P_{out} flowing are obtained by deriving the empirical equations on P_{out}. These marginal losses are contaminated with calibration effects and measurement errors.

CONSIDERATIONS ON EQUIVALENT RESISTANCES OF LINES AND SUBSTATIONS IN THE ELECTRICAL SYSTEM

The losses estimated deviate from the theoretical I^2R as the power flow increases, as shown in Figure V.23.

These deviations (of predicted losses to theoretical losses) are approximately constant on the whole range of power out P_{out}, indicating a possible mismatch with the nominal resistances.

Consequently, a regression derivation was made to determine the empirical values of resistances in the lines and substations, accommodating thus any calibration defects or measurement errors, by the following equation:

$$R_{emp} = \frac{abs\left(P_{in} - P_{out}\right)}{3 \cdot \left(I_{in}\right)^2} = \beta_0 + \beta_1 \cdot P_{out} + \beta_2 \cdot \left(P_{out}\right)^2 + \varepsilon \qquad (19)$$

This resulted in constant resistances for lines B03, B05 and B07, similar to the nominal values, in inconclusive resistance values for line C21 and substation Gurue, and in P_{out} dependent resistances for substations Ceramica, Mocuba and Molocue (Table V.28).

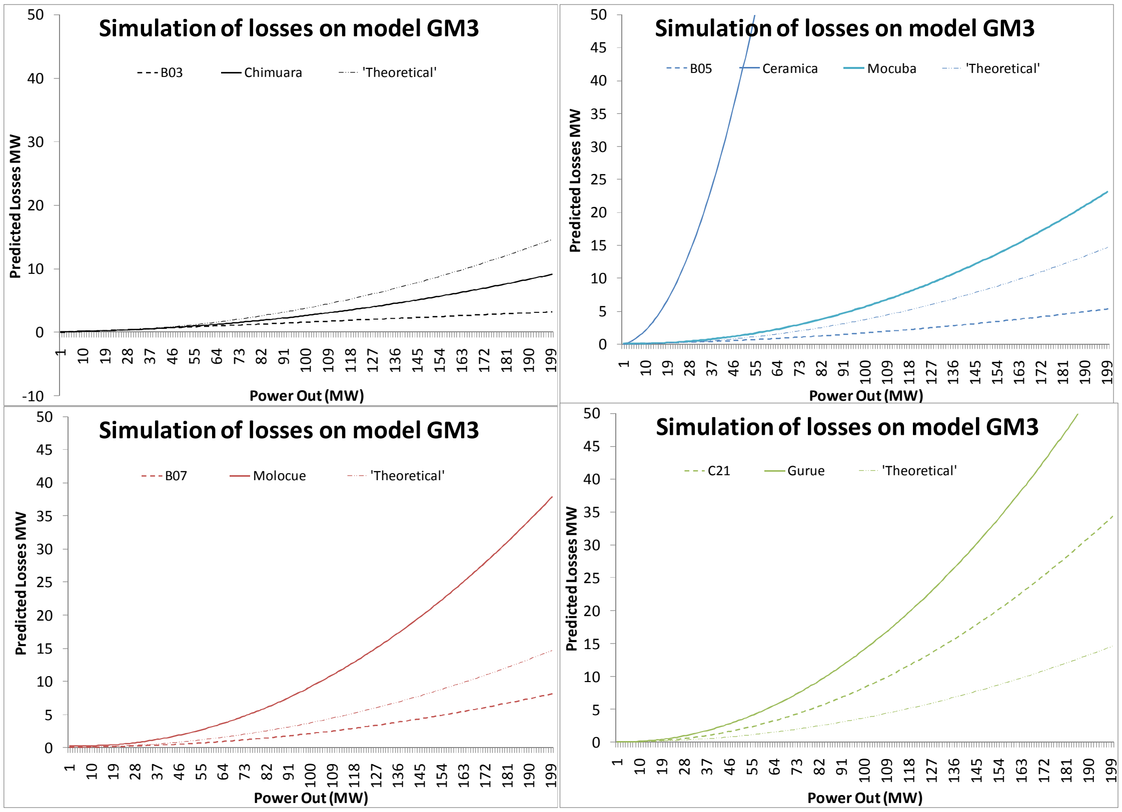

Figure V.23 - Comparison of I^2R losses regression-predicted for each system's component and the analytical (theoretical), for a summer day at peak hour

Table V.28 - Empirical Resistances of the system's components

Component	R_{emp} [Ohms]	Remarks
B03	8.92	$R_{nom} = 11.2$
B05	19.00	$R_{nom} = 11.5$
B07	10.89	$R_{nom} = 11.3$
C21	-5.64	Inconclusive
Chimuara	16.35	$R_{nom} = 14.8$
Ceramica	$66.64 - 16.22*P_{out} + 1.06*(P_{out})^2$	$R^2 = 30\%$
Mocuba	$122.21 - 4.01*P_{out} + 0.03*(P_{out})^2$	$R^2 = 35\%$
Molocue	$145.05 - 5.10*P_{out} + 0.05*(P_{out})^2$	$R^2 = 45\%$
Gurue	-3.01	Inconclusive

The comparison of the theoretical losses I^2R calculated with the nominal resistances (Table V.25) and with the empirically derived (Table V.28) show approximate results only for lines B03, B05 and B07 and for substation Chimuara. In conclusion, calibration and human errors are present and significant in the active power measurements recorded for the start and the outing of line C21 and all substations with exception of Chimuara. If the observed power losses in substations Ceramica, Mocuba and Molocue are corrected by the empirically derived resistance

$$\Delta P_{corrected} = \frac{\Delta P_{observed}}{\mathrm{R}_{emp}} \quad [\mathrm{MW}] \tag{20}$$

and the regression represented in (18) is re-run, we obtain the coefficients shown in Table V.32 in the appendix and the following corrected marginal losses per each component of the electrical system. These losses are corrected for the calibration defects and the measurement (human) errors:

$$\begin{array}{ll}
\multicolumn{2}{l}{\text{The corrected marginal losses (Lines):}} \\
\text{B03:} & m_{B03}^{loss} = 1.66\% \\
\text{B05:} & m_{B05}^{loss} = 0.68\% + 0.02\% \cdot P_{out}^{B05} \\
\text{B07:} & m_{B07}^{loss} = 0.05\% + 0.04\% \cdot P_{out}^{B07} \\
\text{C21:} & m_{C21}^{loss} = -0.84\% + 0.18\% \cdot P_{out}^{C21} \\
\multicolumn{2}{l}{\text{The corrected marginal losses (Substations):}} \\
\text{Chimuara:} & m_{Chimuara}^{loss} = 0.58\% + 0.04\% \cdot P_{out}^{Chimuara} \\
\text{Ceramica:} & m_{Ceramica}^{loss} = 4.04\% + 0.46\% \cdot P_{out}^{Ceramica} \\
\text{Mocuba:} & m_{Mocuba}^{loss} = -2.58\% + 0.10\% \cdot P_{out}^{Mocuba} \\
\text{Molocue:} & m_{Molocue}^{loss} = -0.40\% + 0.02\% \cdot P_{out}^{Molocue} \\
\text{Gurue:} & m_{Gurue}^{loss} = -1.07\% + 0.30\% \cdot P_{out}^{Gurue}
\end{array} \tag{21}$$

The resulting estimation of losses is much closer to the theoretical I^2R (Figure V.24). With exception of line B03 for which a constant marginal loss is recorded (a linear dependency on the outing power), the other components (lines and substations) show a quadratic relation of the power losses with the power flowing in the system.

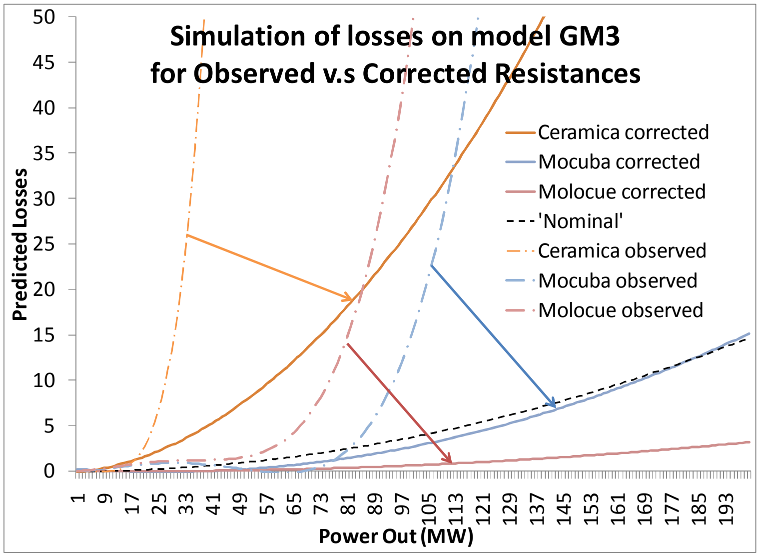

Figure V.24 - Comparison of I^2R theoretical losses for Ceramica, Mocuba and Molocue substations, calculated before and after correction of the observed losses by the empirical resistance

It is important to note that because the load levels do not vary widely during the sample year (2007), the loss estimations are more accurate closer to the 2007 load levels. This fact also explains the error of estimating negative 'loss' for a no-load condition ($P_{out} = 0$).

FORECASTING WITH ESTIMATED LOSSES

The losses derived from the observations on the I^2R can be used for forecasting the total power to be taken at the source (Matambo substation) from the initial knowledge of demand at the distribution outlets of Chimuara, Ceramica, Mocuba, Molocue and Gurue substations, by the following equation:

$$
\begin{aligned}
P_h^{\text{Matambo}} = &\left(1+c_{\text{B03}}^{loss}\right)\cdot\left(1+c_{\text{Chim}}^{loss}\right)\cdot\Big[P_{\text{h}}^{\text{Chim}}+\left(1+c_{\text{B05}}^{loss}\right)\cdot\Big[P_h^{\text{Cera}}\cdot\left(1+c_{\text{Cera}}^{loss}\right)+\ldots\\
&+\left(1+c_{\text{Mocu}}^{loss}\right)\cdot\Big[P_h^{\text{Mocu}}+\left(1+c_{\text{B07}}^{loss}\right)\cdot\left(1+c_{\text{Molo}}^{loss}\right)\cdot\Big[P_h^{\text{Molo}}+\ldots\\
&+\left(1+c_{\text{C21}}^{loss}\right)\cdot\left(1+c_{\text{Guru}}^{loss}\right)\cdot P_h^{\text{Guru}}\Big]\Big]\Big]\Big]
\end{aligned}
\qquad (22)
$$

The loss coefficients are calculated as the ratio of the empirically estimated losses to the correspondent power out:

$$
c_{SE/LN}^{loss} = \frac{\Delta P_{corrected}}{P_{out}} \qquad (23)
$$

Simulations for load flows using the software PSS/E, for 2008 resulted in a power taken at Matambo of 97.1 MW, for distribution loads of 12.60 MW, 11.60 MW, 2.60 MW, 58.10 MW and 7.40 MW respectively at substations Chimuara, Ceramica, Mocuba, Molocue and Gurue. Simulations for 2009 resulted in a power taken at Matambo of 134.4 MW, for distribution loads of 7.20 MW, 17.50 MW, 4.00 MW, 86.90 MW and 10.90 MW respectively at the substations.

By assuming these loads to occur at the peaking hour of a summer day, the demand for power at Matambo was estimated by (22) and (18) with the (corrected) coefficients of Table V.32. At the peak hour it is estimated a power demand in Matambo of 99.69 MW in 2008, i.e. 2.7% higher than the forecasted by PSS/E, and of 141.6 MW in 2009, i.e. 5.4% higher than the forecasted by PSS/E. Although the results are only approximate as compared with PSS/E forecast, given the presence of calibration defects and measurement errors in the data set, they are deemed sufficient to validate the calculation of losses and the use of the estimations in the forecast of demand for power.

Billing for power taken (by the generator company) is made for real power recordings, which themselves may contain calibration defects or errors, i.e. if PSS/E forecasts can be interpreted as the lower limits of power taking, the above estimations can be interpreted as the upper limits.

TRANSMISSION LOSS ALLOCATION TO DISTRIBUTION NETWORKS

The half-ring formation of the 220 kV transmission network makes loss allocation to the distribution areas a policy matter: if loss allocation were based on the distance from the source, then the farthest distribution areas would be burdened with higher losses. It so happens that these are the poorer areas too (the north), i.e. the poorer would be charged higher electricity rates, thus violating the letter of the law[125] that establishes one tariff system for the whole country with no geographical differentiation as a way of promoting development in the least favored provinces. Still, an internal accurate accounting for decomposed costs is necessary for loss reduction investments and management strategies.

This study proposes to allocate the losses in the network proportional to the energy distributed in each area, i.e. the higher the volume of energy taken from the network, the higher the burden in losses in the power flows. Table V.26 lists the distribution areas radiating from each substation and their distributed energy on year 2007.

The allocation of transmission losses per distribution area was calculated from the yearly share of the total distributed energy (Table V.26), and resulted in the hourly transmission loss equations per distribution area shown in equation (24):

[125] Boletim da Republica, I Série, nº 74, 2º Suplemento, Conselho de Ministros, Decreto-Lei 38/77 de 27 de Agosto, 1977.

$$
\begin{aligned}
&E_{\text{Tete}}^{TR-loss} = 15.4\% \cdot E_{\text{B03}}^{loss} + 94.3\% \cdot E_{\text{Chim}}^{loss} \\
&E_{\substack{\text{Morrumbala} \\ \text{Mopeia,Rio}}}^{TR-loss} = 0.9\% \cdot E_{\text{B03}}^{loss} + 5.7\% \cdot E_{\text{Chim}}^{loss} \\
&E_{\substack{\text{Quelimane} \\ \text{Namacurra, Inhassunge}}}^{TR-loss} = 17.8\% \cdot E_{\text{B03}}^{loss} + 21.2\% \cdot E_{\text{B05}}^{loss} + 100\% \cdot E_{\text{Cera}}^{loss} \\
&E_{\substack{\text{Mocuba} \\ \text{Maganja, Pebane}}}^{TR-loss} = 4.3\% \cdot E_{\text{B03}}^{loss} + 5.1\% \cdot E_{\text{B05}}^{loss} + 100\% \cdot E_{\text{Mocu}}^{loss} \\
&E_{\text{Nampula \& northeast}}^{TR-loss} = 51.7\% \cdot E_{\text{B03}}^{loss} + 61.8\% \cdot E_{\text{B05}}^{loss} + 83.9\% \cdot E_{\text{B07}}^{loss} \\
&E_{\text{Molocue}}^{TR-loss} = 0.8\% \cdot E_{\text{B03}}^{loss} + 0.9\% \cdot E_{\text{B05}}^{loss} + 1.3\% \cdot E_{\text{B07}}^{loss} + 100\% \cdot E_{\text{Molo}}^{loss} \\
&E_{\text{Cuamba, Lichinga}}^{TR-loss} = 6.5\% \cdot E_{\text{B03}}^{loss} + 7.8\% \cdot E_{\text{B05}}^{loss} + 10.5\% \cdot E_{\text{B07}}^{loss} + 70.8\% \cdot E_{\text{C21}}^{loss} \\
&E_{\text{Gurue, Ile, Namarroi}}^{TR-loss} = 2.7\% \cdot E_{\text{B03}}^{loss} + 3.2\% \cdot E_{\text{B05}}^{loss} + 4.4\% \cdot E_{\text{B07}}^{loss} + 29.2\% \cdot E_{\text{C21}}^{loss} + 100\% \cdot E_{\text{Guru}}^{loss}
\end{aligned}
\tag{24}
$$

In these equations, the quantities $E_{SE/LN}^{loss}$, where SE/LN stands for the name of the substation (SE) or the line (LN), represent the loss equations estimated by regression by equation (18), of corrected coefficients shown in Table V.31 and Table V.32 at the end.

PAST METHODOLOGICAL APPROACHES ON DISTRIBUTION LOSSES

Distribution losses have long been calculated using the 'equivalent hours loss factor', or simply the 'loss factor', first developed by Buller and Woodrow as cited by Gustafson and Baylor (1988):

$$L_f = \chi \cdot L_d + (1-\chi) \cdot (L_d)^2 \tag{25}$$

The constant coefficient in this equation χ was initially value at 0.3 by Buller and Woodrow, then corrected to a range varying between 0.15 and 0.30 (Gustafson 1983), and later corrected yet again to 0.08 (Gustafson and Baylor 1988; Gustafson and Baylor 1989). A recent use of this equation in the estimation of distribution losses for the Indian system has placed χ at 0.2 value (Rao and Deekshit 2006).

The level of detail and the quality of the data characterizing the power flows in a distribution network determine the level of detail in the loss estimation procedures. Losses in transformers, capacitors and line segments are modeled with various complexities. Even analytical models of distribution losses require some level of approximation (Vempati, Shoults et al. 1987; Baldick and Wu 1991), given the complex nature of the power flows within the individual components and also in the network itself, see (Schultz 1978) for a model of a rectangular-equivalent network. The use of percent-values to estimate losses in individual components is first formalized by Flaten (1988), however this approach also requires detailed data that is not always readily available, and issues of loss allocation to the delivery points still are unresolved. In public utilities, it is quite common the attribution of a constant percent-value of losses per transformer and other equipment, based on recommendations of manufacturers, see for example pages 88-91 of ABB's switchgear manual (ABB 1988). Regression derivations of loss equations have also been used to model losses in the network feeders (Sun, Abe et al. 1980; Chen, Hwang et al. 1994).

Planning for distribution losses can determine the viability of a supply system as total losses can be as high as 40% in some systems (Dortolina and Nadira 2005). Distribution losses are composed of technical losses, resulting from the power flows in the networks, and non-technical losses, resulting from metering defects and human error in the metering, billing and collection processes. Not always is possible to differentiate these two types of losses.

The method of loss estimation needs to conform to data availability and its complexity is determined by the cost-burden of these losses. In this study, because of data limitations, the estimation of distribution losses is very simple and based on monthly energy flows data and basic interruption indicators.

DISTRIBUTION LOSSES

Technical losses in the distribution networks can only be approximated, by using the hour-equivalent approach by equation (25), with a constant of $\chi = 0.2$. The load factors are calculated per distribution network per month by dividing the monthly-billed energy to the monthly-recorded peak load multiplied by the hours of the month. The monthly losses are shown in Figure V.25 and the yearly average losses, from the calculated monthly losses, are presented in Table V.29.

Table V.29 - Yearly average losses in the distribution areas

SE	Names of the Distribution areas	L_f	Loss
Chimuara	Tete	27%	20%
	Morrumbala, Rio, Mopeia	12%	16%
Ceramica	Quelimane, Namacurra, Inhassunge	33%	NA
Mocuba	Mocuba, Maganja, Pebane	40%	2%
Molocue	Nampula and the northeast	29%	NA
	Molocue	23%	2%
Gurue	Cuamba and Lichinga	24%	13%
	Gurue, Tea plant., Ile, Soc.	28%	2%

The losses thus estimated are quite high and require validation from better data. Meter readings for Ceramica and Molocue distribution are not available. In addition, the use of a constant factor of 0.2 has not been tested for the Mozambican networks. Consequently, the distribution losses here estimated should be used with great caution, and more detailed studies on the distribution losses are recommended. The loss factors thus calculated are quite high, but possibly not too far from the mark, as distribution losses recorded at 23% in total during 2007 and are currently planned for 20%[126] level (EDM 2007).

[126] In the US, total electric losses of transmission and distribution, are currently 7% (internet source: http://www.eia.doe.gov/emeu/aer/txt/ptb0801.html)

The distribution networks operate with interruptions that constitute sources of non-served energy, or losses to the company. Losses of energy in the medium-voltage (MV) feeders due to interruptions in percent-values $c_{ka-month}^{loss\_qual}$ were calculated using the reported interruptability indicator SAIDI ("duration of interruption index"):

$$c_{ka-month}^{loss\_qual} = \frac{\sum_{kan} (\mathrm{SAIDI})_{\substack{\text{per PDE}\\ \text{at 'kan'}}} \cdot N_{\substack{\text{per PDE}\\ \text{at 'kan'}}}}{T_{\substack{\text{hrs}\\ \text{month}}} - \sum_{kan} (\mathrm{SAIDI})_{\substack{\text{per PDE}\\ \text{at 'kan'}}} \cdot N_{\substack{\text{per PDE}\\ \text{at 'kan'}}}} \tag{26}$$

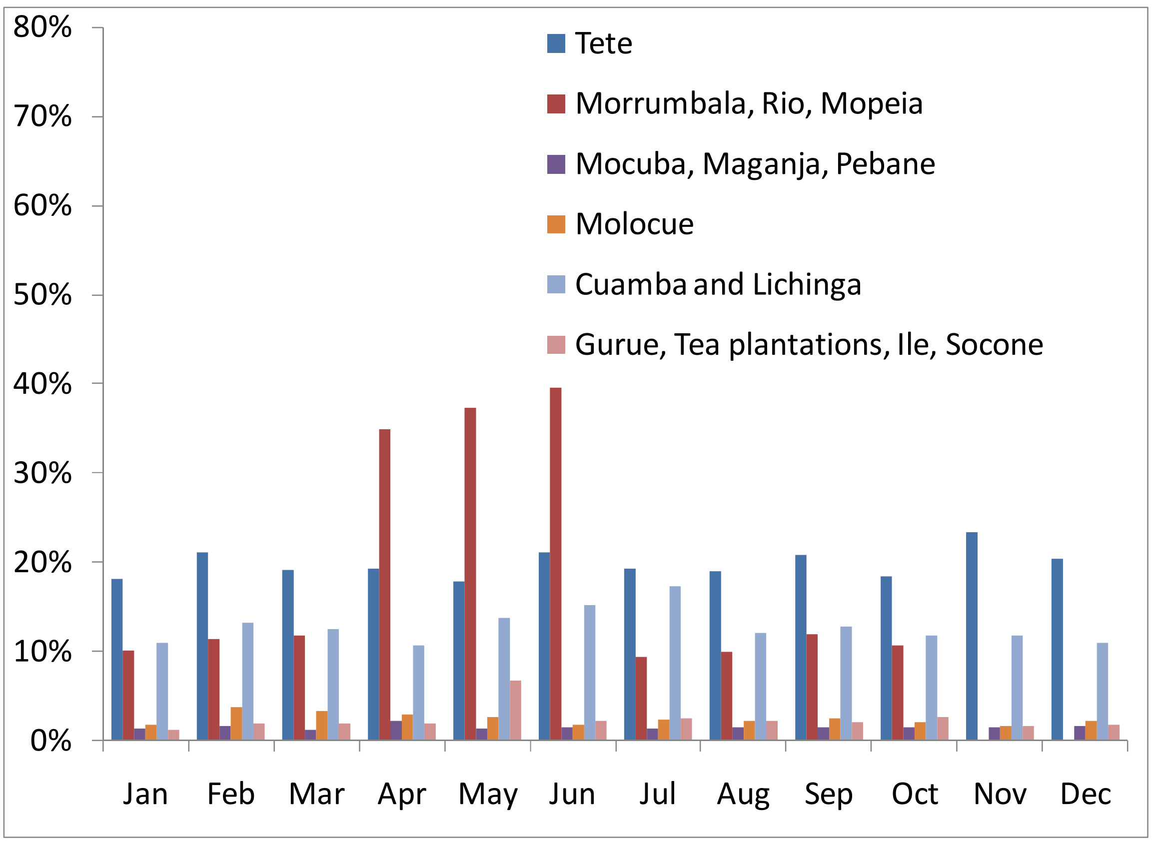

Figure V.25 - Monthly losses estimated for the distribution areas

Where the index *'ka'* stands for each distribution area and *'kan'* stands for the measurement (delivery) points in the distribution network. SAIDI measures the average duration of faults per distribution transformer station (PDE). The quantity N_{PDE} is the number of transforming stations in the distribution area (node) and $T_{hrs\text{-}month}$ is the duration of the period under analysis. Distribution data on interruptions and the energy losses from interruption records are presented in Table V.30.

The percent loss coefficients of Table V.29 and Table V.30, summed and multiplied by the respective distribution area energy flow, will calculate the energy loss in the distribution system (approximate). The high losses recorded in Chimuara and Gurue distribution may result from metering defects rather than actual losses, as the equivalent-hours loss factor L_f is applied to the maximum monthly-recorded loss in the network. Although the estimation of distribution losses is not very accurate, it was made so that for each distribution areas these losses could be added to the transmission losses previously calculated and allocated as per (24). Further studies must be conducted to adjust the constant χ in the equivalent-hours loss factor equation (25).

Table V.30 - Yearly quality-of-supply indicators in distribution areas

Substation	Feeder	No. of PDEs	SAIDI [hrs/yr-PDE]	Energy Loss [MWh/year]	
Chimuara	B04	1	52:59:00	273.56	0.6%
	E01 - E02	18	10:15:00	58.59	2.1%
Ceramica	E01 - E04	141	01:10:00	1001.98	1.9%
Mocuba	E05, E08	8	26:33:00	311.29	2.4%
Molocue	B08	1	65:21:00	1137.87	0.8%
	E05	11	09:24:00	27.09	1.2%
Gurue	C22	1	71:38:00	156.91	0.8%
	EL1 - EL4	35	11:41:00	384.95	4.7%

CONCLUSIONS

LIMITATIONS OF THE METHODOLOGICAL APPROACH

The empirical formulation of transmission losses using quadratic regression and the dependency on the squared electrical current and resistance of the system's component is theoretically sound, as it represents a relation that has been proven true (analytically) for technical losses of energy flows. Effects such as the seasonality of the load profiles[127], weather patterns[128] and the environment-specific[129] dependency of losses can also be included as explanatory variables in the empirical derivations, making loss formulation more exact.

However, the accuracy of estimations in regression derivations is determined by the quality of the observed variables. In this particular study, although hourly data was used, the following limitations apply and affect the dependability of the results, namely:

- The data set only covered the period of one year of power flows. During this year (2007) demand levels did not vary much (there was no significant load growth) in any of the distribution feeders. Consequently, the observed data characterizes flows only for a relatively short range of load flows. The estimations show lower accuracy for load flows progressively farther from this range (see accuracy of power forecast for 2009 and 2010 load levels, section "Forecasting with estimated losses").
- The low load levels may be the reason for insignificant seasonality of load profiles, in other words, the observed data does not show significant variations in the load profiles along the year. Consequently, the seasonality of the load was not modeled.

[127] Lower load variation (min-to-max) during summer because of the use of air-conditioning systems? Or during winter because of more intense nocturnal industrial production? Variations in the load profile between summer and winter?

[128] Temperature, humidity, presence of high winds, etc.

[129] Line segments crossing forested areas for example.

- There was no temperature data on an hourly or even daily basis for the system's substations. Consequently, weather patterns were not modeled. The same is true for environmental characteristics.
- The data revealed calibration defects and measurement errors that only partly could be isolated from the observed values.

The method used to estimate **transmission losses** proved to give reasonably accurate results in spite of the limitations of the data set, above listed.

The estimation of the **distribution losses** is much more imprecise. Distribution networks are usually mesh-like and with many delivery points. Power can flow through different branches of the network, during the day or the year, depending on the opening and closing of switchgear from operational requirements and due to the solicitation for power consumption. Distribution losses originate in the conductors and measurement systems:

- Purely technical distribution losses result from the power flow and from the reactive and inductive effects in the electrical conductors. These losses are proportional to the length of the network (resistance) and the energy flow, i.e. they are some factor of the squared electrical current and resistance of the network. They may be modeled simply, by finding an empirical factor that better describes the average loss behavior in the network and incorporates effects of mesh type and density, average operating conditions and average weather effects. Extensive observation of power flows and the detailed model of I^2R losses is analytically possible. However, its cost effectiveness is doubtful.
- The losses resulting from calibration and measurement errors can be huge given the large number of measurement points. These losses originate in the malfunctioning,

the deficient calibration or the non-existence of measuring devices[130], and in the reliability of the recording systems[131].

- Sometimes distribution losses also include the losses resulting in the billing process. Between the meter readings and the issuing of the monthly bill there may be discrepancies that constitute losses to the company, though of administrative origin. These losses are modeled when observations for energy supplied are collected from the billing records, rather than from the distribution feeders' metering systems.
- Losses due to interruptions in the supply are also averaged, as only approximately may the electrical company estimate the non-served energy per interruption of each branch. These losses are calculated by estimating the average power flowing in the branch and calculating the duration of interruption. The accuracy of this estimation depends on the reliability of the records on time and duration of interruptions and on the detail of the power flows in the interrupted branches.

Distribution loss estimation is consequently always approximate. The method used in this study is an empirical method that establishes a dependency of losses in the load factors of the network. Unfortunately, no estimation of the empirical coefficient χ was possible and this study used the latest coefficient established for distribution networks in India. There is no evidence that this is an appropriate coefficient other than the results of this study that show losses in the range currently estimated at the national level in Mozambique.

In this study, data to model distribution losses was limited to data from the billing records (i.e. administrative errors are incorporated in the calculated losses) and with a regularity of monthly energy flows. Furthermore, the data is aggregated per distribution area rather than

[130] Energy and power meters required regular maintenance and calibration and are expensive to replace

[131] Are the meter readings done manually, digitally? How often?

per feeder/branch of the networks. Finally, the data on distributed energy does not distinguish between residential, commercial or industrial supplies, and the losses are thus aggregated for all consumer categories. Given these limitations, the estimated distribution losses should be cited with great caution.

SUMMARY OF THE RESULTS

This study developed empirical loss equations for four transmission lines and five substations in the 'Linha Centro-Norte' (LCN) in Mozambique, calculated the respective marginal loss equations and demonstrated their use in forecasting the total power taking at the source (Matambo substation). The results are of satisfactory accuracy, within 5% of the forecasts by the PSS/E load flow simulations.

The dataset revealed calibration defects and measurement errors in the active power records, particularly prominent in the substations of Ceramica, Mocuba and Molocue. These effects were corrected-for in the loss equations; however, future works should include upgrading and calibration of the measurement equipment. The transmission loss coefficients, estimated for 2007, are 1.5% for lines B03 and C21 and for substation Chimuara, 1.1% and 0.8% respectively for lines B05 and B07, 2.2% for Ceramica, 0.01% for Mocuba, 0.04% for Molocue and 1.8% for Gurue substations.

The allocation of transmission losses was formulated by proportional weights of energy flows in the distribution areas, thus ensuring that distance from the source will not penalize poor communities with a higher loss (cost) burden.

Finally, distribution losses in areas supplied by the LCN substations under study were simply calculated from a very small dataset on distributed energy flows, with results in the range of 20% or less. Caution is made in the use of the loss factors and energy losses thus estimated as the constant in the equivalent-hour loss factor equation was not validated for the Mozambican networks. However, the method is applicable and it should reveal sufficient accuracy on future studies with more detailed distribution data.

NOMENCLATURE

SC = system's component

R_{nom} = nominal resistance of SC [Ohms]

R_{emp} = empirically derived resistance of SC [Ohms]

P_{in} = active power incoming into SC [MW]

P_{out} = active power outgoing out of the SC [MW]

$P_h^{Matambo}$ = active power measured in Matambo [MW]

V_{in} = voltage of power incoming into SC [kV]

I_{in} = Phase current flowing into SC [kA]

H_h = h[th] element of Hour vector 1x23

M_m = m[th] element of Season vector 1x3

$m_{SE/LN}^{loss}$ = marginal loss of substation SE or line LN [%]

$c_{SE/LN}^{loss}$ = loss coefficient of substation SE or line LN [%]

$\Delta P_{corrected}$ = power losses observed [MW]

$\Delta P_{observed}$ = power losses corrected [MW]

$E_{SE/LN}^{loss}$ = hourly power loss predicted by (18) with coefficients corrected shown in Tables A1 and A2 [MW]

$E_{dist}^{TR-loss}$ = hourly transmission power loss allocated to distribution area 'dist' [MW]

L_f = distribution loss factor [%]

L_d = load factor [%]

χ = constant of loss factor estimation

ka = index referring to distribution network (DN) ‘ka’

kan = index referring to delivery area (DA) ‘kan’ in DN ‘’ka’

N_{PDE} = number of delivery points in DA ‘kan’

SAIDI = duration of interruption index [hrs]

$T_{hrs\text{-}month}$ = hours of the month under consideration [hrs]

$c_{ka-month}^{loss-qual}$ = loss factor in distribution network ‘ka’ due to interruption events [%]

Table V.31 – Regression statistics

Statistics:	R^2	F-statistics	p-value	Error Variance
B03	84.2%	1.45E+03	0.00	0.01
B05	79.9%	1,192.58	0.00	0.00
B07	89.2%	2,519.39	0.00	0.00
C21	50.7%	311.85	0.00	0.00
Chimuara	90.9%	2,996.21	0.00	0.01
Ceramica	95.3%	6,062.87	0.00	0.01
Mocuba	89.3%	2,533.01	0.00	0.01
Molocue	80.0%	1,202.06	0.00	0.02
Gurue	80.8%	1,280.84	0.00	0.00

Table V.32 - Regressors from derivations with uncorrected and corrected datasets

	...for uncorrected dataset									...for corrected dataset		
Regressors:	B03	B05	B07	C21	Chimuara	Ceramica	Mocuba	Molocue	Gurue	Ceramica	Mocuba	Molocue
Constant	-0.16	-0.03	0.03	0.08	-0.04	-0.05	0.15	0.37	0.08	-0.2008	0.3328	0.0413
P_{out}	0.02	0.01	0.001	-0.01	0.01	0.05	-0.004	-0.01	-0.01	0.0404	-0.0258	-0.004
P_{out}^2	0.0000	0.0001	0.0002	0.001	0.0002	0.0157	0.0006	0.001	0.0015	0.0023	0.0005	0.0001
H1	-0.052	-0.024	-0.002	0.001	-0.0265	-0.0232	0.0187	0.0462	0.0018	-0.0077	0.0067	0.0016
H2	-0.054	-0.024	-0.001	0.001	-0.0277	-0.0174	0.0167	0.0444	0.0018	-0.0071	0.0074	0.0016
H3	-0.047	-0.023	-0.004	0.001	-0.0282	-0.0185	0.0191	0.0532	0.002	-0.0064	0.0079	0.0018
H4	-0.041	-0.024	-0.010	0.002	-0.0305	-0.021	0.0213	0.0502	0.0022	-0.0069	0.0076	0.0017
H5	-0.062	-0.026	-0.012	0.003	-0.0294	-0.016	0.0236	0.0562	0.0032	-0.0075	0.009	0.0018
H6	-0.046	-0.027	-0.010	0.003	-0.0317	-0.0191	0.0288	0.06	0.0031	-0.0081	0.0094	0.0021

	...for uncorrected dataset									...for corrected dataset		
Regressors:	B03	B05	B07	C21	Chimuara	Ceramica	Mocuba	Molocue	Gurue	Ceramica	Mocuba	Molocue
H7	-0.015	-0.022	-0.010	0.000	-0.0234	-0.0063	0.0244	0.0398	-0.0006	-0.0084	0.0081	0.0014
H8	-0.010	-0.007	-0.009	-0.004	-0.0088	0.005	0.0105	0.0043	-0.0048	0.0013	0.0049	0
H9	-0.015	-0.005	-0.007	-0.004	-0.004	0.0029	0.0033	-0.0129	-0.0059	0.0036	0.0022	-0.0007
H10	-0.006	-0.003	-0.007	-0.006	0.0021	0.0039	0.002	-0.0148	-0.0079	0.0048	0.0013	-0.0008
H11	-0.011	-0.003	-0.005	-0.006	0.004	0.0001	0.0011	-0.0144	-0.0081	0.0044	0	-0.0008
H12	-0.037	-0.007	-0.008	-0.006	-0.0026	-0.0129	0.0035	-0.0092	-0.0077	0.0006	0.0021	-0.0005
H13	-0.037	-0.014	-0.006	-0.005	-0.0192	-0.0064	0.0045	-0.0062	-0.0068	0.0009	0.0038	-0.0001
H14	-0.029	-0.015	-0.007	-0.005	-0.0173	-0.008	0.0055	-0.0037	-0.0069	0.0019	0.0035	0
H15	-0.042	-0.012	-0.008	-0.005	-0.0096	-0.0082	0.0078	-0.0084	-0.0073	0.0005	0.0032	-0.0003
H16	-0.049	-0.015	-0.006	-0.005	-0.0102	-0.0134	0.0094	-0.0002	-0.0069	-0.0048	0.0048	0.0001
H17	0.078	-0.003	-0.001	-0.004	-0.0055	-0.0194	0.0048	0.0018	-0.0047	-0.0098	0.0024	0.0001
H18	0.232	0.065	0.027	0.003	0.0598	0.0294	-0.0414	-0.0738	0.0056	0.0171	-0.0221	-0.0022
H19	0.196	0.090	0.036	0.009	0.1041	0.0696	-0.0502	-0.0748	0.0133	0.0166	-0.0117	-0.002
H20	0.136	0.072	0.029	0.010	0.0861	0.0669	-0.0603	-0.0828	0.0131	0.0068	-0.0194	-0.0025
H21	0.044	0.040	0.015	0.007	0.0382	0.0389	-0.0459	-0.0736	0.0099	0.0083	-0.0231	-0.0026
H22	-0.032	0.012	0.004	0.004	0.0136	0.0095	-0.0208	-0.0311	0.0064	0.0088	-0.0123	-0.0013
H23	-0.041	-0.008	0.004	0.002	-0.0126	-0.0128	-0.0012	0.0093	0.0032	-0.0016	-0.001	0.0003
M1	-0.024	-0.009	-0.002	-0.001	-0.0089	0.008	-0.0053	-0.0029	-0.0017	-0.002	0	-0.0001
M2	-0.023	-0.004	0.002	0.001	-0.0034	-0.0088	-0.0163	-0.0489	0.0019	0.002	0.0006	-0.0013
M3	0.024	0.008	0.000	0.001	0.0122	0.0004	0.0269	0.0543	0.0012	0.0005	0.0005	0.0013

APPENDIX V.1: CHARACTERISTIC DATA OF THE NORTHERN ELECTRICAL GRID IN MOZAMBIQUE

Table V.33 – Main lines in the Northern Electrical Transmission Network in Mozambique

Starting Bus	Destination Bus	Code	Design Voltage kV	Length Km	Thermal Limit MVA
Songo	Matambo	B01	220	120	247
Songo	Matambo	B02	220	115	477
Matambo	Caia	B03	220	294	477
Matambo	Caia	B04	220	291	477
Caia	Nicuadala	B05	220	154	477
Nicuadala	Quelimane	B51	220	20	239
Nicuadala	Mocuba	B05	220	108	477
Mocuba	Alto Molócuè	B07	220	151	239
Alto Molócuè	Nampula 220	B08	220	183	239
Alto Molócuè	Gurúè	C21	110	75.7	99

Data was collected on an hourly basis for each day of each month of the year 2007, in each substation of the grid, i.e. 8760 values for each variable under study (voltage, active power and reactive power readings at each incoming and outgoing line of each substation)[132]. This hourly characterization allows for the representation of any seasonal variation present in the electricity supply of each substation as well as the daily profiles of each measuring point.

[132] Daily readings for the energy meters' readings, at the incoming and outgoing lines of each substation, were recorded at 00:00 hours of each day of 2007. However, this data shows great inaccuracies and the authors opted for using only the active power readings as basis for calculating energy losses.

Table V.34 – Main substations in the Northern Transmission Network in Mozambique

Name	Transformer	Reactor	Capacitor	Incoming and Outgoing lines	
Matambo	-	65 MVAr, 33 kV	10 MVA, 33 kV	B01-220 kV B02-220 kV	B00-220kV B03-220kV B04-220kV
Chimuara	56 MVA	15 MVAr, 220 kV 20 MVAr, 33 kV		B03-220 kV B04-220kV	B05-220kV
Quelimane	50 MVA	20 MVAr, 33 kV		B05/B51-220kV	
Mocuba	280 MVA	20 MVAr, 33 kV		B05/B52-220kV	B07-220kV
Molocue	151 MVA	50 MVAr, 7.7 kV	C30 7.7kV	B07-220 kV	B08-220kV
Nampula	100 MVA	20 MVAr, 33 kV		B08-220 kV	

Table V.35 – Nominal resistances to power flow

	Ohms	Formula
B03	11.2	$R_{\text{line}} = R_{\text{per km}} \cdot L_{\text{km}}$
B05	11.5	
B07	11.3	(data in Table V.33)
C21	7.9	
Chimuara	14.8	$R_{\text{substation}} = \begin{cases} R\,@\,220kV & \text{for Chimuara, Ceramica,} \\ & \text{Mocuba and Molocue} \\ R\,@\,110kV & \text{for Gurue} \end{cases}$
Ceramica	24.3	
Mocuba	23.5	
Molocue	35.3	
Gurue	16.1	(data from EDM's technical database)Table V.33

The data recorded contains errors that can be originated at the meters themselves (calibration defects), and result from the manual recording which was done in two stages: from the meters to the daily (paper) recording form, and from this form to the digital format in excel. The correction of typing mistakes was made, and some of the obviously recording errors were corrected in consultation with the substation staff. Notwithstanding the presence of outliers in the corrected sample, the authors still accept as sufficiently accurate the derivations made from these data.

The load levels in the system are not very large, see Figure V.26:

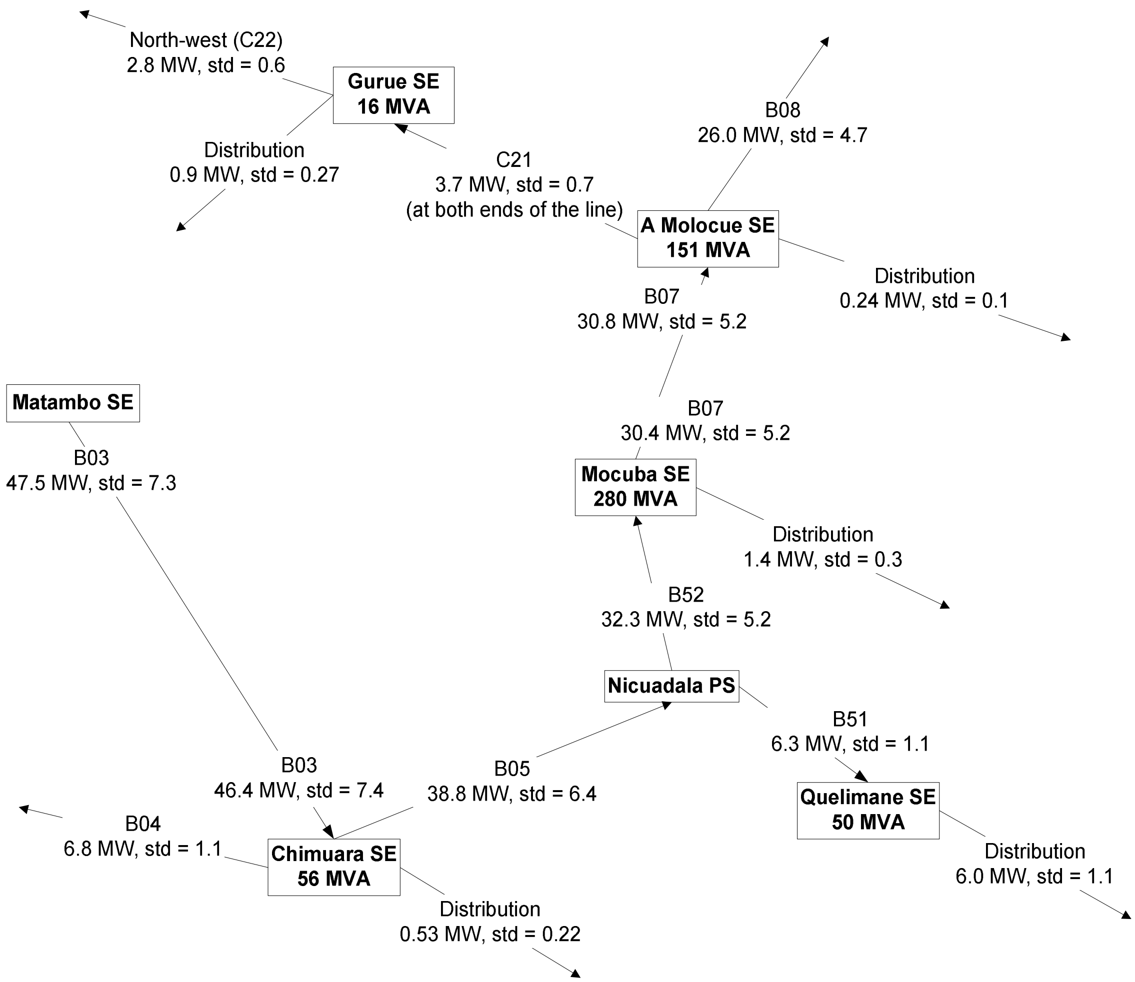

Figure V.26 – Means and standard deviations in the recorded (active) power flows

Energy supply[133] originates in Matambo substation and is feed into B03 transmission line, at 220 kV, with a mean (trimmed to 5% of the non-zero observations, to account for outliers and zero records) of 47.5 MW and a standard deviation (STD) of 7.3 MW 'towards'

[133] Note that this description explains the route of power flows, which is however instantaneously transmitted

Chimuara. In Chimuara, the energy flow is 'backed' into B04 line to supply Tete[134] (at 110 kV, with a mean load of 6.8 MW and 1.1 STD), feeds the distribution network at 110 kV and 33 kV (0.53 MW, 0.22 STD), and continues 'towards' Ceramica and Mocuba, at 220 kV (38.8 MW, 6.4 STD). In Ceramica, it is transformed down to 33 kV and distributed (6.0 MW, 1.1 STD); in Mocuba it is transformed down to 33 kV for local distribution (1.4 MW, 0.3 STD) and continues to Molocue at 220 kV (30.4 MW, 5.2 STD). At Molocue, part of the flow continues, at 220 kV to the Nampula substation and the Northern-Eastern districts (26 MW, 4.7 STD), part is transformed down to 110 kV and transferred to Gurue substation and the north-west (3.7 MW, 0.7 STD), and part is transformed down to 33 kV and distributed locally (0.24 MW, 0.1 STD). Finally at Gurue, the energy is transferred to Cuamba and Lichinga at 110 kV (northern-western districts), 2.8 MW, 0.6 STD, and transformed down to 33 kV to supply the nearby distribution networks (0.9 MW, 0.27 STD).

THE DISTRIBUTION NETWORKS

Table V.36 shows the recorded yearly energy and peak load in each of the distribution feeders. The yearly average load received in Chimuara (48 MW, 3.5 STD) is partly returned to Tete, through the B04 transmission line (7.5 MW, 1.8 STD), and forward to Quelimane (5.3 MW, 0.6 STD) by way of the B05 line. The B05 line transmits to Mocuba substation, through Molocue substation (lines B07 and B08), to supply Nampula and the northern-eastern load centers (26.1 MW, 2.9 STD).

Although a slight reduction of electrical loads is recorded in the colder months of June and August, it is not significant across the year, see Figure V.27. Variances in the monthly data indicate that results on the Tete supply (B04 line) are of higher uncertainty than peak and mean loads for the Nampula supply (B08 line). The calculation of the energy losses in the

[134] This arrangement was a temporary solution, but prevalent during all year of 2007

distribution feeders will use the monthly data on billed energy in the distribution areas, and the records of energy meter readings, active and reactive power levels, and voltage readings in the outgoing distribution lines (feeders) in the substations.

Table V.36 – Characteristics of the distribution feeders (2007) in the LCN system analysis

Substation	Feeder	Voltage kV	Names of the Distribution areas	Distributed energy MWh/year	Peak Load MW
Chimuara	B04	220	Tete	44,955	11.0
	E01 - E02	33	Morrumbala, Rio, Mopeia	2,722	1.1
Ceramica	E01 - E04	33	Quelimane, Namacurra, Inhassunge	52,049	11.2
Mocuba	E05, E08	33	Mocuba, Maganja, Pebane	12,523	2.4
Molocue	B08	220	Nampula and the northeast	151,391	35.0
	E05	33	Molocue	2,268	0.6
Gurue	C22	110	Cuamba and Lichinga	19,032	5.0
	EL1 - EL4	33	Gurue, Tea plats., Ile, Socone	7,857	1.9

See Table V.37 for the yearly indicators of interruption levels. In this table, SAIDI corresponds to the average duration of interruption per PDE (transforming stations connected to the feeder), SAIFI corresponds to the average number of interruptions per PDE, and SARI the average time of interruption in the respective feeders. Chimuara distribution shows the longest interruptions (average 1 hour 54 minutes per interruption), while Ceramica register the shortest (average 35 min per interruption).

Yearly energy losses due to interruptions are in the order of 0.6% to 4.7% of the total energy distributed per feeder, with the higher losses recorded at voltages of 33 kV, particularly in the Gurue distribution network.

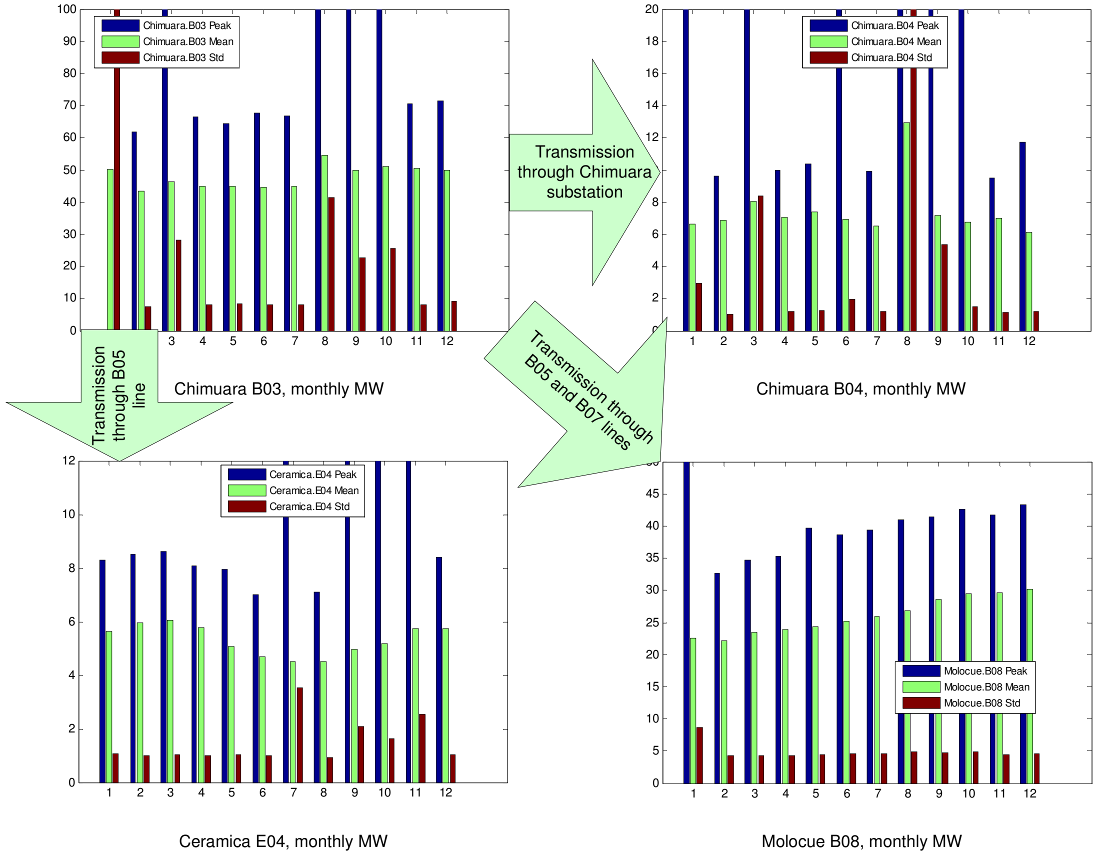

Figure V.27 – Monthly loads at line (B03) and the main load centers

Table V.37 – Interruption records for the distribution feeders during 2007

Substation	Feeder	Number of PDEs	SAIDI [hrs/yr-PDE]	SAIFI [interrup./yr-PDE]	SARI [hrs/interrup.]
Chimuara	B04	1	52:59	26	2:02
	E01 - E02	18	10:15	5.8	1:46
Ceramica	E01 - E04	141	1:10	2	0:35
Mocuba	E05, E08	8	26:33	14	1:53
Molocue	B08	1	65:21	49	1:20
	E05	11	9:24	8.6	1:05
Gurue	C22	1	71:38	122	0:35
	EL1 - EL4	35	11:41	15.4	0:45

The transmission losses increase with distance from the source making the more remote distribution networks chargeable with higher losses than those closer to the source. However, these remote areas are also the least developed, and the Mozambican government established as a pro-development policy that electricity rates would be the same across the country, regardless of the geographic location[135]. Internal accounting in the electric company however needs to differentiate the networks in their respective shares of costs, so that performance evaluations are made. This study proposes to allocate transmission losses of the whole system to the distribution networks in shares proportional to their yearly energy flows.

Based on the yearly energy flows in the distribution networks during 2007, Table V.36, the following allocation of energy losses in the transmission segments of the LCN system was made, by the following principles:

- losses in the transmission lines are proportionally allocated to the distribution networks based on their yearly share of energy flows
- substation losses are entirely allocated to their respective distribution networks.

The allocation of energy losses of each system's component is presented in Table V.38. The far off networks are not penalized by their distance from the power source, for example Gurue will only be allocated 2.7% of the energy losses occurring in line B03. However, if the Gurue substation performs poorly, the distribution network of Gurue will bear the full burden of its losses. Nampula and the northeast distribution networks will bear the higher share of losses as they consume about 50% of the total energy flow. The transmission losses

[135] Source: Boletim da Republica, I Série, nº 74, 2º Suplemento, Conselho de Ministros, Decreto-Lei 38/77 de 27 de Agosto, 1977.

thus allocated and the respective distribution losses of the individual networks can be used to evaluate the networks' overall performance.

Table V.38 – Allocation shares of transmission energy losses to the distribution networks

	Tete	Morrum-bala, Rio, Mopeia	Quelimane Namacurra Inhassunge	Mocuba Maganja Pebane	Nampula and the northeast	Molocue	Cuamba and Lichinga	Gurue Ile, Socone
Line B03	15.4%	0.9%	17.8%	4.3%	51.7%	0.8%	6.5%	2.7%
Chimuara	94.3%	5.7%						
Line B05			21.2%	5.1%	61.8%	0.9%	7.8%	3.2%
Ceramica			100%					
Mocuba				100%				
Line B07					83.9%	1.3%	10.5%	4.4%
Molocue						100%		
Line C21							70.8%	29.2%
Gurue								100%

APPENDIX V.2: DATA PREPARATION AND CALCULATIONS

THE DATA

During the year 2007, metering of power flows in the Linha Centro Norte (LCN, the center northern transmission system in Mozambique) was still done with both digital and analog instruments and recorded in paper-forms, from where data was manually digitized into excel spreadsheets. This has lead to paper and digital records with missing values, and to typing errors, that made the analysis of power flows and correspondent losses imprecise.

The data collected consists of hourly readings of active and reactive power flows and voltages, taken in each line of each substation under analysis. Daily readings of energy meters per line were collected, but due to many missing values and obvious recording errors, this set of data was not used. Consequently, for the estimation of losses only the hourly readings of power (active and reactive) and voltages were used. For each substation, data was organized in tables of 8760 rows, corresponding to the 8760 hours of year 2007, and *'3n'* columns, corresponding to three times the number (*n*) of incoming and outgoing transmission and distribution lines in the substation. The accuracy of the records varies between substations and consequently the data-cleanup approach uses different outlier-levels for each component of the transmission system.

For each substation and each transmission line, a data structure was created with a matrix 8760 x 3N containing the hourly records for voltage, active power and reactive power of each incoming and outgoing line of the substation (a total of N lines per substation). These data structures, per substation and per transmission line, were successfully used to estimate empirical hourly power (energy) losses in each of these system's components, by run of several functions constructed in MATLAB. This appendix will present the programming routines and explain the sequence of data-cleanup followed. The actual MATLAB program is presented in Annex 3.

THE MATLAB PROGRAMMED ROUTINES AND FUNCTIONS

THE DATA-CLEANUP ROUTINES

Before regression could be run and the Current and Power-Factor variables be built, the recorded hourly data had to be cleaned out of missing and outlier values, and this was conducted in three steps, namely:

- Voltage hourly records on the inflowing and out flowing power, at each substation and transmission line, were reviewed. The outlier values (at three standard deviations radius of the mean) and the zero (missing) values were replaced by the mean value of voltage, previously calculated for the nonzero records only
- The hourly records of active and reactive power, entering and outing each substation and line, were reviewed. The outlier values (at *N* standard deviations radius of the mean, trimmed by 50% of the sample) were identified for deletion, with *N* taking the value of $N = 5$ for all components.
- The hourly records of active power entering each substation and transmission line and their (calculated) losses by equation (27), were reviewed. The zero (missing) values were identified for deletion.

The data sets for each component of the system were consequently reduced from 8760 rows to a number as described in Table V.39. In line B03, the cleanup reached 13% due to missing values from Matambo substation for the month of November. Trimming the sample for 1% to 5% of the higher and lower losses was tested and rejected as giving very poor results (in the derivation by regression).

Table V.39 – Results from the cleanup of the dataset. Response Variable is calculated as per equation (27)

System's component	New size of dataset	New response (mean)	New response (std-deviation)	records removed	% removed
Line B03	7609	2.91	3.33	1151	13.1%
Line B05	8433	2.07	2.69	327	3.7%
Line B07	8544	1.24	1.38	216	2.5%
Line C21	8521	0.09	0.08	239	2.7%
SS Chimuara	8417	1.14	2.01	343	3.9%
SS Ceramica	8364	0.27	0.23	396	4.5%
SS Mocuba	8556	0.71	0.44	204	2.3%
SS Molocue	8463	1.00	0.38	297	3.4%
SS Gurue	8561	0.05	0.04	199	2.3%

DATA PREPARATION AND DERIVATION APPROACH GM1

The derivation of the empirical functions for losses in each transmission line and substation is done by multilevel linear regression, in which the **response variable** is the calculated hourly power loss as a percentage of the power out, i.e. the difference between the active power in and the active power out divided by the power out, in absolute values

$$c^{loss} = abs\left(\frac{P_{IN} - P_{OUT}}{P_{OUT}}\right) \tag{27}$$

Although some records have negative responses, these were transformed into positive responses on the assumption that the regression derivation formulates loss effects and measurement errors effects regardless of the direction of their 'flow'. The dependency of the percent-losses on the power outing of each substation and line is consistently negative, indicating that as load increases, the percent-losses decrease. This effect may be explained by having the recorded losses reasonably independent of the power flowing through the system and varying within a constant range, or having higher loads to bring the system's equipment into the operating ranges of higher efficiencies. This behavior means that percent-losses are lower at peaking times, though not necessarily by much.

Figure V.28 and Figure V.29 show the percent-losses per day, calculated as per equation (27) but with daily energy instead of hourly power. With exception of Ceramica, Molocue and Gurue substations, the daily losses are in general constant and negatively mildly dependent on the peak-load levels.

The negative dependency on load is more evident on the hourly losses, see Figure V.30 and Figure V.31, from which it can be concluded that in general losses reduce with load, but overall are fairly constant on a daily basis. The intersects of the linear fitting for hourly percent-loss are 4.6% for line B03, 4% for line B05, 5% for line B07, 2.6% for line C21, 1.2% for substation Chimuara, 8% for Ceramica, 5.1% for Mocuba, 5.9% for Molocue and 1.5% for Gurue. These values can be interpreted as the no-load losses that occur in these system's components, with higher loads reducing the hourly losses. With exception of Ceramica, Molocue and Gurue substations, the other system's component record average daily losses in the order of 3% for line B03, 0.34% for line B05, 1.4% for line B07, 1.4% for line C21, 1.8% for substation Chimuara and 2.5% for Mocuba.

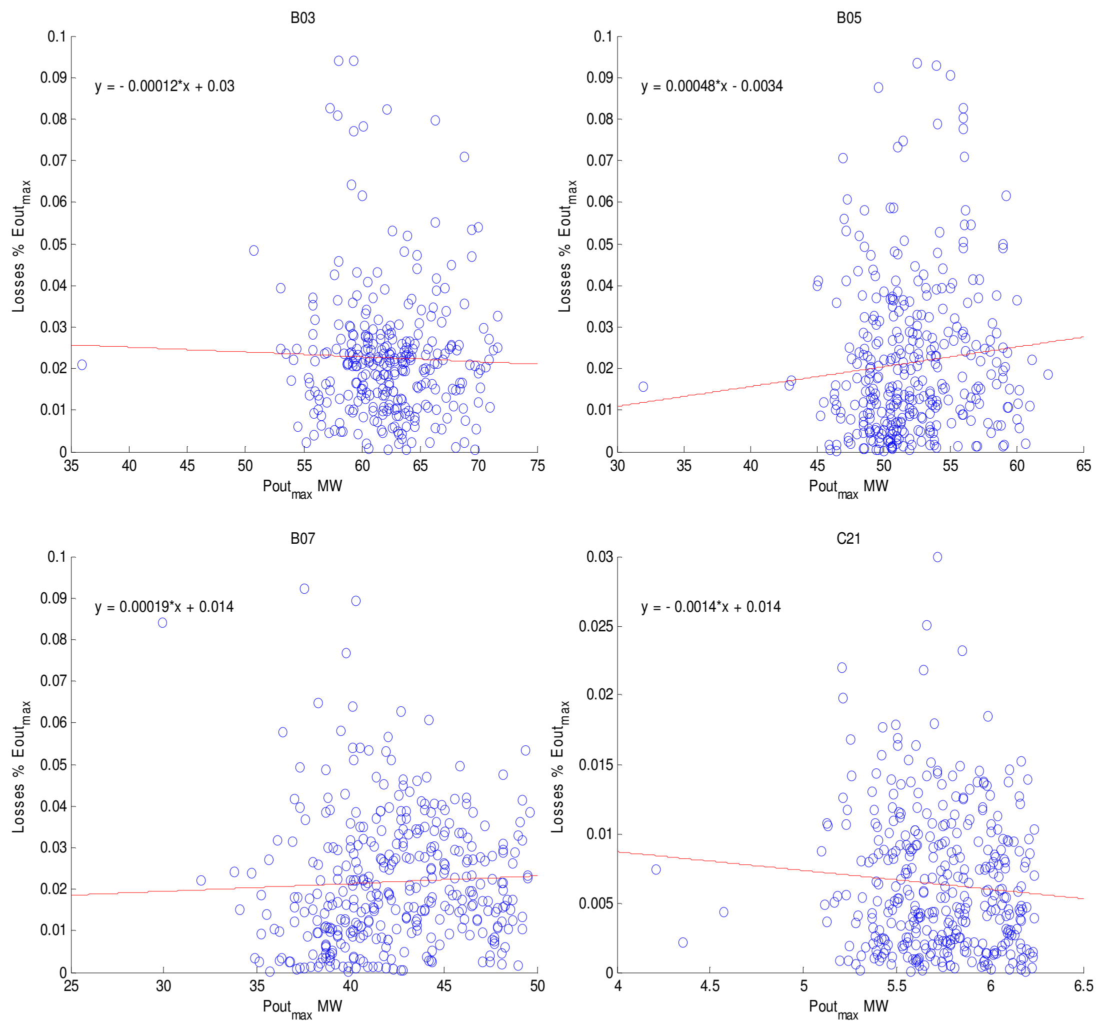

Figure V.28 – Daily Energy Losses recorded in the Transmission lines

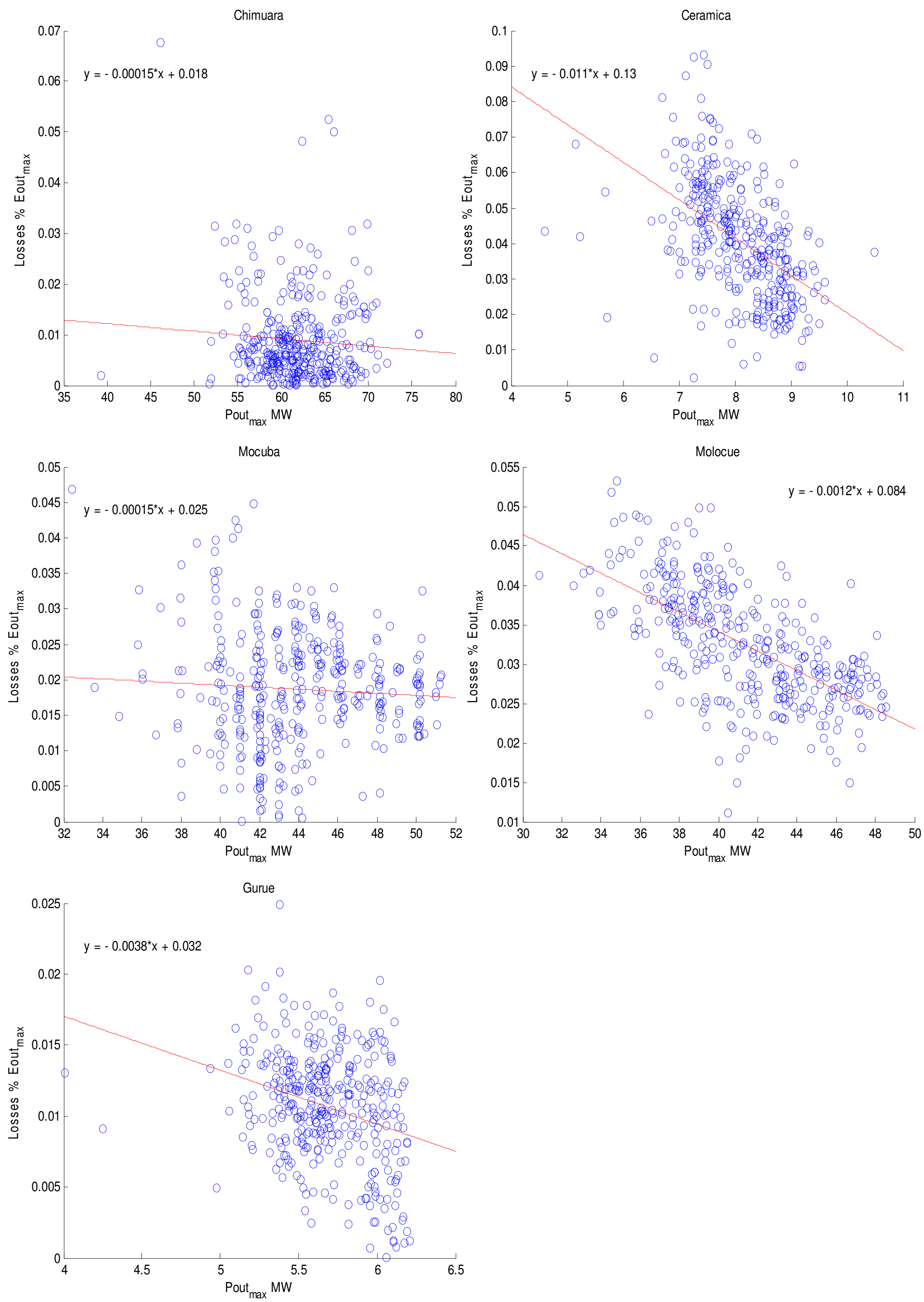

Figure V.29 – Daily Energy Losses recorded for the Substations

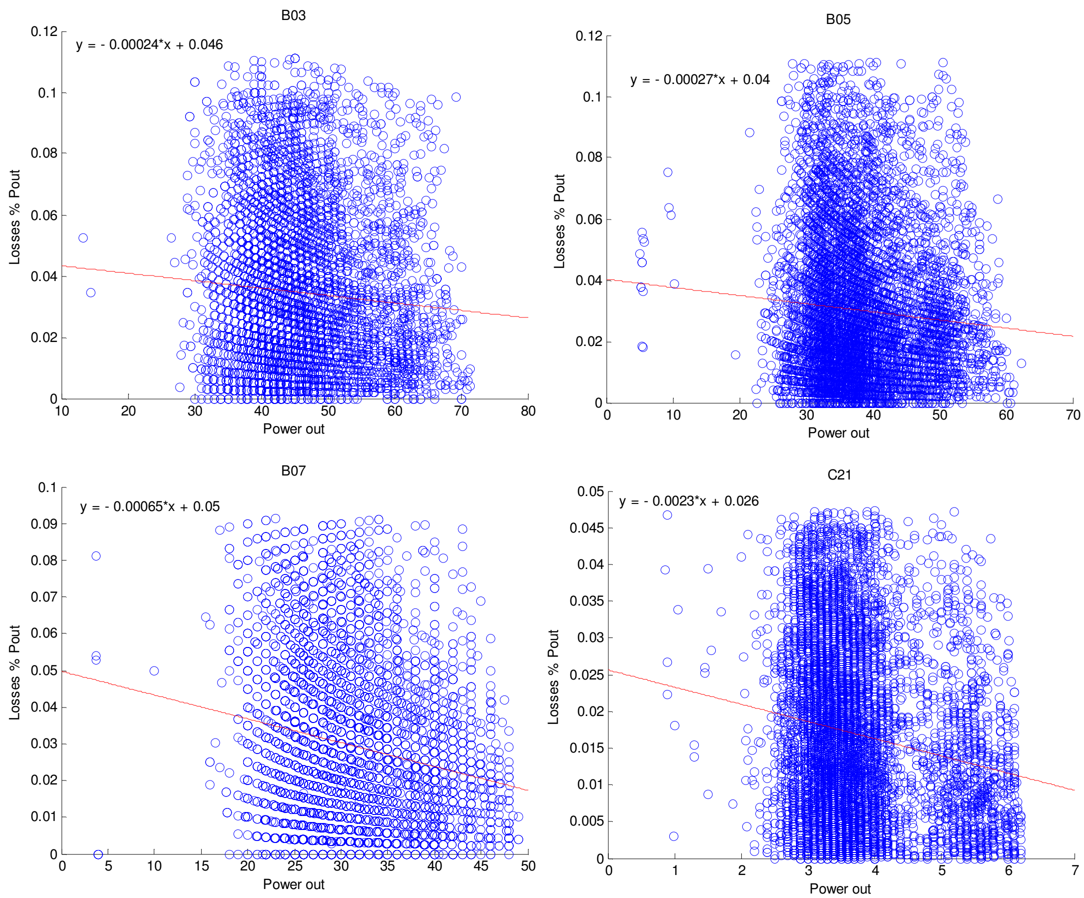

Figure V.30 – Hourly Energy Losses recorded for Transmission lines

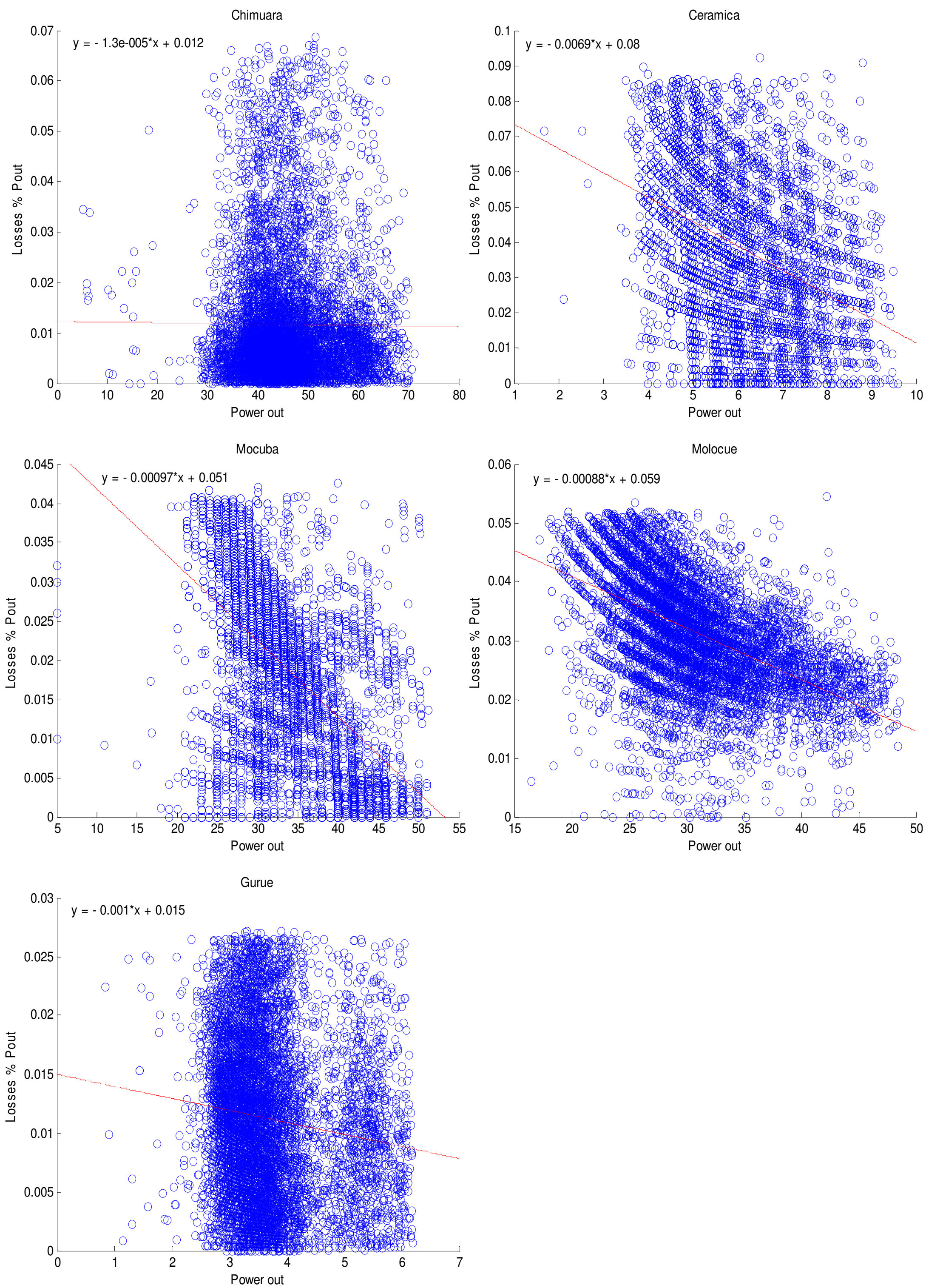

Figure V.31 – Hourly Energy Losses for the Substations

The explanatory variables in the regression derivation are a combination of the hourly active current out[136], calculated as the ratio of the active power out and the line voltage $I_{out} = \dfrac{P_{out}}{\cos\varphi_{out} \cdot V_{out}}$, the power factor $\cos\varphi_{out} = \cos\left(arc\tan\dfrac{Q_{out}}{P_{out}}\right)$ and three matrix variables representing the hour of the day (*H*), the season (*M*) and whether the day is a weekday or a weekend day (*W*).

These variables were constructed as follows:

- The hour variable *H* is a matrix of 8760x23 size, in which the rows represent each hour of the year and the columns represent the hours between 1 and 23, taking the value of 1 when the column number coincides with the hour of the day. At zero hours all columns of this variable take the value -1, thus centering the regression derivation and minimizing the effects of co-linearity of the hourly records.
- The season variable *M* is a matrix of 8760x3 size, in which the rows represent each hour of the year and the columns represent the seasons of Spring (March and April), Winter (May to August) and Fall (September and October), taking the value of 1 when the column number coincides with the season it represents. For the Summer (November to February) all columns of this variable take the value -1, thus centering the regression derivation. The seasons[137] were established based on the mean maximum temperature registered in these months, calculated from records of years 1971 to 2000

[136] The regression with individual outing line measures of power and power factor were run and it did not significantly change the results of the estimation.

[137] Selected based on the mean of recorded maximum temperatures, for years 1971 to 2000: temperatures of summer months > 32 ^{o}C, fall and spring months between 30 – 31 ^{o}C, winter months < 29^{o}C. Source of climate data: www.inam.gov.mz

- The weekday variable is a vector of 8760x1 size, in which the rows take value 1 when the day of the record is a weekday, or a value of -1 when it corresponds to a weekend day.

The grouping by seasons reduced the number of cross-effects explanatory variables without significantly affecting the outcome of the derivation because a pre-analysis of the typical load profiles showed very small variations between these groups.

The explanatory variables were then arranged into a 8760x125 matrix, of which columns 2 to 6 contains the data on the hourly current and power factors, columns 7 to 33 contain the variables H, M and W, and the rest of the columns contain respectively the cross effects of hour to weekday (*H*W*) and of hour to season (*H*M*):

$$X_{8760\times125} = \begin{vmatrix} \{1\}_{8760\times1} & \{I_{OUT}\}_{8760\times1} & \{I_{OUT}{}^2\}_{8760\times1} & \{\cos\varphi_{OUT}\}_{8760\times1} \ \cdots \\ \cdots \ \{\cos\varphi_{OUT}{}^2\}_{8760\times1} & \{I_{OUT}\cdot\cos\varphi_{OUT}\}_{8760\times1} & \{H\}_{8760\times23} \ \cdots \\ \cdots \ \{M\}_{8760\times3} & \{W\}_{8760\times1} & \{H\cdot W\}_{8760\times23} & \{H\cdot M\}_{8760\times69} \end{vmatrix} \tag{28}$$

T tests were conducted[138] for the significance of the variables and interestingly it as found that variable W (weekday/weekend) is not significant below the 5% level, and the same can be said for all the cross effect terms *(H*W)* and *(H*M)*. Cross effects between the hour-variable *H* and the outing-current I_{OUT} and the power factor *cosφ* were also tested and revealed insignificance below the 5% level. The **explanatory matrix of the first level regression** was then reduced to:

$$X_{8760\times32} = \begin{vmatrix} \{1\}_{8760\times1} & \{I_{OUT}\}_{8760\times1} & \{I_{OUT}{}^2\}_{8760\times1} & \{\cos\varphi_{OUT}\}_{8760\times1} \ \cdots \\ \cdots\{\cos\varphi_{OUT}{}^2\}_{8760\times1} & \{I_{OUT}\cdot\cos\varphi_{OUT}\}_{8760\times1} & \{H\}_{8760\times23} & \{M\}_{8760\times3} \end{vmatrix} \tag{29}$$

[138] For this evaluation the authors used the 'stepwise' regression function from the statistical toolset of MATLAB

and the empirical formulation of power flow losses (coded GM1 for purposes of future comparison) for substations and transmission lines took the final form:

$$abs\left(\frac{P_{in}^{SE/LN}-P_{out}^{SE/LN}}{P_{out}}\right)=\alpha_0^{SE/LN}+\alpha_1^{SE/LN}\cdot I_{out}^{SE/LN}+\alpha_2^{SE/LN}\cdot\left(I_{out}^{SE/LN}\right)^2+$$
$$+\alpha_3^{SE/LN}\cdot\cos\varphi_{out}^{SE/LN}+\alpha_4^{SE/LN}\cdot\cos^2\varphi_{out}^{SE/LN}+$$
$$+\alpha_5^{SE/LN}\cdot I_{out}^{SE/LN}\cdot\cos\varphi_{out}^{SE/LN}+\sum_{i=1}^{23}\alpha_{6i}^{SE/LN}\cdot H_i^{SE/LN}+ \tag{30}$$
$$+\sum_{j=1}^{3}\alpha_{7j}^{SE/LN}\cdot M_j^{SE/LN}+\varepsilon_{loss}^{SE/LN}$$

where

$$I_{out}^{SE/LN}\equiv\frac{P_{out}^{SE/LN}}{V_{out}^{SE/LN}}\quad;\quad\cos\varphi_{out}^{SE/LN}\equiv\cos\operatorname{atan}\left(\frac{Q_{out}^{SE/LN}}{P_{out}^{SE/LN}}\right)$$
$$\alpha_0^{SE}=\beta_0+\beta_1\cdot\left(P_{cap-inst}^{SE}\right)^2+\beta_2\cdot\left(Q_{cap-inst}^{SE}\right)^2+\beta_3\cdot\left(Year_{overall}\right)+\varepsilon_{SE}$$
$$\alpha_0^{LN}=\beta_0+\beta_1\cdot L_{km}^{LN}+\beta_2\cdot S_{cap-inst}^{LN}+\varepsilon_{LN}$$

The thus predicted loss coefficients $c_{SE/LN\_PREDICTED}^{loss}$ were then used to estimate power requirements at the source of the system's power, as per equation (31):

$$P_h^{\text{Matambo}}=P_{\text{h}}^{\text{Chimuara}}\cdot\left(1+c_{\text{B03}}^{loss}\right)\cdot\left(1+c_{\text{Chim}}^{loss}\right)+\left(1+c_{\text{B03}}^{loss}\right)\cdot\left(1+c_{\text{Chim}}^{loss}\right)\cdot\ldots$$
$$\ldots\cdot\left(1+c_{\text{B05}}^{loss}\right)\cdot\left\{\begin{array}{l}P_h^{\text{Ceramica}}\cdot\left(1+c_{\text{Ceram}}^{loss}\right)+P_h^{\text{Mocuba}}\cdot\left(1+c_{\text{Mocuba}}^{loss}\right)+\\+\left(1+c_{\text{Mocuba}}^{loss}\right)\cdot\left(1+c_{\text{B07}}^{loss}\right)\cdot\left(1+c_{\text{Molocue}}^{loss}\right)\cdot\\\cdot\left[P_h^{\text{Molocue}}+P_h^{\text{Gurue}}\cdot\left(1+c_{\text{C21}}^{loss}\right)\cdot\left(1+c_{\text{Gurue}}^{loss}\right)\right]\end{array}\right\} \tag{31}$$

Where P_h stand for the load profile at the distribution networks of each studied substation and $c_{SE/LN}^{loss}$ stand for the empirically derived loss coefficients in each of the system's substations and lines.

Measurement and calibration errors introduced variability in the data set as previously discussed. Smoothing the active power data in and out, with a window of 3 hours using a moving average has only slightly improved the results (R^2). Consequently, the empirical analysis needs to be reformulated for an alternative approach, to obtain loss profiles that can be taken as reasonably accurate. Note that these profiles have not yet been measured or estimated, so this derivation is opening new ground.

ALTERNATIVE DERIVATION APPROACH GM2

Rather than modeling the losses, we set the incoming hourly active power as dependent on the outgoing power, and then calculated the losses from the predicted difference, as follows:

$$P_{in}^{SE/LN} = \alpha_0^{SE/LN} + \alpha_1^{SE/LN} \cdot P_{out}^{SE/LN} + \sum_{i=1}^{23} \alpha_{6i}^{SE/LN} \cdot H_i^{SE/LN} + \sum_{j=1}^{3} \alpha_{7j}^{SE/LN} \cdot M_j^{SE/LN} + \varepsilon_{loss}^{SE/LN} \quad (32)$$

This derivation is coded GM2, equation (32), and the regression coefficients $c_{SE/LN}^{loss} = abs\left(\frac{P_{in\_PREDICTED}^{SE/LN} - P_{out}^{SE/LN}}{P_{out}^{SE/LN}} \right)$ are then compared with those estimated by GM1 derivation, equation (30). The source of the system's power in Matambo is then calculated, as per equation (31), and compared with the GM1 results.

ALTERNATIVE DERIVATION APPROACH GM3

The three-phase losses to model may also be calculated as the squared incoming current multiplied by the resistance as follows:

$$\begin{aligned} \Delta P_{pred}^{loss} = \left(I_{in}^{SE/LN}\right)^2 \cdot R = \alpha_0^{SE/LN} + \alpha_1^{SE/LN} \cdot P_{out}^{SE/LN} + \alpha_2^{SE/LN} \cdot \left(P_{out}^{SE/LN}\right)^2 + \ldots \\ + \sum_{i=1}^{23} \alpha_{6i}^{SE/LN} \cdot H_i^{SE/LN} + \sum_{j=1}^{3} \alpha_{7j}^{SE/LN} \cdot M_j^{SE/LN} + \varepsilon_{loss}^{SE/LN} \end{aligned} \quad (33)$$

where

$$I_{in}^{SE/LN} = \frac{\sqrt{\left(P_{in}^{SE/LN}\right)^2 + \left(Q_{in}^{SE/LN}\right)^2}}{\left(V_{in}^{SE/LN}\right)^2}$$

This derivation is coded GM3, equation (33), and the coefficients $c_{SE/LN}^{loss} = \frac{\Delta P_{pred}^{loss}}{P_{out}^{SE/LN}}$ are then compared with those estimated by GM1 and GM2 derivations, equation (30) and (32). The source of the system's power in Matambo is calculated, equation (31), and compared with the GM1 and GM2 results.

THE RUN OF THE REGRESSION ROUTINES GM1, GM2 AND GM3

The regression derivations ran with MATLAB's function 'regress' on the response vector and the explanatory matrix, which uses an 'ordinary least squares derivation', constructed respectively as per equation (30) for GM1 derivation, per equation (32) for GM2 derivation and per equation (33) for GM3 derivation. Although there is a good correlation between the active power incoming into a line or substation and the outing current and power factor, the actual loss as per equation (27) is poorly correlated with the outing power (Table V.40).

Table V.40 – Statistics of 1st level regression on the power losses

	GM1 derivation		GM2 derivation		GM3 derivation	
	R^2	P-value	R^2	P-value	R^2	P-value
B03	25.9%	0.00	98%	0.0	84%	0.0
B05	12.9%	0.00	98%	0.0	80%	0.0
B07	4.2%	0.00	99%	0.0	89%	0.0
C21	9.3%	0.00	100%	0.0	51%	0.0
Chimuara	3.3%	0.00	99%	0.0	91%	0.0
Ceramica	13.4%	0.00	99%	0.0	95%	0.0
Mocuba	29.0%	0.00	100%	0.0	89%	0.0
Molocue	41.2%	0.00	100%	0.0	80%	0.0
Gurue	7.0%	0.00	100%	0.0	81%	0.0

In the GM1 derivation, the coefficients R^2 are small with exception in the estimation of losses in Mocuba and Molocue substations and in transmission line B03, while in the GM2 and GM3 derivations the determination coefficients are extremely high (above 80%). The second level regression to characterize the inter-substation and inter-line variations gave good results with a high p-values (p-values of lines: 5%, 22% and 6.6% and p-values of substations: 25.4%, 24.3% and 29%, respectively for derivations GM1, GM2 and GM3), see Table V.41 and Table V.42.

Table V.41 – 2nd level regression on the substations inter-variability

Coefficients: -->	Constant B_0	Transformer Power squared MVA	Reactor Power squared MVA	Year of last overall
GM1:	73.92	0.00000	0.0000	-0.04
GM2:	58.44	0.00000	0.0002	-0.03
GM3:	62.62	0.00000	0.0000	-0.031
Statistics: --->	R^2	F	P	Error Variance
GM1:	100%	213.33	5%	0.00
GM2:	97%	10.96	22%	0.02
GM3:	95%	5.86	29%	0.01

Interpreting, the intersect-values of estimated losses in substations are not fully explained by their installed transformer and reactor capacities squared. However, the year of the last overall of the substation impacts the losses negatively. On the other hand, the line length and the line thermal limit are good explanatory's for the variability between losses in transmission lines: higher line lengths higher losses (intersects), higher thermal limits of conducting wires, lower losses. The high p-values are to be expected given the small number of lines (only 4) and substations (only 5) in the sample.

Table V.42 – 2nd level regression on the lines inter-variability

Coefficients: -->	Constant	Line length km	Thermal Limit MVA	
GM1:	0.21	-0.004	0.002	
GM2:	-1.33	0.06	-0.03	
GM3:	0.33	-0.011	0.006	
Statistics: --->	**R^2**	**F**	**P**	**Error Variance**
GM1:	94%	7.23	25.4%	0.00
GM2:	94%	7.98	24.3%	0.11
GM3:	100%	114.37	6.6%	0.00

The prediction of losses in the substations, using forecasted demand levels in each of the distribution networks calculated with software PSS/E for 2008/09 show that loss coefficients derived by the GM1 model are much higher than those by the GM2 and GM3 models. A forecast of the power taken at Matambo, equation (31), also shows fitter results for models GM2 and GM3. The estimated power at peak-time of models GM2 and GM3 are close to the PSS/E simulation results, respectively a deviation of 2.82% and 2.7% of the forecasted 97.1 MW for 2008, and a deviation of -0.45% and 5.4% of the forecasted 134.4 MW for 2009, see Figure V.32.

The prediction by model GM2 of active power-in as a function of the power-out is so accurate that the MW losses calculated using these predictions coincide with the theoretical loss curves for each line and substation $3 \cdot \left(I_{phase}\right)^2 \cdot R_{phase-phase}$, where $R_{phase-phase}$ is the nominal resistance calculated from the system's characteristics (Appendix V.1). This model is consequently rejected because it is predicting the theoretical losses and not the real losses of the system.

The same calculation was made for the predicted power-in by model GM1, and the results though reasonably good for low loads, indicate high deviations from the theoretical I^2R losses at higher loads, i.e. as the low coefficients R^2 indicate, the loss estimations by model GM1 are not very accurate, Figure V.33.

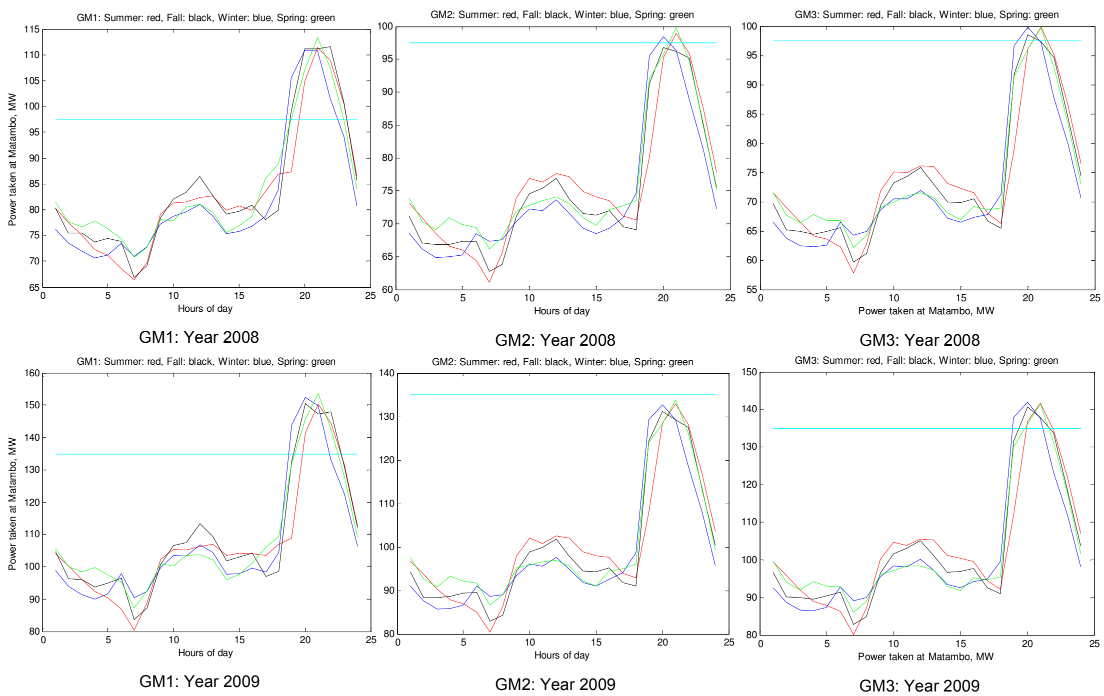

Figure V.32 – Forecast of the power taken at the Matambo based on PSS/E simulations

Model GM3 on the other hand shows good approximation with exception of for substations Ceramica, Mocuba and Molocue. In these system components, the observed data contain deviations that we corrected for, by assuming they reflect changes in the component overall electric resistance in relation to the nominal recorded value. The corrections where made by comparing the nominal and the observed losses, and calculating the corresponding 'empirical' resistances. Then the GM3 derivations were rerun for the new (ohmic) resistances, and we obtained losses much closer to the theoretical (expected) curves, see Figure V.34. After the corrections for the resistances in Ceramica, Mocuba and Molocue substations, the estimated losses are much closer to the theoretical losses, although Ceramica is still quite deviated from the theoretical curve. Note that losses in the Gurue substation and the line C21 are so small that the estimated curves cannot be relied upon for these two components.

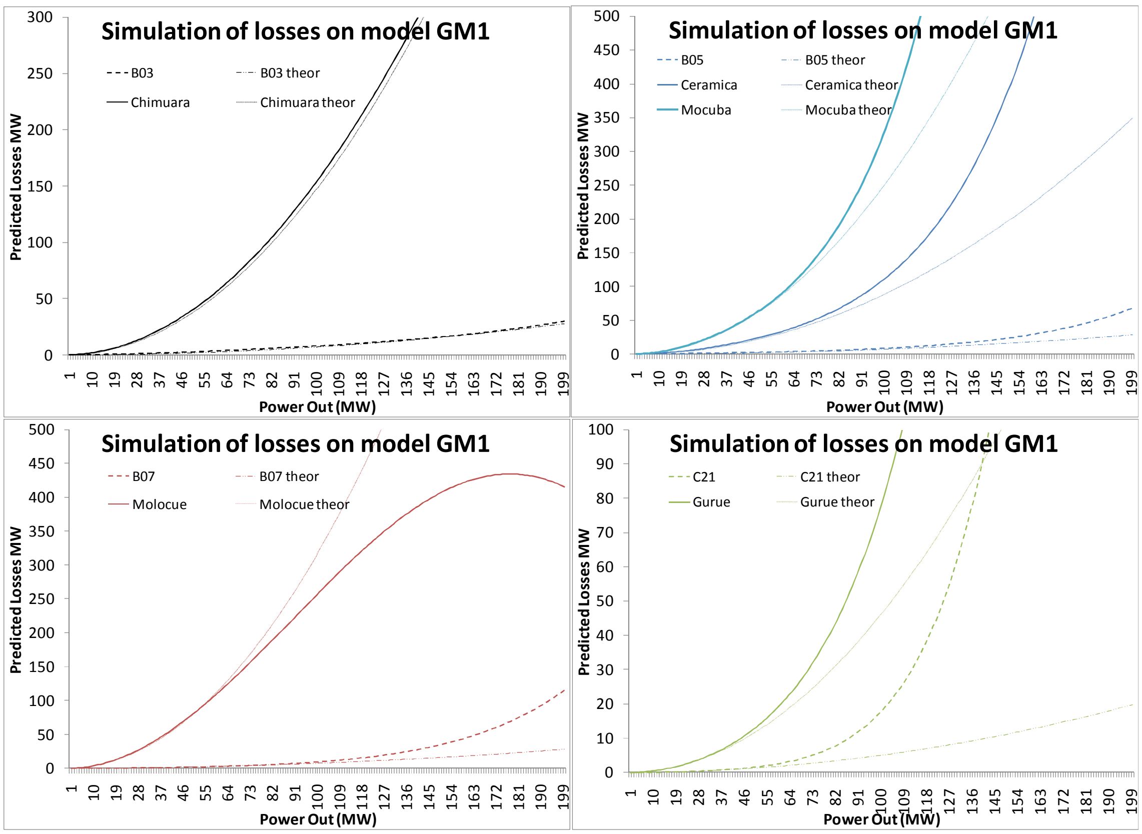

Figure V.33 – Calculation of I^2R losses using by model GM1

Model GM3 is selected as the more accurate and the losses estimation will then be based in the empirical equation (33), with the corrected coefficients presented in Table V.43.

A simulation of power losses at the peak-hour for each of the system's components using model GM3 formulation, shows asymptotically decreasing ratios to the theoretical losses, rapidly converting to a fixed loss level, mostly the ration 1, see Figure V.35.

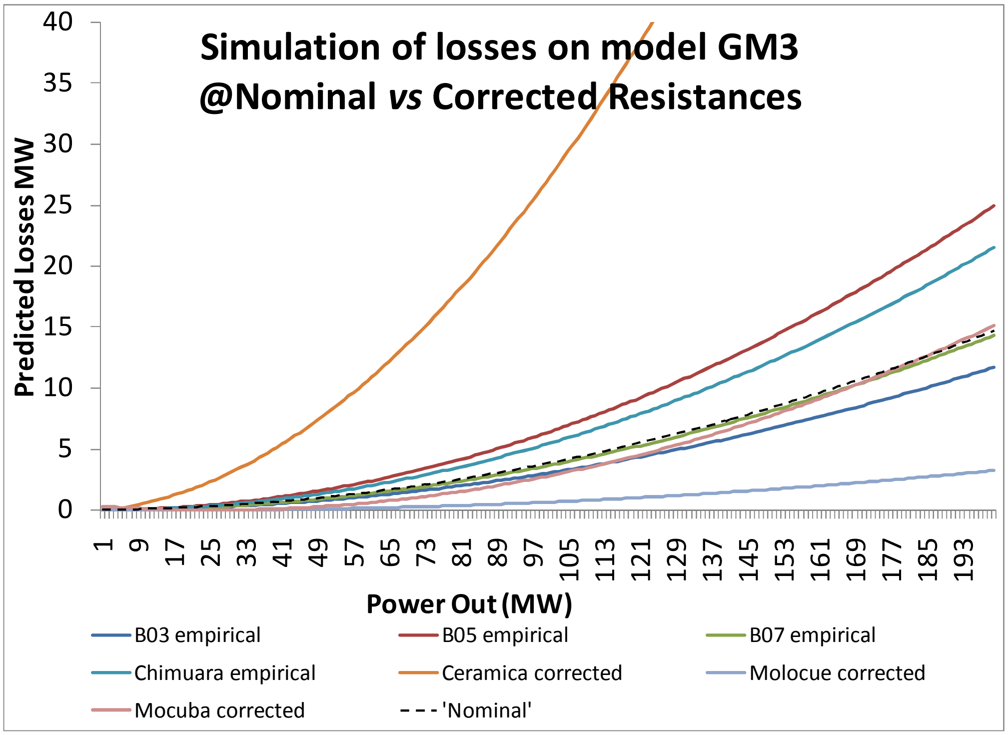

Figure V.34 - Calculation of I^2R losses using by model GM3

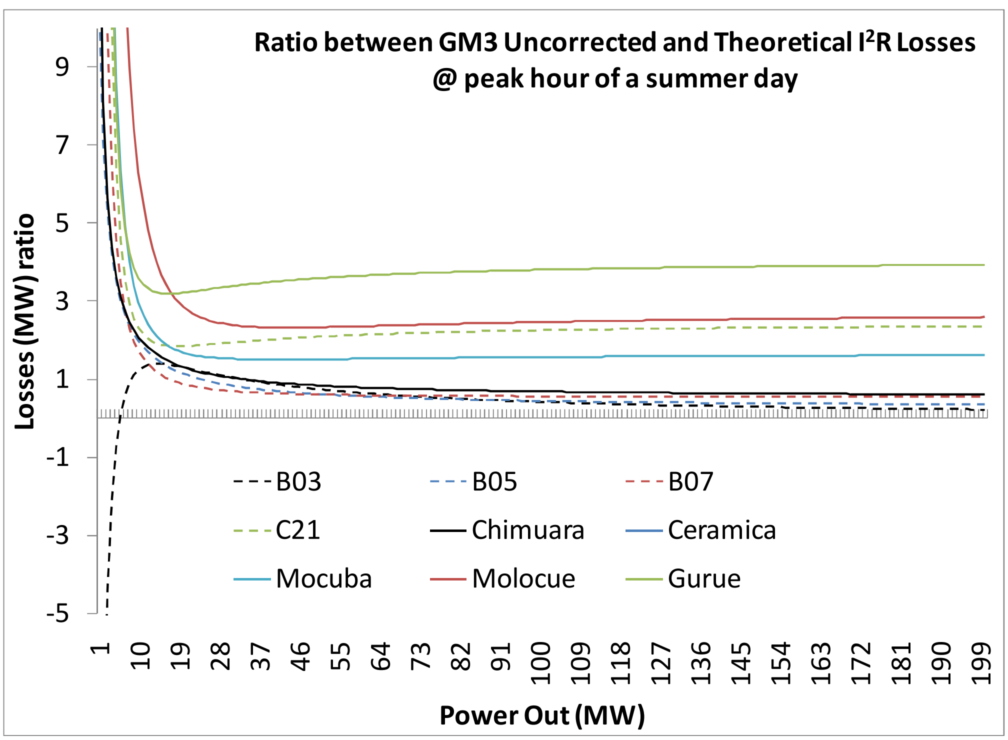

Figure V.35 – Ratio between uncorrected GM3 simulated losses and the theoretical losses

The percent-losses are generally small at peak times and regular along the day, for both simulations on forecasted loads for 2008 and 2009. Seasonal variation of predicted losses in the GM3 model is also small, as expected given the small variations in load profiles recorded for the 2007 year in each of the system's component lines and substations (Figure V.36).

As load increases in the PSS/E forecast by about 50% between 2008 and 2009, so the predicted losses decrease increasing the accuracy of the empirical formulation (Figure V.32) because of the negative active power term.

The convergence of losses to a fixed value in each of the system's components Figure V.35 indicates that as the load levels increase, i.e. as the electricity consumption increases, losses in the transmission system tend to be independent of the load and take a fixed percent value of the power flow.

This derivation is marred by two conditions that, given the data set available for the study, are unavoidable. They are the time-series nature of the data set, which introduces some co-linearity in the prediction of the hourly losses, and the limitation of a peaking active power that does not vary much along the sample year. As more data become available, for increased peaking load levels, the second limitation may be resolved, and the formulation can be increasingly more accurate.

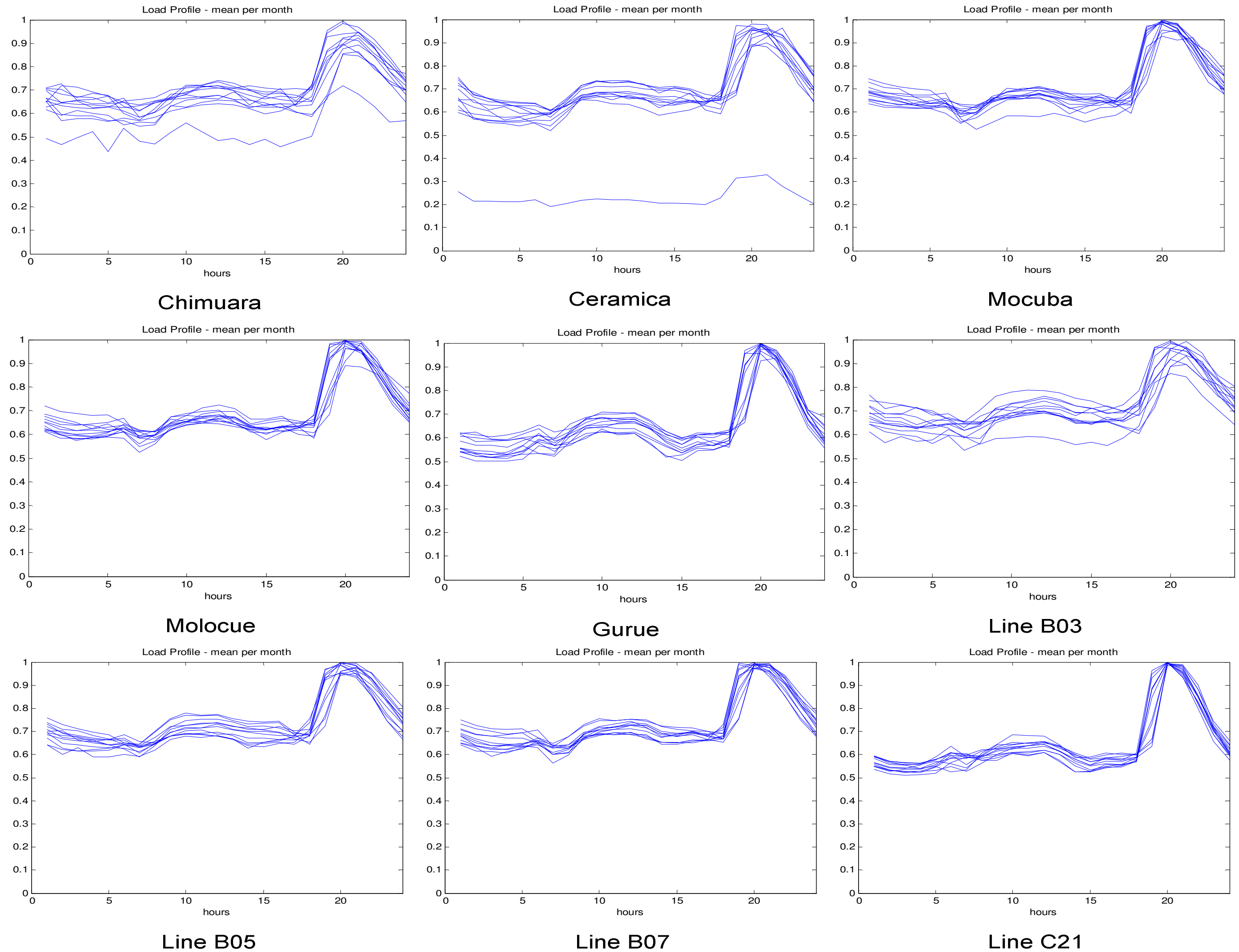

Figure V.36 – Load profiles (averaged) for each month of 2007

Table V.43 – Coefficients of regression for each system's component (GM3 corrected)

Regressors:	B03	B05	B07	C21	Chimuara	Ceramica	Mocuba	Molocue	Gurue
Constant	-0.16	-0.03	0.03	0.08	-0.04	-0.2008	0.3328	0.0413	0.08
P_{out}	0.02	0.01	0.001	-0.01	0.01	0.0404	-0.0258	-0.004	-0.01
P_{out}^2	0.0000	0.0001	0.0002	0.001	0.0002	0.0023	0.0005	0.0001	0.0015
H1	-0.052	-0.024	-0.002	0.001	-0.0265	-0.0077	0.0067	0.0016	0.0018
H2	-0.054	-0.024	-0.001	0.001	-0.0277	-0.0071	0.0074	0.0016	0.0018
H3	-0.047	-0.023	-0.004	0.001	-0.0282	-0.0064	0.0079	0.0018	0.002
H4	-0.041	-0.024	-0.010	0.002	-0.0305	-0.0069	0.0076	0.0017	0.0022
H5	-0.062	-0.026	-0.012	0.003	-0.0294	-0.0075	0.009	0.0018	0.0032
H6	-0.046	-0.027	-0.010	0.003	-0.0317	-0.0081	0.0094	0.0021	0.0031
H7	-0.015	-0.022	-0.010	0.000	-0.0234	-0.0084	0.0081	0.0014	-0.0006
H8	-0.010	-0.007	-0.009	-0.004	-0.0088	0.0013	0.0049	0	-0.0048
H9	-0.015	-0.005	-0.007	-0.004	-0.004	0.0036	0.0022	-0.0007	-0.0059
H10	-0.006	-0.003	-0.007	-0.006	0.0021	0.0048	0.0013	-0.0008	-0.0079
H11	-0.011	-0.003	-0.005	-0.006	0.004	0.0044	0	-0.0008	-0.0081
H12	-0.037	-0.007	-0.008	-0.006	-0.0026	0.0006	0.0021	-0.0005	-0.0077
H13	-0.037	-0.014	-0.006	-0.005	-0.0192	0.0009	0.0038	-0.0001	-0.0068
H14	-0.029	-0.015	-0.007	-0.005	-0.0173	0.0019	0.0035	0	-0.0069
H15	-0.042	-0.012	-0.008	-0.005	-0.0096	0.0005	0.0032	-0.0003	-0.0073
H16	-0.049	-0.015	-0.006	-0.005	-0.0102	-0.0048	0.0048	0.0001	-0.0069
H17	0.078	-0.003	-0.001	-0.004	-0.0055	-0.0098	0.0024	0.0001	-0.0047
H18	0.232	0.065	0.027	0.003	0.0598	0.0171	-0.0221	-0.0022	0.0056
H19	0.196	0.090	0.036	0.009	0.1041	0.0166	-0.0117	-0.002	0.0133
H20	0.136	0.072	0.029	0.010	0.0861	0.0068	-0.0194	-0.0025	0.0131
H21	0.044	0.040	0.015	0.007	0.0382	0.0083	-0.0231	-0.0026	0.0099
H22	-0.032	0.012	0.004	0.004	0.0136	0.0088	-0.0123	-0.0013	0.0064
H23	-0.041	-0.008	0.004	0.002	-0.0126	-0.0016	-0.001	0.0003	0.0032
M1	-0.024	-0.009	-0.002	-0.001	-0.0089	-0.002	0	-0.0001	-0.0017
M2	-0.023	-0.004	0.002	0.001	-0.0034	0.002	0.0006	-0.0013	0.0019

CHAPTER VI: DYNAMIC MODEL OF DOMESTIC ENERGY CONSUMPTION IN A POOR HOUSEHOLD

INTRODUCTION

Poor households consume a variety of energy sources to satisfy their energy needs for mostly cooking and lighting (Campbell, Vermeulen et al. 2003). The energy ladder concept states that poor households rely mostly in low-grade sources (firewood, charcoal) while wealthier households rely preferably in higher-grade sources such as electricity (Hosier and Dowd 1987; Masera, Saatkamp et al. 2000; Bose and Shukla 2001) [139]. In reality, the energy mix does not fully conform to the energy ladder concept: richer households may retain charcoal as a cooking source while using electricity as a lighting source and for other uses.

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[139] Low-grade sources, by the concept of the energy ladder, can have several definitions. Hosier and Dowd (1987) were the first to describe an "energy ladder" in the context of Zimbabwean communities, and the first differentiation used is whether the sources are non-commercial (fuelwood, charcoal) or commercial (oil, electricity). The authors also make reference to "high quality carriers" which can be interpreted in many ways:

- In terms of energy content per volume of solid fuel: fuelwood (15.1 MJ/kg) at the lowest, passing through kerosene (43.12 MJ/kg) up to LPG (45.84 MJ/kg), see (Kadian, Dahiya et al. 2007)
- In terms of ease of use: at the worse, charcoal and fuelwood with the lowest ranks, and electricity with the highest, passing through kerosene and LPG, see (Gupta and Kohlin 2006)
- In terms particulate emissions: dung cake the biggest pollutant, with 0.1879 g/MJ, followed by charcoal (0.0923 g/MJ) and wood (0.687 g/MJ), and at the lowest pollutant, kerosene (0.0163 g/MJ) and electricity (no particulate emissions), see (Kadian, Dahiya et al. 2007)
- In terms of the source's energy price and payments modalities, fuelwood cheaper and small (daily) payments, electricity more expensive and lumpy payments – see Table 2 in (Leach 1992)

In later applications, the energy ladder was mostly defined cost-wise: low grade sources being the preferred by low-income families and high-grade the preferred by high-income families. Chapter 4 discusses the energy ladder in Mozambique, assumed fuelwood, charcoal, kerosene, LPG and electricity, and finds that it is inverted on price per useful-unit of energy.

The use of a higher-grade energy source, such as electricity, can satisfy domestic needs such as refrigeration, can support educational activities and allows for the diversification of income-generating activities that will take the household out of poverty (Ellis 1998; Abdulai and CroleRees 2001). The substitution for charcoal as a cooking source by kerosene or electricity may also significantly impact the health of a family by reducing particulate emissions (van Horen, Eberhard et al. 1993; Smith, Apte et al. 1994). As electricity can only be consumed in electrical devices, or appliances, that provide utility to the household, households need to invest in energy consuming appliances in order to transition from low to high-grade sources and to increase their energy consumption (Tyler 1996; Tiwari 2000; Jenkins and Scott 2007). The household choice of energy sources thus depends not only on the price of the sources but also on the cost of investment in the appliances required to consume those sources (Reddy 1995; Masera, Saatkamp et al. 2000; Reddy 2004). Evidence shows that a low electricity price alone will likely not promote the adoption of electricity as a domestic source; other factors, such as the ownership of appliances and the understanding of the source, are also determining. For example, the social tariff for electricity consumption in Mozambique is equivalent to 14 cents $/kWh (EDM 2007), much lower than the market prices for charcoal at 17 cents $/kWh in 1997 (Falcão 1999), and for kerosene at 59 cents $/kWh in 2006 (Mozambique 2007). Still, only 8.2% of the population was consuming electricity in 2006.

As the household increases its energy cost by transitioning to higher-grade sources and also increases its energy consumption (higher-grade sources usually serve more needs, though at higher efficiencies, and households tend to consume more energy per month), it also needs to increase its income-base to avoid bankruptcy. Poor households generally do not have many extra hours of work to sell, as they are already working many hours per day[140]. To increase wages, the labor force must be educated to perform in the commercial or industrial labor markets. Alternatively, a household can invest in income-generating capital stocks to finance the added cost of utilizing new appliances and the increased cost of energy consumption. The path of investment in energy-consuming assets and income-generating stocks determines the path to energy transition up the energy ladder and to higher levels of consumption.

This chapter presents a theoretical model for utility maximization of a poor household, obtained from consuming leisure and non-energy goods, and from owning energy-consuming appliances. The household evolves over time by allocating its residual net income (defined as the amount of income available for investment following consumption of non-capital goods) to productive (income-generating) investments and to energy-consuming appliances (the asset base). The share of investment in energy consuming appliances is hereafter called the *asset ladder rule*. The *asset ladder rule* is a new quantity that characterizes the household's path to maximize the net present value of the stream of utility of its consumption and energy goods, while transitioning up the energy ladder and evolving out of poverty. First order conditions are derived and interpreted, and a typical utility function is used to simulate the correspondent *asset ladder rule* and development of the household under varying parameter assumptions.

These simulations help identify factors that may help a household evolve by increasing its consumption and by adopting higher-grade energy sources such as electricity, which in turn provide it with higher utility and increase its productivity. The simulations show the

[140] A study to Indonesia shows that the very poor work about 44 hours per week (Bird and Manning 2008), and in Tanzania, rural women's work is estimated at about 2600 hours per year, i.e. more than 7 hours per day 365 days a year (Lado 1992).

dependency in the problem's parameters of the new quantity, the *asset ladder rule*, an endogenous quantity that represents the partitioning of net (residual) incomes for investments in appliances versus productive stocks, in a utility maximization behavior. The simulations are basis for a discussion on policies that promote the adoption and the consumption of electricity as a higher-grade source, in Chapters 7 and 8. The findings of the numerical simulations provide a basis for the discussion on the role of tariffs and on the importance of having access to credit in the promotion of use and of higher consumption of electricity by households. The parameters used in the model are correlated to operating characteristics of electrical appliances, and from this correlation some recommendations on technological and policy approaches are made.

THE THEORETICAL FORMULATION

THE CONCEPTUALIZATION

Households obtain utility (benefits) from the consumption of goods and services. The household can also choose between the allocation of labor to a productive activity, from which it will earn income that in turn allows expenditures in goods and services (that provide utility), and the allocation of its time to a leisure activity that gives direct utility to the household.

The household's pursuit of benefits, reflecting its preferences regarding consumption goods and leisure, and the stock of energy-consuming appliances is described by the following *utility function*:

$$U = U\left(L, N, A\right) \tag{34}$$

where L represents the flow of leisure time the household may opt to consume, N represents the flow of goods and services consumed in the household that are not energy sources or appliances, and A represents the value of energy-consuming appliances owned by the household. The arguments of the utility function are time dependent; however, the notation *(t)* is suppressed for clarity.

From all these variables, the household obtains utility. The specific shape of this utility function is unknown for the Mozambican households; consequently, the theoretical model will be formulated for a general form of the utility function. The numerical simulation, in the last section, will use a Cobb-Douglas utility function; however, further research is needed for future studies.[141]

The consumption of energy sources, such as charcoal for cooking or electricity for refrigeration, does not provide utility directly. Rather, energy consumption is an input in the operation of domestic appliances that provide utility themselves (Willett and Naghshpour 1987). For example, stoves provide utility in cooking, refrigerators provide utility in cooling and kerosene lamps provide utility in lighting.

Assuming rational behavior, the household makes choices concerning its income earning activities and its consumption of goods and services that will maximize the net present value of household utility over a planning horizon.

This paper uses the proposed model to analyze behavior given an initial injection of capital for income generation $K\left(t=0\right)=K_0$. The returns on the initial investment and its wages,

[141] The utility function of equation (34) should be investigated keeping in mind that 1) the variable N includes food items and it has probably the highest utility coefficient of all. Leisure L has probably the lowest utility coefficient of all, as poor households will work if a job is available, in order to support their expenses in food and in energy Appliances provide services to the household and satisfy essential needs such as cooking and lighting. Consequently, the utility coefficient of variable A should be smaller but not too distant from the coefficient for N.

after paying for current expenses in leisure, non-energy goods and energy consumption, will allow it to generate a net (residual) income

$$I\left(L,N,A,K\right)=r\cdot K\left(t\right)+P_L\cdot\left[L_{\max}-L\left(t\right)\right]-P_N\cdot N\left(t\right)-P_E\cdot E\left(A\right)\cdot A\left(t\right) \tag{35}$$

that depends on the amount of leisure and non-energy goods consumed, as well as the quantity of the income-generating stocks and energy-consuming appliance stocks.

More specifically, the household's environment is described by the following assumptions:

1. Net income available for investment in income-earning stocks or electricity-using stocks is defined as

$$I\left(L,N,A,K\right)=r\cdot K+P_L\cdot\left[L_{\max}-L\right]-P_N\cdot N-P_E\cdot E\left(A\right)\cdot A, \tag{36}$$

where r is the average return rate of the portfolio of income-generating stocks K, L is leisure-time consumed in time period t , priced at the wage rate P_L and maximized at L_{max}, N represents all non-energy goods and services consumed at time t and priced at an average price of non-energy goods P_N, and A represents the value of the asset base (the energy-consuming appliances) whose operating cost rate is $E\left(A\right)\cdot P_E$. In other words, net income is defined as the sum of interest and labor income less household expenditures on non-energy consumables and operation of the energy goods. The cost of energy consumption is a factor of the value of the appliances A, described by function *E(A)* developed in Appendix VI.2, and of the price if the energy source P_E.[142]

[142] The electricity consumption per unit of investment in appliances is a decreasing function *E(A)*

2. The portfolio of energy-consuming appliances A and income-generating stocks K evolve according to the equations:

$$\begin{aligned}\dot{A} &= \mu \cdot I\left(L, N, A, K\right) - \gamma A \\ \dot{K} &= \left(1-\mu\right) \cdot I\left(L, N, A, K\right)\end{aligned} \tag{37}$$

where μ is the share of the net income allocated to the investment in appliances (a control variable) and γ is the depreciation rate of the energy stocks. In other words, the net income at each time will be shared between the investment in appliances $\dot{A}$ and the investment for income generation $\dot{K}$. μ is formally the *asset ladder rule*. . This variable can explain the household's choices between productive investments and energy-consuming utility-providing appliances, under specific conditions. The quantity is endogenous and will be dependent on the problem's parameters.

These assumptions have the following implications:

1. For an household to evolve, i.e. for it to increase its consumption levels it requires generating a positive net income, i.e.

$$I\left(L, N, A, K\right) > 0. \tag{38}$$

2. As household consumption increases, on leisure, non-energy goods and on energy sources, which are inputs for operating appliances (asset base), it will have, eventually, to also increase its income generating base (productive stock) in order to maintain the positive net income

$$\text{if} \quad \dot{L} > 0 \;\;, \quad \dot{N} > 0 \;\;, \quad \dot{A} > 0 \;\;, \;\text{then after some time} \quad \dot{K} > 0 \tag{39}$$

3. The rate of return of the total productive investments $K = \sum_j K_j$ is assumed constant and independent of the value of the productive stock, for simplification (see Appendix VI.1). Similarly, the depreciation rate for appliances is assumed constant and independent of the value of the asset base, for simplification (see Appendix VI.1).
4. Investments in domestic appliances, of different costs, end-uses and energy sources, burden the household with an additional operating cost rate of $E\left(A_j\right) \cdot P_E$ that is specific of each appliance/source. For simplification (see Appendixes 4.1 and 4.2), it is assumed that all appliances consume an average amount of energy $E(A)$ for which the household has to pay an average price of energy acquisition P_E. For the whole asset base, the cost rate of the energy consumption is $E(A) \cdot P_E$.

The household will maximize the utility of consuming leisure, non-energy goods and of owning appliances that consume energy, subject to the constraints of labor-hours availability, over an infinite time horizon:

$$
\begin{aligned}
&\max_{\mu,L,N} \int_0^{+\infty} e^{-\delta \cdot t} \cdot U(L,N,A) \cdot dt \\
&\text{s.t.} \\
&\quad \dot{A} = \mu \cdot I(L,N,A,K) - \gamma \cdot A \quad \text{and} \quad \dot{K} = (1-\mu) \cdot I(L,N,A,K) \\
&\quad I(L,N,A,K) = r \cdot K + P_L \cdot (L_{\max} - L) - P_N \cdot N - P_E \cdot E(A) \cdot A \\
&\quad A(0) = A_0 \quad , \; K(0) = K_0 \quad , \; \mu \in [0,1] \quad , \; L \in [0, L_{\max}] \quad , \; N \geq 0
\end{aligned}
\tag{40}
$$

where L represents the leisure consumption [hr]
N represents the non-energy goods consumption [unit]
μ represents the share of the net income reserved for investment in the asset base
A represents the asset base (value of appliances for energy consumption) [$]
K represents the productive capital (for income generation) [$]
δ represents the social discount rate in each time interval

U(L,N,A) represents the utility function of the household
t is the time variable
L_{max} represents the maximum possible leisure hours to consume
I(L,N,A,K) represents the net income [$]
r represents the rate of return of productive capital
P_L represents the price of labor/leisure hours [$/hr]
P_N represents the price of non-energy goods [$/unit]
γ represents the rate of depreciation of the asset base
E(A) represents the energy consumption rate of the asset base [GJ/$]
P_E represents the price of energy, averaged for the domestic mix [$/GJ]

THE NECESSARY FIRST ORDER CONDITIONS

There are three control variables (μ, L and N) and two state variables (A and K), and the problem has inequality constraints that need to be incorporated in the solution. To solve the dynamic problem, we write the Lagrangian:

$$\begin{aligned}\mathcal{L} = U\left(L,N,A\right) + \lambda_A \cdot \left[\mu \cdot I\left(L,N,A,K\right) - \gamma \cdot A\right] + \lambda_K \cdot \left(1-\mu\right) \cdot I\left(L,N,A,K\right) + \\ + \phi_1 \cdot \left(1-\mu\right) + \phi_2 \cdot \mu + \phi_3 \cdot L + \phi_4 \cdot \left(L_{\max} - L\right) + \phi_5 \cdot N\end{aligned} \tag{41}$$

The Lagrangian is linear in the *asset ladder rule* (μ), equation (41), and exists in a closed set $\mu \in \left[0,1\right]$, which results in a singular optimal solution (Goetz 1997; Caputo 2005). We can solve the problem, with the following notation:

$$\frac{\partial U}{\partial L} = U_L \;\; ; \;\; \frac{\partial U}{\partial N} = U_N \;\; ; \;\; \frac{\partial U}{\partial A} = U_A \;\; ; \;\; I = I\left(L,N,A,K\right) \;\; ; \;\; E = E\left(A\right) \tag{42}$$

The first order necessary conditions are:

$$\begin{aligned}\mathcal{L}_L = \frac{\partial \mathcal{L}}{\partial L} \overset{set}{=} 0 \quad \Rightarrow \quad & U_L - \left[\mu \cdot \lambda_A + \left(1-\mu\right) \cdot \lambda_K\right] \cdot P_L + \phi_3 - \phi_4 = 0 \\ & \Rightarrow \mu \cdot \lambda_A + \left(1-\mu\right) \cdot \lambda_K = \frac{U_L - \phi_4 + \phi_3}{P_L}\end{aligned} \tag{43}$$

$$\mathcal{L}_N = \frac{\partial \mathcal{L}}{\partial N} \overset{set}{=} 0 \qquad \Rightarrow \qquad U_N - \left[\mu \cdot \lambda_A + (1-\mu) \cdot \lambda_K\right] \cdot P_N + \phi_5 = 0$$
$$\Rightarrow \mu \cdot \lambda_A + (1-\mu) \cdot \lambda_K = \frac{U_N + \phi_5}{P_N} \tag{44}$$

which combined results in

$$\frac{U_N + \phi_5}{P_N} = \frac{U_L + \phi_3 - \phi_4}{P_L} \tag{45}$$

The current cost of utility added by the cost of maintaining the consumption of *N* equals the current cost of utility added by the cost of maintaining leisure and reduced by the benefit of keeping leisure at a constrained maximum. In other words, the marginal benefit (utility) from each dollar spent in non-durable consumption (commodity N) equals the marginal benefit (utility) from each dollar not earned by choosing leisure (commodity L) over labor sales. As long as leisure consumption is non-zero and below the maximum, and the consumption of non-energy goods is also above zero, the marginal utility per dollar of leisure must equal the marginal utility obtained per dollar of non-energy goods consumed:

$$\frac{U_N}{P_N} = \frac{U_L}{P_L} \quad \text{when} \quad L \in (0, L_{\max}) \quad \text{and} \quad N > 0 \tag{46}$$

Another necessary first order condition for a maximum states that:

$$\mathcal{L}_\mu = \frac{\partial \mathcal{L}}{\partial \mu} \overset{set}{=} 0 \qquad \Rightarrow \qquad (\lambda_A - \lambda_K) \cdot I - \phi_1 + \phi_2 = 0 \tag{47}$$

The solution to the problem is found in the Hamiltonian $\mathcal{H}(L, N, \mu, A, K)$, which, as the Lagrangian $\mathcal{L}$, is linear on μ with a coefficient $(\lambda_A - \lambda_K) \cdot I$. A negative coefficient will reduce the Hamiltonian value with exception of when μ is null. Similarly, a positive coefficient will increase the value of the Hamiltonian for a maximum μ. The solution thus requires an evaluation of μ in the interval $\mu \in [0,1]$, namely:

$$
\begin{aligned}
&\text{if} \quad (\lambda_A - \lambda_K)\cdot I < 0 \quad \Rightarrow \quad \mathcal{H}(L,N,\mu,A,K) \ \text{ is max at } \mu{=}0 \\
&\text{if} \quad (\lambda_A - \lambda_K)\cdot I > 0 \quad \Rightarrow \quad \mathcal{H}(L,N,\mu,A,K) \ \text{ is max at } \mu{=}1 \\
&\text{if} \quad (\lambda_A - \lambda_K)\cdot I = 0 \quad \Rightarrow \quad \mathcal{H}(L,N,\mu,A,K) \ \text{ is max for all } \mu \in (0,1)
\end{aligned} \tag{48}
$$

These three conditions effectively construct the switching function of μ as $\sigma = (\lambda_A - \lambda_K)\cdot I$ such that:

$$
\mu = \begin{cases} 0 & \text{for} \quad \sigma < 0 \quad \Rightarrow \quad \lambda_A < \lambda_K \\ \in (0,1) & \text{for} \quad \sigma = 0 \quad \Rightarrow \quad \lambda_A = \lambda_K \\ 1 & \text{for} \quad \sigma > 0 \quad \Rightarrow \quad \lambda_A > \lambda_K \end{cases} \tag{49}
$$

Interpreting, the household will invest all its net income in productive activities when the current value of the shadow prices of these are higher than the current value shadow price of appliances $\lambda_A < \lambda_K$. In contrary, the household will invest all its net income in domestic appliances when their shadow price is currently valued higher than that of the productive stock $\lambda_A > \lambda_K$. The singular solution is complicated, and thus we rely on simulation results for insight.

The first order conditions for the state variables in current value terms, establishes that:

$$
\begin{aligned}
&\mathcal{L}_A = \frac{\partial \mathcal{L}}{\partial A} \overset{set}{=} \delta\cdot\lambda_A - \dot{\lambda}_A \\
&\quad \Rightarrow U_A - \left[\mu\cdot\lambda_A + (1-\mu)\cdot\lambda_K\right]\cdot\left(E + \frac{\partial E}{\partial A}\cdot A\right)\cdot P_E - \gamma\cdot\lambda_A = \delta\cdot\lambda_A - \dot{\lambda}_A \\
&\quad \Rightarrow \dot{\lambda}_A = (\delta+\gamma)\cdot\lambda_A - U_A + \left[\mu\cdot\lambda_A + (1-\mu)\cdot\lambda_K\right]\cdot\left(E + \frac{\partial E}{\partial A}\cdot A\right)\cdot P_E
\end{aligned} \tag{50}
$$

$$
\begin{aligned}
&\mathcal{L}_K = \frac{\partial \mathcal{L}}{\partial K} \overset{set}{=} \delta\cdot\lambda_K - \dot{\lambda}_K \\
&\quad \Rightarrow \left[\mu\cdot\lambda_A + (1-\mu)\cdot\lambda_K\right]\cdot r = \delta\cdot\lambda_K - \dot{\lambda}_K \\
&\quad \Rightarrow \dot{\lambda}_K = \delta\cdot\lambda_K - \left[\mu\cdot\lambda_A + (1-\mu)\cdot\lambda_K\right]\cdot r
\end{aligned} \tag{51}
$$

Which combined with equation (44) take the form:

$$\begin{aligned} \dot{\lambda}_A &= (\delta+\gamma)\cdot\lambda_A + \frac{U_N+\phi_5}{P_N}\cdot P_E\cdot\left(E+\frac{\partial E}{\partial A}\cdot A\right) - U_A \\ \dot{\lambda}_K &= \delta\cdot\lambda_K - \frac{U_N+\phi_5}{P_N}\cdot r \end{aligned} \tag{52}$$

Interpreting, the appreciation of the current value shadow price of investments in energy-consuming appliances $\dot{\lambda}_A$ over time, equals its discounted and depreciated portion $(\delta+\gamma)\cdot\lambda_A$, increased by its portion of the operating-cost-rate of the asset-base $\frac{U_N+\phi_5}{P_N}\cdot P_E\cdot\left(E+\frac{\partial E}{\partial A}\cdot A\right)$, and reduced by the marginal utility of the asset base U_A. The rate of change of the shadow price of investments in energy-consuming appliances increases with the discount and the depreciation rates and with the operating cost-rate of appliances, but decreases with the utility per dollar invested in appliances.

Similarly, the appreciation of the current value shadow prices of productive investments $\dot{\lambda}_K$ equals its discounted portion $\delta\cdot\lambda_K$ reduced by its portion of the productive-stock return-rate $\frac{U_N+\phi_5}{P_N}\cdot r$. The higher the return-rate of productive stocks the lower the future value of productive stocks.

The increased efficiency of energy consumption of an asset base (lower operating cost) will reduce rate of change of the future value, same as a higher marginal utility of the asset base. Similarly, higher rates of return for the productive stocks will slow down the growth of their future value.

Note that the marginal utility per dollar spent in non-energy goods $\frac{U_N + \phi_5}{P_N}$ corresponds to the current shadow price of total investment $\lambda = \mu \cdot \lambda_A + (1-\mu) \cdot \lambda_K$, equation (44), and to the shadow prices of each investment $\lambda = \lambda_A = \lambda_K$ when $\mu \in (0,1)$, which results in the following relation for the future value of investments:

$$\lambda = \frac{U_A}{r + \gamma + P_E \cdot \left(E + \frac{\partial E}{\partial A} \cdot A \right)} \quad \text{when} \quad \mu \in (0,1) \tag{53}$$

The denominator of equation (53) represents the opportunity cost of investing in appliances per dollar invested. A household will price investments very high when the opportunity costs of investing in appliances are low or when the utility obtained from operating appliances per dollar invested is high. High return rates of productive investments, or high depreciating and operating cost rates of appliances, will lower the future price of investments and will encourage the household to acquiring appliances.

This situation is counterintuitive yet logical: investments in productive stocks must occur in order to finance the added operating cost of new appliances, and so higher rates of return in productive stock or higher operating and depreciation costs of appliances will incent the increase of investments (the decrease consumption of commodities) by lowering the price of investments.

A TYPICAL UTILITY FUNCTION AND A NUMERICAL SOLUTION

The optimal singular solution within the interval $\mu \in (0,1)$ must satisfy the necessary first order conditions and the sufficient second order conditions, must also be true, see Appendix VI.1. Not knowing the shape of the utility function of Mozambican households, it was assumed a utility function of the Cobb-Douglas logarithmic form, well known in the consumer theory:

$$U(L,N,A) = \ln(\alpha) + \beta_L \ln(L) + \beta_N \ln(N) + \beta_A \ln(A) \quad \text{where all} \quad \beta \in [0,1] \quad \text{and} \quad \sum \beta = 1$$

such that

$$U_L = \frac{\beta_L}{L} > 0 \quad ; \quad U_N = \frac{\beta_N}{N} > 0 \quad ; \quad U_A = \frac{\beta_A}{A} > 0 \tag{54}$$

$$U_{LL} = -\frac{\beta_L}{L^2} < 0 \quad ; \quad U_{NN} = -\frac{\beta_N}{N^2} < 0 \quad ; \quad U_{AA} = -\frac{\beta_A}{A^2} < 0 \quad ;$$

$$U_{LN} = U_{NL} = U_{LA} = U_{AL} = U_{NA} = U_{AN} = 0$$

THE NUMERICAL ALGORITHM

To solve numerically a discrete time version of problem in equation (40), the library CompEcon in MATLAB was used, for the case of discrete time, continuous states and continuous controls, infinite horizon, deterministic policy iteration (Newton) algorithm (Miranda and Fackler 2002).

To run this algorithm, the author programmed in MATLAB , calls to function *dpsolve* in CompEcon library. The control variables were bounded by the requirement of not having a negative net income, i.e. the household does not consume more than it earns, in each moment of time. The productive capital stocks cannot be sold, and the value of the asset base (appliances) can only depreciate by a factor of γ (see Appendix VI.1 for MATLAB code).

The state space is two dimensional (*A* and *K* variables) and 36 (6x6) collocation nodes were used in the numerical derivation. Results for the optimal path are only approximate. The basis-functions used to approximate the value function at the collocation nodes were Chebychev and the algorithm used Newton iteration and a deterministic approach, for an infinite time horizon. The problem contains three control (action) variables constrained to their ranges, respectively $\mu \in [0,1]$, $L \in [0,L_{max}]$ and $N \in [0,\infty)$. Furthermore, given the linearity of the Hamiltonian on control μ, the net income must be limited to the positive range $I \geq 0$, i.e. variables L and N are bounded by the need to maintain a positive net income, in other words $P_L \cdot L + P_N \cdot N \leq r \cdot K + P_L \cdot L_{\max} - P_E \cdot E \cdot A$. Furthermore, for leisure consumption of less than L_{max} these two commodities (leisure and non-energy goods) will split the budget by their relative prices of utility, equation (45).

NUMERICAL SIMULATIONS

To test the nature of the asset ladder rule, a numerical example was solved, with the following parameters:

$$\begin{array}{l} L_{\max} = 220 \text{ hr/month} \quad , \quad \delta = 0.9 \quad , \quad K_0 = \$1000 \quad , \quad A_0 = 1 \ \$_{\text{invested}} \\ \beta_L = 0.2 \quad , \quad \beta_N = 0.4 \quad , \quad \beta_A = 0.4 \quad , \quad r = 3\%/\text{month} \quad , \quad \gamma = 0.833\%/\text{month} \\ P_L = 0.2 \text{ \$/hr} \quad , \quad P_N = 1.0 \text{ \$/unit} \ , \quad P_E = 0.14 \text{ \$/kWh} \ , \quad \alpha = 1 \end{array} \tag{55}$$

$$\text{assumed} \quad E(A) = \begin{cases} 0 & \text{for} \quad A \leq 100 \ \$_{\text{invested}} \\ 1.1173 \cdot A^{-0.3844} & \text{otherwise} \end{cases} \qquad \text{in} \quad [\text{ kWh/month/}\$_{\text{invested}}]$$

$$\frac{\partial E(A)}{\partial A} = \begin{cases} 0 & \text{for} \quad A \leq 100 \ \$_{\text{invested}} \\ -0.4295 \cdot A^{-1.3844} & \text{otherwise} \end{cases} \qquad \text{in} \quad [\text{ kWh/month/}\left(\$_{\text{invested}}\right)^2]$$

$$\frac{\partial^2 E(A)}{\partial A^2} = \begin{cases} 0 & \text{for} \quad A \leq 100 \ \$_{\text{invested}} \\ 0.1651 \cdot A^{-2.3844} & \text{otherwise} \end{cases} \qquad \text{in} \quad [\text{ kWh/month/}\left(\$_{\text{invested}}\right)^3]$$

Where L_{max} corresponds to 22 working days at 10 hours per day of labor, P_L corresponds to earnings of 2 $/day at 10 hours/day of labor, P_N corresponds to the consumption of 1 $/day in food and other non-energy necessities. Variable P_E corresponds to the social electricity tariff in Mozambique, available to low-income households that consume up to 100 kWh per month. The return rate r is set this high because small investments by households have shown to generate high returns in short periods[143]. The depreciation γ is calculated at a constant rate for 10 years of lifetime, with no residual value. Finally, the function for energy

[143] As high as 5.7%/month in Sri Lanka (Woodruff, McKenzie et al. 2007). A net return of 26% (time frame unclear) in Mozambican farming households, on every dollar invested (Pearce and Reinsch 2005) was also recorded.

consumption per unit capital invested E is estimated in Appendix VI.2. The utility coefficients were selected assuming that households would prefer equally non-energy items (like food and clothes) and appliances (to consume energy, for cooking and lighting), and would value leisure at a much lower rate. The sensitivity analysis of the section "Varying the wage rate" shows that the higher the wages, the lower households consume leisure hours, i.e. the lower the leisure utility coefficient. The discount rate is selected taking into consideration that Mozambique has experienced low single digit inflation rates in the past years.

The results of the optimization are shown in Figure VI.37, run for a period of 240 months or 20 years, starting with an initial credit of $K_0 = \$500$ with a rate of return of 3% per month, and starting with an asset base of $A_0 = \$1$ value. The residuals are within $\$10^{-4}$ of the final value, i.e. the solution approximates the optimal path with acceptable accuracy. All appliances to acquire by the household will consume electricity. In Figure VI.37:

a) Graph a) shows the evolution of the ownership of productive stocks (K) overtime, from an initial stock of \$500 in month *0* to \$1149 after 20 years of activity.
b) Graph b) shows the evolution of the ownership of energy-consuming appliances (A) overtime. Note that this stock only starts to grow in month 121st (the first month of the 11th year), corresponding to a non-zero asset ladder rule, and reaches the value of \$182 after 20 years of activity.
c) Graph c) shows the quantity of kWh consumed by the newly acquired appliances. This consumption only increases when capital A is higher than \$100, which corresponds to the electrical connection (see Appendix VI.2 for details on the shape of the electricity consumption function).

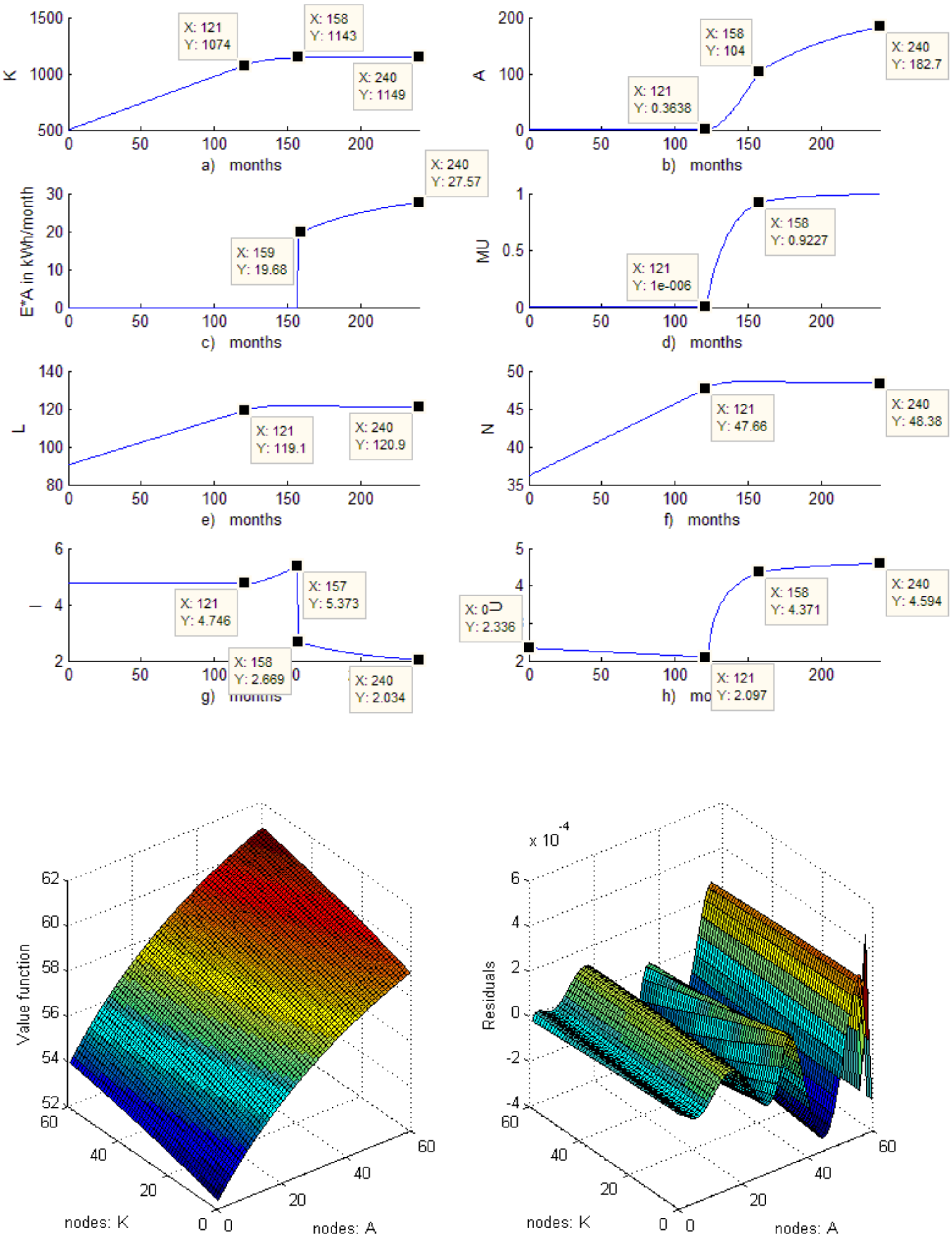

Figure VI.37 – Optimal path in 20 years, Value Function and Residuals

d) Graph d) shows the time path of the *asset ladder rule*, indicating that initially the household will only invest for income generation, to ensure the sustainability of its increased consumption in leisure and in non-energy goods, see Graphs e) and f) respectively. Initially, most of the returns earned from the initial credit K_0 and from the sale of labor are used to increase consumption of leisure and non-energy goods (respectively 90 hours and 36 units per month) and to invest in the productive stock. Only in the year 11th the household will start investing in electrical appliances, and only by month 158th (in the14th year) the household has managed to invest in the asset base and accumulated enough for an electrical connection ($A = \$104$).

e) Graphs e) and f) show the correspondent consumption paths for leisure (L) and non-energy goods (N), as determined by equation (45). The consumption of these two variables has as aggregated utility coefficient of 0.6, higher than the utility obtained from the electrical appliances (0.4): for this reason, their consumption is prioritized and the acquisition of appliances only occurs at a later stage of evolution.

f) Graph g) represents the evolution of the net income, equation (36). By the year 11th (month 121), when the consumption of leisure (L) and non-energy goods (N) levels out and the household starts investing in appliances (A), the net income increases: the accumulated investment in appliances corresponds to the cost of the electrical connection, which does not add costs in energy consumption to the household. When the household reaches the investment of \$104, in month 158, the net income reduces drastically to pay for the added electricity consumption of the initial \$4 in appliances, as a cost of electricity will be added to the expenditures in other commodities. Investments after this time occur at a much slower pace, as they entail additional costs in electricity.

g) Graph h) represents the evolution of the utility, equation (54). Between month 121 and month 158, the utility almost doubles, with the addition of utility from operating appliances.

Increased consumption and investment in appliances gives utility to the household, and its evolution depends on the available funds to invest in new appliances and to consume more leisure, non-energy goods and electricity, and the preferences of the household. Thus after the month 158, the utility growth is slight.

After 20 years, the household has not yet fully acquired the electrical lighting system (an asset base value of \$200, see Table VI.44). By this time, the consumption of leisure and non-energy goods levels to about 120 hours and 48 units per month respectively: this corresponds to a working regime of 5 hours per day for 20 days a month. The productive stock also increases to a level of \$1149, supporting the additional expenses. The household increases its consumption of leisure, non-energy goods and energy, and its ownership of appliances and productive stocks, though at an increasingly slower rate. The 3% return rate on productive investments and the wages of the worked hours (L_{max}-L) maintain these levels of consumption. The *asset ladder rule* stays very close to value one after month 158, thus channeling most of the net income into the acquisition of appliances.

In summary, an household earning \$0.2 per hour of labor, being able to work for a maximum of 220 hours per month and given an initial credit of \$500 from which it can earn 3% per month constant, for the market conditions described in equation (55), will not be able to afford an electrical connection before the 14th year (month 158). Even after 20 years, it will still have no funds to pay for and sustain the electricity consumption of a television-set, a refrigerator and a computer, and will only have installed 80% of the average electrical lighting system and (see Table VI.44). The access to electricity at low prices and to a credit of \$500 is not sufficient to increase the household's consumption of electricity to the basic levels described in Table VI.44, even after 20 years. Policies that establish lines of credit to promote electricity consumption must consider market parameters: this type of household, with these preferences at these prices, does not begin investing in the energy goods until it has more or less reached the steady-state level of consumption of non-energy goods and leisure. Programs to incent electricity consumption should take into account the fact that households value, possibly even more, the consumption of non-energy goods and are willing to retain a low-grade source for their domestic energy needs to augment their consumption of preferred commodities.

Note that this simulation is simplified by assuming constant market characteristics over time, by averaging return rates of productive stocks and cost rates of appliances, , assuming deterministic rates of return, choosing a simple Cobb-Douglas functional form, and other simplifying assumptions.

What can then speed up the evolution of the household towards higher consumption levels that it can sustain form its own earnings? The next section analyses the effect of parameter variation in the optimal paths.

ANALYSIS OF SENSITIVITY OF VARIABLE BEHAVIOR TO SOME PARAMETERS

VARYING THE INITIAL CREDIT

An increase in the initial credit K_0 results in a faster evolution towards the sustainable (consumption of commodities and energy whose costs are fully covered by the household's earnings from productive stocks and labor sales) consumption as shown in Figure VI.38. In other words, the consumption of leisure and non-energy goods reaches the levels of maximum utility sooner and the productive stocks can sooner sustain the costs of electricity consumption in newly acquired appliances. However, the general pattern of household development remains the same. In Figure VI.38, the blue lines represent the smaller initial credit ($200) and the green lines represent the highest initial credit ($800). The red lines correspond to $500 of initial credit and represent the household of Figure VI.37.

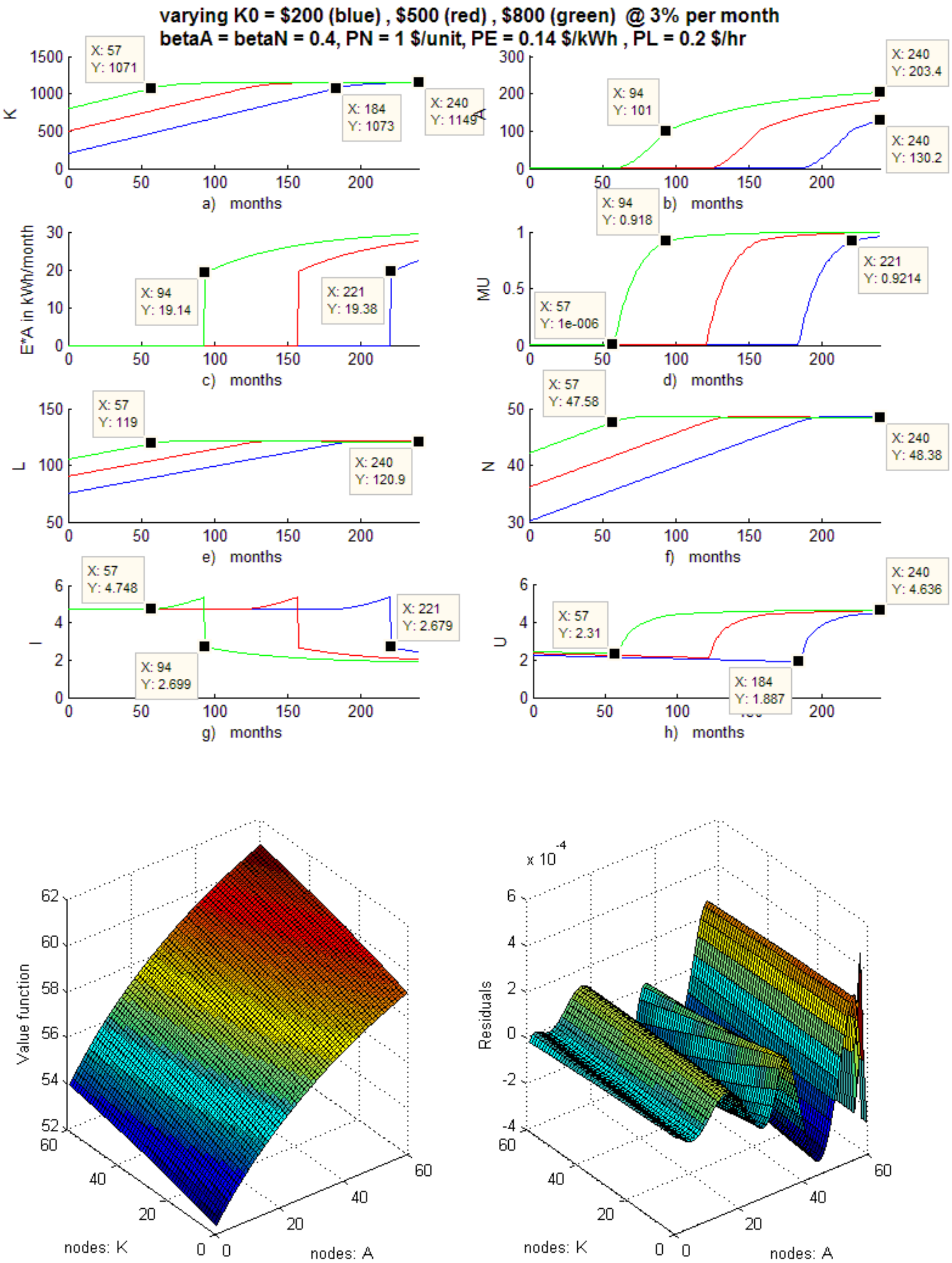

Figure VI.38 – Increasing the initial credit for productive investment

The high-cost energy consumption in the newly acquired appliances does not provide enough utility to compete with the low-cost leisure and non-energy goods. If the energy consumption can be made cheaper or the utility obtained from the appliances can be made higher, the household will certainly reserve a higher part of its budget to invest and increase its energy consumption base. Although utility, as an expression of an household's preferences, is usually taken as given, marketing the various end-uses of electricity and the opportunities they create, for example in terms of increased productivity of self-production activities and time saving, may actually change the information set over which choices are made.. It is however important to consider that preferences shift between commodities and that if a household ranks electrical lighting very high when compared with leisure time (high utility for electricity), it might just prefer to keep cooking with charcoal – instead of changing to electrical cooking - and spend the extra income in food. This complexity is not part of these simulations (low utility for electricity).

VARYING THE ENERGY PRICE

The expectation is that a reduction in the energy price can increase the cost effectiveness (reduce the cost of utility) of investments in appliances, resulting in the household total investment to be higher in the long term. However, results show precisely the opposite: a reduction in the energy rate will result in a faster acquisition of appliances but in a smaller accumulated value of investment, in the long term, Figure VI.39.

The blue line represents the path for a household accessing electricity at the price PE = 0.05 \$/kWh. The household uses the earning from the initial credit of \$500 to sustain fully the consumption of L and N, at levels that are constant throughout the 20 years of simulation.

All residual net income is invested in appliances, and for all the period of time the household does not need to increase its income base, i.e. the productive stock remains at \$500 level and the asset ladder rule equals 1 all time. The residual net income slightly reduces when appliances start consuming electricity (month 69) and so the investments in appliances grow at a much slower rate after that.

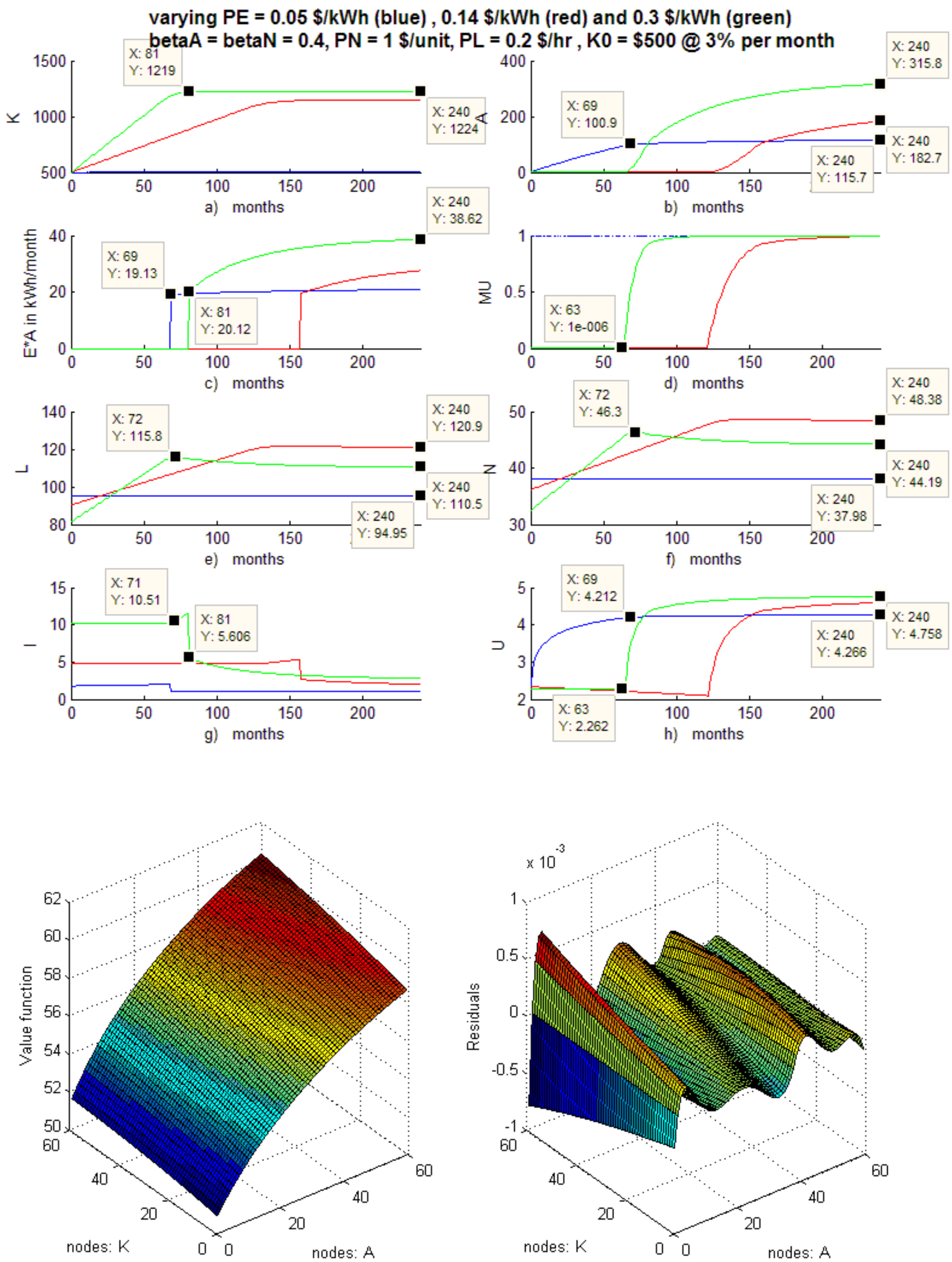

Figure VI.39 – Varying the energy price

The household gains utility immediately from the start at a more or less constant rate, because the consumption and the investments are also more or less constant throughout. However, by the year 20 the household only accumulates $115, sufficient for the electrical connection and very few lights. This household also shows a lower consumption (and utility) level at 95 hours and 38 units per month, respectively for leisure and non-energy good.

When the energy price is increased to 0.14 $/kWh (red line) the household starts at a smaller level of consumption of N and L, and diverts all its net income to productive investments. It is still not capable of sustaining the depreciation and operating costs of appliances, so their acquisition is delayed.

The household increases consumption of commodities at the same time it increases its income basis. At about month 150, it has accumulated enough productive stocks to sustain investments in appliances, and it has also reached the level of consumption in L and N where utility more or less constant.

At this time, the asset ladder rule changes over a short period from near zero to near one, and most net income is channeled for the acquisition of appliances. The household has reached a level of productive stocks and labor earnings that can sustain the additional costs of depreciating and operating appliances.

The higher energy price (in red) delays investments in electrical appliances and forces the household to increase its productive stock in order to sustain future costs of electricity. Notwithstanding the delay and higher price, because the productive stock is increased, the net income also increases in the beginning, and household will be able to invest more in appliances and will end up with an electrical connection and about 80% of the lighting system, a total of $182 in electrical appliances after 20 years.

So from this result it would seem that a higher electricity price promotes a delayed but higher sustained investment in electrical appliances, by the end of 20 years of activity. This surprising effect is more evident with the simulation run for an even higher electricity price (30 cents $/kWh, in green). Smaller consumption of leisure and non-energy goods results in a faster growing productive stock and a faster availability to invest in appliances (month 64). Therefore, the household can reach the level of $315 in appliance ownership, which corresponds to having achieved the electrical connection and the sustainable acquisition and operation of lights and a color TV (see Table VI.44 in appendix). Note also that the household is necessarily better off. Rather, it chooses to sacrifice (less discounted) utility in the short run for higher levels in the long-run.

When the price increases even further to 0.30 $/kWh (green line), the operation of electrical appliances becomes expensive, and so the household must make some decisions. The utility function used does not contain total interchangeability, i.e. even if the preferences for non-energy goods (N) and for appliances (A) are the same, $\beta_N = \beta_A = 0.4$, consuming 2n units of non-energy goods will give less utility than consuming n units of non-energy goods, and investing in appliances for the same corresponding value. This means that the household will maximize utility by consuming commodities and by investing in appliances. A higher energy price will require a higher income to sustain the operating costs, and the household seems to provide just that: lower consumption levels, higher investment in productive stocks and a delayed investment in appliances. This effect is a result of equation (53), by which high energy prices reduce the shadow price of investment and incentive the household to invest in productive stocks in order to finance the more expensive energy source.

For the low-energy price (blue), the asset ladder rule remains at one. For the high-energy price (red), the *asset ladder rule* increases at a slower pace from zero to one. For the very high-energy price (green), the household evolves faster because it needs to first accumulate productive stocks before investing in appliances.

To test this effect, the optimization algorithm was run for higher marginal utility of appliances ($\beta_A = 0.6$) and lower marginal utility of consumption goods ($\beta_N = 0.3$ and $\beta_L = 0.1$), see Figure VI.40.

The high utility obtained from appliances incents the household to invest instead of consuming leisure and non-energy goods. In this simulation, there is no investment in productive stocks for any level of electricity price tested. Again, the household reaches a higher accumulative value of appliances in the long term for the case of higher energy prices, resulting from the significant reduction of consumption in leisure and non-energy goods. However, the utility gained overtime is about the same: higher prices of energy will basically switch the household choice from consumption to investment, but utility registers only slight gains.

The effect of an increase in the price of electricity is better seen when comparing simulations for which the household preferences for appliances is much higher than for consumption commodities, i.e. the household will preferably invest in appliances from the start. It is clear that higher prices result in:

- Significantly lower consumption of non-energy commodities
- Higher investment levels in appliances
- Higher overall utility levels for the household

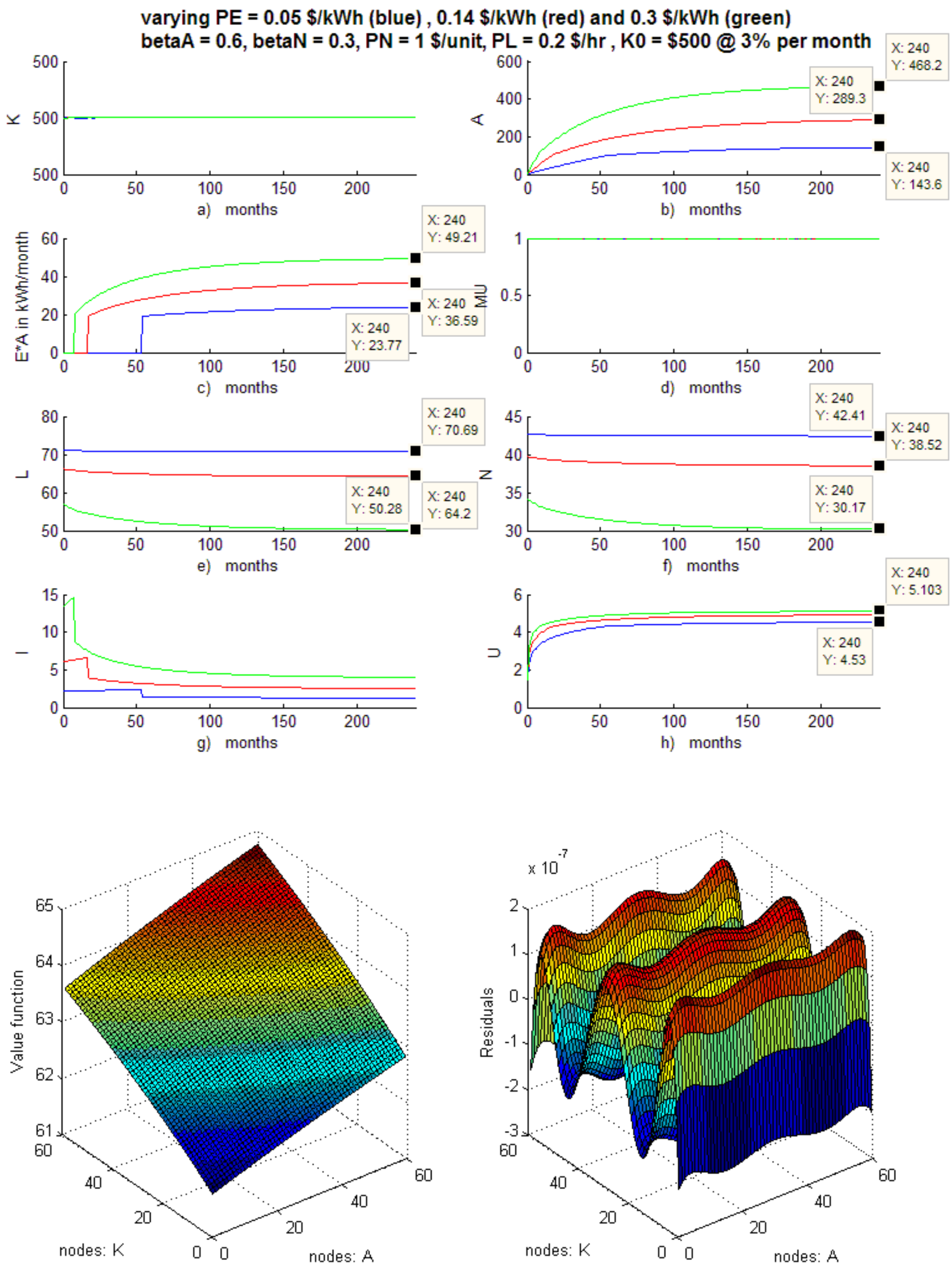

Figure VI.40 – Rerun of the optimization for varying electricity prices

The household knowing that the consumption of energy will be more expensive because of higher prices, will reduce the consumption of commodities and will accumulate faster in the form of productive investments, which in turn will allow for higher net incomes, higher and faster investments in appliances and bigger expenses in energy costs. Although counterintuitive, if the household intends to obtain utility from appliances, it will save and accumulate in order to achieve it, sacrificing thus the consumption of commodities.

From the results of Figure VI.39, aligned with those of Figure VI.40, it can be concluded that the higher the productive stock, the higher the net income and the investment in appliances, and the faster this investment is made. Extrapolating, this result confirms the need for acquiring new income generating capabilities (by poor families) as a condition to evolve to higher consumption levels and to became an electricity consumer.

In addition, the shape of the utility function, in other words, the value of commodities affect the way households such that they may select a more costly consumption, as shown in results of Figure VI.40. It is necessary a more thorough investigation in the interdependencies of utility functions versus commodity prices and the corresponding optimal behaviors.

VARYING THE RATE OF RETURN IN PRODUCTIVE INVESTMENTS

These simulations are assuming that the return rate on productive investments does not change over time. Higher rates of return generate more earnings for the household and it should make investments in appliances more attractive However, results of Figure VI.41 indicate that as the household earns a higher income it will increase its consumption of leisure and non-energy commodities and it will invest in productive stocks to sustain the increased monthly cost.

The household consumes leisure and non-energy goods first and only then switches to investment in appliances. The investment in appliances is delayed significantly when the rate of return increases and this delay is determined by the time at which the consumption of those two commodities (leisure and non-energy goods) level out.

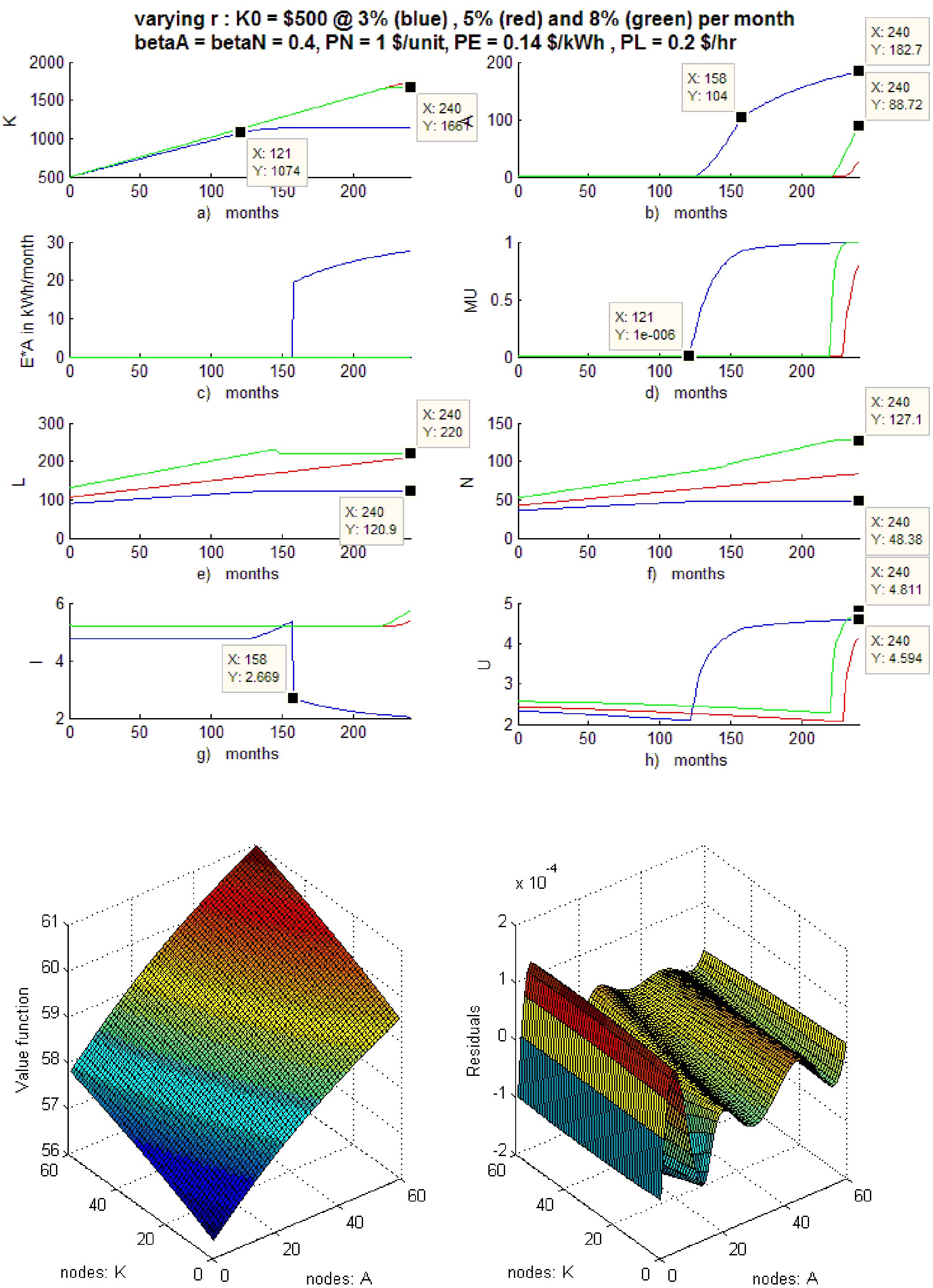

Figure VI.41 – Varying the rate of return in productive investments

At 3% return rate per month (blue) by the end of the first year, consumption of leisure and non-energy goods reaches respectively 93 hours and 37 units per month. Investments in appliances however are delayed until the year 11th (158th month). As the return rate increases to 8% per month (green), the household takes on additional consumption of leisure (220 hours by year 20th), forcing the ownership of appliances to reduce to $88 by year 20th (the electrical connection is unaffordable) and forcing the productive stock to increase up to $1661 after 20 years.

The highest asset ownership ($182, corresponding to only 80% of electrical lights – see Table VI.44 in appendix) but lowest long-run utility level is achieved with a rate of return of 3% on the productive stocks.

Even if the value of appliances does not always increase with increases in the rate of returns, because of the cost-utility balance between leisure, non-energy goods and appliances, as the rate of return increases the *asset ladder rule* tends to remain at the zero level for much longer, and only take values closer to one at later months.

The ownership of larger productive investments of higher return rates, as discussed before, favors the earlier and higher investment in appliances, if the household's preferences are so inclined.

VARYING THE WAGE RATE

The previous simulations have shown a tendency to consume leisure; in other words, not to work the maximum hours possible. In some simulations, households end up working only half of their monthly time thus reducing the available funds for investments in appliances. This behavior does not seem to be very realistic, but is implied by the shape and the parameters used in the utility function. What would happen if each hour of leisure would be more costly – or each hour worked would be better compensated?

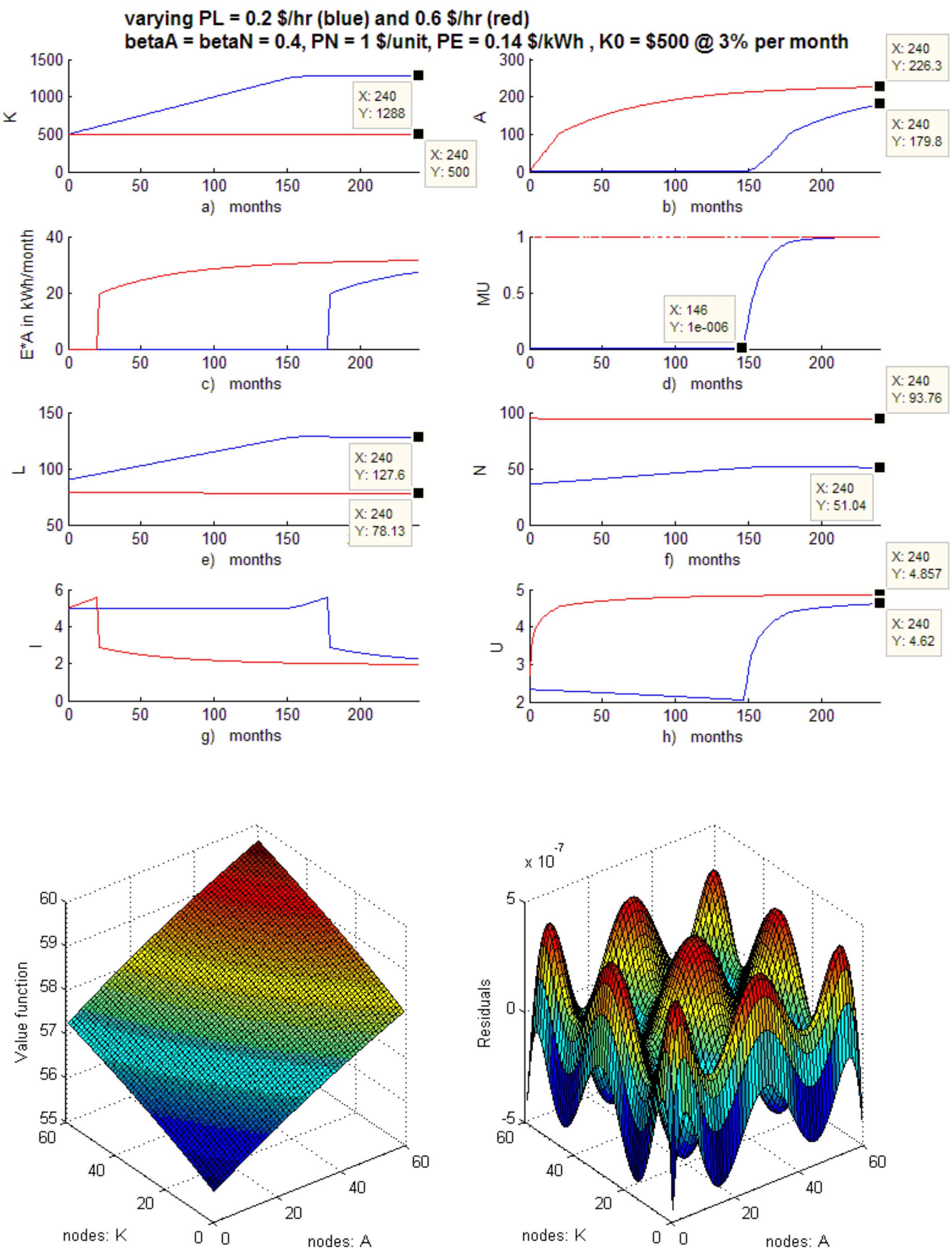

Figure VI.42 – Varying the wage rate

The algorithm simulated the optimal solution for two prices of labor (wages), see Figure VI.42 above, with the following results:

- The lower the wage rate (blue) the higher the consumption of leisure, or the less hours per month are worked for income, and vice-versa higher wages (red) result in more hours worked and les leisure time.
- Higher wages and less leisure time leave funds available for investment in appliances. By the end of the second year (month 21st) the household has invested in the electrical connection and by the end of 20 years it will have acquired (and operates in a sustainable manner) the full electrical lighting system and saved $26 for a color TV (see Table VI.44 in appendix).
- Because of larger investment in appliances, the utility gained by the household is actually higher for the higher wage - less leisure's case (red) than the lower wages' case (blue).

This simulation shows the interdependency of prices and utility coefficients in the household choice for consumption versus investment. For this reason, more information regarding consumer tradeoffs along these dimensions should be investigated, so that the simulations reflect behaviors that are more true to empirical reality.

DISCUSSION OF THE OPTIMAL PATHS AND INFLUENCING FACTORS

The above simulations were made for a household seeking to maximize the utility of its increased consumption and investments, while maintaining its ability to pay for the additional costs they entail, for the period of 20 years.

A simulation is run for conceding a credit of a $1000 at 3% return, to a household earning about $100 per month (0.6$ per hour), valuing utility as $\beta_A = 0.6$ and $\beta_N = 0.3$. The asset ownership value can be as high as $347 after 20 years, with some increases in consumption of non-energy goods, from 48 to 114 units per month, see Figure VI.43. After 20 years, the household has only invested in the electrical connection and the full lighting system, and it is $73 short of the value for a color TV.

The *asset ladder rule* grows in a logarithmic form between zero and one, and the productive stock must also grow to sustain the added costs of consumption (blue). In the new household (red lines – high initial credit, high wages and high preferences for electricity), the productive stock and wages generate sufficient income to support the additional consumption and the investment in appliances. Also the household utility is slightly higher in the new (red) simulation case.

These simulations show the dependency of the optimal paths for the controls and state variables, and particularly of the *asset ladder rule*, on the parameters of the problem. For simplicity sake, the new energy source to consume is assumed to be only electricity, i.e. energy transition in the simulated households constitute the adoption of electricity as a domestic source.

The utility function can determine whether the household will prioritize consumption or investment in appliances, as it will choose the best value utility giving variable. If the consumption of leisure or non-energy goods is cheap and high utility giving, the household will not transition to electrical power by investing in the electrical connection and appliances.

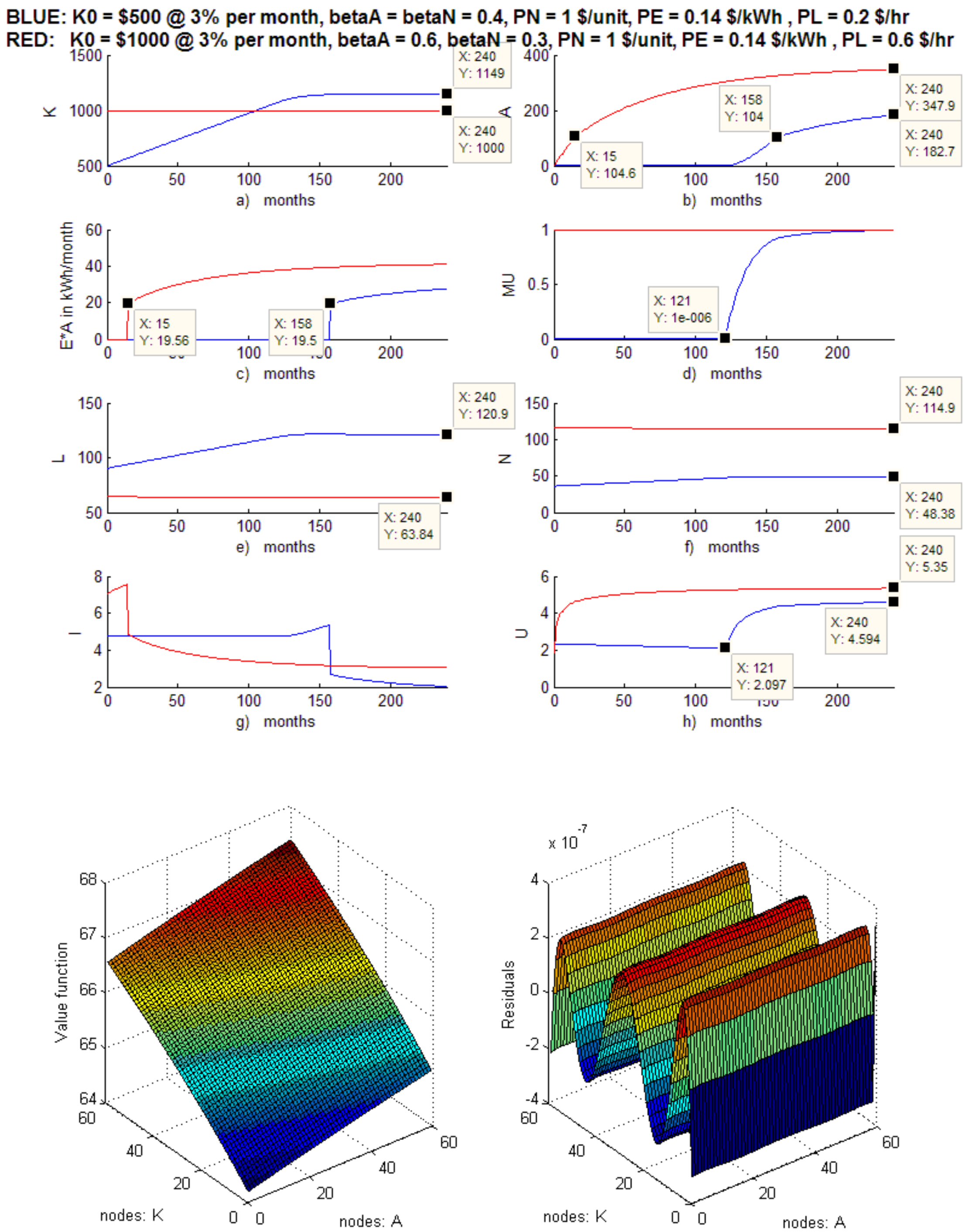

Figure VI.43 – Simulation of a credit of $1000 at 3% return per month, to a $100/month salary household that values appliances with a higher preference for electric appliances *versus* the household modeled in Figure VI.37

However, high earnings will result in not only increased consumption of leisure and non-energy gods, but also in investments in energy-consuming assets that also provide utility. This behavior can explain the energy ladder as originally conceptualized and simultaneously the discrepancies found. High-income households will transition to higher sources but not necessarily so, as considerations of utility and cost-benefit are part of the household's choices.

The transition from, for example, biomass to electricity, can provide more utility to the household, can serve its needs better, but it is not necessarily the highest utility choice it can make within its budget limitations. The household may also opt for the adoption of electricity only for low-demand high-utility needs, such as refrigeration for example, but keep biomass in the high-demand cooking activity. Whenever utility from electrical appliances is comparable to the utility obtained from increasing consumption, and if the cost of electricity is higher than the cost of leisure and/or non-energy goods consumption, the household will prioritize consumption of commodities and delay the energy transition processes until it earns sufficient to support the high-energy costs. In this case, the *asset ladder rule* will tend to take values close to zero. However, for high utility low cost energy transition processes, the household will split its earnings into increasing consumption and into investing in energy-consuming utility giving assets. In this case, the *asset ladder rule* will tend to take values other than zero, depending on the cost of providing utility of investment versus consumption.

High labor prices (wages) will stimulate long labor hours and less leisure, and the increasing in the consumption of non-energy goods and in investments in the asset base. The same is true for households that do not value leisure as much as the services that energy-consuming appliances may provide. In other words, households may be willing to work more for earnings that will pay investments and operating (energy and depreciation) costs of electrical lighting and a TV set, for example.

Whenever the household finds optimal to invest in energy-consuming appliances and to sustain it need to also invest in productive stocks so its earnings increase, the *asset ladder rule* will change from zero to one, such that utility is maximized and sustainability (a non-zero net income) is assured.

In conclusion, energy transition can optimally occur if the household perceives it as high value input into household utility (high β_A), and if the energy price and the appliances' efficiency incents the investment (in productive stocks before investing in appliances) to the detriment of consumption of leisure and non-energy goods. The provision of an initial credit for income generation is necessary to alter the household status and move it into increasing its consumption or into investing in a sustainable manner. In all simulations the household evolved slowly over the period of 20 years, i.e. policies for development must be long term.

RECOMMENDATIONS FOR FURTHER WORK

Energy transition can only occur if the household values it as a high utility-providing choice, when compared with consumption of other items such as leisure and non-energy goods. This perception is a result of access to information on the usefulness of the new energy source being promoted, and of the combination of low prices (in the supply market) and high efficiency of uses of the appliances to invest in. Research the demand for electricity versus other commodities (to establish preferences for Mozambican households) and to develop information dissemination approaches that increase the utility valuation of investments in electrical appliances are needed for a more accurate study of household's behavior. Furthermore, regulations concerning efficiency rates for electrical appliances can help promote the transition from traditional low-grade sources to electricity in the domestic settings. High-energy prices have shown in the simulations to incent investment rather than consumption, when utility gains are not interchangeable between consumption of non-energy goods and leisure and investment in appliances. Nevertheless, it is intuitive to expect that, if the household earns enough to acquire appliances and to consume, that low operating costs of appliances will result in an increase of investments in appliances and as such will facilitate electricity to become a domestic source for the poor. Further investigations are however recommended.

The theoretical model and the numerical simulations confirm that if no investment funds are available to increase the income-generating stock and if no investment is made to increase the ownership of appliances that consume high-grade sources, the household will not evolve and will not transition to sources such as electricity. The productive investment portfolios, available to evolving households and their respective return rates need to be identified and described mathematically, so that the household behavior in increasing its productive stock may be better characterized.

The asset base used in these simulations was approximately derived by assuming that electricity consumption between Mozambique and the US only varies in its diversity, not on its intensity, which of course is not a very accurate assumption. However, no data was available to characterize the end uses and the intensity of consumption of electricity in Mozambique, and the random manipulation of data seemed unwise. So a survey of the available electrical appliances in the Mozambican market, in terms of capital cost and electricity intensity, as well as time of use and preferences in the acquisition 'order for a poor family, is needed so that energy consumption rates *E(A)* and typical depreciation rates of the asset base $\gamma(A)$ can be more accurately derived.

Finally, a study on the energy prices, the composition of the consumer population and the detailed cost burdens, is needed so that domestic tariffs effectively promote domestic consumption. Currently the social tariff is at 0.14 $PPP/kWh with a limit of 100 kWh per month (EDM 2007), which barely cover lighting and a small TV consumption (Appendix VI.2). Recommendations are made that this consumption level and possibly the price are reviewed in order to better serve evolving poor.

The above theoretical study demonstrated that the current price of electricity (EDM) allows the household to invest and to evolve out of poverty to a better life quality, under certain conditions such as credit access. Furthermore, the numerical example showed that a small investment credit could change the consumption levels and the owned assets of an evolving household. The question of whether electricity can be a source of the poor is positively answered and the requirements for its sustainability are identified, namely:

a) credit to invest and increase consumption in a sustainable manner
b) information programs to increase the utility valuation of electricity as a domestic source. If households are better informed on the electricity prices (for example, the social rate), on possible credits for acquisition of appliances and other benefits instituted to promote electrical connections and consumption, they may prefer electricity to other sources, and possibly, they may also increase its preferences for electricity consumption in detriment of leisure or other commodities.
c) access to cheap and efficient appliances. Cheap appliances will allow the household to serve its needs faster, for example completing the full lighting system much earlier than 20 years in simulation of Figure VI.42 for a wage rate of 0.2$/hour of

labor. Efficient appliances will have a lower consumption rate E(A), i.e. the cost burden of operating electrical appliances will be lower.

d) opportunity for income-generating investments/activities. Households need to increase their income-generating capabilities, more likely through self-employment in services, artisanal production or farming activities.

e) and electricity prices for domestic consumers coupled with the provision of high utility from electrical appliances and income generating opportunities.

The *asset ladder rule* depends on the parameters of the problem, in all simulations, it actually changed very fast from zero to one, after the household accumulated enough productive stock to finance the operating costs of appliances. This suggests that households will delay investment in appliances until they have reached a steady level of consumption, and only then they switch to energy consuming. As a result, it is important to consider, in policy making, that households have preferences competing with the ownership and operation of appliances that may actually prevent the success of electrification programs.

APPENDIX VI.1: SUPPLEMENTING THE THEORETICAL MODEL

SOME ASSUMPTIONS IN THE THEORETICAL AND NUMERICAL SOLUTION

In the main presentation, the rate of return of productive investments is assumed to be constant for any value of *K*. This is a simplification because, in period t_j, each investment in productive (income generating) activities $\dot{K}\left(t_j\right) = K_i$ has its own particular rate of return r_j. If investments for income generation are diversified into a portfolio of investments $\vec{K} = \left\{K_j\right\}$, the average rate of return of the total stock in productive investments $K = \sum_j K_j$ will be an average rate that depends on the composition of the portfolio $r = r\left(\left\{K_j\right\}\right)$ that simplified can be represented as dependent on the size of the total stock, i.e. $r = r\left(K\right)$.

$$r = r\left(K\right) \tag{56}$$

Similarly, the depreciation rate of operating appliances is assumed to be constant on time, regardless of the value of the asset base. In reality, appliances have a reposition cost (depreciation) that is specific and constant for each A_j. This depreciation rate γ_j represents the rate of wear and tear that a normal (average) usage of the appliance brings. In other words, this rate represents the value of the appliance that needs to be replaced because of its usage, in each period. For simplification, the average depreciation rate of the whole asset base is:

$$\gamma = \gamma\left(A\right) \tag{57}$$

The investments in domestic appliances, of different costs, end-uses and energy sources, $\dot{A}(t_j) = A_j$, burden the household with an additional operating cost rate of $E(A_j) \cdot P_E$ that is specific of each appliance/source. As the asset base grows into a set of appliances $\vec{A} = \{A_j\}$, the average operating cost rate associated with the total asset base $A = \sum_j A_j$ will depend on the composition of the asset base $E(A) \cdot P_E = E(\{A_j\}) \cdot P_E$. Each appliance consumes, on an average domestic usage, a certain amount of energy E_j for which the household has to pay an average price of energy acquisition P_E. The household will spend $E_j \cdot P_E$ of its asset value in acquiring energy to run each of its appliances. Simplifying for the whole asset base, the cost rate of the energy consumption is

$$E \cdot P_E = E(A) \cdot P_E \tag{58}$$

If more than one source of energy is consumed in the asset base, the energy price P_E is a composition of the prices of each individual source in the energy mix. Appendix VI.2 presents a rough derivation of a function for electricity consumption in a typical household *E(A)*, though better data and more accurate analysis on this particular derivation are needed.

The system will have a maximum if the utility function is concave. The signs of the principal minors of the Hessian matrix establish the validity of the system's solution, in the range $\mu \in (0,1)$, namely:

$$\mathcal{H} = \begin{bmatrix} H_{LL} & H_{LN} & H_{LA} & H_{LK} \\ H_{NL} & H_{NN} & H_{NA} & H_{NK} \\ H_{AL} & H_{AN} & H_{AA} & H_{AK} \\ H_{KL} & H_{KN} & H_{KA} & H_{KK} \end{bmatrix} \tag{59}$$

Where *H* is the Hamiltonian of the problem:

$$\mathrm{H} = U(L,N,A) + \lambda_A \cdot \mu \cdot I(L,N,A,K) + \lambda_K \cdot (1-\mu) \cdot I(L,N,A,K) \tag{60}$$

THE FIRST PRINCIPAL MINOR MUST BE NEGATIVE OR NULL:

$$H_{LL} = \frac{U_{LL}}{P_L} < 0 \tag{61}$$

The marginal utility of leisure must be diminishing, i.e. $U_{LL} < 0$. Intuitively and to conform with economic theory, the marginal utility of non-energy goods must also be diminishing, $U_{NN} < 0$, and the cross effects must be symmetric and positive: $U_{LN} = U_{NL} > 0$.

THE SECOND PRINCIPAL MINOR MUST BE POSITIVE OR NULL:

$$\det\begin{bmatrix} H_{LL} & H_{LN} \\ H_{NL} & H_{NN} \end{bmatrix} = \det\begin{bmatrix} \frac{U_{LL}}{P_L} & \frac{U_{LN}}{P_L} \\ \frac{U_{NL}}{P_L} & \frac{U_{NN}}{P_N} \end{bmatrix} = \frac{U_{LL} \cdot U_{NN} - U_{LN} \cdot U_{NL}}{P_L \cdot P_N} \geq 0 \tag{62}$$

It will be positive only if $U_{LL} \cdot U_{NN} - U_{NL}^2 \geq 0$, in other words the cross effects must be smaller or similar than the rates of change of the marginal utilities with leisure and non-energy goods respectively This condition establishes the concavity of the utility function on L and N, to be expected for the diminishing marginal utilities.

THE THIRD PRINCIPAL MINOR MUST BE NEGATIVE OR NULL:

$$\det\begin{bmatrix} H_{LL} & H_{LN} & H_{LA} \\ H_{NL} & H_{NN} & H_{NA} \\ H_{AL} & H_{AN} & H_{AA} \end{bmatrix} = \det\begin{bmatrix} \frac{U_{LL}}{P_L} & \frac{U_{LN}}{P_L} & \frac{U_{LA}}{P_L} \\ \frac{U_{NL}}{P_N} & \frac{U_{NN}}{P_N} & \frac{U_{NA}}{P_N} \\ U_{AL} & U_{AN} & U_{AA} \end{bmatrix} \leq 0 \tag{63}$$

$$\Rightarrow \frac{U_{LL}}{P_L}\cdot\frac{U_{AA}\cdot U_{NN}-U_{AN}\cdot U_{NA}}{P_N} - \frac{U_{LN}}{P_L}\cdot\frac{U_{NL}\cdot U_{AA}-U_{NA}\cdot U_{AL}}{P_N} + \frac{U_{LA}}{P_L}\cdot\frac{U_{AN}\cdot U_{NL}-U_{AL}\cdot U_{NN}}{P_N} =$$
$$= \frac{1}{P_L\cdot P_N}\cdot\begin{bmatrix} \left(U_{LL}\cdot U_{NN}-U_{NL}{}^2\right)\cdot U_{AA} - U_{LL}\cdot U_{AN}\cdot U_{NA} + U_{LN}\cdot\left(U_{NA}\cdot U_{AL}+U_{AN}\cdot U_{LA}\right) \\ -U_{NN}\cdot U_{AL}\cdot U_{LA} \end{bmatrix} \leq 0$$

If we assume diminishing marginal utilities of asset ownership and positive-symmetric cross-effects $U_{AA}<0$; $U_{AN}>0$; $U_{AL}>0$, we obtain the following concavity condition:

$$\left(U_{LL}\cdot U_{NN}-U_{NL}{}^2\right)\cdot U_{AA} \geq U_{LL}\cdot U_{AN}{}^2 + U_{NN}\cdot U_{AL}{}^2 - 2\cdot U_{LN}\cdot U_{AN}\cdot U_{AL}$$

Where

$$U_{LL}\cdot U_{AN}{}^2 + U_{NN}\cdot U_{AL}{}^2 - 2\cdot U_{LN}\cdot U_{AN}\cdot U_{AL} \leq 0 \quad \text{and} \quad U_{LL}\cdot U_{NN}-U_{NL}{}^2 \geq 0$$

THE FOURTH PRINCIPAL MINOR MUST BE POSITIVE OR NULL:

$$\det\begin{bmatrix} H_{LL} & H_{LN} & H_{LA} & H_{LK} \\ H_{NL} & H_{NN} & H_{NA} & H_{NK} \\ H_{AL} & H_{AN} & H_{AA} & H_{AK} \\ H_{KL} & H_{KN} & H_{KA} & H_{KK} \end{bmatrix} = \det\begin{bmatrix} \frac{U_{LL}}{P_L} & \frac{U_{LN}}{P_L} & \frac{U_{LA}}{P_L} & \frac{\mu}{1-\mu}\cdot\frac{U_{LA}}{P_L} \\ \frac{U_{NL}}{P_N} & \frac{U_{NN}}{P_N} & \frac{U_{NA}}{P_N} & \frac{\mu}{1-\mu}\cdot\frac{U_{NA}}{P_N} \\ U_{AL} & U_{AN} & U_{AA} & \frac{\mu}{1-\mu}\cdot U_{AA} \\ \frac{\mu}{1-\mu}\cdot U_{AL} & \frac{\mu}{1-\mu}\cdot U_{AN} & \frac{\mu}{1-\mu}\cdot U_{AA} & \left(\frac{\mu}{1-\mu}\right)^2\cdot U_{AA} \end{bmatrix} = 0 \tag{64}$$

This solution assumes that by definition the variability of the investments are related by the asset ladder rule as follows:

$$\frac{\partial A}{\partial K}=\frac{\partial A/\partial t}{\partial K/\partial t}=\frac{\dot{A}}{\dot{K}}=\frac{\mu\cdot I}{(1-\mu)\cdot I}=\frac{\mu}{1-\mu} \tag{65}$$

In summary, if the utility variables show diminishing utilities and the positive symmetry of the cross-effects in the marginal utilities is true, the sufficient conditions for a maximum in the optimal solution require concavity in the 'three variable' utility space by the following conditions:

$$\begin{aligned}
&U_{LL}\cdot U_{NN}-U_{NL}{}^{2}\geq 0\\
&\left(U_{LL}\cdot U_{NN}-U_{NL}{}^{2}\right)\cdot U_{AA}-\left(U_{LL}\cdot U_{AN}{}^{2}+U_{NN}\cdot U_{AL}{}^{2}-2\cdot U_{LN}\cdot U_{AN}\cdot U_{AL}\right)\leq 0\\
&\text{where}\\
&U_{AA}<0 \quad ; \quad U_{LL}<0 \quad ; \quad U_{NN}<0\\
&U_{AN}=U_{NA}>0 \quad ; \quad U_{AL}=U_{LA}>0 \quad ; \quad U_{LN}=U_{NL}>0
\end{aligned} \tag{66}$$

These conditions must be true for each specific form of the utility function used.

NUMERICAL ALGORITHM: MATLAB CODE

The following code was programmed to perform the Newton iteration routine, defined by function *dpsolve* from CompEcon library (Miranda and Fackler 2002).

```
function [out1,out2,out3] = func3(flag,s,x,e,delta,r,PL,PN,PE,alpha,betaL,betaN,betaA,
gamma,Lmax,MUmax)
 [n,ds] = size(s);   dx = size(x,2);
% extract controls and states
 L = x(:,1);   N = x(:,2);   MU = x(:,3);
 A = s(:,1);   K = s(:,2);
% electricity consumption per asset value only starts after electrical connection
 E = 1.1173.*(A.^(-0.3844));
 indx = find(A<=100);      % cost of electrical connection $100
 E(indx,1) = 0;
% Net income and utility function
 I = r.*K + Lmax.*PL - L.*PL - N.*PN - E.*PE.*A;
 U = log(alpha) + betaL.*log(L) + betaN.*log(N) + betaA.*log(A);
```

```
 switch flag
  case 'b'                    % lower and upper bounds of the action
     out1 = ones(n,dx).*1E-06;                      % action vector nx(dx) – lower bound
     temp = r.*K + Lmax.*PL - E.*PE.*A;          % condition for I>=0
    N2 = temp.*betaN./(betaL+betaN)./PN;
    L2 = temp.*betaL./(betaL+betaN)./PL;
     L2(find(L2 > Lmax)) = Lmax;
     N2(find(L2 > Lmax)) = (temp(find(L2 > Lmax)) - Lmax.*PL) ./ PN;
     out2 = [ones(n,1).*L2,ones(n,1).*N2,ones(n,1).*MUmax];     % upper bound nx(dx)
  case 'f'                 % reward function
     out1 = U;                                          % function nx1
     out2 = zeros(n,dx);                 % 1st derivative matrix nx(dx)
     out2(:,1) = betaL./L;               % 1st derivative on L
     out2(:,2) = betaN./N;               % 1st derivative on N
     out3 = zeros(n,dx,dx);              % 2nd derivative matrix nx(dx)x(dx)
     out3(:,1,1) = -betaL./(L.^2);       % 2nd derivative on LL
     out3(:,2,2) = -betaN./(N.^2);       % 2nd derivative on NN
  case 'g'   % state transition function
     out1 = [ MU.*I  - gamma.*A + A , (1-MU).*I + K ];     % functions nx(ds)
     out2 = zeros(n,ds,dx);                % 1st derivative matrix nx(ds)x(dx)
     out2(:,1,1) = MU.*(-PL);              % 1st derivative of g1 on L
     out2(:,1,2) = MU.*(-PN);              % 1st derivative of g1 on N
     out2(:,1,3) = I;                      % 1st derivative of g1 on MU
     out2(:,2,1) = (1-MU).*(-PL);          % 1st derivative of g2 on L
     out2(:,2,2) = (1-MU).*(-PN);          % 1st derivative of g2 on N
     out2(:,2,3) = -I;                     % 1st derivative of g2 on MU
     out3 = zeros(n,ds,dx,dx);       % 2nd derivative matrix nxx(ds)x(dx)x(dx)
     out3(:,1,1,3) = -PL;            % 2nd derivative of g1 on LMU
     out3(:,1,3,1) = -PL;            % 2nd derivative of g1 on MUL
     out3(:,1,2,3) = -PN;            % 2nd derivative of g1 on NMU
     out3(:,1,3,2) = -PN;            % 2nd derivative of g1 on MUN
     out3(:,2,1,3) = PL;             % 2nd derivative of g2 on LMU
     out3(:,2,3,1) = PL;             % 2nd derivative of g2 on MUL
     out3(:,2,2,3) = PN;             % 2nd derivative of g2 on NMU
     out3(:,2,3,2) = PN;             % 2nd derivative of g2 on MUN
 end
end
```

APPENDIX VI.2: DOMESTIC ENERGY CONSUMPTION VERSUS THE ASSET BASE – FUNCTIONAL FORM

In a policy making setup, the initial investment credit K_0 is given in order for the household to evolve in its consumption of electricity, up to a level $E(A)\cdot A$, which corresponds to the per household minimal electricity consumption that the policy is aiming for.

The determination of the appropriate level for the monthly electricity consumption $E(A)\cdot A$ depends on available appliances in the local markets, their prices and electricity consuming characteristics, as well as durability. The 2006 electricity average consumption in Mozambique was 89 kWh/household-month in 2006, below the current limit of 100 kWh/month for the social rate of 0.14$PPP/kWh (EDM 2007). In the US households consume electricity for a wide range of utilities (EIA 2001). Although US households consume about 3 times the monthly electricity of Mozambican households, this difference may be attributed to the wider range of utilities rather than to major differences in power ranges and usage time - the variations in household energy intensity are more related to the variety of energy uses *rather than variations in the total consumption of each end-use*[144]. Consequently, it will be assumed that the consumption for lighting[145], refrigeration and

[144] Although this approach is a rough approximation, it is still valid on the basis that poor households consume most of their energy in the form of direct energy (cooking, heating, lighting, transportation) while richer households tend to increase their share of indirect energy (in the form of goods and services) in the total demand (Vringer and Blok 2000). This approximation is used in forecasting electricity consumption by detailing the end-uses served in the household (Parti and Parti 1980; Bartels and Fiebig 1996; Larsen and Nesbakken 2004).

[145] Lighting energy shows the highest variation. In India an average of 336.5 kWh/year per household was estimated for 2001 electricity consumption (Kadian, Dahiya et al. 2007). The US average lighting is at 940

media access in the US also correspond to the minimum needed for a household in Mozambique[146,147], at the average levels shown in Table VI.44.

We can establish that the household needs to own the value correspondent to the electrical connection A_{ec} = *$100* to be able to consume electricity, and that below this asset level, it will consume mostly biomass and kerosene for cooking and lighting. The consumption of biomass and kerosene is assumed at a constant level of 181 kWh/household-month in useful energy units, average calculated from the records on household energy consumption of the 2002/3 IAF survey (INE 2007).[148]

With these assumptions, the electricity consumption dependency on the asset values, in the intertemporal utility model, takes the form (curve fitting by MATLAB, Figure VI.44, above):

$$
\begin{aligned}
E(A) &= 1.1173 \cdot A^{-0.3844} \quad [\text{ kWh/month} / \$_{\text{invested}}] \\
\frac{\partial E}{\partial A} &= -0.4295 \cdot A^{-1.3844} \quad [\text{ kWh/month} / (\$_{\text{invested}})^2] \\
\frac{\partial^2 E}{\partial A^2} &= 0.1651 \cdot A^{-2.3844} \quad [\text{ kWh/month} / (\$_{\text{invested}})^3]
\end{aligned}
\tag{67}
$$

If at the end of the modeling period the household is consuming more than 337 kWh/month (a value of $2077 in assets), the household will have evolved up to an acceptable level of life conditions (as listed in Table VI.44).

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kWh/year per household (EIA 2001), while in Norway in 1990, the household average consumption in lighting was 2700 kWh/year. Efficiency gains and climate differences may account for such big variation.

146 Confirmed by the recommendations on the Sida workshop for new energy policy (Arvidson 2005)

147 The concept of energy-poverty applied to the poor of developed countries contains a list of energy end-uses that constitute the basic-needs of a household, which includes lighting, refrigeration, climate control, etc (Roberts 2008). It is time that a energy basic-needs' bundle be defined for the poor of the developing countries too (Birol 2007).

148 The calculated biomass and kerosene consumption, averaged at 181 kWh/month per household, shows that the limit of 100 kWh/month for the social rate is about half of the current useful energy consumption of an average Mozambican household. In other words, if a household plans to transition from biomass to electricity it will not benefit from the social tariff.

Table VI.44 – Electric appliances in an average household

Activity	US records (EIA 2001)	kWh/month per HH	Investment Cost $PPP[149]
Electrical Connection	-	-	$100 [150]
Lighting	940 kWh/year-HH	78.3	$100
Color TV	313 kWh/year-HH	26.1	$220
Refrigerator	1462 kWh/year- HH	121.8	$425
VCR/DVD	118 kWh/year- HH	9.8	$50
Stereo	70 kWh/year- HH	5.8	$142
PC and Printer	384 kWh/year- HH	32	$1,040
	Total	273.8	$2,077

Appliances from Sears:

Sears color TV: Sansui 27 in. (Diagonal) Class CRT SDTV with ATSC/QAM Digital Tuner
Sears DVD player: Sony 1-Disc DVD Player with Progressive Scan
Sears refrigerator: kenmore 18.2 cuft top freezer
Sears stereo: Sharp 160W MICRO SYSTEM WITH IPOD DOCK
Sears PC+Printer: Hewlett-Packard Hewlett-Packard HP S3650F Pavilion Desktop PC + Brother Compact Laser Printer

Appliances from IAF survey for Mozambican households:

Color TV : 560 $PPP
Refrigerator: 1,442 $PPP
Stereo: 475 $PPP
PC and Printer: 2,462 $PPP

[149] The investment costs correspond to prices of featured equipment in Sears website, on February 20 2009. Comparison with recorded values of assets for the Mozambican households during survey IAF 2002/3 (INE 2007) indicate that in Mozambique appliances prices are about 2.6 more expensive than those selected from Sears store.

[150] The electrical connection average cost is obtained from EDM records (EDM 2005)

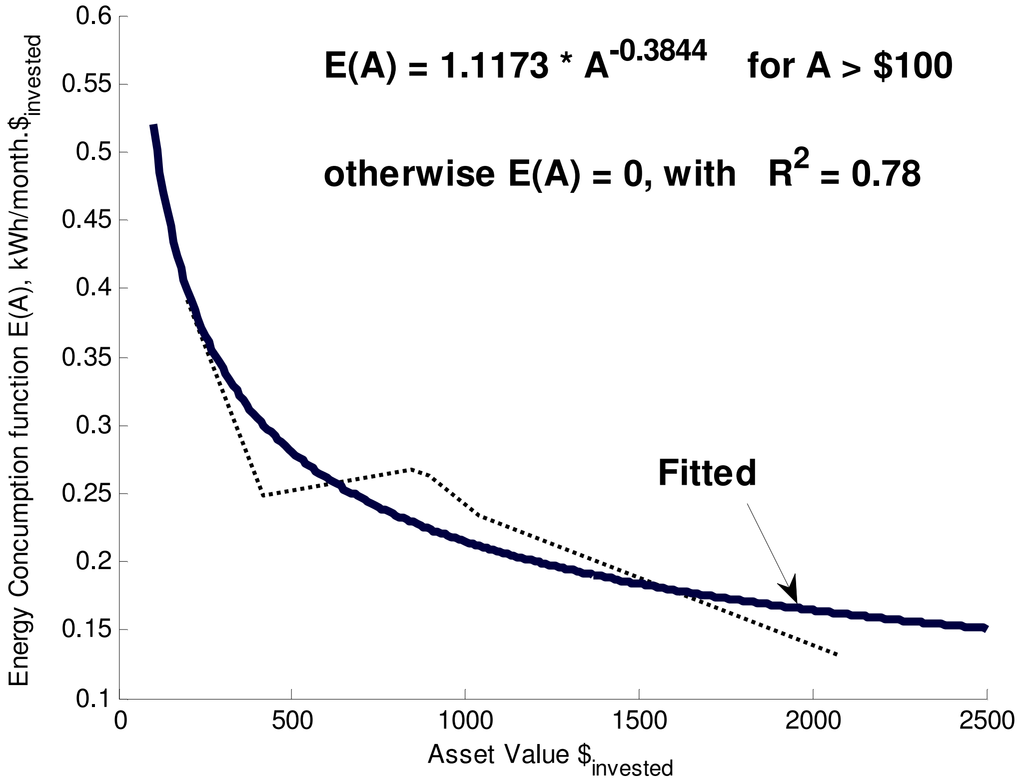

Figure VI.44 – Approximate function for electricity consumption

This formula will be used in the numerical exemplification of the theoretical model. However, caution is made in that it is only an approximation. Detailed studies on the electrical consumption per end-use and the more common appliances (and their average costs, power taking and efficiency) owned progressively by households increasing their income are needed, so this function may more accurately represent a progression on electricity consumption per unit investment in appliances.

CHAPTER VII: PRICES, TARIFFS AND POLICY RECOMMENDATIONS

INTRODUCTION

Electricity rates (or tariffs) in Mozambique are designed for the aggregated consumption at the national level, and are not network-specific (Mozambique 1985; Mozambique 2003). However, due to variations in the composition of the consumer population, the average prices of electricity are distinct between networks. For example, in the Northern network only 38% of the electricity supplied in 2006 was for domestic consumption, while in Quelimane 49% of the yearly consumption was domestic (EDM 2007). Domestic consumers pay different energy rates, depending on their consumption level; unfortunately consumption and billing data is not detailed for each domestic category in the database for operations in the northern networks, and approximations to the average price paid by consumers had to be made.

The assumption that cheap energy rates will result in the adoption of electricity, at least as a lighting source by the poor, is not aligned with observed household behavior. For example, , we observe households retaining kerosene as a main lighting source when cheap electricity prices are available (Brouwer and Falcao 2004). Access to credit and other factors, influence the energy transition behavior, see Chapters 4 and 6. When combined with credit access, low prices should facilitate the consumption of electricity by low-income families. Electricity rates (and the correspondent average prices) should be designed to a full cost-recovery level to ensure viability on the suppliers-side, without significantly affecting consumption levels and the ability to pay for electrical consumption, on the consumers-side. In this way, electrification for domestic consumption may finally be deemed viable.

The previous chapters calculated the price elasticities of domestic demand for electricity in the Northern provinces (Chapter 3) and the loss equations for the electrical supply from the northern transmission line (Linha Centro-Norte, LCN, Chapter 5). This chapter calculates the electricity average cost curves, corresponding to zero profits, and the demand curves representing the households' willingness to pay, in each of the LCN networks. The demand and the average cost curves are plotted and the prices corresponding to a zero profit condition, for the consumption level that corresponds to zero excess demand at a given zero-profit price, are determined. The correspondent welfare losses/gains and the methodological limitations of the tracing of demand-average cost curves are then discussed.

The last section of this chapter presents the current rate design for electricity and discusses how it facilitates (or prevents) new connections and more consumption of electricity, and how the current tariffs align with the requirements of low prices for the poor and of full cost recovery for the supplier. Policy implications to electrification and to domestic electricity are discussed, under the terms mandated by the current tariff regulation (Mozambique 1985; Mozambique 2003).

THE DEMAND-SUPPLY CURVES FOR DOMESTIC ELECTRICITY

DEMAND CURVES

The monthly average price in the northern grid is recorded at *0.3172 $PPP/kWh* for year 2007, and is slightly higher than the national average electricity price of *0.28 $PPP/kWh* in 2006 (EDM 2007), as a result of differences in the consumer population. Losses (incurred by the supplier) in the electrical flows and in the billing systems are also different between networks. The average price in the north (*0.3172 $PPP/kWh*) is obtained by calculating the average monthly unit values of electricity consumption for each network of the northern grid, Figure VII.45. The data comes from the supplier's database for 2007, Table VII.48 at the end of this chapter.

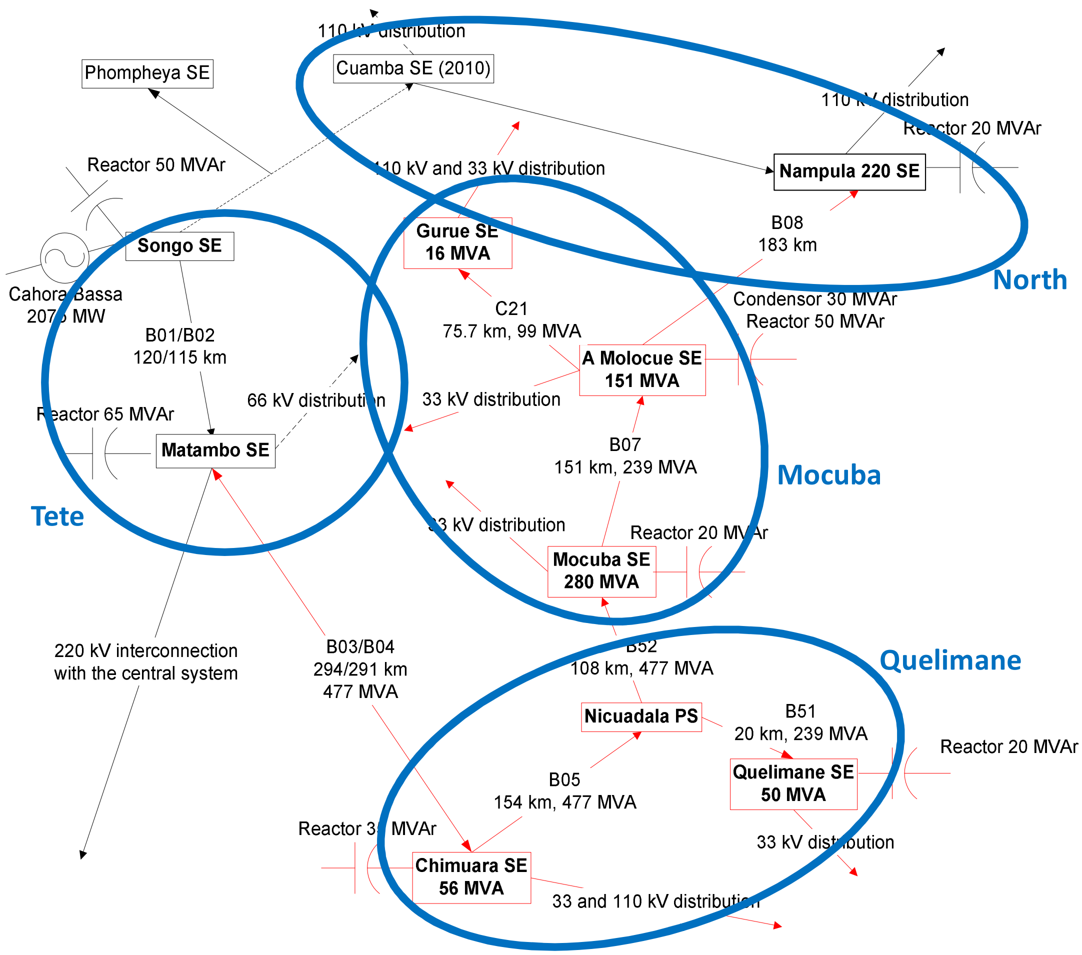

Figure VII.45 – Distribution networks on the transmission grid

Given that demand curves are not easily estimated from the available financial data, some assumptions and simplifications were made:

1) The elasticity for electricity demand calculated (Chapter 3) from the data survey on households of 2002/3 (INE 2007) is representative of the average domestic consumer in the northern electrical grid (LCN)
2) The own-price elasticity of demand for the northern provinces in 2002/3, $\varepsilon = -0.43$, is mostly unchanged in 2006/7
3) The average monthly unit-values (prices), paid by consumers in each distribution network, are calculated without differentiating domestic from agricultural, commercial and industrial consumers, Table VII.45 for the tariffs in 2006. This approximation was necessary due to the unavailability of collection data, decomposed by consumer categories, for each of these networks[151].
4) The demand curves for domestic electricity take the constant elasticity form (Simon and Blume 1994), derived from the formulation of own-price elasticity ε as follows:

$$\varepsilon = \frac{\partial \ln q_D^{dis}}{\partial \ln p} = -0.43 \qquad \Rightarrow \qquad q_D^{dis} = \alpha_D^{dis} \cdot p^{-0.43} \tag{68}$$

By taking the average price of electricity $p_{avg\,2007}^{dis}$ at 2007 load levels (EDM 2007; United-Nations 2007), it is possible to calculate the coefficients of the demand equations α_D^{dis} for each distribution network, namely (Table VII.46):

$$\text{demand:} \quad \alpha_D^{dis} = q_{avg\,2007}^{dis} \cdot \left(p_{avg\,2007}^{dis}\right)^{0.43} \tag{69}$$

[151] Data for 2006 places the average price at 0.31, 0.33, 0.31 and 0.29 $PPP/kWh respectively for Tete, Quelimane, Mocuba and the North. Records show that although domestic consumers constitute about 90% of all consumers, the domestic consumption only corresponds to 38%-49% of the total distributed in these networks. No detail was available to calculate more precisely the average price to domestic consumers, consequently the average price for all consumers, from the 2007 database, is used (EDM 2007).

Table VII.45 – Electricity tariffs in Low-voltage, in Mozambique, 2006[152,153]

Domestic tariffs			
Consumption ranges	**Prepaid meters**	**Regular meters**	**+ Fixed Rate**
Social rate (tariff)	14.16 cents \$PPP/kWh (limit: 100 kWh/month)	14.16 cents \$PPP/kWh (limit: 5 amps)	-
From 0 to 200 kWh	39.28 cents \$PPP/kWh	30.81 cents \$PPP/kWh	9.92 \$PPP/month
From 201 to 500 kWh		41.06 cents \$PPP/kWh	
Higher than 500 kWh		43.13 cents \$PPP/kWh	
Agricultural tariffs			
Consumption ranges	**Prepaid meters**	**Regular meters**	**+ Fixed Rate**
From 0 to 200 kWh	43.22 cents \$PPP/kWh	31.50 cents \$PPP/kWh	9.92 \$PPP/month
From 201 to 500 kWh		44.35 cents \$PPP/kWh	
Higher than 500 kWh		48.53 cents \$PPP/kWh	
Commercial tariffs			
Consumption ranges	**Prepaid meters**	**Regular meters**	**+ Fixed Rate**
From 0 to 200 kWh	39.51 cents \$PPP/kWh	34.51 cents \$PPP/kWh	9.92 \$PPP/month
From 201 to 500 kWh		49.29 cents \$PPP/kWh	
Higher than 500 kWh		53.93 cents \$PPP/kWh	

Table VII.46 – Data for the estimation of demand curves

Distribution Networks	Average 2007 $q^{dis}_{avg\,2007}$ GWh/month	Monthly average 2007 $p^{dis}_{avg\,2007}$ \$PPP/kWh	Demand Coefficient α^{dis}_{D}
Tete	3.6974	0.34	2.3251
Quelimane (plus Morrumbala)	4.5097	0.28	2.6087
Mocuba (plus Molocue and Gurue)	1.8714	0.31	1.131
North (Nampula, Cuamba, Lichinga)	13.9711	0.33	8.6734

[152] Conversion at 7133 MTn/\$PPP in 2006 (United-Nations 2007; World-Bank 2007)

[153] The last rate revision was made in February 1, 2006, in accordance with article 12th of the Decree 29/2003 of June 23rd, as published in the supplier's link: http://www.edm.co.mz/noticias/incremento.php

The inverse demand curves for the four distribution networks represent the willingness to pay for electricity by domestic consumers and are thus:

$$\begin{array}{ll} \text{Tete:} & p_D^{Tete} = 7.1149 \cdot \left(q^{Tete}\right)^{-2.3256} \\ \text{Quelimane:} & p_D^{Quel} = 9.2990 \cdot \left(q^{Quel}\right)^{-2.3256} \\ \text{Mocuba:} & p_D^{Mocu} = 7.3314 \cdot \left(q^{Mocu}\right)^{-2.3256} \\ \text{North:} & p_D^{Nort} = 151.9991 \cdot \left(q^{Nort}\right)^{-2.3256} \end{array} \qquad (70)$$

The regional demand curves are plotted in Figure VII.46. These inverse demand curves would be more accurate if they had been calculated with price elasticities of demand specific to each distribution network; however only the elasticity for the whole northern region was available. Further research and work is needed to more precisely estimate demand curves for each of the distribution networks in the electrical grid.

AVERAGE COST CURVES

The unit-costs of generation, transmission and distribution are calculated at the regional level (total cost per electricity units flowing in the systems) and are not specific to each distribution network. However, transmission and distribution losses do vary by region. Losses, in transmission and distribution can vary due to technical and management reasons, and sometimes they cannot be recovered, because electricity tariffs are not readily upgraded to the current loss levels. As a result, the company operates at a deficit and full-cost recovery mandate for tariff design is not met. The company has operated with a deficit (or negative profit) in 2005 and 2006 (EDM 2007)[154].

[154] Although there is a law that establishes the mechanism for tariff design and rate upgrade (Mozambique 1985; Mozambique 2003), given that electricity price is such a sensitive economic (and political) issue, tariff review does not happen automatically and as often as it should. Tariffs are supposed to respond to inflation rates and cost factors through a formula approved in the law. Note however that the government still requires its

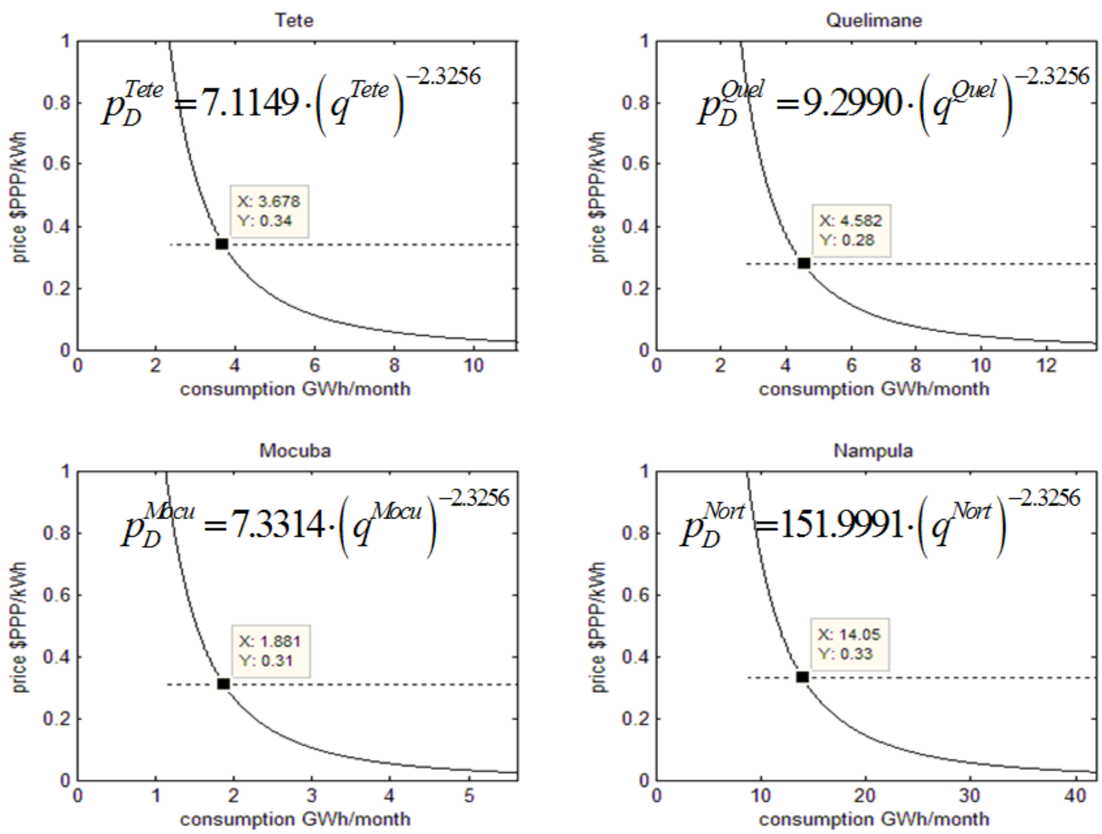

Figure VII.46 – Demand curves for the northern networks in 2007

To estimate average cost curves that incorporate transmission and distribution losses in the northern networks, the following approximations are made:

a) The 2007 average price of electricity in the northern areas covers the full cost of generation, transmission and distribution, without any losses in these electrical systems. In other words, the average price of electricity in 2007, $p_{avg\,2007} = 0.3172$ \$PPP/kWh corresponds to the unit-cost of generation, transmission and distribution for the northern region.

b) The introduction of a loss factor in the above unit cost will allow the recalculation of the average cost of supply to incorporate electrical losses. The cost factors are

approval of tariff reviews and delays it when inconvenient (the latest tariff review occurred in October 2006 - http://www.edm.co.mz).

estimated in Chapter 5 (equations (21) to (24) and in Table V.29) and represent the differentiated transmission and distribution losses in each of the northern networks. Although these loss rates have been calculated for a limited range of power consumption, it is assumed they are valid for larger power flows.

The average cost curves can then be traced from the following relation:

$$p = AC = \left(1 + c_{loss}^{dis}\right) \cdot p_{avg\,2007} = \left(1 + \varphi_1 + \varphi_2 \cdot q_{avg\,2007}^{dis} \cdot \frac{1000 \cdot 12}{8760}\right) \cdot p_{avg\,2007} \quad [\$PPP/kWh] \qquad (71)$$

where $p_{avg\,2007} = 0.3172$ \$PPP/kWh is the average price in the northern areas during 2007 (assumed equal to unit cost without losses) and c_{loss}^{dis} is the percent-loss factor of the load flowing in the network, in turn dependent on the average monthly electricity supplied in the network $q_{avg\,2007}^{dis}$ [GWh/month]

For each network, the loss coefficients take the values of Table VII.47. These losses are linear on the average monthly energy supplied in the network, and will increase with an increased load flow.

Table VII.47 – Data for the estimation of average cost curves

Distribution Networks – Feeders	Average 2007 $q_{avg\,2007}^{dis}$ GWh/month	Loss-factors in 2007
Tete	3.796	$c_{loss}^{Tete} = 0.0080 + 0.000548 \cdot q_{avg\,2007}^{Tete}$
Quelimane – Quelimane	4.336	$c_{loss}^{Quel} = 0.0448 + 0.006301 \cdot q_{avg\,2007}^{Quel}$
Mocuba – Mocuba	1.044	$c_{loss}^{Mocu} = -0.0247 + 0.00137 \cdot q_{avg\,2007}^{Mocu}$
North – Nampula	12.614	$c_{loss}^{Nort} = 0.0132 + 0.004795 \cdot q_{avg\,2007}^{Nort}$

The average cost curves take the form of equation (72):

$$\begin{aligned}
&\text{Tete:} && AC_S^{Tete} = 0.3197 + 0.000174 \cdot q^{Tete} \\
&\text{Quelimane:} && AC_S^{Quel} = 0.3314 + 0.001999 \cdot q^{Quel} \\
&\text{Mocuba:} && AC_S^{Mocu} = 0.3094 + 0.000435 \cdot q^{Mocu} \\
&\text{Nampula:} && AC_S^{Nort} = 0.3214 + 0.001521 \cdot q^{Nort}
\end{aligned} \tag{72}$$

The average cost curves represent the price-quantity combinations the monopolistic firm (EDM) will offer at a zero-profit condition. As can be seen in Figure VII.47[155], the marginal cost of supplying electricity is low, as follows:

$$\begin{aligned}
&\text{Tete:} && MC_S^{Tete} = 0.3197 + 0.000348 \cdot q^{Tete} \\
&\text{Quelimane:} && MC_S^{Quel} = 0.3314 + 0.003998 \cdot q^{Quel} \\
&\text{Mocuba:} && MC_S^{Mocu} = 0.3094 + 0.00087 \cdot q^{Mocu} \\
&\text{Nampula:} && MC_S^{Nort} = 0.3214 + 0.003042 \cdot q^{Nort}
\end{aligned} \tag{73}$$

When pricing is based on the average cost, producer surplus is assumed zero. Consequently, changes in welfare by adjusting prices to the average cost level will really correspond to welfare changes for the consumers. If the average prices to the consumer in each of the northern networks were to be altered to the above estimated average cost, for current consumption levels, what would be the impact in the consumer welfare? Are current average prices in the northern networks equal, smaller or larger than the estimated average cost of supply?

[155] Dotted lines represent the current average monthly price of electricity in each of these networks.

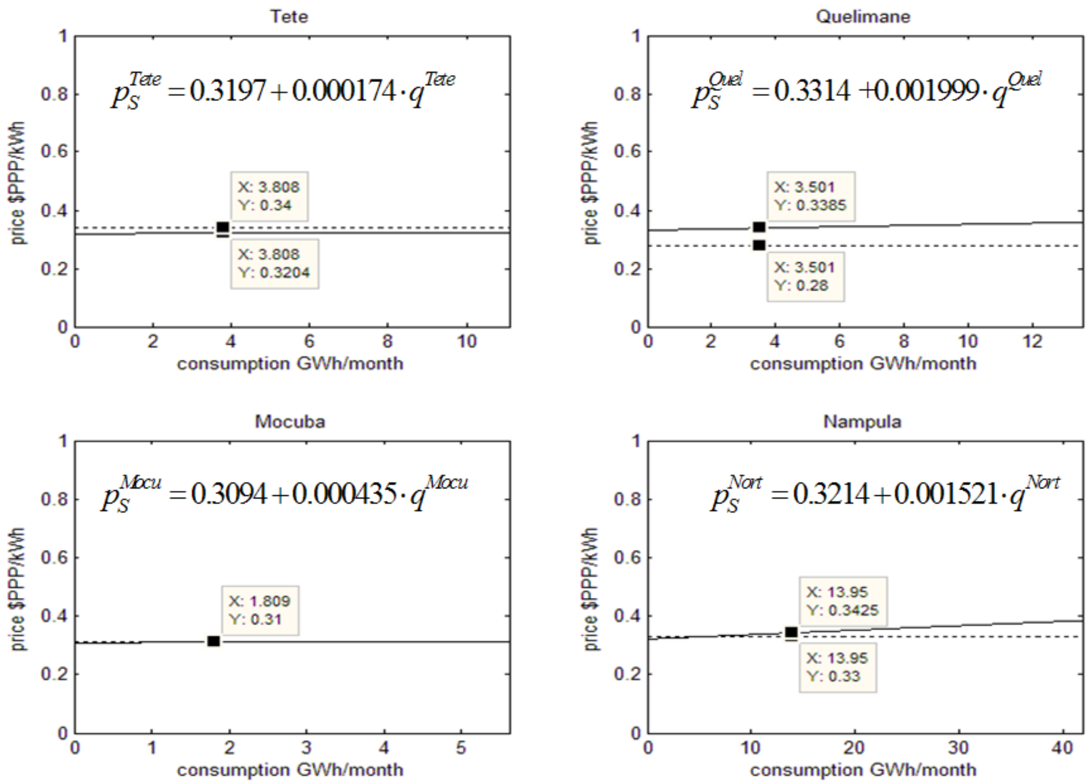

Figure VII.47 – Average cost curves in 2007

PRICES AND WELFARE EVALUATIONS

The national company (EDM) has been very successful in extending the infrastructure to areas with no electrical grid. In the past 28 years, EDM has built more than 3000 km of 66 kV lines and above, rehabilitated, upgraded and expanded distribution systems. Demand for electrical power has grown from a mere 200 MWh/year in 1960 to about 1600 MWh/year in 2005[156] (Fernando 2006), bringing the hydropower from Cahora Bassa to all provincial capitals (Sebitosi and da Graça 2009).

The Energy Strategy (Mozambique 2000a) and the creation of an entity for electricity regulation – Concelho Nacional de Electricidade, CNELEC (Mozambique 2000b) allows private operators in the generation, distribution, commercialization of electricity; only

[156] Excluding small district generators and private generation, of whatever source.

transmission systems remain under the full control of the national (public) company (EDM). The objective of the change was to accelerate electrification (access) and stimulate electricity consumption, by introducing competition in the electricity sector. In other words, the national public company will have to compete with private operators in the access to investment loans and in the provision of services.

The change has been slow as the market is still small and the public company can compete with private operators in many instances - see the example of ENMO in Vilanculos (Cockburn and Low 2005). However there are already call to the partition of the company into smaller companies, as a way of increasing efficiency and competitiveness in the distribution market (Nhete 2007). For this reason, it is important to evaluate the adequacy of current (average) prices to the cost recovery function, and how they were to change if tariffs were to vary between networks.

Figure VII.48 shows that in some (northern) networks, the current average price paid by consumers (2007) is different from the zero-profit price that ensures full cost recovery, namely the average unit cost, above estimated to incorporate transmission and distribution losses. More specifically, in Tete the supplier company (EDM) is running a profit of 72 thousand dollars per month, but is in deficit in Quelimane, Mocuba and Nampula, respectively with 35, 0.3 and 170 thousand dollars per month. During year 2007, the electricity supplier (EDM) has incurred in a total deficit of about 133 thousand dollars per month.

The profit or deficit amounts per network were calculated graphically, as the area of the rectangle defined by the difference between the average price (at consumption level that corresponds to zero excess demand at a given zero-profit price $q^{dis}_{0\text{profit}}$) and the average cost at a zero profit condition $p_{0\text{profit}}^{dis} = AC_S^{dis}\left(q_{0\text{profit}}^{dis}\right)$ (positive for a profit condition, negative for a deficit condition) times the 2007 consumption level:

$$\pi^{dis} = \left[p_{avg\,2007}^{dis} - p_{0\text{profit}}^{dis} \right] \cdot q_{avg\,2007}^{dis} \tag{74}$$

The total consumer surplus is approximately 1.95, 2.12, 0.97 and 7.1 million $PPP per month, for the distribution networks of Tete, Quelimane, Mocuba and Molocue, respectively, at the 2007 load levels and average prices. Consumer surplus was also graphically calculated for each of the networks, as the area of the polygon between the demand curve and the average price, namely:

$$CS^{dis} = \int_0^{q_{avg\,2007}^{dis}} \left[\alpha_D^{dis} \cdot q^{-2.3256} - p_{0\text{profit}}^{dis} \right] \cdot dq \tag{75}$$

What is the impact of price variations in the welfare of the consumer population? Can prices be adjusted to the full cost-recovery level without reducing significantly the consumption of electricity? This analysis is made by plotting the above-derived demand and average cost curves and finding the prices that maximize consumer surplus at a zero-profit condition for the firm.

The average cost and demand curves for each of the distribution networks take the forms plotted in Figure VII.48 above. There was:

1. An overcharging[157] by 2 cents $PPP/kWh in Tete (the average cost line crosses demand level at 32.04 cents, when the current average price is at 34 cents).

[157] The terms overcharge and undercharge refer to the position (higher or lower) of the current average price (in 2007) relative to the equilibrium price, or the price that corresponds to the average cost.

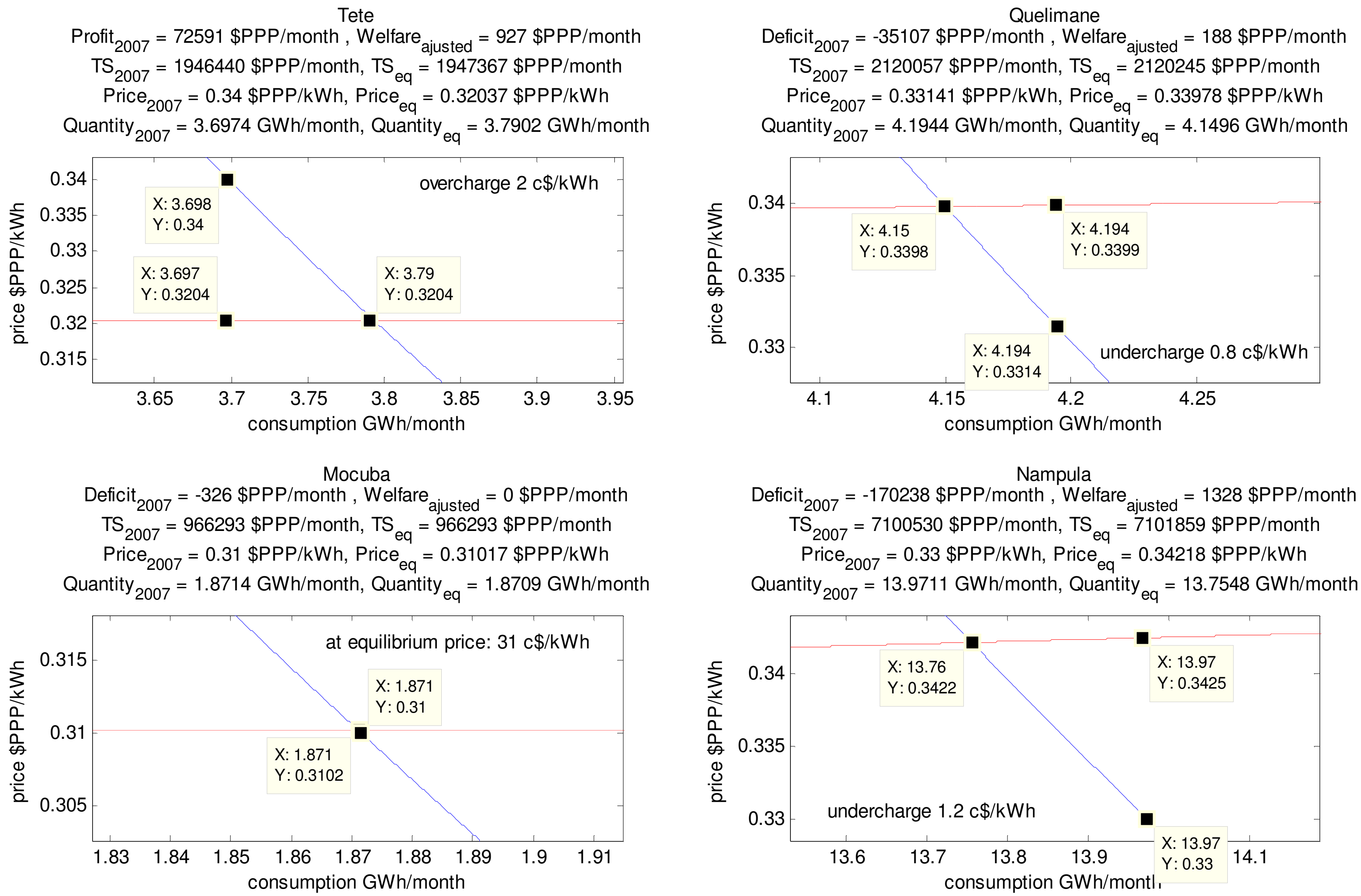

Figure VII.48 – Supply and demand curves for the northern networks

The total welfare gain from reducing average price to its zero-profit level amounts to only 927 \$PPP/month, because consumers increase their welfare but suppliers loose an unwarranted profit of 72.6 thousand dollars per month;

2. An undercharge in Quelimane with the cost-recovery price estimated at 33.9 cents \$PPP/kWh and the current average price only at 33.1 cents, for the 2007 load levels[158]. The application of the zero-profit price will slightly reduce demand from the current 4.19 GWh/month to 4.15 GWh/month. Although consumer's welfare is reduced, the supplier recovers the operating deficit of 35.1 thousand dollars per month and the correspondent total welfare gain is barely 188 \$PPP/month;
3. A equilibrium situation in Mocuba, at 31 cents \$PPP/kWh for 1.87 GWh/month, with no significant change in consumer's welfare and with an almost zero-profit condition for the supplier
4. A small undercharge in Nampula, with the cost-recovery price estimated to be 34.22 cents \$PPP/kWh and the current average price only at 33 cents \$PPP/kWh, for the 2007 load levels. Total welfare gain amounts to 1328 \$PPP/month, as although consumer welfare will reduce, the supplier will recover the deficit of 170,238 \$/month.

In summary, Tete overcharged by 2 cents \$PPP/kWh, Quelimane undercharged by 0.8 cents \$PPP/kWh, Mocuba charged the equilibrium price of 31 cents \$PPP/kWh and Nampula undercharged by 1.2 cents \$PPP/kWh, relative to the price that ensures full cost recovery.

The above study shows that the average prices of electrical supply, charged in the two biggest networks in the northern grid (Quelimane and the North) are actually below their

[158] The initial price average was for 28 cents \$PPP/kWh, see Table VII.46. However this average price was recalculated for the range of the supply curve to 33.1 cents \$PPP/kWh, see Figure VII.48.

cost-recovery level. Changing prices to cost-recovery levels barely affects consumption (1.5% reduction, from 23.73 to 23.68 GWh/month). This change corresponds to an average regional price increase of 1.85 cents $PPP/kWh (6% of the 2007 average price in the northern grid, 31.72 cents $PPP/kWh), or to a bare 22.5 cents $PPP/month for each family connected to the grid. Adjustments of prices to the level of cost-recovery will only slightly improve total welfare by 2443 $PPP/month, as consumer welfare overall reduces by 130 thousand dollars and the supplier recovers 133 thousand dollars of deficit.

THE LIMITATIONS OF THE METHODOLOGICAL APPROACH

The demand and average cost curves for each of the distribution networks of the LCN are approximately derived, because:

- The calculation of own-price elasticity of demand could only be made for the northern region as a whole and not for individual distribution areas.
- The demand curves could only be derived for the major communities in three distribution networks (Quelimane, Mocuba and the North), which contain more than one community with electricity supply. Thus, these demand curves are representing demand behaviors in the communities of higher (dominant) loads, instead in the whole network.
- The average cost curves for the distribution networks are also approximate, as the loss coefficients estimated in Chapter 5, particularly those relating to distribution losses, are approximate. Furthermore, these losses are estimated based in only one year of operational records, i.e. may be inaccurate in higher load levels.
- No interruption losses in distribution and transmission systems are incorporated in the estimation of supply losses for the networks, because the probability of interruption has not yet been reliably estimated.

- Finally, the average electricity prices in the northern region, used to derive the coefficients for the demand and average cost functions, includes not only domestic consumption but also commercial and industrial consumption, as more detailed billing and consumption data was not available.

Although this analysis is quite simple (estimated demand and average cost curves should be used with caution) it is still indicative that there is room for price adjustments in the northern grid to ensure the regulatory zero-profit condition. From the estimated average cost curves, the supplier has incurred in deficit in 2007. Financial records indicate deficits for the whole company in 2005 and 2006 (EDM 2007).

This evaluation is not extensive enough to allow precise policy decisions regarding price adjustments. However, the analysis shows that a network-specific price design may better compensate the supplier for its full costs while not significantly affecting overall welfare, as opposed to a central tariff design that resulted in deficits in 2005 and 2006. A full cost-recovery condition will introduce a cost of losses in the average prices of specific networks, thus allowing for loss monitoring and containment at the local levels. It will also allow the supplier a better planning for expansion and a better provision services, ultimately benefiting electrical consumers. More data collection is recommended, for the demand and the supply sides, to be able to better represent the respective demand and average cost curves in the northern grid.

POLICY APPROACHES VERSUS ELECTRICITY RATES

The national electricity company of Mozambique (EDM) has a tariff regime designed to stimulate industrial consumption. It also contains a pro-development function, in the cheapening of rates for very small domestic consumers, Table VII.45. The rates are undifferentiated by geographic location, to establish equal opportunity for development regardless of the distance from the power source and the level of investments required to provide electricity to a particular location.

Rate design, by regulations, should: a) ensure full cost-recovery by the supplier, b) promote higher consumption of electricity in households, and c) promote the adoption of electricity by poor families (Mozambique 1985; Mozambique 2003; EDM 2007). However, in reality, the electrification rate of Mozambique has only reached 8.2% of the population in 2006 and the average domestic consumption is only of 89 kWh/month per household, about a third of the US energy consumption (EIA 2001; EDM 2007).

The government of Mozambique has mandated cheap rates for poor families, however it does not seem to be enough. So the question is whether the current rate design fulfills the regulatory objectives with regard to development support and poverty alleviation of households, or not?

To which extent does the current rate design meet the regulatory requirements of full cost-recovery?

Current tariffs are designed at the national level and do not differentiate between distribution networks, i.e. all consumers of the same class pay the same rate regardless of their location. However, losses and the composition of the consumer population are different between networks, resulting in differences in the average price of electricity between networks (see "The demand-supply curves for domestic electricity"). The previous analysis indicates that, in the northern distribution networks, the current prices deviate from the zero-profit price. As a result, the electricity company registered a deficit of $133,000 per month and the total welfare loss was of $2443 per month in 2007 in the northern system.

Recommendation: Adjusting prices per distribution network to their cost-recovery level will not significantly change consumption levels (an overall 1.5% reduction of current consumption) and will only slightly affect average prices (6% increase of current average price), for all networks in the north. Consumers will have to pay for the additional 1.85 cents $/kWh; however, the company will operate at a zero-profit level, as intended in the regulatory setup. Tariff design should take into consideration loss differentiation between distribution networks and adjust average prices to their zero-profit levels to meet with regulatory rules and to stimulate loss containment and better service by the supplier's local branch.

To which extent does the current rate design meet the regulatory requirements of promoting electricity consumption in the domestic sector?

The current research indicates that there is room for improvement in the electricity rate design for domestic consumers, namely that rates should be specific to each distribution network, to incorporate loss variation between networks and to stimulate higher efficiency. Higher electricity prices (when adjusted to the cost-recovery level for Quelimane and the North) may reduce consumer welfare, but will avoid losses by the supplier and the overall society's welfare will improve. Consumers, though paying more for their consumption, will experience very small variations in the consumption levels.

The previous analysis was made for the average price in each distribution network, and was unspecified for characteristics of the local domestic sector. Electricity rates for the domestic consumer are stepped per ranges of consumption, following the principle of higher rates for higher consumption, Table VII.45. This design has the following rational: higher consumption levels correspond to a more reliable, thus more expensive infrastructure, and to a higher usage of the electrical networks. In other words, larger domestic consumers are charged with a larger portion of the capital costs of the infrastructure, and have a higher rate per energy unit consumed[159].

Domestic consumers are known as "captive" (in the regulatory lexicon) in that they cannot easily negotiate electricity rates and are forced to take them as determined by the company and regulatory body. This condition and the lack of existence of an alternative competitive electricity supply, facilitates prices that may be deviated from their zero-profit, mandated but not enforced by centrally designed tariffs. Is it possible that by charging higher prices for higher consumption levels, the domestic rates are effectively curbing the intensification of domestic electricity use in the Mozambican households?

The fixed rate, paid monthly by all domestic consumers (excepting those benefiting from the social tariff), is set to account for administrative costs. It can increase the unit expenditure by 9.92 cents $/kWh (at 100 kWh per month) down to 1.98 cents $/kWh (at 500 kWh per month) or less, see Table VII.45.

The fixed rate transforms an increasing energy price into a decreasing energy price, with increased consumption, see Figure VII.49, in other words, **the current rate design meets the condition that promotes consumption - higher consumption, lower average prices**.

It is important to note that a domestic consumer with a regular meter and not benefiting from the social rate (social tariff) will experience very high average prices for consumption levels below 64 kWh/month. Average prices are cheapest for consumption between 64 and 200 kWh/month, and are approximately constant (43 - 46 cents/kWh) for consumption above 200 kWh/month (Figure VII.49).

[159] Domestic rates are only composed of a connection fee (fixed rate) and an energy price, while industrial rates contain also a capacity rate designed to cover investment costs.

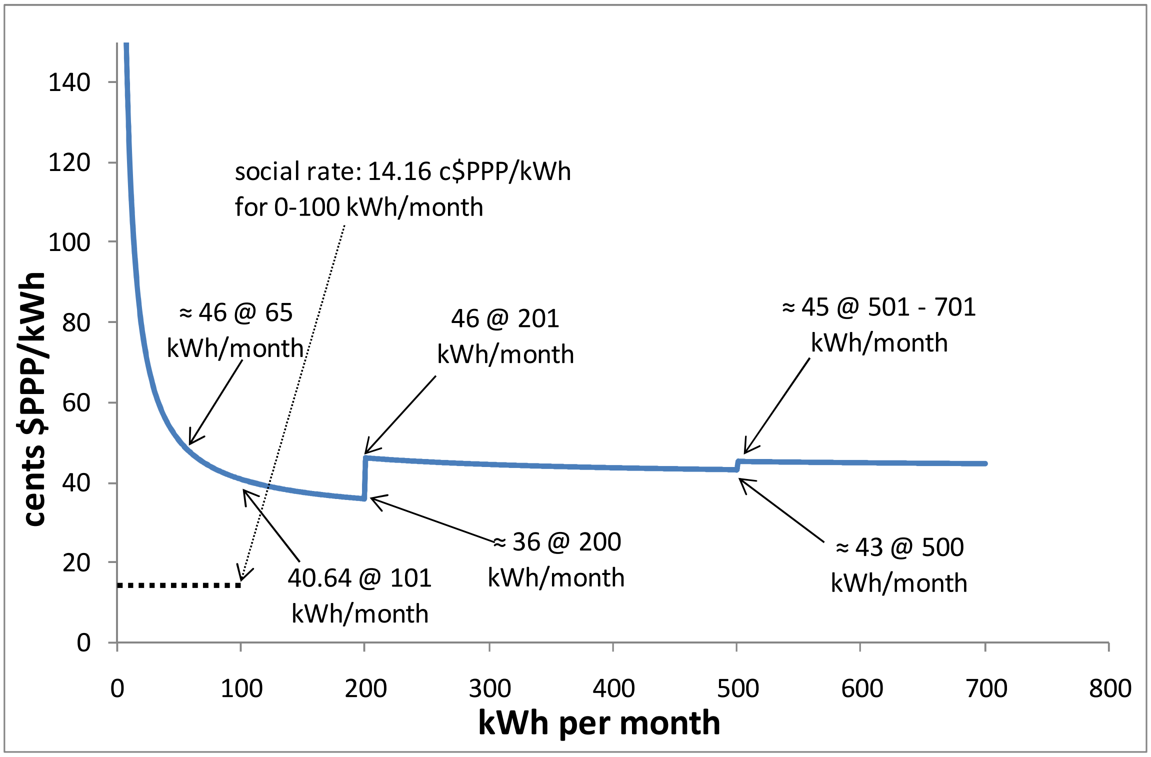

Figure VII.49 – How the fixed rate alters the average price for electricity

Note also that the social rate is only applicable to consumers that meet some criteria, such as being declared poor by their community's administrative office, i.e. to benefit from the social rate there is a bureaucratic procedure that most consumers do not follow. As a result, the social rate is being used by less than 1% of domestic consumers (EDM 2007), in a country where in 2004 the headcount poverty index was estimated at 54% (Mozambique 2004). This situation can also explain why the average price of electricity (calculated in the order of 32 cents $/kWh, in section "Price and welfare evaluations") is closer to the energy price of domestic consumers of less than 200 kWh/month than to the social rate of 14.16 cents $/kWh.

Furthermore, the social rate only applies to consumption below 100 kWh, i.e. it can barely cover a lighting system and a color TV (see Table VI.44). Refrigeration facilities will not be accessible as it would take these households to consumption levels above 100 kWh/month (for which the social rate does not apply) and they may not recur to kerosene for refrigeration, as it is more expensive than electricity at 59 cents $PPP/kWh in 2006 (Mozambique 2007). In other words, the current limit for a social rate implies that the subsidy will only cover lighting and that poor households must still live without the benefits of food refrigeration facilities[160].

Given that the energy (generation) price is relatively cheap at the source in the Northern provinces (2.4 to 3.0 cents $/kWh at Cahora Bassa/Matambo 220 kV bus bars in 2008 prices), the basic energy prices in 2008 (not including the fixed rate effect, Table VII.45) are 4.7 to 18 times higher than the source's price. In other words, consumers benefiting from the social rate pay about 11.1 cents $PPP/kWh for the transmission, distribution and commercial operations, and investments. Higher consumers pay about 40.7 cents $PPP/kWh for these operations, and if the effect of the fixed rate is incorporated they pay 42.7 cents $PPP/kWh (or more) for transmission, distribution and commercial operations, investments and administration. In other words, it seems that the cost of operations and investments in the system is quite high for the northern domestic consumers. Further investigations will clarify whether current tariff levels align with the development role of electricity supply.

Recommendation: The social rate was established to promote electricity consumption and to support development. Its limits and the rules of its application should be reviewed so that it may effectively serve its purpose. The proportion of domestic consumers benefiting from the social rate should be closer to the current headcount poverty index, thus reflecting the socio-economic reality of the population. Furthermore, investigations to detail the operating

[160] In Zimbabwe, the lifeline tariff is applied to the first 300 kWh per month (Campbell, Vermeulen et al. 2003). In South Africa, the government instituted as free the first 50 kWh/month of electricity, EBSST (electricity basic services support tariff) - http://www.iea.org/textbase/pm/?mode=weo&id=3459&action=detail.

and the investment cost portions within the domestic tariffs are necessary, so the correspondent capital returns are better understood and tariffs' design can meet the full cost-recovery and zero-profit requirement.

To which extent does the current rate design meet the regulatory requirements of promoting electrification of the country and population?

Electrification and the expansion of the consumer population (new connections) are investments for which the supplier must mobilize funds and generate returns to pay off its debt. In other words, electrification and new connections require either cheap financing from the government or donors, or subsidized investment from these institutions, or a sufficiently wealthy population to pay for the capital costs themselves. This research did not decompose the average prices into its cost components and the assumption is that the calculated zero-profit maximum-consumer-surplus (equilibrium) prices will cover all costs, including those of investment.

Chapter 4 of the current document showed that prices of electricity per useful-energy unit are actually lower than biomass and kerosene's. The energy ladder is inverted on price per useful-energy unit, i.e. although biomass and kerosene are more expensive than electricity, the majority of the Mozambican households is still mostly dependent on the former sources. A low price of an energy source is thus not the only factor influencing the adoption of electricity by households. The question is then what conditions (other than affordable prices) facilitate/promote the adoption of electricity as a domestic source?

Chapter 4 discusses the likelihood of a Mozambican household becoming an electricity consumer. The odds are of 50 times for urban households as opposed to rural, 9 times for the households who access drinking water from a piped system, and 5 times for those whose dwelling has concrete walls (as opposed to mud or wood walls). In summary, urbanization and the ownership of wealth are determining factors for the adoption of electricity as a domestic source.

The hypothesis that the ownership of appliances is pre-condition to the consumption of electricity has been suggested previously (Willett and Naghshpour 1987; Abdulai and CroleRees 2001; Campbell, Vermeulen et al. 2003; McKenzie 2005; Louw, Conradie et al. 2008). The current research tested and quantified this hypothesis by developing an intertemporal utility maximization model whose solution describes the investment and the consumption behavior of an evolving household. The results of Chapter 6 indicate that if energy can only be consumed through appliances (electricity is such a source), the household must also increase its income generating assets i.e. the household must acquire wealth in order to increase its energy consumption.

Furthermore, the household generally invests first in direct utility providing commodities (leisure and non-energy goods) while increasing its income-generating stocks and only then, it invests in appliances. Increasing the initial credit (to push the household out of its "stagnation" stage) will result in larger and faster investments in appliances and expenses in other commodities. The higher the utility gained from consuming energy (electricity) through appliances, the sooner the household will invest in those and the lower the expenses in other commodities. However, the household response to varying energy prices is not as straightforward: when the energy price is high, the household must increase its investment in income-generating stocks and it does so, reducing its expenses in other commodities. As a result, the net income available is significantly higher and the household can then acquire appliances that are more expensive and consume energy at a higher level.

The simulations presented in Figure VI.40 show that at an energy price of 30 cents $PPP/kWh, which is approximate to the above calculated cost-recovery price, a household can invest and sustain the cost of $468 in appliances after 20 years. This amount corresponds to the electrical connection, the full electric lighting system, a color TV and still 10% of the investment and operating cost of a refrigerator (see Table VI.44). The conclusion taken is not that a price increase results in higher investments; rather that price is not the only factor driving the investment behavior of a household. In other words, the utility households gain from consuming energy through appliances versus the utility of other commodities is also a determining factor: households will not consume what they do not value, and they will maximize the benefit gained from each dollar spent or invested.

A household can only evolve if it increases its consumption and its ability of paying for increasing consumption costs. A household can only consume electricity if it earns enough to pay for investment in appliances and for the additional costs of the electricity consumption. A household can only evolve if it increases its income-generating assets (financial, physical or human), i.e. if it acquires wealth.

<u>Recommendation:</u> This research indicates that low prices will not make a household evolve to higher consumption levels, on their own. Although the social rate is competitive with the prices of other domestic sources, and may incentive higher consumption levels for those already connected, it will not promote new connections if not combined with credit facilities and opportunities for new earnings. The household must access credit and have opportunities to increase its income-generating assets in order to adopt electricity and acquire the appliances needed for its consumption. Electrification programs that support development must associate cheap prices and a credit facilitation system to be effective.

Table VII.48 – Electricity consumption and collection amounts for the northern networks (EDM 2007)

Sales 2007 per distribution areas 10^6 MTn											
Distr. Networks	Yearly total	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Tete	89.82	7.70	7.09	8.83	9.49	9.93	6.17	8.64	9.18	14.12	8.66
Quelimane	90.30	9.34	9.69	9.82	9.00	9.11	9.03	8.33	8.98	8.71	8.29
Mocuba	41.03	4.04	3.89	4.00	4.19	4.28	4.09	3.82	4.08	4.42	4.24
North	326.99	46.28	26.29	30.01	32.92	31.59	32.49	30.25	31.84	33.86	31.47
Sales 2007 per distribution areas GWh											
	Yearly total	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Tete	36.97	3.13	3.34	3.42	4.06	3.93	3.65	3.46	4.28	3.59	4.11
Quelimane	45.10	4.73	4.60	5.05	4.78	4.42	4.42	4.06	4.13	4.27	4.63
Mocuba	18.71	2.03	1.86	2.13	2.63	1.86	1.56	1.50	1.63	1.69	1.82
North	139.71	14.64	13.61	14.70	12.78	12.19	12.20	14.76	14.53	14.67	15.65
AVG price of sales 2007 [$PPP/kWh], conversion @ MTn/$PPP: 7.13377											
	Yearly avg	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Tete	0.34	0.34	0.30	0.36	0.33	0.35	0.24	0.35	0.30	0.55	0.30
Quelimane	0.28	0.28	0.30	0.27	0.26	0.29	0.29	0.29	0.30	0.29	0.25
Mocuba	0.31	0.28	0.29	0.26	0.22	0.32	0.37	0.36	0.35	0.37	0.33
North	0.33	0.44	0.27	0.29	0.36	0.36	0.37	0.29	0.31	0.32	0.28

CHAPTER VIII: CONCLUSIONS AND THE WAY FORWARD

THE WORK DONE

Can electrification support household development and conversely, can households support investments on the expansion of the electrical grid through their electricity consumption? This question is complex, and the research could not fully answer it. However, the results of the study show that electricity, desirable for domestic consumption as it services utilities needed for a good life, can be competitive with other sources, if some conditions are met.

As described in the introduction chapter of this document, the research focused on two specific aspects of the main problem, namely:

1) What is the average price in each community supplied from an electrical grid that ensures the recovery of costs by the supplier and encourages the consumption of electricity by poor households?
2) What is the rationale of energy transition as explained by the progression of ownership of energy consuming appliances by evolving households?

These two questions were answered in the various chapters, in the following way.

FIRST QUESTION

The study focused on determining the price of electricity that households are willing to pay while ensuring cost-recovery to the supplier, i.e. the price of electricity corresponding to an equilibrium between consumers and the suppliers.

To achieve this, first price and income elasticities of demand for various domestic sources were calculated (Chapter 3) based on data collected during the household survey of 2002/3 (INE 2007), using an econometric method developed by Angus Deaton (Deaton 1987; Deaton 1988; Deaton 1990; Kedir 2005). The price elasticity of demand for electricity in the northern provinces was used to estimate demand curves for the four distribution networks in the northern grid (Chapter 7).

Then loss equations were derived for the transmission and the distribution networks in the northern grid, based on operational records for 2007 (EDM 2007), using quadratic regression and proportional weight allocation (Chapter 5). These losses were then used to estimate average cost curves, representing a zero profit condition, for the distribution networks in the northern grid (Chapter 7).

The current average price paid by consumers in the four distribution networks for 2007 was evaluated in the demand-average cost graphs (Chapter 7), showing that Tete network is charging more than the cost recovery condition requires, and Quelimane and Nampula networks must increase their current prices to this level. The current prices in Mocuba network are very close to the cost recovery price and should not be changed. Although these demand-supply graphs are drawn with many approximations, they indicate that electricity price adjustments can result in overall welfare gains of about 2443 $PPP per month, and that the current deficit of 133 thousand dollars per month, on the supplier's operations, can be recovered (from the consumers, whose welfare reduces accordingly). Although the price increase will initially benefit the supplier, it will ultimately also benefit consumers, as a debt-free supplier will be able to provide better service to consumers.

Furthermore, results of Chapter 4 show electricity to be actually cheaper per-unit-of-useful-energy than firewood and that those households consuming electricity are actually spending less than the ones consuming firewood are. In other words, electric consumers are better served at cheaper prices than biomass consumers are, and the traditional energy ladder (placing firewood at the bottom and electricity at the top) is actually inverted on price per-unit-of-useful-energy.

The cost recovery prices for the 2007 load levels in the northern networks (Chapter 7), in the order of 31 to 34 cents $PPP/kWh, are triple of the unit expenditures on electricity estimated from data from the household survey of 2002/3 (Chapter 4), in the range of 10 cents $PPP/kWh for the whole country. This difference results from the survey having a major representation of poor consumers and from the incorporation of domestic, commercial and industrial consumption in the estimated cost-recovery prices. Still, the cost-recovery prices are smaller than the unit expenditures (unit values) recorded for firewood consumers (100 - 128 cents $PPP/kWh) in the survey data (Chapter 4). Also, the cost-recovery electricity prices are in the same range as charcoal's recorded expenditures (14 - 30 cents $PPP/kWh), Figure IV.11, confirming the competitiveness of electricity with other sources.

The inverted energy ladder (Chapter 4) clearly demonstrated that electricity consumption is ultimately beneficial to households, both on the quality of the service it provides and on the price of useful-units consumed, as other authors have also established (Bose and Shukla 2001; Cockburn and Low 2005; Raineri and Giaconi 2005; Kebede 2006). In other words, the inverted energy ladder (on price) favors electrification as a strategy to development and poverty alleviation. However, evidence shows that connected households still consume firewood or charcoal as domestic sources, and do not replace these with electricity consumption. The question is then what makes Mozambican households transition from biomass to electricity?

SECOND QUESTION

The study analyzed the extent to which ownership of assets or wealth are determining factors in transitioning from biomass to electricity (Elkan 1988; Reddy 1995; Tyler 1996; Gupta and Ravindranath 1997; Tiwari 2000).

In the estimation of price and income elasticities of demand (Chapter 3), explanatory variables used were proxies for asset ownership. Results show that asset ownership is a significant factor in the demand response to changes in price, for the individual energy sources.

In Chapter 4, a logistic regression estimated the likelihood of adopting electricity as a domestic source, based on the 2002/3 IAF survey of Mozambican households. Results indicate that wealth, more specifically the ability to acquire electric appliances, favors electricity as a domestic source and that in the absence of wealth, even urban households will be less likely to adopt electricity in the domestic setting.

To further study the impact of asset ownership in the household evolution for higher consumption levels, a theoretical (dynamic) model was formulated (Chapter 6) with a new concept, that of the *asset ladder rule*. The quantity represents the share of the net income that the household spends in acquiring energy-consuming appliances over time, as opposed to investing in income-generating stocks or to increases in the consumption of leisure or non-energy goods. The *asset ladder rule* represents the path to a household evolving by increasing its consumption of leisure, non-energy goods, and of energy sources consumed in a growing asset-base (ownership of appliances), while increasing its income generation stocks that sustain the costs of additional consumption.

Numerical simulations varying market characteristics and household preferences were made, to study the sensitivity of the household behavior to these parameters. The results show that households:

a) will evolve faster and to higher consumption/investment levels if the initial credit is higher;
b) will reduce the consumption of leisure if the wages are higher;
c) will plan for higher energy costs by from the start reducing its consumption of leisure and non-energy goods and invest in productive investments instead, until it can afford the investment in appliances. As a result, high energy costs actually result in a higher investment in appliances, however still a lower utility for the household;
d) Finally, higher rates of return increase the opportunity cost of investing in appliances and as a result households will increase their consumption of non-durable commodities and investment in appliances will be delayed.

The sensitivity analysis can be expanded, however the most important finding is that no household will evolve, increasing its consumption, if it does not increase its income generating capabilities. So, development programs must consider this aspect necessarily and institute means through which households may increase their incomes.

Furthermore, it is clear that sources that require appliances to be consumed, such as electricity, can be used if the household can spend investment money in appliances in addition to the added costs of energy consumption. This model clarified the need to plan for investments in appliances as well as the operating costs of using electricity, i.e. low prices of electricity will not alone result in an increased electricity consumption. The numerical simulations showing that household facing higher energy prices will actually end up with a higher value in appliances, although its utility satisfaction may be lower, reinforce the notion that low prices are not sufficient to incentive new connections and increased consumption of electricity.

SUMMARY RESULTS OF THE WORK

THE SUSTAINABLE PRICE OF ELECTRICITY FOR DOMESTIC CONSUMPTION

The demand for electricity by households showed own-price elasticity of -0.51 at the national level, and -0.43 for the northern provinces only (Chapter 3). The income elasticity of electricity demand was calculated at 0.51 at the national level, and 0.39 for the northern provinces. The cross-price elasticities between sources are in general very small.

Using the own-price elasticity for electricity demand in the northern areas, inverted demand curves were derived for the networks of Tete, Quelimane, Mocuba and the North region with acceptable accuracy (Chapter 7), as follows:

$$\begin{array}{ll} \text{Tete:} & p_D^{Tete} = 7.1149 \cdot \left(q^{Tete}\right)^{-2.3256} \\ \text{Quelimane:} & p_D^{Quel} = 9.2990 \cdot \left(q^{Quel}\right)^{-2.3256} \\ \text{Mocuba:} & p_D^{Mocu} = 7.3314 \cdot \left(q^{Mocu}\right)^{-2.3256} \\ \text{North:} & p_D^{Nort} = 151.9991 \cdot \left(q^{Nort}\right)^{-2.3256} \end{array} \tag{76}$$

The estimation of the transmission and distribution loss equations for the distribution feeders in the northern grid (Linha Centro-Norte, Chapter 5) resulted in the following inverted supply (cost-recovery, zero profit) curves (Chapter 7):

$$\begin{array}{ll} \text{Tete:} & p_S^{Tete} = 0.3197 + 0.000174 \cdot q^{Tete} \\ \text{Quelimane:} & p_S^{Quel} = 0.3314 + 0.001999 \cdot q^{Quel} \\ \text{Mocuba:} & p_S^{Mocu} = 0.3094 + 0.000435 \cdot q^{Mocu} \\ \text{Nampula:} & p_S^{Nort} = 0.3214 + 0.001521 \cdot q^{Nort} \end{array} \tag{77}$$

The cross of these curves resulted in the equilibrium electricity prices for Tete (32 cents \$PPP/kWh), Quelimane (33.9 cents \$PPP/kWh), Mocuba (31 cents \$PPP/kWh) and Nampula (34.2 cents \$PPP/kWh), for 2007 load levels, which represent a welfare gain of about 2443 \$PPP/month. The average national price in 2006 (with which the company had a yearly deficit), was recorded at 26 cents \$PPP/kWh, well below the levels domestic consumers are willing to pay in the northern areas. These results show that there is room for price adjustment to change average electricity prices to the level of full cost-recovery. Market prices for kerosene and LPG were recorded both at 59 cents \$PPP/kWh in 2006 (Mozambique 2007), well above the current average prices and higher than the calculated cost-recovery prices, for 2007 load levels. In other words, electricity is definitely competitive with kerosene and the difference between these sources is that the first does not require expensive appliances to be used, while the second does. On the other hand, electricity is safer and more efficient in household uses, more desirable.

The comparison of unit expenditures in energy sources across the country (Chapter 4) shows that electricity and kerosene are cheaper per-unit-of-useful-energy than charcoal and firewood, in other words, the energy ladder is inverted on price. If households own the appliances, they may serve their domestic needs at a cheaper price per-unit-of-useful-energy by consuming electricity. Biomass consumers waste energy and end up paying more for their necessities than they would if they were consuming electricity or kerosene. The choice for electricity however does not fully depend on the price, as other chapters verified.

At 2007 load levels, the cost-recovery electrical price varied approximately in the range of 31 to 34 cents \$PPP/kWh in the northern provinces, well above the national average of 28 cents \$PPP/kWh in 2007. Comparison between sources shows that electricity is price competitive with biomass and kerosene in the domestic setting, while being more efficient, safe and versatile in its use, which favors electrification as a poverty alleviation and household development tool.

ASSET OWNERSHIP IS DETERMINING OF DOMESTIC ELECTRICITY CONSUMPTION

The derivations of price and income elasticities of demand (Chapter 3) showed that the presence of appliances was a determinant factor in the consumption of the various energy sources. The effect of appliances in households' consumption of electricity is quantified in Chapter 4, while determining the odds of being an electricity consumer. In this case, the assumption made was that households owning wealth (piped drinking water and concrete walls) would also have the capability of acquiring electrical appliances. Thus, wealth becomes an indicator for determining the probability of households adopting electricity as a domestic source. This estimation, after discounting for the presence of an energy mix (other sources such as charcoal or kerosene), showed that wealthy charcoal users in an urban environment have a high probability of being electricity users, but a kerosene user in the same conditions has much lower probability of becoming an electricity user. Rural households are significantly less probable to be electricity users. Non-wealthy households, even in urban environments, are also much less probable of becoming electricity users.

Concluding, urban households are 50 times more likely of being electricity users than rural households, and wealthy households are up to 46 times more likely of being electricity users than those without piped drinking water and concrete walls. The capability to acquire electric appliances (wealth) is necessary to adopt electricity as a domestic source. In the absence of wealth, even urban households will be significantly less likely to adopt electricity as a source.

Income is not a significant factor in the likelihood of a household being or not an electricity user (Chapter 4). This result is not unexpected, as households of varying incomes are still not electricity users, and vice-versa. Being an electricity user is more dependent on the location (whether the household has access to the electricity grid, more likely in urban areas) and on the household wealth, namely whether it owns assets (concrete walls, etc) which in turn make the household more likely to acquire an electrical connection and appliances.

Urbanization and wealth are the major factors determining the likelihood of a household becoming an electricity consumer. The lack of wealth (poverty) may thus be the reason why the poor (including the urban) do not generally adopt electricity as a domestic source, even if its price per-unit-of-useful-energy is significantly lower than biomass sources.

Similarly, the calculation of price elasticities showed that demand for energy sources is not very responsive to income variations (Chapter 3). The simulations of Chapter 6 indicate that the household will only increase the value of owned appliances if it increases its income earning capabilities, regardless of the level of income at which it started. A high-income household, consuming kerosene for lighting and spending all its income in food and other non-energy commodities, will not be able to consume electricity if it does not: 1) save to invest, 2) re-budget to sustain the operating costs of appliances (energy). In other words, the adoption of electricity as a domestic source requires more of a dynamic behavior in the household rather than high-income levels at the start.

The theoretical model (Chapter 6) confirms the need to invest in appliances before electricity may be consumed, and establishes behavioral rules that favor investment particularly when electricity prices are high. Even if the poor can afford to pay for the monthly electricity consumption costs, if they don't own an electrical lighting system or a refrigerator, they may not consume it, in other words, if consumers cannot invest in electrical appliances they will not use electricity as a domestic source, even when prices are low.

This study also showed that being a charcoal user slightly reduces the likelihood of being an electricity user, but consuming kerosene drastically reduces this likelihood. Kerosene is mostly used as a lighting source and does not require any expensive appliance to burn, i.e. kerosene consumption is a serious detriment for households to transition to electricity for lighting.

RATIONALE OF HOUSEHOLD'S ENERGY TRANSITION AND EVOLUTION

The theoretical model (Chapter 6) describes the household allocation of funds to the consumption of leisure, non-energy goods and investments, both in energy consuming appliances and in income-generating stocks, over time, in a sustainable manner.

When the consumption of leisure or non-energy goods is high-utility giving and of low-cost, the household will not invest immediately in the electrical connection and appliances. High earnings will result in not only increased consumption of leisure and non-energy goods, but also in investments in energy-consuming assets, i.e. high-income households will eventually transition to higher-grade sources (electricity). This behavior can explain the energy ladder as originally conceptualized and its discrepancies: larger-income families increase first the consumption of commodities giving direct utility (leisure and non-energy goods). The transition to electricity, which only occurs with investment in appliances, is delayed, as considerations of utility and cost-benefit are part of the household's choices.

The transition from, for example, biomass to electricity, can provide more utility to the household, can serve its needs better, but it is not necessarily the highest utility choice it can make within its budget. Although the level of income does not determine the choice for domestic source, it still limits the expenditure in energy and other (needed) commodities.

Whenever utility from electrical appliances is comparable to the utility obtained from increasing consumption, and if the cost of electricity is higher than the cost of leisure and/or non-energy goods consumption, the household will prioritize consumption rather than the energy transition processes. In this case, the *asset ladder rule* will tend to take values close to zero. However, for high-utility low-cost energy transition processes, the household will split its earnings into increasing consumption and into investing in energy-consuming utility giving assets. In this case, the *asset ladder rule* will tend to take values between zero and one, depending on the cost of providing utility of investment versus consumption.

The temporal shape of the *asset ladder rule* depends on the problem's parameters, namely return rates of productive investments, operating costs and depreciation rates of the investments in energy-consuming appliances, wages, prices of non-energy goods, discount rates and of course, on the value of the initial credit for investment. Still, the numerical examples run for the theoretical model (Chapter 6) confirm the high burden that the acquisition and operation of energy consuming appliances has in the household's budget and that sustainability can only be achieved with the coupling of investments for increased energy consumption with investments to increase the household income. Favoring the energy transition processes are the availability of cheap (low investment cost), simple (high utility), durable (low depreciation rate) and efficient (low energy consumption/cost) appliances, and the opportunity for productive investments of high returns, such as the provision of services and training for higher wages.

The results of Chapter 6 show that electrification programs, to be successful in targeting poor populations, need to be complemented with credit facilities, market boosts and price design so that the adoption of the new source becomes competitive with just increasing consumption. Households also must wisely choose to increase their income basis, in parallel with increasing their consumption and wealth, which is not always the rational choice for them (Tomer 2008). The asset ladder rule for an evolving household will thus vary between zero and one and, increasing its consumption and appliances ownership and its income generating stocks.

The simulations for varying parameters in Chapter 6 indicate that after the initial injection of credit K_0 the household will slowly evolve up to higher consumption and ownership levels Policies for development must thus have a relatively long timeframe.

POLICY IMPLICATIONS

There is evidence that households maintain a mix of sources in developing countries, and only transition fully to electricity when not only income and investment funds are available, but also when lifestyles so require (Hiemstra-van der Horst and Hovorka 2008). However, it has also been shown that only by accessing sources of higher efficiency, cleanness and practicality/variety of use, may households evolve to better quality of life and to more opportunities for education and income-generation (Kanagawa and Nakata 2008; Mulder and Tembe 2008; Prasad 2008; Rao, Miller et al. 2009). Up to now, the poor and policy makers have deemed electricity unaffordable, a luxury that only higher-income households can dream to access and consume. Developing countries consume mostly inefficient sources such as biomass, and grid electricity only accounts for about 4% in Africa, with domestic consumption levels comparable to the nineteen century's in Europe (Wolde-Rufael 2006). To establish a minimum standard of living, higher than the currently defined poverty-line of

$1 per day per capita[161], the recognition that the poor are not only active participants of society (Sebitosi and Pillay 2005), but also they are potential consumers in growing service-providing industries like energy supply industries (Hammond, Kramer et al. 2007) is needed. The lack of access to electricity is not just a consequence but also a cause for poverty and entails high economic costs to the country (Sebitosi and Pillay 2005; Hammond, Kramer et al. 2007). The access to reliable and efficient energy sources is a prerequisite to poverty alleviation (Sida 2005; United-Nations 2007).

This study showed that, in Mozambique, electricity is a competitive domestic source and can improve significantly the lives of the low-income families, by providing them with efficient and varied services and opportunities. However, policies must be put in place to facilitate the access to the electrical grid, through electrification programs, and to make affordable electric appliances that will provide households with domestic utilities and promote social and economic growth. Electrification programs can be more effective for domestic consumers if parallel credit systems are instituted to provide an opportunity for growth, as numerically demonstrated in Chapter 6. In other words, electrification programs must contain:

- Grid expansion projects that increase access to domestic consumers, combined with price regulations that limit prices to affordable levels. The national public electricity company (EDM) is already electrifying the country (EDM 2005) and providing a lifeline (social) cheap tariff for low-income consumers (Mozambique 1985). However, a better combination of efforts to integrate grid and non-grid electrification initiatives is necessary. Furthermore, the social tariff should be

[161] The first Millennium Development Goal is to halve the current number of people living with $1 or less per day (United-Nations 2007), however the fulfillment of other MDG require much more than household income growth: infrastructure development is part of the solution (Sarkar 2007).

adjusted to a higher level of consumption (currently at 100 kWh per month it can only sustain electrical lighting and a small color TV) and its application should be more widespread, so the poor may also benefit from cheap energy for refrigeration and computing facilities.

- Credit facilities that allow households to evolve out of poverty, by increasing their income and investing in energy-consuming appliances and by increasing their consumption of non-energy goods. The combination of micro-credit and banking services with electrification programs can provide opportunities for the suppliers and financial institutions (the poor constitute the majority of the population and their potential as borrowers and consumers has not yet been tapped into) and for the consumers, that will benefit from an opportunity to improve their lives.
- The promotion and increased access to efficient, simple and low cost electrical appliances that provide utility but are affordable, durable and low energy intensive, will make the transition to electricity affordable. Appliances relatively simple to use and durable can also be a good choice for households that are technologically illiterate, facilitating the transition from biomass to electricity.
- The creation of more opportunities for investments for income generation, whether in the form of physical stocks or as human capital (education: higher wages and better employment opportunities). If the country's economic development results in better and more employment opportunities and a higher demand for goods and services, the individual households will more easily find activities through which to improve their lives. This development may be better monitored and promoted with flexible, geographically diverse, development policies and programs that make use of the local resources and opportunities. In other words, the local economic development that precludes and also results from electrification efforts, must be

planned taking into account the local specificities and opportunities for social development, as much as electrification projects require surveys of the local topography and the management of local markets.

The reduction of poverty and the provision of humane living-standards to all the population is a goal that can only be achieved by a combination of efforts in all fronts. Electricity, as the ultimate domestic source, certainly has an important role to play.

ANNEX: MATLAB CODE

The calculations in this study were programmed in software MATLAB, version 2007 for students (http://www.mathworks.com/), and the code is in the CD attached. This chapter presents the data structure in each calculation and the commands to run the MATLAB code. The first step is to path (in MATLAB) folder *MATLAB code* and subfolders.

Code for Chapter 3

1) Open folder: *secondDeaton*
2) Open data file: *HHraw.mat*
3) Call for elasticity estimation for separate sources (data per household) function: *[HHnonZ,Cluster,Deat,Direct,compareEP,compareEX,corrBudExplan] = MyHouseholdRun(HH,0,12,[7:16],'A','A')*
4) The results are presented in the following data structures:
5) Intermediate calculation structures: *HH, HHnonZ, Cluster, Direct* and *Deat*
6) Report structures:
   - *compareEP* (own-price elasticities, comparing Deaton derivation - column 1, with direct derivation – column 2)
   - compareEX (income elasticities, Deaton - column 1, direct– column 2)
   - the elasticities calculated are saved in structure *Deat* (.EP and .EX)

Code for Chapter 4

1) Open folder: *PCAanalysis*
2) Open data file: *PCA1.mat*
3) Call logistic regression routine for GM3: *run_correlations*
4) Save workspace as data file: *PCA1_run.mat*

5) Report structures where the logistic regression results are stored: *Firew, Charc, Keros, Elect*

Code for chapter 5

1) Open folder: *Grid model*
2) Open data file: *RawGridData.mat*
3) Call building function and regression routine for GM1 and GM4 (unused): *masterGridModel*
4) Save workspace as data file: *NoOutliersDataRegressed.mat*
5) Call data shaping function: *dataPreparation*
6) Save workspace as data file: *rawDataPIN.mat*
7) Call regression routine for GM2: *regressPIN*
8) Call data shaping function: *distLoadProfiles*
9) Open data file: *distributionLosses.mat*
10) Call regression routine for GM3: *runCalcResistances*
11) Save workspace as data file: *severalDerivations.mat*
12) Call plotting function: *severalplots*
13) Report structures containing loss equation coefficients and the statistics of regression derivations: *rptGM1*, *rptGM2* and *rptGM3*

Code for Chapter 6

1) Open folder: *optimization*
2) Call for varying parameters simulation: *call_simulation*
3) Report structures, source for plotting: *oneunA, oneunB, oneunC, oneunD, oneunE, singlerun, lastrun*

Code for chapter 7

1) Open folder: *SupplyDemand*
2) Open data file: *SupplyDemandData.mat*
3) Call analytical calculation and plotting routine: *call_supplydemandLCN*

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