Residential Energy Use Scenarios

M.Sc Thesis
Sustainable Development - Energy and Resources

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Preface

This document is presented as my final thesis for the Master Degree of *Sustainable Development – Energy and Resources* for Utrecht University. The work presented here was performed during an internship at the *Netherlands Environmental Assessment Agency (Planbureau voor de Leefomgeving, PBL)*. The purpose of the internship was to expand a model for the residential energy demand of Indian households made by Dr. Bas van Ruijven (REMI) to a global scale. The work undertaken can be summarized by the following stages:

- Perform a literature review of residential energy use to gain an in-depth understanding of this sector
- Understand the conceptual grounding and technical aspects of the REMI model
- Gather data on a global scale for key aspects of residential energy use
- Perform regression analysis on this data
- Adjust and expand REMI in order to make it more appropriate on the global scale
- Calibrate the new model (REMG) to historic data in order to make the model operational

Once the model was developed, a scenario analysis was performed in order to test its various aspects and also to complete the research for my thesis.

This document is composed of two parts. The first part is the scenario analysis which was performed with the model on certain key developing regions, and is the main body of my master thesis. This document has been prepared with publication in mind and thus should be treated as an ‘extended’ paper. This first part will be subsequently shortened and made more focused and submitted for publication.

The second part is a data and technical report on the model. It explains in detail the data which was gathered, how this data was used and the assumptions made in order to develop the model. It offers insight on how the model works the data limitations and explains how the calibration was performed. It is written for the aid of future users of the model. Concerning this thesis it should be considered supplementary material as an indication of the volume of work which has been done in order to complete the thesis.

Acknowledgements

This research would not have taken place without the opportunity presented and diligently supervised by Bas van Ruijven and Detlef van Vuuren. Their help is greatly appreciated. I want to thank Bert de Vries for introducing me to systems modeling through his lectures and for directing me towards Bas and Detlef. I also want to thank Martin Patel who offered significant advice and guidance. I am grateful to the staff of the Netherlands Environmental Assessment Agency for their encouragement, willingness to help whenever requested and the interesting conversations they offered which gave me much insight on a plethora of topics. Finally I want to thank my friends and family for their constant and unconditional support.

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PART I - RESIDENTIAL ENERGY USE SCENARIOS

Abstract

The energy services demanded within the residential sector are diverse. As households get richer the evolution of their energy use is two-fold: the service the energy provides, and the energy carrier used. These dimensions are studied together in order to achieve a holistic understanding of the effect of the residential sector in the joint climate and development problems. We developed a stylized bottom up system dynamic residential energy use model in order to analyze how energy use of households develops and the corresponding use of fuels which are used in order to meet this demand. The model furthermore disaggregates between urban and rural households as well as income quintiles within these two classes. Subsequently the model was used in order to analyze possible future developments of residential energy demand in five developing world regions: India, China, Pacific Asia, South Africa and Brazil. The future storylines are based on the possibility of efficiency improvement, changes in income inequality, introduction of climate policy, and financial aid in order to promote the use of cleaner fuels.

1 Introduction

Energy use and supply play a key role in issues such as air pollution, climate change, environmental degradation, resource scarcity, geopolitical tension and development. Whereas so far global energy use has been dominated by industrialised countries, presently the energy consumption of developing nations is rapidly rising. While increasing energy use is often needed for economic development in developing countries, supplying it could potentially lead to the problems listed above.

An important sector for future energy use in both developed and developing countries is the residential sector. In OECD countries residential energy use accounts for 20% of total final energy consumption, while the global average is estimated at 35% (IEA, 2004; IEA, 2007). Energy and development share an intimate relationship with energy being a prerequisite for, as well as a result of, development. Economic development stimulates energy demand and a virtuous circle of energy infrastructure and economic development follows. Conversely there is a vicious cycle of energy poverty and economic under-development which many developing countries are struggling to overcome (IEA, 2004b). In 2000 the international community made a commitment to the Millennium Development Goals (MDGs); a series of quantitative and time-bound targets aimed at tackling poverty, hunger, illiteracy, gender equality, infant mortality, health, environmental sustainability and partnerships. Residential energy use forms a key factor to meeting many of the goals when considering indoor air pollution, fuel collection and its implications, disease transmission and unsustainable use of biomass (Modi *et al.*, 2005; IEA, 2010).

These considerations make it important to explore possible future trends in global residential energy use. Most global energy models describe future residential energy demand based on simple relationships between energy consumption and income or GDP per capita. Yet it is understood that the elements which make up residential energy demand are highly heterogeneous, related to a number of different energy functions which are fulfilled in households. It is likely that future trends, especially in developing countries, can only be fully understood if this heterogeneity is accounted for given the broader socio-economic and environmental factors which dictate residential energy use. Such factors include household income, cultural traits, climatic conditions and access to different energy forms. This study attempts to understand and subsequently project residential energy use with the aid of a systems dynamic model based on a detailed description of the underlying drivers of residential energy use. Van Ruijven argued that such a disaggregated approach based on physical indicators might be more appropriate for developing countries given the rapid transitions and the more limited role of market dynamics (Shukla, 1995; van Ruijven, 2008; van Ruijven *et al.*, 2008b).

In order to better understand global residential energy use, we developed a stylized bottom up global energy model that is based on an explicit representation of five main energy functions in households and their main drivers. The model addresses heterogeneity by distinguishing between urban and rural population classes and furthermore disaggregates between income quintiles of the respective classes. In this paper the model is applied to develop detailed projections for residential energy use for India, China, South Africa, Brazil and South East Asia. These countries/regions were selected due to their importance for global energy use and their status as newly industrialized countries and their climatic and social-economic differences.

The model is used in order to provide insight on the future of residential energy use of these regions and how the regions differ amongst themselves. It is also interesting to understand how specific policy measures aimed towards a specific goal (reduce emissions, improve accessibility to modern fuels) may affect other elements of residential energy use. This approach provides a holistic view of residential energy use and the inter-relatedness and trade-offs one encounters when trying to meet climate and development goals.

More specifically we seek to answer the following questions considering a time frame till 2030:

1. What are the future trends of the residential energy use for India, China, South East Asia, South Africa and Brazil, and how do these trends differ between these regions?
    a. What are the main drivers of these differences?
    b. How do these trends relate to development and climate issues?
2. What are the impacts of specific policy interventions aimed at reducing greenhouse gas emissions and providing access to clean cooking fuels in these five regions?

The model is based on a previous model developed and made operational for the Indian residential sector (van Ruijven, 2008; PBL, 2009). Once the model was adapted for use for other countries and validated based on available historic data, we used it to describe possible future trends based on the scenarios currently being developed by the Global Energy Assessment (IIASA, 2010). These scenarios are attractive in the context of this paper given their intention to be relevant for both environmental and development issues related with future energy use. The scenarios pursued include baselines, climate policy (carbon tax) and access policy (subsidies, financing). Furthermore, the choice of scenarios is appropriate to test the various aspects of the model as well as its sensitivities.

In this paper, section 2 describes the methodology of the analysis by presenting the REMG model. In the same section the scenarios used in the study are qualitatively described. Section 3 summarizes the results of the scenarios. In section 4 the results are parameterized according to the *Energy Development Index* which has been proposed by the *International energy Agency* (IEA). Finally section 5 discusses the implications of the results together with some concluding thoughts.

2 Methodology

How energy use develops depends on the interactions between economic, human and physical domains. In other words it is important to take account of the relationships between income levels, preferences, technology, resource availability, climatic conditions etc. Models are often used in order to adequately represent the feedbacks and tradeoffs between these factors. The usefulness of a system dynamics model is tested for in this paper by looking into baseline trends but also the ability to analyze the effects of specific policy interventions.

2.1 *Residential Energy Model – Global*

REMG is a stylized bottom up system dynamic model which distinguishes between different energy functions and specifically models how the demand for these energy functions is met[1]. The model has been built around a set of first order assumptions based on an extensive literature review concerning the residential energy use on a global scale. The cornerstone of the analysis is that as countries become richer it is likely that demand for energy services will increase. Following this, energy use in developing countries can be best understood by focusing on specific end use functions (services) and their drivers (Schipper *et al.*, 1996; Howell *et al.*, 2005). In the literature, the concept of the energy ladder is often used to describe empirical trends from traditional fuels (e.g. wood and coal) towards modern fuels (natural gas and electricity). This concept is adopted as an explanation for how people are more likely to use more convenient fuels as they become richer (Hosier *et al.*, 1987). Another important factor of the model is the recognition of heterogeneity. To account for this, both income groups and urban/rural classes have been identified as the most statistically significant in determining a households' energy consumption patterns (Pachauri, 2004).

The data requirement of the REMG model is considerable. Data is required for the drivers such as household expenditures, household sizes and income inequality. Following this data is also required for the energy consumption for the end use functions in relation to these drivers. This includes ownership rates and unit energy consumption of household appliances and data on useful energy requirement for cooking and heating. Finally, information concerning fuel choice for each end use function is required. A further difficulty which had to be overcome is that the methods deployed in energy surveys vary amongst them, leading to data which may not be comparable. Though there is limited availability for some world regions for all or parts of this data, especially across time series, there still was enough data to determine relationships and calibrate the model

Household information and appliance ownership was primarily collected from censuses and surveys of each country but also from the *World Development Indicators* of the *World Bank* (NBSC, ; NSSO, 1997; SSA, 2002; NSSO, 2004; SSA,

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[1] The REMG is based on a previous model which focused on the residential energy use of India. The current set up is designed to work on a global scale (by disaggregating the world to 26 regions) and ultimately it is to be applied to the TIMER/IMAGE and GISMO modelling frameworks in order to achieve an integrated assessment approach accounting for climate and resource feedbacks.

2007; NIS, 2009; WDI, 2009). For income inequality within regions databases of the World Bank were used (World-Bank, 2009; World-Bank, 2010). Total final consumption of energy for the residential sector on a global scale is available from the International Energy Agency, which also breaks down the energy use to different fuels (IEA, 2007). Furthermore, more detailed data concerning the urban/rural divide, energy use per energy function, fuel shares, fuel subsidies etc, were gathered from scientific papers and independent databases (Xiaohua *et al.*, 2002; Jannuzzi *et al.*, 2004; Gangopadhay *et al.*, 2005; Tonooka *et al.*, 2006; LBNL, 2008; Peng *et al.*, 2010). Further data concerning the difference in cooking fuels between urban and rural households is available from the *World Health Organization* (WHO, 2010).

The model was calibrated against the available data in order to ensure that key indicators match historic observations. The calibration aimed to ensure that household properties, appliance ownership, cooking fuel choice and final energy use reflected the data mentioned above as much as possible. A more detailed overview of the data collection, how it was used and model calibration is available in the *Data and Technical Report* attached as Part II of this document.

The model has five exogenous drivers which determine five end use functions. Once the useful energy demand of each end use function is determined fuels are allocated based on relative costs. A description of the relationships between the drivers and the end use energy functions is shown in Figure 1. The overall causal relations which drive the model are shown in Figure 2. The available energy carriers for each end use function are listed in Table 1. Throughout this paper 'Traditional Biomass' and 'Coal' are referred to as 'Solid fuels' while the rest are considered modern fuels. The REMG model is capable of handling more advanced fuels such as Hydrogen and modern bio-energy. However, due to data restrictions on price and energy use as well as the fact that the predictions are only till 2030, the choice of available fuels is conservative and so they have not been included. In REMG, the energy demand for the end-use functions is determined on a household level. Sections 2.1.1 and 2.1.2 describe end use function and fuel allocation mechanisms in more detail.

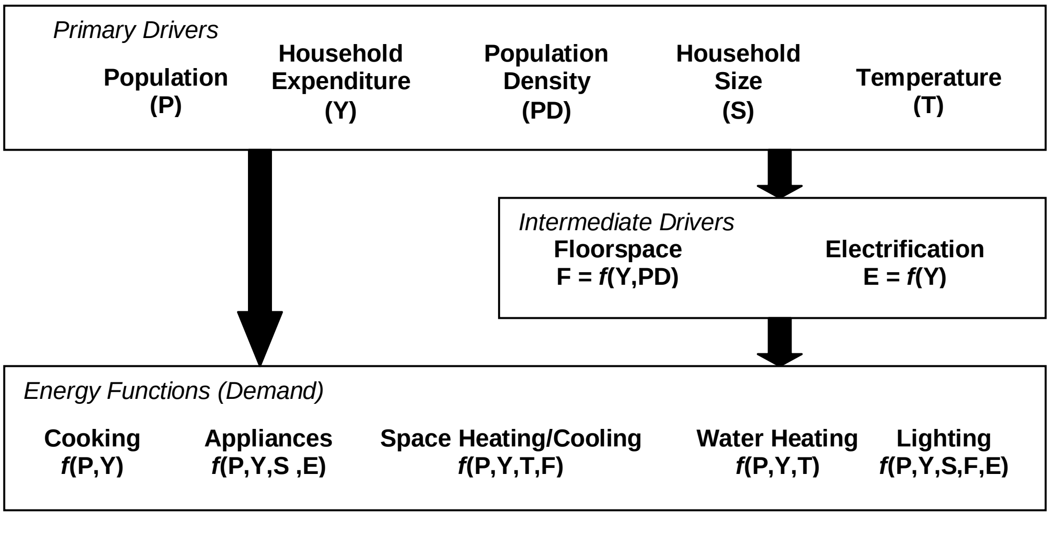

Figure 1. Relationship between drivers and energy functions; all drivers (except for population density and temperature) defined for urban/rural classes and income quintiles.

Table 1. Energy carriers available for each end use functions.

Cooking	**Appliances**	**Space Heating/Cooling**	**Water Heating**	**Lighting**
Coal	Electricity	*Coal*	*Coal*	Kerosene
Traditional Biomass		*Traditional Biomass*	*Traditional Biomass*	
Kerosene		Liquid	Liquid	
Liquid Petroleum Gas		Natural Gas	Natural Gas	Electricity
Natural Gas		Hydrogen	Hydrogen	
Modern Bio-Energy		Modern Bio-Energy	Modern Bio-Energy	
Electricity		Secondary Heat	Secondary Heat	
		Electricity	Electricity	

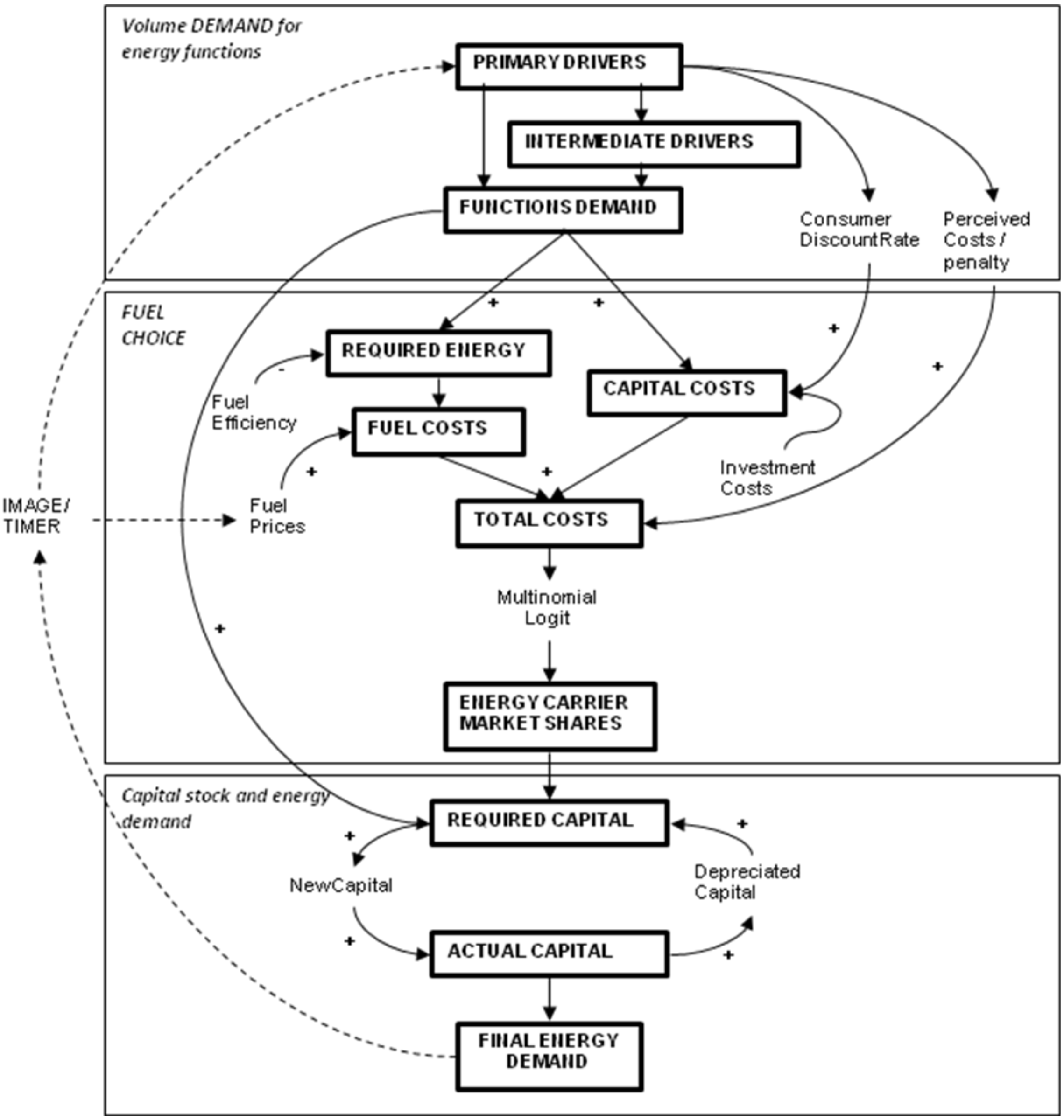

Figure 2. Causal relation diagram of main indicators of REMG.

2.1.1 End Use Functions

Five end use functions which have been identified as the most important (IEA, 2004). In REMG they are specifically modelled mathematically where appropriate .The volume demand of these end use functions are determined in terms of *Useful Energy* (UE), that is, energy delivered to the end-use functions adjusted for conversion efficiency between energy carriers. In all the following equations the subscript ‘*R’* denotes Regional variation*, ‘p’* denotes urban/rural class difference, ‘*q’* denotes income quintile, and ‘*a’* different appliances.

Cooking: In developing regions where total energy demand is still low, cooking represents the most significant end-use function of households; while the exact opposite is true for developed countries where the other end use functions take precedence (Schipper *et al.*, 1996; IEA, 2006). We analyzed historic data for cooking energy use in different parts of the world with the range of all values collected (69 data points) being 0.77 – 7.22 MJ$_{\mathrm{UE}}$/cap/day. However the vast majority (44) clustered around 1.5 and 3.5 MJ$_{\mathrm{UE}}$/cap/day. No statistically significant relationship could be found between energy for cooking and income or geographical region since even within the same region there often was a wide range of values depending on data source. Therefore it was assumed that all regions have an average constant consumption of 3 MJ$_{\mathrm{UE}}$/cap/day. A histogram of the data is shown in Figure 3.

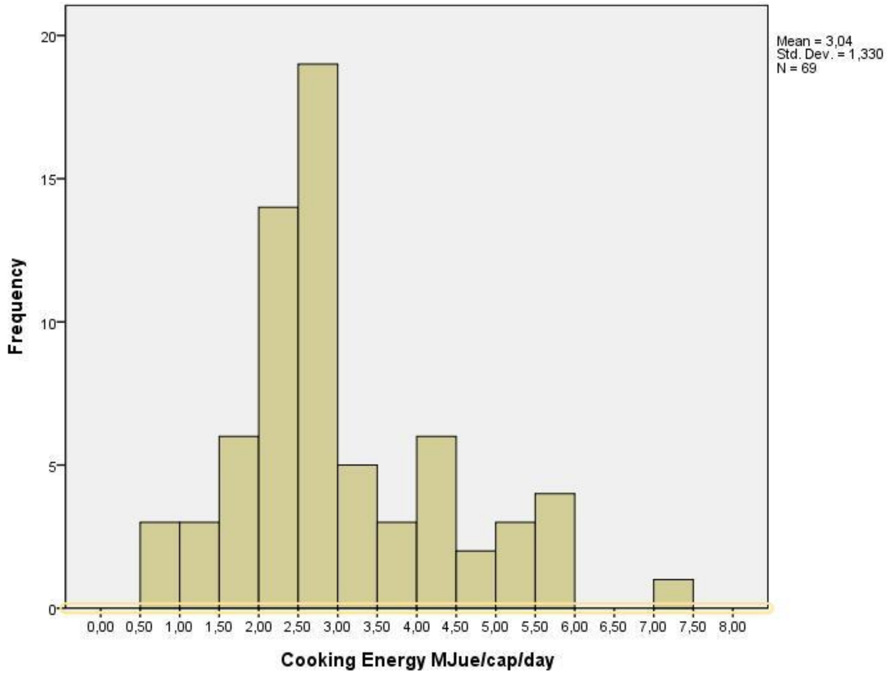

Figure 3. Useful energy for cooking histogram (MJue/cap/day).

Appliances: The use of energy for appliances represents another important end-use function. For this purpose three different categories of appliances are included. These include food storage and processing, washing/cleaning and entertainment. Within these categories 8 indicative appliances are modeled. Ownership levels are assumed to be driven by household expenditures. The appliance ownership growth is based on the gompertz function as shown in Equation 1.

$$Penetration_{R,p,q} = Saturation_{R} \times EXP\left(-\varphi 1_{R,p} \times EXP\left(-\left(\frac{\varphi 2_{R,p}}{1000} \right) \times HHExp_{R,p,q} \right) \right)$$

Equation 1

Where *HHExp* is the household expenditures disaggregated for regions, urban/rural class and income quintiles. The saturation is the maximum number of appliances per household which may vary with time. The gompertz parameters (φ1 and φ2) are region and class specific determined via regressions. In order to determine energy use, the ownership levels are multiplied by the unit energy consumption, which also includes standby energy use which may be significant (Rosen *et al.*, 2000; Loveday *et al.*, 2008; Ajay-D-Vimal Raj *et al.*, 2009). Major energy consuming appliances such as refrigerators, washing machines, clothes dryers and dish washers have an autonomous as well as a price induced energy efficiency improvement. The autonomous energy efficiency improvement is assumed to be a simple decay over time as verified from data (IEA, 2004; Bogdan *et al.*, 2008; Weiss *et al.*, 2008; CEC, 2009; Cardoso *et al.*, 2010).

$$UEC = \alpha_{R,a} \times \beta_{R,a}^{(t-1971)} + UECm_{R,a}$$

Equation 2

Where α and β can vary in order to change the rate of autonomous decline and *UECm* is an assumed limit to UEC.

For the price induced energy efficiency improvement, the UEC is also related logarithmically to the cost of electricity (coe). This is based on the effect of a change in electricity price on the total costs (annualized capital and annual fuel) based on current price and UEC ranges. The coefficients α and β of Equation 3 are determined based on the most attractive option for any given consumer discount rate. Thus for low-income households with high consumer discount rates where capital costs are important, the effect of a higher cost of electricity is lower. The consumer discount rate is discussed in greater detail in section 2.1.2.

$$UEC_{R,\ p,\ q,\ a} = \alpha_{R,\ p,\ q,\ a} \times Ln\left(coe_{R}\right) + \beta_{R,\ p,\ q,\ a}$$

Equation 3

Space Heating and Cooling*:* In richer households, this function represents the greatest share of energy demand. Space heating and cooling demand are modeled as a function of floorspace, heating degree days and heating intensity ($kJ_{UE}/m^2/HDD$) directly after Isaac and van Vuuren (Isaac *et al.*, 2009).

$$HeatUE_{R,p,q} = Population_{R,p,q} \times FloorSpace_{R,p,q} \times UEInt_{R} \times HDD_{R}$$

Equation 4

Where *UEInt* is the useful energy heating intensity ($kJ_{UE}/m^2/°C/yr$) and *Floorspace* is in m^2/cap. Energy use of air conditioners is based on penetration, unit energy consumption (*UEC*) and efficiency improvement:

$$ACEnergy_{R,p,q} = Households_{R,p,q} \times Penetration_{R,p,q} \times \frac{UEC_{R,p,q}}{Efficiency\ Change}$$

Equation 5

The UEC is adjusted for efficiency changes to the average Energy Efficiency Ratio (EER) projections (Rong *et al.*, 2007). The penetration depends on an expenditure based gompertz growth towards a climate based maximum saturation value. The relationship between maximum saturation and cooling degree days (*CDD*) is exponential and has a maximum of 100% (Sailor *et al.*, 2003; McNeil *et al.*, 2007). The UEC has a linear relationship with CDD and a logarithmic relationship with income in order to account for multiple ownership of air cooling appliances:

$$UEC_{R,p,q} = CDD_R \times \left(0.6053 \times \ln\left(HHExp_{R,p,q}\right) - 3.1897\right)$$

Equation 6

Water Heating: This demand is modeled as a stylized growth dependant on income towards a maximum value driven by household expenditures. The data used to construct this relationship comes from a number of sources covering many climatic regions (NRCan, ; Tyler *et al.*, 1990; IEA, 2004; EIA, 2005; Utlu *et al.*, 2005; DoECC, 2009; FSO, 2010; Rosas-Flores *et al.*, 2010).

$$WaterUE_{R,p,q} = MaxUE_R \times \left(1 - EXP\left(3.356 \times EXP\left(-\left(\frac{0.237}{1000}\right) \times HHExp_{R,p,q}\right)\right)\right)$$

Equation 7

Where *MaxUE* is the maximum useful energy requirement for water heating based on a linear increase with HDD.

Lighting: While in low income countries lighting may account for a significant share of total electricity use, in OECD countries it represents only a small share (IEA, 2008; Weiss *et al.*, 2008). In households which lack access to electricity, lighting demand is met by a given quantity of kerosene (Mills, 2005). For electrified households lighting demand is driven by floorspace and there is a choice between incandescent and compact-fluorescent bulbs. Data suggests that lighting demand at frozen efficiency forms a linear relationship with floor space. Thus we first estimate the number of lighting fixtures per household. This multiplied by the average wattage of lights (assumed uniform) gives the total lighting capacity of the household. Finally this can be multiplied by a Lighting-Hours factor determined from data in order to give the annual energy use.

$$LightingEnergy_{R,p,q} = 0.68 \times Floorspace_{R,p,q} \times Wattage \times LightingHoursFactor$$

Equation 8

The wattage is determined by a choice between incandescent lighting and compact fluorescent lighting based on the annual fuel and capital costs. Market shares of the respective technologies are allocated based on the multinomial logit function (explained below). The costs of incandescent lamps are set as constant while there is a decrease in the price for compact fluorescent bulbs towards minimum (Oosterhuis, 2007; Weiss *et al.*, 2008).

2.1.2 Fuel Allocation

The next step is to determine what fuels are used in order to meet the volume demand. The energy carriers which are incorporated in this study are coal, traditional biomass, liquid fuels (kerosene and LPG), natural gas, secondary heat and Electricity. The availability of these fuels per end use function is outlined in Table 1. For appliances (including space cooling equipment) only electricity is used. For lighting either electricity or kerosene is used based on if the household is electrified. For space/water heating and cooking fuel allocation undergoes a choice function. Four key dynamics dictate fuel choice: 1) A multinomial logit allocation based on relative costs, 2) Income based perceived costs accounting for aspects such as behavior and accessibility 3) the consumer discount rate of the different income classes indicating upfront cost barriers and 4) stock turnover delays.

First the multinomial logit function is used to allocate fuel shares (*MS)* for each energy carrier (*EC)* based on relative costs (*C)*. The multinomial logit is used in such a way so as to simulate the concept of the energy ladder. This is done by 1) introducing income dependant discount rates and 2) a second income dependent factor representing the importance of perceived (non-monetized) costs. The assumption is that as households get richer, they switch towards cleaner, more efficient and convenient fuels; thus away from coal and traditional biomass and towards kerosene, LPG, natural gas and electricity (Hosier *et al.*, 1987; van Ruijven *et al.*, 2008b). The fuel ladder concept has been criticised as an over simplification since households tend to use multiple fuels rather than completely switch from one to another (Masera *et al.*, 2000). In this modelling exercise since market shares of multiple fuels are determined (on a quintile basis) rather than a single fuel dominating, the multiple fuel 'stacking' is represented within the fuel ladder. Movement down the fuel ladder may be possible under price hikes however this movement is only possible under persistently higher energy prices. The multinomial logit is described by:

$$MS_{R,p,q,EC} = \frac{e^{-\lambda C_{R,p,q,EC}}}{\sum_{EC=1}^{EC_{tot}} e^{-\lambda C_{R,p,q,EC}}}$$

Equation 9

The costs include both monetary and non-monetary (perceived) costs. The monetary costs are the sum of the annualized capital costs and the annual fuel costs. Perceived costs represent the fact that fuel choice is not only the product of economic factors alone; especially in poorer households where decisions are based more on cultural aspects. Many of these aspects include specific traditional cooking methods as well as cooking for large groups where traditional biomass is more effective than modern fuels (Masera *et al.*, 2000; Farsi *et al.*, 2007; Maconachie *et al.*, 2009). It is assumed that these perceived costs reduce with income. The assumption is that as income increases and household members take part in employment/education, time scarcity and rational behavior means that the gravity of the above mentioned factors falls. Availability and use of fuels in each region depends on historic data while use of electricity for a cooking/heating fuel also depends on electrification rates. For future projections, the use of natural gas is dictated by the share of natural gas which has to be imported, determined from TIMER runs.

The consumer discount rates are important in determining the annualized capital costs. Discount rates are higher for low income households being around 80% compared to 10% for affluent households. This problem stems from the decreased liquidity of the poor. Furthermore poor households cannot afford loans with high interest rates, and thus upfront capital costs pose a significant barrier. Discount rates decrease with income and thus annualized costs also decrease with income (Train, 1985; Reddy, 1996).

The market shares determined from Equation 9, determine the new (marginal) stock required. Delays in vintage stock turnover have been introduced in order to account for a time-lag in fuel switching. These delays in stock turnover apply to appliances as well. The delays are based on technical lifetimes of cooking/heating capital and appliances as well as a 10 year smoothing (5 years for appliances) in order to avoid spasmodic behaviour during sudden changes in (exogenous) energy carrier price or household expenditures.

The quantity of fuel required to meet the demand is determined by the conversion efficiency. A literature review of cooking and heating efficiencies of fuels was conducted yielding a range of efficiencies, the most common of which were used (Lefevre *et al.*, 1997; Lucky *et al.*, 2001; Xiaohua *et al.*, 2002; Utlu *et al.*, 2005; Visser, 2005; Reddy *et al.*, 2006; Anozie *et al.*, 2007; Saidur *et al.*, 2007).

2.2 *Scenario Storylines*

The main questions of this paper are approached by adopting the storylines of the Global Energy Assessment (GEA) of the *International Institute of Applied* Systems *Analysis* (IIASA, 2010). The GEA scenarios are constructed around a single normative scenario development and are based on a number of requirements in order to achieve sustainable development, i.e. improving energy access, reducing air pollution, avoiding dangerous climate change and improving energy security. Within this scenario, three possible pathways are described under which these goals can be met (IIASA, 2010):

1. *Supply (GEA-High):* Make improvements on the supply side of energy in order to meet these targets.
2. *Efficiency (GEA-Low):* Make end use efficiency improvements in order to reduce the energy demand.
3. *Mix (GEA-Mix):* A mid-point between the other two.

For each of these scenarios first a baseline has to be determined. This baseline only reflects the main technological and socio-economic assumptions but does not explicitly focus on the targets. In this study we use the first two pathways (*GEA-L* and *GEA-H*) as baselines. Following that we introduce two experiments focusing on more stringent climate policy and improved access to modern cooking fuels. The climate policy experiment is performed on the GEA-M baseline while the Access policy is performed on the GEA-L and GEA-H baselines.

2.2.1 Baselines

The GEA-L and GEA-H storylines were chosen in order to study the effect of energy efficiency and economic inequality. Since the GEA-L case is based on a reduction of demand in energy, the rate of energy efficiency improvement of appliances and cooling devices is increased. Furthermore cooking and heating efficiencies of the different fuels increase to the maximum values seen today. For the GEA-H storyline it is assumed that little towards nothing is done in order to promote energy efficiency. Thus current autonomous trends are scaled back slightly for appliances and cooling devices while cooking and heating efficiencies stay at current values.

The GEA-L pathway implies a more equal distribution of wealth while the GEA-H implies the opposite. Within REMG these are reflected through a reduction in the difference between the urban and rural shares of the GDP under the GEA-L storyline, while there is an increase in the urban-rural difference in the GEA-H storyline (IIASA, 2010). Concerning the distribution amongst quintiles, in the GEA-L storyline GINI coefficients converge to the lowest observed (global) value of 2000 in 2030. Conversely, in the GEA-H storyline each region's GINI coefficient to the highest value which is observed in the 2000 global data (Table 2).

Table 2. Value GINI coefficients in 2000 and the value they converge to under both baselines.

		Urban	**Rural**
2000	*India*	36.4	29.8
	China	32.2	36.3
	Pacific Asia	38.7	32.8
	South Africa	53.2	50.5
	Brazil	56.7	52.8
2030	*GEA-L*	28.2	26.4
	GEA-H	63.8	58.7

2.2.2 Climate Policy

We set up an experiment in order to look into the impact of climate policy on emissions as well as the effect of this policy on development goals. Climate policy is represented by a constant carbon tax of 20, 50 and 100 $\$_{2005}/tCO_2$ introduced on fuels. The underlying hypothesis is that by internalizing externalities the cost of dirtier fuels increases; thus becoming less attractive. For industrial users of energy who use commercial fuels and for affluent households, where decisions are more rational, this may be true. However, the effect is less clear when traditional fuels are used as well since they are unlikely to have a tax enforced on them. The experiment is performed on the GEA-M baseline, which assumes business as usual efficiency development and constant economic inequality compared to 2000.

2.2.3 Access Policy

This experiment is conducted in view of the importance of cooking fuels at meeting certain development goals. Poor households primarily cook with solid fuels, and especially traditional biomass, which leads to a number of issues. Often traditional biomass has to be gathered far away form the households and the task is conducted by women and children. This has important ramifications concerning education of children, employment and empowerment of women, safety as well as health issues from carrying heavy loads over long distances. Furthermore, the use of traditional biomass increases indoor air pollution and thus has a detrimental effect on mortality rates. It is also important to consider effects on the environment from the haphazard gathering of biomass. Goals such as gender equality, education, employment, infant mortality and environmental sustainability can all be tackled via providing access to affordable clean fuels (Modi *et al.*, 2005; Gaye, 2007)

Thus we have looked into the possibility of limiting the population dependant on solid fuels and promote more modern energy carriers for cooking. It is attempted to meet this goal via a combination of fuel subsidies and micro financing.

3 Results

In the following sections the results from the baselines and experiments are outlined for each region. Where appropriate, the difference between urban/rural localities and income quintiles are also highlighted. At the end of each subsection some general observations are made in relation to the scope of this paper. Since this paper focuses on development and security issues the results presented focus around energy functions, energy use, emissions and access to clean cooking fuels.

3.1 *Baselines*

All regions are projected to increase their household expenditures by 2030. Thus total energy demand increases but also the energy functions performed diversify. Figure 4 and Figure 5 show the final energy use by end use function in 2007 and in 2030 under the two baselines for each of the studied regions for urban and rural households.

The first functions households meet are cooking and lighting, as these represent the most basic functions; with cooking taking up the lion’s share of the energy needs. This is evident since in all regions in 2007 cooking has the highest energy use. As households get richer appliance energy use and space/water heating gain importance. Space and water heating are the first to grow and it is worth noticing that in China and South Africa, due to climatic conditions, this growth is large. Similar behaviour is witnessed in modern day Northern Europe and North America due to similar climatic conditions. On the other hand, in Brazil, Pacific Asia and India space cooling is important. In this case space cooling is under appliances and thus these regions have increased appliance energy use compared to space heating (only to increase with affluence as the uptake of air conditioners becomes more pronounced). Lighting is always a minor end use function.

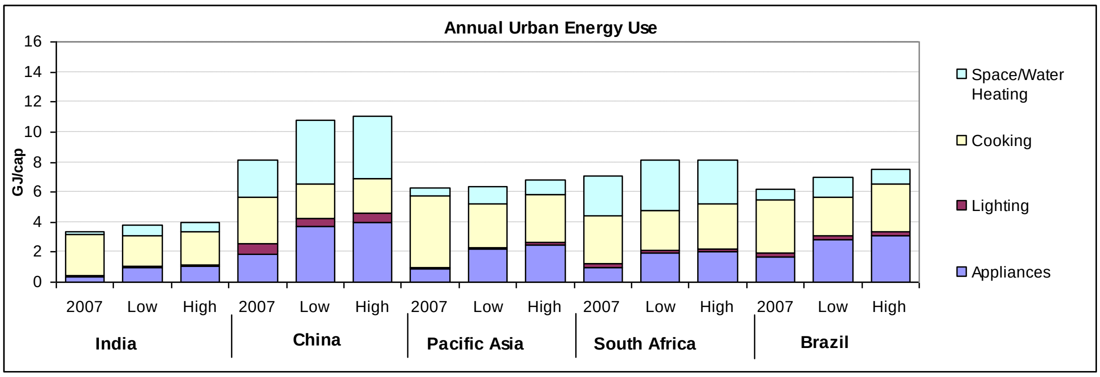

Figure 4. Annual final energy use per capita (GJ_{SE}/cap) by end-use function for the baselines, Urban.

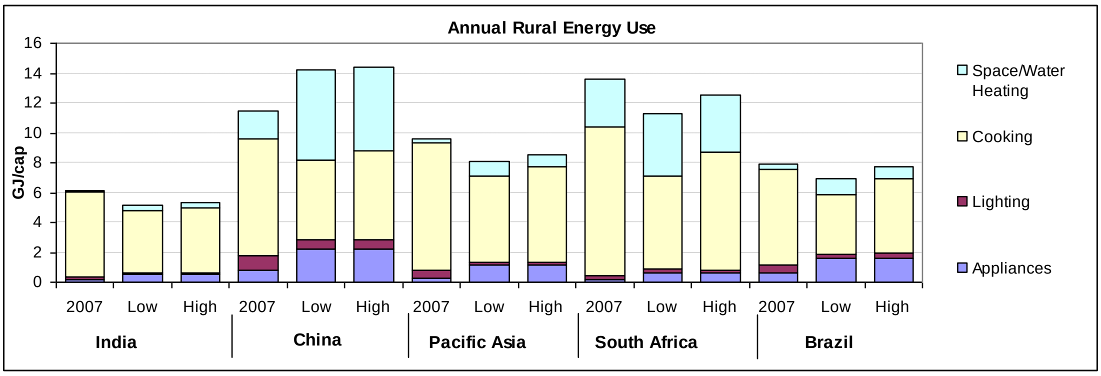

Figure 5. Annual final energy use per capita (GJSE/cap) by end-use function for the baselines, Rural.

As can be seen, under the GEA-H scenario the energy demand for space/water heating and appliances is projected to be less than in the GEA-L case, even though the efficiency is much lower. This arises due to economic inequality where poorer households fail to diversify their energy use. This is demonstrated in Table 3 where under the GEA-H baseline the poorest households dedicate more of their available energy to cooking, while in the richest households cooking accounts for a smaller share compared to GEA-L.

Table 3. Difference in share of cooking as end use function between 2007 and the two baselines. For lowest (U1) and highest (U5) urban quintiles.

	U1			**U5**		
	2007	*GEA-L*	*GEA-H*	*2007*	*GEA-L*	*GEA-H*
India	*0.92*	0.74	0.80	*0.64*	0.34	0.31
China	*0.63*	0.32	0.42	*0.19*	0.11	0.11
Pacific Asia	*0.91*	0.61	0.76	*0.46*	0.24	0.20
South Africa	*0.79*	0.44	0.68	*0.30*	0.24	0.23
Brazil	*0.89*	0.59	0.83	*0.31*	0.22	0.16

The total final energy use per capita (Figure 6 and Figure 7) for the residential sector depends on two aspects 1) To what level the energy functions are being met? 2) At what efficiency are they being met? The efficiency depends on what fuel is being used and how it is used. As indicated, at low income levels cooking dominates the residential energy use. Moreover, this energy demand is met primarily with traditional fuels due to poverty which is only aggravated from inequality. With increasing income levels, it is expected that households will switch towards cleaner fuels which may reduce the total per capita energy consumption; this is clear for rural households except in China (this trend is explained in greater detail in sections 3.1.1 to 3.1.5).

For urban households generally the decrease in per capita energy consumption is absent. This is because urban households are richer than rural ones and so the transition towards modern fuels is less important. Instead energy consumption for other functions increases rapidly. This is seen by the increased use of electricity for appliances and secondary heat (in China) for space heating.

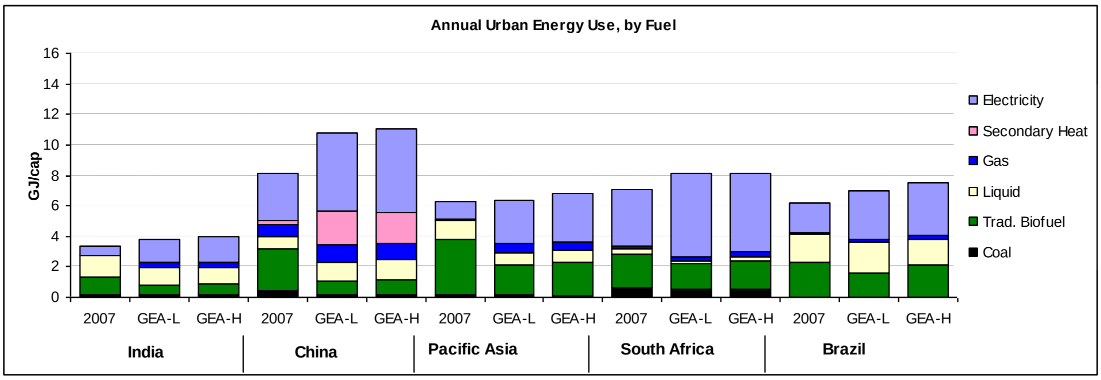

Figure 6. Annual final energy use per capita (GJ_{SE}/cap) by fuel for the baselines, Urban.

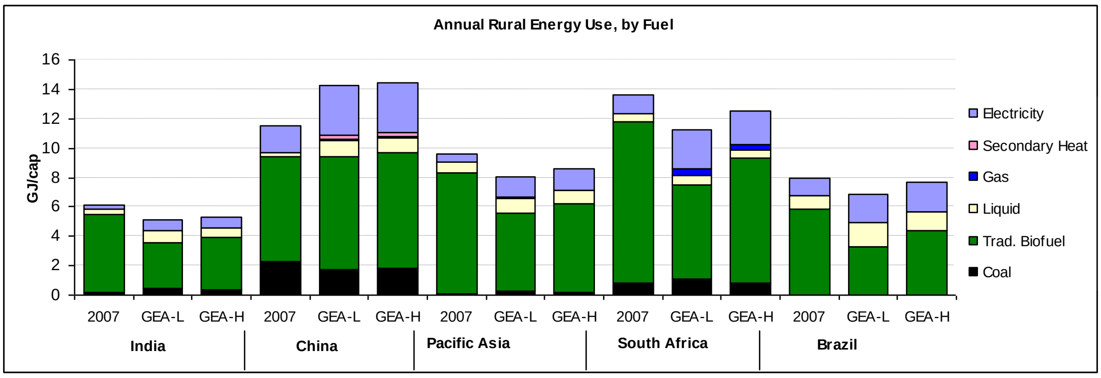

Figure 7. Annual final energy use per capital (GJ_{SE}/cap) by fuel for the baselines, Rural.

Figure 8 and Figure 9 show the difference in emission profiles for urban and rural households respectively with and without emissions from fuel wood. Net fuel wood emissions are ideally zero, but in most cases this fuel is not harvested completely sustainably. In this study it has been assumed that 60% of fuel wood is harvested sustainably (Reddy *et al.*, 2006). Some key observations can be made. Firstly, the GEA-H baseline always has higher emissions and this is expected due to the reduced efficiency and slower rate of fuel switching. Interestingly, the reduction in energy use under the GEA-L baseline does not have an equal reduction in emissions. This is because the relative emission factors between fuels do not differ that much, but more importantly the emission factor of electricity in these regions (except for Brazil) is very high. Thus the adoption of electricity for cooking or heating, electrification leading to electric lighting and the uptake of appliances increases emissions. Thus through fuel switching total energy use falls, but emissions increase if electricity is adopted. Urban persons emit more (when excluding biomass) than rural households due to their higher affluence and thus increased use of energy and electricity in particular.

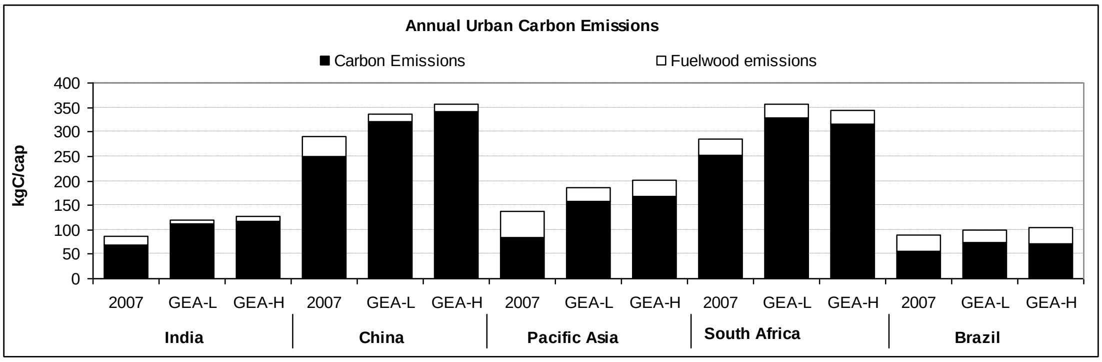

Figure 8. Carbon emissions (including electricity) (kgC/cap), with and without fuelwood,for the baselines. Urban.

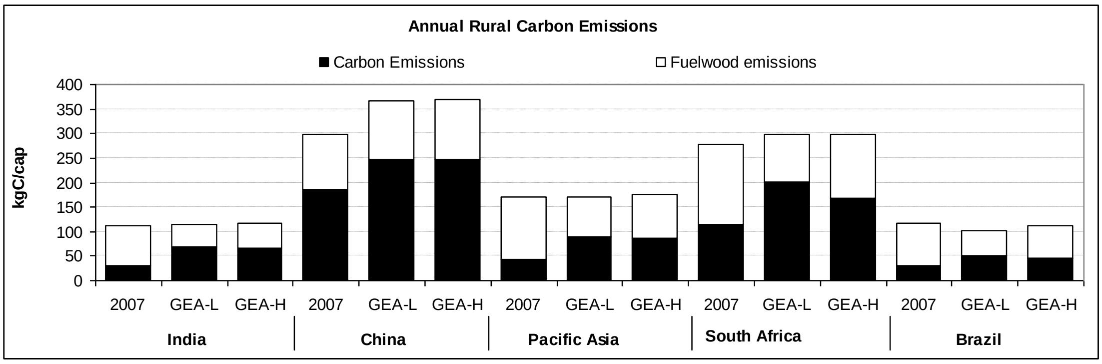

Figure 9. Carbon emissions (including electricity) (kg/C/cap), with and without fuel wood, for the baselines, Rural.

South Africa and Brazil offer an interesting comparison. Both these countries have similar welfare levels (in economic terms) yet different climatic conditions. This leads to heating demand being the main energy function for South African homes while appliance use grows significantly for Brazil. Both regions have similar total final energy use and a similar fuel mix, but yet South African emissions are disproportionately large. The disparity arises due to the very large difference in emission factor for electricity each region has, with the South African value standing at ≈50kg/GJ while the Brazilian value is ≈10 kg/GJ. The difference in emissions between the regions is greater for urban households due to the prevalence of electricity in urban South Africa.

3.1.1 India

Figure 10 shows the urban and rural quintile shares of cooking capital (by fuel) for 2007 and for 2030 under the two baselines. As can be seen Indian households primarily cook with LPG or traditional biomass. In urban households LPG is the most prevalent clean fuel with small amounts of publicly subsidized kerosene as well as electricity being used. For rural households traditional biomass is by far the most widely used fuel with the richest households also using small amounts of LPG. Coal and natural gas are generally not used much.

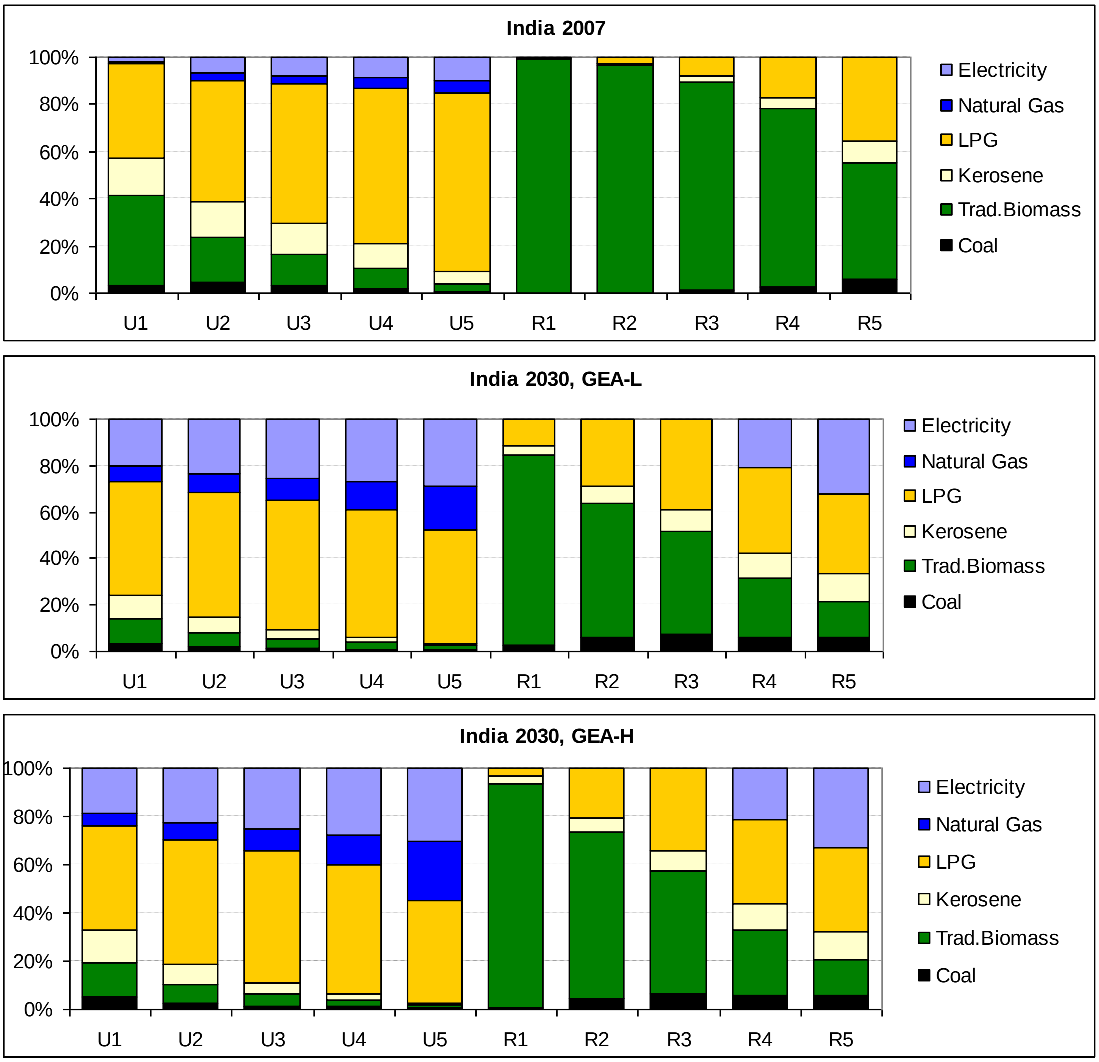

Figure 10. Shares of cooking capital in India in 2007 and in 2030 under GEA-L and GEA-H, Urban/Rural quintiles.

By 2030 LPG remains the dominant clean fuel with significant increases in rural households. For urban households, traditional biomass and to a lesser extent LPG is being replaced by electricity and by a small fraction of natural gas. Natural gas use is limited since India has to import significant fractions of its natural gas making electricity a more secure and thus more attractive fuel. The main difference between the baselines however is the projected divergence of rich and poor households. Under the GEA-H scenario 20% of the U1 households still cook with traditional fuels while under the GEA-L baseline this is only 14%. Meanwhile the richest urban households enjoy a greater penetration of natural gas and electricity and have long ceased using traditional fuels in addition to having moved on to meeting other energy functions as shown earlier. The inequality problem is even more evident in rural households where under the GEA-H baseline in the three lowest quintiles 93%, 73% and 57% respectively cook with traditional fuels. In the same quintiles under the GEA-L baseline 84%, 63% and 51% cook with traditional fuels while the top two quintiles do not vary much between baselines. This illustrates the problems in inequality where the poorest households tend to suffer disproportionately.

The difference between the baselines comes primarily due to differences in household expenditure, which in turn affects the ability for a household to purchase a clean fuel cooking stove. Inequality also limits other factors such as access to education and information relating to the advantages of cleaner fuels which keeps the perceived costs high.

3.1.2 China

In China fuel use is focused on electricity, some natural gas, LPG, traditional biomass and significant quantities of coal, especially in rural households. In our projections electricity gains an advantage. Meanwhile, natural gas gets marginalised since it is predicted in TIMER runs that China is going to become a major importer of natural gas in the first half of the century; meaning that electricity becomes more attractive. Due to China's abundance of coal, rural households continue to use it in both baselines. As with India, there is a higher penetration of cleaner fuels under the GEA-L baseline. Under the GEA-L baseline 8% of urban and 53% of rural households still cook with traditional fuels by 2030. Under the GEA-H baseline the numbers are 9% and 60% respectively.

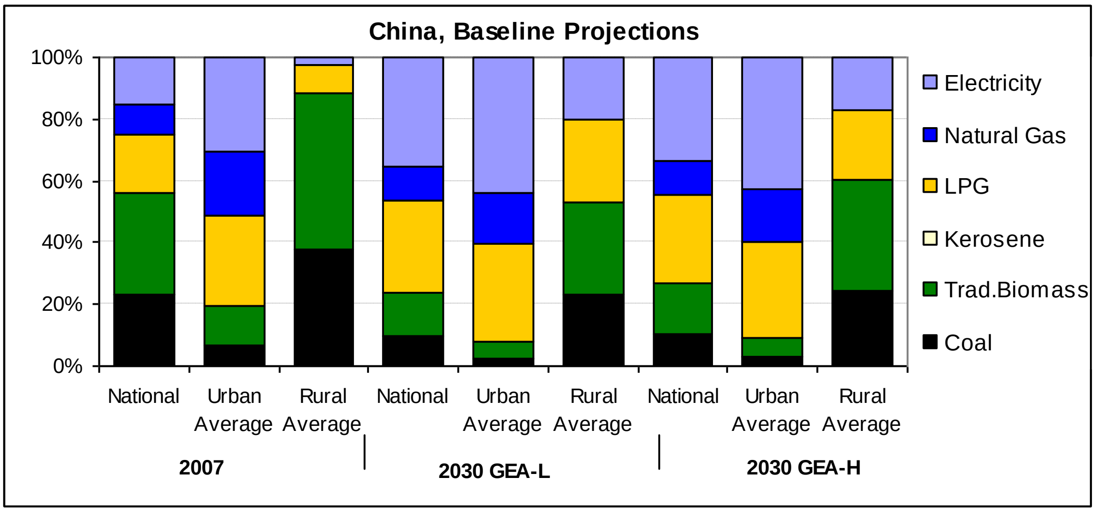

Figure 11. Shares of cooking capital in Total, Urban and Rural China in 2007 and under the two baselines.

3.1.3 Pacific Asia

In 2007, the major household fuel for this region is traditional biomass together with LPG while electricity, natural gas and coal are barely used. By 2030 urban households show an increased use of electricity and natural gas according to the model. For rural households LPG is the main clean cooking fuel as electricity penetration is limited due to low electrification rates. Under the GEA-L baseline 13% of urban and 45% of rural households still cook with traditional fuels by 2030. Under the GEA-H baseline the numbers are 16% and 51% respectively.

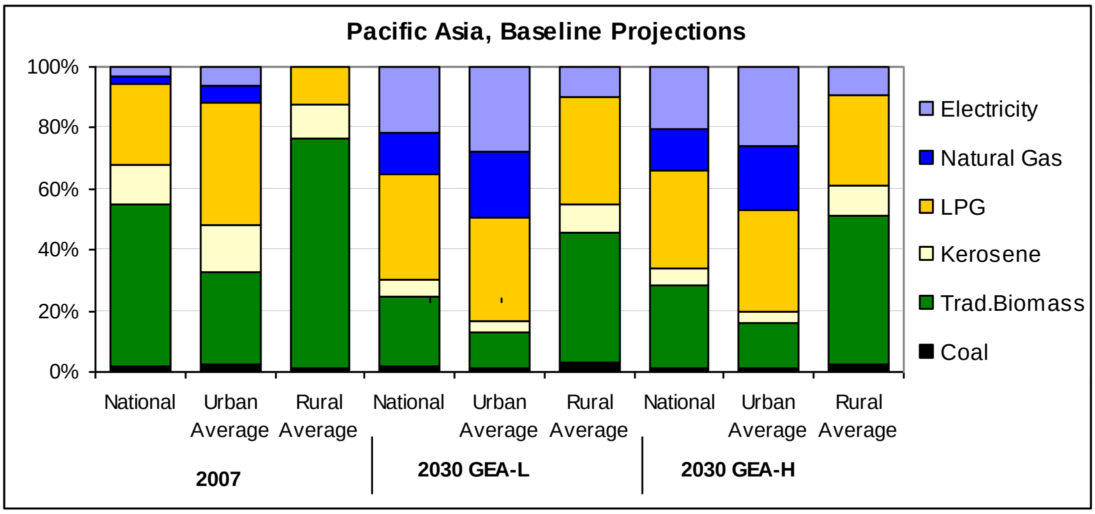

Figure 12. Shares of cooking capital in Total, Urban and Rural Pacific Asia in 2007 and under the two baselines.

3.1.4 South Africa

South Africa relies heavily on electricity for both its cooking and heating needs; this is true also for poor households to some extent. Other fuels used include natural gas, kerosene, traditional biomass and coal. By 2030 it is projected that electricity retains its dominant status while natural gas also increases its share while kerosene, traditional biomass and coal get increasingly marginalised. Under the GEA-L baseline 5% of urban and 35% of rural households are predicted to still cook with traditional fuels by 2030. Under the GEA-H baseline the numbers are 8% and 48% respectively.

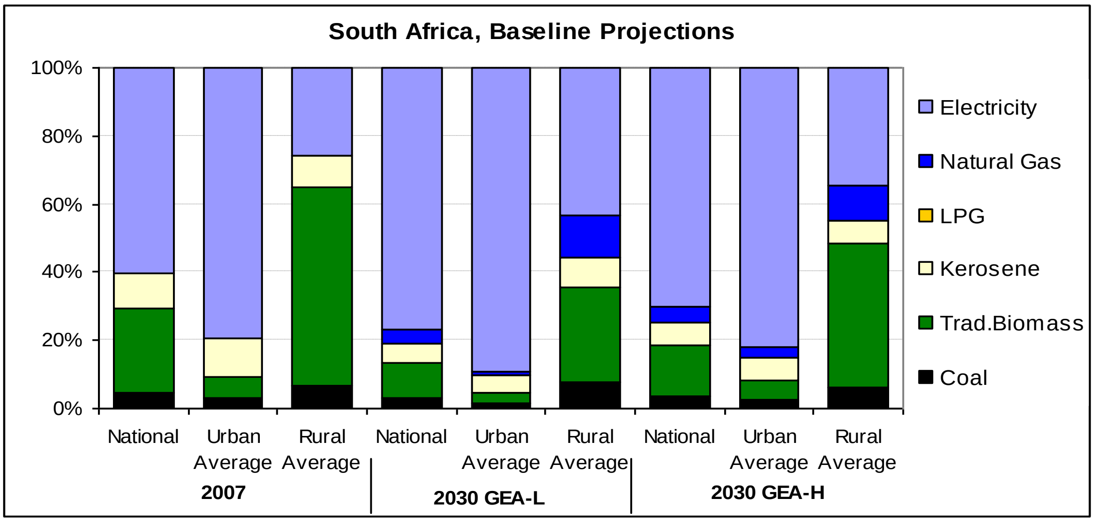

Figure 13. Shares of cooking capital in Total, Urban, and Rural South Africa in 2007 and under the two baselines.

3.1.5 Brazil

In Brazil, fuels used in the residential sector are limited to traditional biomass and heavily subsidised LPG which has significant urban and rural penetration. Coal and electricity are not widely used for cooking purposes. Brazil has a low rural population which explains why the national average is very close to the urban values. Under the baseline scenarios LPG retains its position as the dominant fuel with minor increases in electricity and natural gas. It should be noted that in post-2030 projections natural gas becomes the most significant fuel as Brazil starts to increasingly exploit its natural gas reserves. Electricity is limited to rural households due to low electrification rates. Under the GEA-L baseline 8% of urban and 26% of rural households still cook with traditional fuels by 2030. Under the GEA-H baseline the numbers are 15% and 37% respectively.

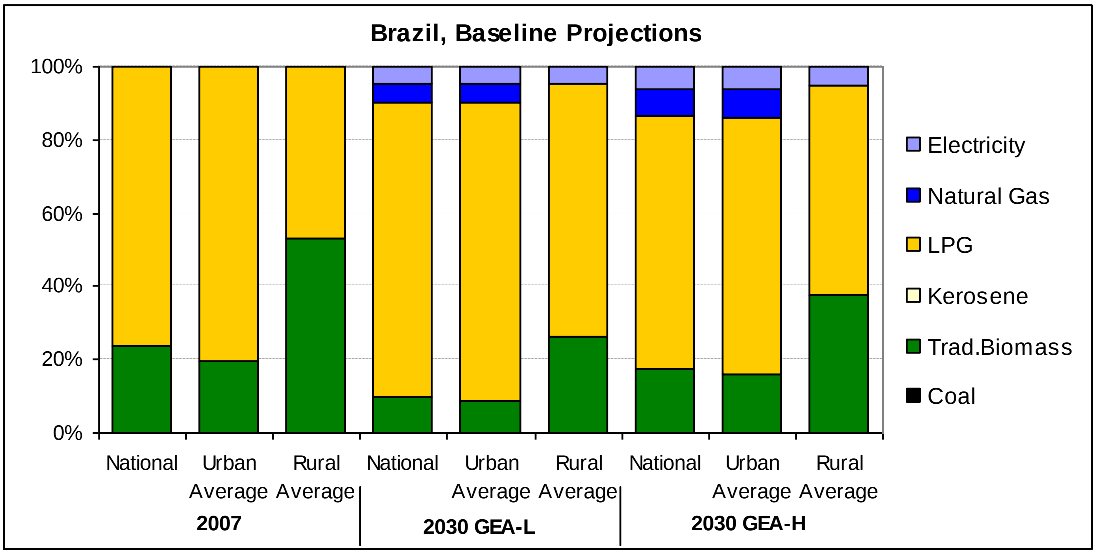

Figure 14. Shares of cooking capital in Total, Urban and Rural Brazil in 2007 and under the two baselines.

3.1.6 Observations on Baseline Projections

The cornerstone of this analysis was that as households get richer their energy use increases. This energy increase is due to the diversification of the use of energy within the household and greater satisfaction of these energy needs. The first energy functions to be met are the cheapest and those required for survival: lighting and cooking. As households get richer heating and the use of basic appliances such as refrigerators and televisions become more important. As affluence increases, appliance use further grows and cooling demand also becomes important.

These trends however also differ between regions for a number of reasons. The amount of energy required for heating and cooling does not only depend on affluence but also on climatic conditions. Very big differences in final energy use are witnessed between regions because of this; as households become richer the main energy function to be met either becomes space/water heating for cold climates, or appliances for warm climates. As countries continue to grow in affluence, air conditioning also becomes an important end-use function. Concerning appliances, behavioural and market conditions are very important. Data shows that China has a very high penetration rate of basic appliances (refrigerators, television) for their household expenditures compared to all other world regions.

To put things into perspective, while it can be seen that for the studied regions energy consumption per capita in 2030 ranges from 4 to 14 $GJ_{SE/cap}$,, for households in Western Europe of the USA have values around 45GJ_{SE}/cap with at least half of this demand coming from space and water heating. Interestingly western regions are not predicted to change much in the studied time frame.

Inequality also plays an important role for the fulfilment of energy functions in a societal context. As demonstrated in section 3.1, increased inequality not only increases the difference of energy function satisfaction between the rich and the poor, but also the energy carriers they use in order to meet these functions. Thus while rich households go on to meet other less basic energy functions from cooking such as heating with modern fuels, the poorest households only meet the basic functions and are forced to use solid fuels. Initial inequality is also important, since it can be seen that for South Africa and Brazil there is a very large difference between the GEA-L and GEA-H baselines concerning fuel use. This is due to their very high initial levels of inequality in 2000 (Table 2).

Efficiency also has a small effect when it comes to fuel switching since a more efficient stove requires less fuel and thus lower fuel costs. Efficiency plays a more important role in energy security and climate. Inefficient use of energy means that more of it has to be supplied, and this supply has to be secure in order to ensure price stability. Inefficient use of energy also means that the emissions increase.

From the above observations in can be inferred that the GEA-L baseline is the most attractive. Due to its more equal distribution of wealth, a greater number of households can meet their energy needs. Furthermore, due to the increased efficiency these energy needs are met at with reduced final energy demand, however, emissions are greater due to increased use of electricity. Thus the importance of providing clean electricity is highlighted. Further insight on this is provided in the first experiment conducted, described in the next section.

3.2 *Climate Policy*

The first policy experiment which we performed was to impose a carbon tax on the commercial fuels, but not traditional fuels. Carbon taxes of 20, 50 and 100 $\$_{2005}/tCO_2$ are imposed on the fuels and the ensuing fuel prices and emission factor of electricity are determined from TIMER runs. Subsequently, under higher carbon taxes the TIMER model projects that the emission factor of electricity decreases.

The experiment is performed to see the effect of climate policy on development and climate aspects of residential energy use in developing countries. Thus, we ask the following questions: 1) Does a carbon tax promote fuel switching to cleaner fuels? 2) How does it affect the population reliant on solid fuels for cooking? 3) Do the overall emissions fall as planned? The carbon tax is imposed upon the GEA-M baseline (business as usual efficiency improvements and constant inequality compared to 2000). The indicators used are the shares of each fuel in final energy mix, the percentage of population cooking with solid fuels and the carbon emissions per capita.

It is important to note that in the figures below which show fuel shares (Figure 15, Figure 18, Figure 21, Figure 24 and Figure 27) traditional biomass has been omitted. This is in order to indicate how the share of **taxed fuels** changes due to climate policy. In every case the share of traditional biomass increases.

3.2.1 India

After the introduction of the carbon tax, the shares of modern fuels in total final energy use (all end use functions) are shown in Figure 15. Natural gas and electricity shares grow marginally (less than 2%) at the expense of liquid fuels, and coal. The effect is more pronounced in rural households where the use of coal decreases significantly from the baseline under all three tax schemes with subsequent increase in liquid fuels and electricity.

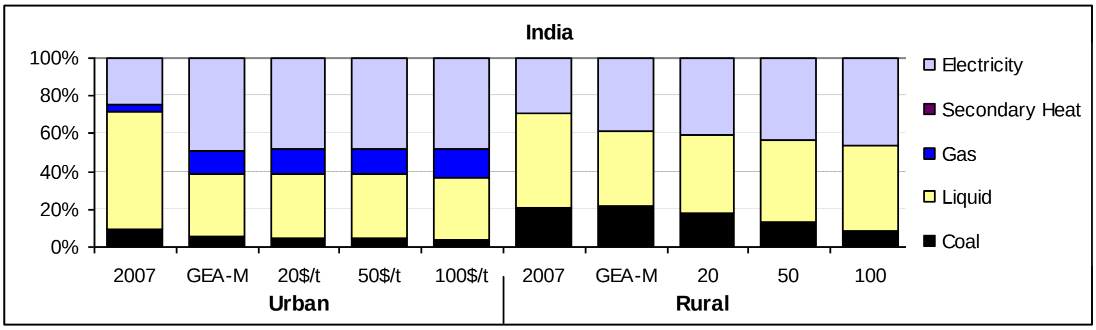

Figure 15. Shares of fuels in final energy use for 2007, 2030 baseline and 20, 50 and 100$/tCO2 tax in India. Urban/Rural. Fuel wood excluded.

Since traditional biomass is not taxed it becomes cheaper than all other fuels and thus increases its share compared to the baseline scenario. For the urban population, under the baseline traditional biomass accounts for 16.2% of final energy use, compared to 31.9% in 2007. Under the 20, 50 and 100$/tCO$_2$ this share increases to 17.8%, 20% and 22.7% respectively. This lack in fuel switching also means that the population reliant on solid fuels is also greater than the baseline. Figure 16 shows the fraction of population cooking with solid fuels. It is evident that between 2007 and 2030 under all cases this fraction reduces.

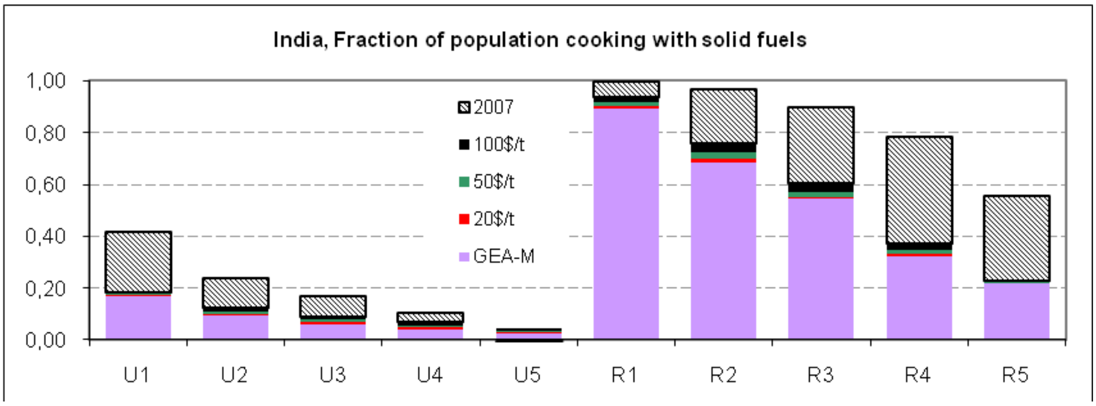

Figure 16. Fraction of population cooking with solid fuels for 2007, 2030 baseline and 20, 50 and 100$/tCO2 tax in India. Urban/Rural quintiles.

The absolute reduction is, however, hampered by climate policy and more stringent policy only serves to aggravate this problem. It is also evident that this effect is different between income classes. For R5 (richest rural quintile) under the baseline the projected population dependant on solid fuels stands at 21.4%. When applying the 100$$_{2005}$/tCO$_2$ tax scheme, the increase is only to 22.6%, while for R4 the numbers are 36.9% compared to a baseline of 32%. For R3 the increase is to 60.1% (54.1% baseline). For R2 it is to 75.9% from 68.1% baseline and for R1 it is 93.3% (89.2%

baseline). Thus it can be seen that the lower quintiles suffer the most. For the urban population the effect is smaller because these households are better off and have already switched fuels to a significant degree. Thus this scheme is most injurious for the population classes which are struggling to switch fuels.

The emissions per capita and per fuel are shown in Figure 17. As explained in section 3.1, between 2007 and 2030 under baseline that total emissions increase due to increased energy demand and especially demand for electricity which is heavily polluting. As can be seen, the reduction in emissions under the tax schemes is attributed to the reduction in emissions from electricity, with emissions from liquid fuels remaining constant while emissions from gas and biomass increase slightly. The effect of electricity decarbonisation is most pronounced in urban households who use significant quantities of electricity. The overall emissions under the most stringent scheme are below those of 2007. This highlights the importance of decarbonisation of electricity.

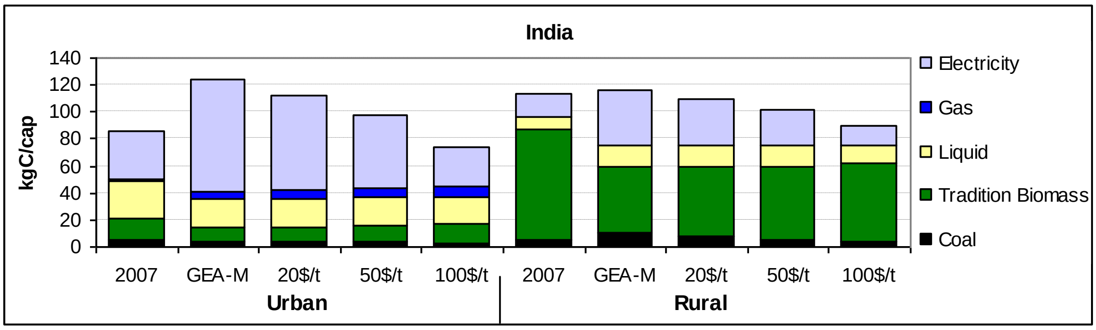

Figure 17. Emission (kgC/cap) for 2007 and 2030 baseline and 20, 50 and 100$/tCO2 tax in India. Urban/Rural.

3.2.2 China

As shown in Figure 18, the carbon tax limits the use of coal while promoting electricity, liquid fuels and gas. The effect is more pronounced in rural households where significant quantities of coal are being used.

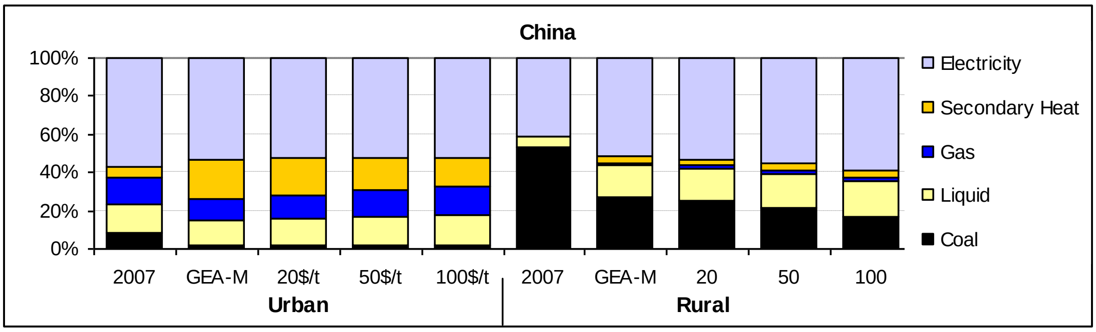

Figure 18. Shares of fuels in final energy use for 2007, 2030 baseline and 20, 50 and 100$/tCO2 tax in China. Urban/Rural. Fuel wood excluded.

Concerning the population relying on solid fuels for their cooking needs, unlike India, urban households are affected more here. This is due to the heavy reliance of rural Chinese households on coal (also considered a solid fuel) even under the baseline case and thus the switch from coal to biomass is not shown here.

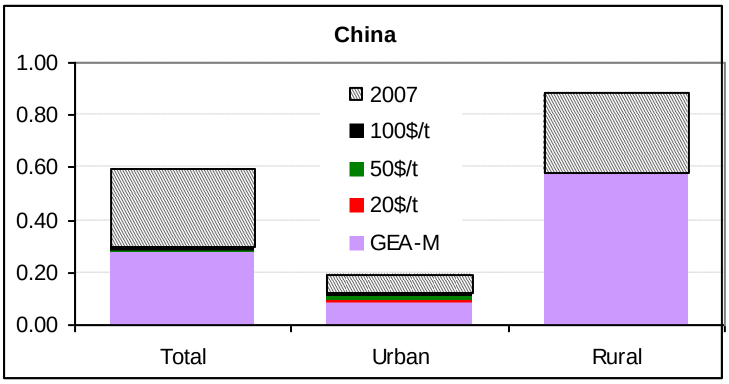

Figure 19. Fraction of population cooking with solid fuels for 2007, 2030 baseline and 20, 50 and 100$/tCO2 tax in China. Urban/Rural.

This switch from coal to traditional biomass is evident from the increase in emissions from traditional biomass and subsequent decrease in emissions from coal for rural households as shown in Figure 20. As expected, decarbonisation of electricity supply under high tax schemes reduces the overall emissions.

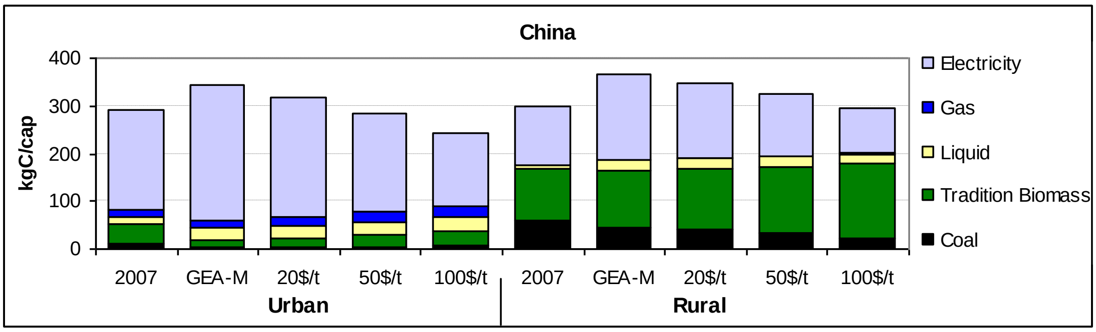

Figure 20. Emission (kgC/cap) for 2007 and 2030 baseline and 20, 50 and 100$/tCO2 tax in China. Urban/Rural.

3.2.3 Pacific Asia

This region replaces coal with electricity and liquid fuels under the tax scheme. However the overall effect for both urban and rural households is minor.

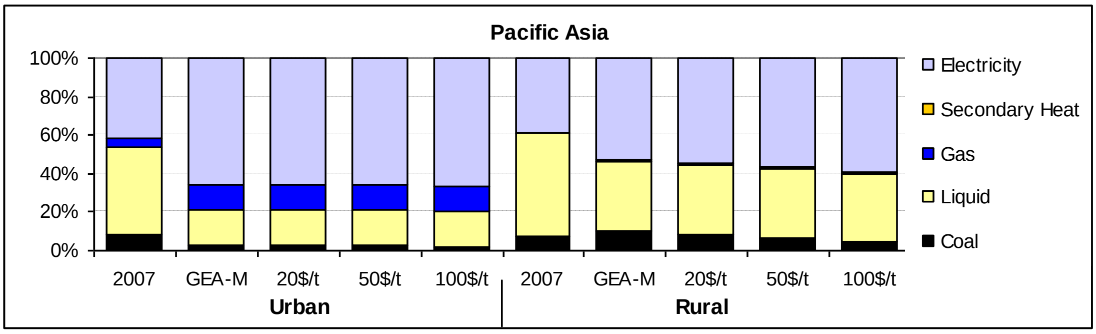

Figure 21. Shares of fuels in final energy use for 2007, 2030 baseline and 20, 50 and 100$/tCO2 tax in Pacific Asia. Urban/Rural. Fuel wood excluded.

The 20, 50 and 100$/tCO$_2$ tax schemes increase the percentage of urban population dependant on solid fuels for cooking to 15.5%, 16.5%, 18% compared to the baseline figure of 14.8% and 51.9%, 53.8% and 57% compared to the baseline figure of 50.6% for rural populations.

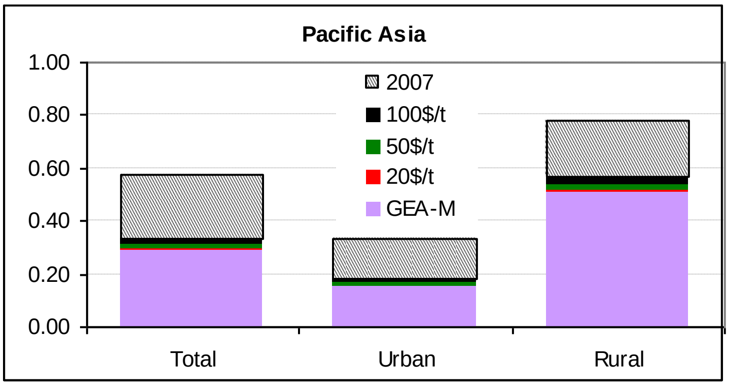

Figure 22. Fraction of population cooking with solid fuels for 2007, 2030 baseline and 20, 50 and 100$/tCO2 tax in Pacific Asia. Urban/Rural.

Concerning emissions, the reduction in overall emissions is greater for urban households which use significant quantities of electricity. Once again emissions from biomass increase with the progressive taxing.

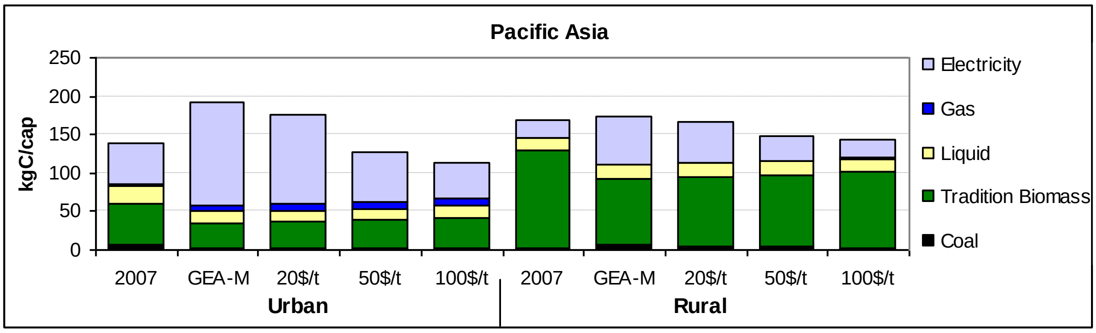

Figure 23. Emission (kgC/cap) for 2007 and 2030 baseline and 20, 50 and 100$/tCO2 tax in Pacific Asia. Urban/Rural.

3.2.4 South Africa

South Africa uses significant quantities of coal and very high levels of electricity, especially for urban households (see Figure 6). Also under the baseline its electricity supply is notoriously dirty compared to the other regions. Because of its extremely dirty electricity supply, the shares of liquid and gaseous fuels increase.

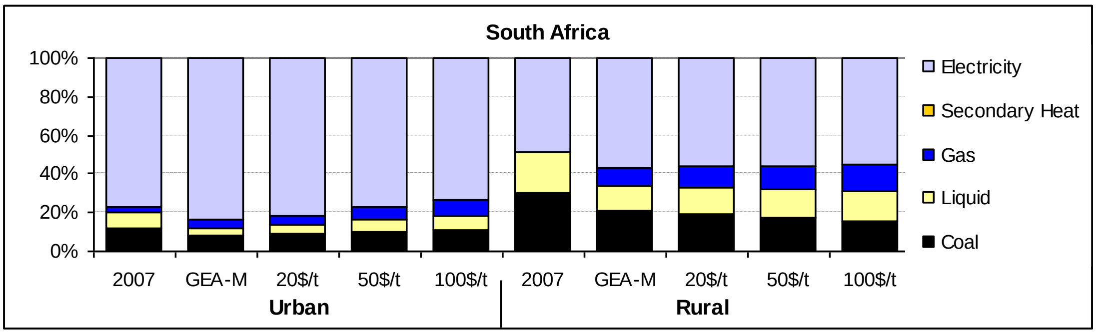

Figure 24. Shares of fuels in final energy use for 2007, 2030 baseline and 20, 50 and 100$/tCO2 tax in South Africa. Urban/Rural. Fuel wood excluded.

For urban households, the tax schemes force the share of urban population reliant on solid fuels (coal) to increase above the 2007 level which is 7%. This is due to the unique properties of urban South Africa where use of electricity is very high as it is the main fuel of choice for all functions, but is also very dirty. The model shows that for rural populations the use of solid fuels increases to 48.3%, 50.2% and 53.2% compared to the baseline of 46.9% for 20, 50 and 100$/t$CO_2$ respectively.

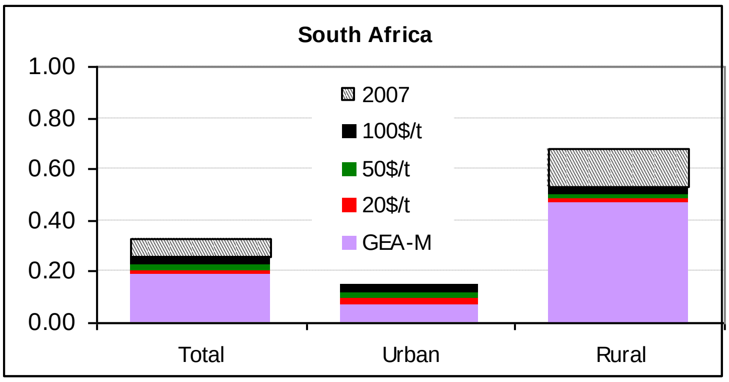

Figure 25. Fraction of population cooking with solid fuels for 2007, 2030 baseline and 20, 50 and 100$/tCO2 tax in South Africa. Urban/Rural.

As expected the majority of emissions in this region are due to the use of electricity. For both urban and rural households the progressive tax scheme increases emissions from traditional biomass and coal due to fuel switching down the energy ladder, but overall emissions decrease due to the decarbonisation of the electricity supply.

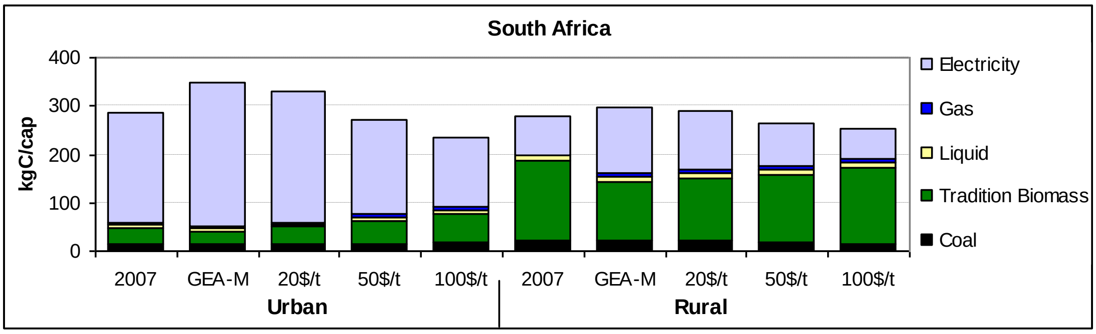

Figure 26. Emission (kgC/cap) for 2007 and 2030 baseline and 20, 50 and 100$/tCO2 tax in South Africa. Urban/Rural.

3.2.5 Brazil

Unlike South Africa, Brazil has a clean supply of electricity and no use of coal. Thus climate policy here promotes the use of natural gas and electricity while reducing the very high reliance on liquid fuels.

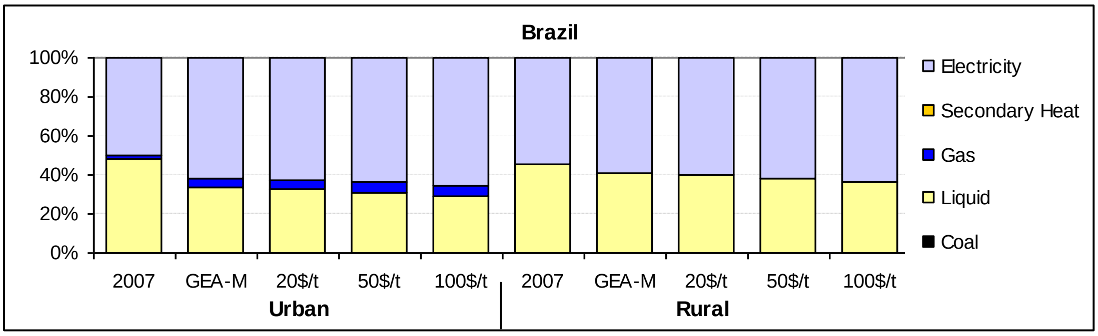

Figure 27. Shares of fuels in final energy use for 2007, 2030 baseline and 20, 50 and 100$/tCO2 tax in Brazil. Urban/Rural. Fuel wood excluded.

Even though electricity is clean here, due to the high use of liquid fuels, the carbon tax forces the poorest household to move down the energy ladder. Thus it is projected that in urban households 15.2%, 16.8% and 19.3% of the population are forced to rely on solid fuels as the carbon tax increases compared to the baseline value of 14%. This results in the same figure as in 2007 under the 100$/$CO_s$ scheme. For rural households the increase is to 37.9%, 40.4% and 44.1% compared to the baseline 36.1% as the tax increases.

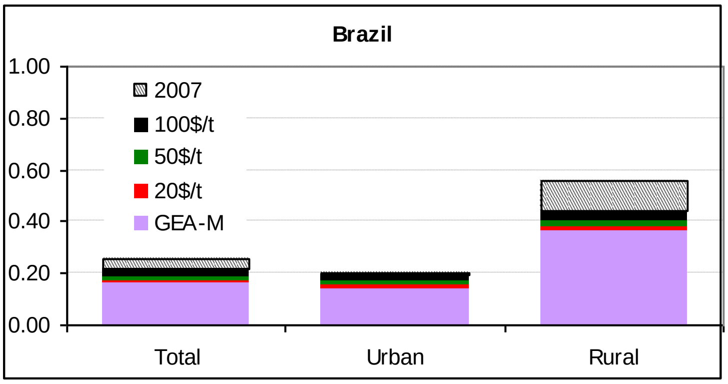

Figure 28. Fraction of population cooking with solid fuels for 2007, 2030 baseline and 20, 50 and 100$/tCO2 tax in Brazil. Urban/Rural.

Due to switching from liquid fuels to traditional biomass, the emissions from liquids decrease while those from biomass increase. Also the emissions from electricity decrease to negligible levels due to further decarbonisation.

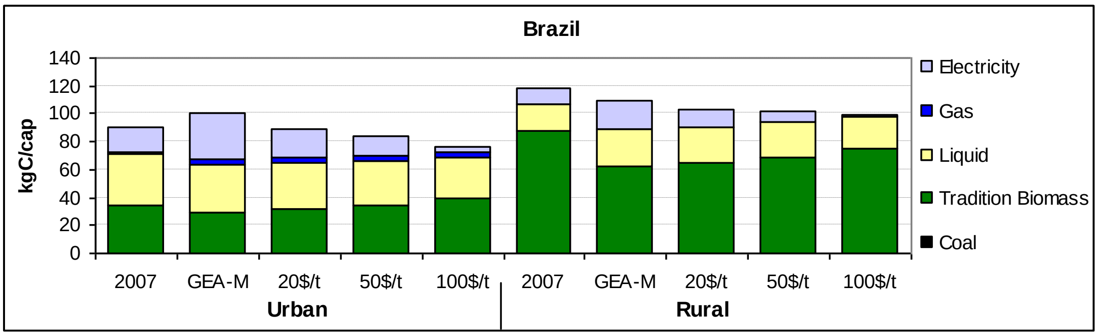

Figure 29. Emission (kgC/cap) for 2007 and 2030 baseline and 20, 50 and 100$/tCO2 tax in Brazil. Urban/Rural.

3.2.6 Overall Effects of Climate Policy

The motivation for a carbon tax is that cleaner fuels become more attractive and thus users turn away from dirty fuels. This is also reflected from the emission factor of electricity which decreases significantly with the higher taxes. However a side effect is that all fuels get more expensive compared to traditional biomass, and only amongst commercial fuels do the cleaner ones get relatively cheaper. A critical aspect here is the importance of perceived costs. In this experiment it is assumed that evolution of the perceived costs does not change compared to the baseline since within the storyline no actions concerning information or increased accessibility are taken. Thus, severe changes in fuel prices are required in order to promote fuel switching.

The taxing of commercial fuels does give rise to a potential perverse side effect. For those households which still depend on traditional biomass fuel switching towards modern fuels is delayed due to increased costs of modern fuels. This leads to projections where fuel switching is limited between taxed fuels, and there is significant movement towards traditional biomass amongst the poorest households. For the richest households there is some movement towards cleaner fuels, but this movement is limited. In the South African case, climate policy acts in such a way that (under stringent policy) the percentage of population dependant on solid fuels in 2030 is greater than that in 2007. Another interesting observation in South Africa is that the electricity supply is so carbon intensive that the use of coal in households seems to increase (Figure 24). However this is because traditional biomass is not included; the absolute use of coal in fact decreases.

From a climate perspective, the carbon tax does perform well. However, for the residential sector, this is not due to fuel switching. In fact, due to the reduced adoption of modern fuel from biomass users, the emissions from biomass increase, but as already noted this depends on the sustainability of biomass harvest.

Concerning appliances, a higher price in electricity may lead to the purchase of more energy efficient units. Historically the energy intensity of large household appliances (refrigerators, washing machines, dish washers and clothes dryers) has decreased autonomously (Consumentenbond, 1964-2008; Schiellerup, 2001; Dale *et al.*, 2002; Laitner *et al.*, 2004; EES, 2006; Weiss *et al.*, 2008; CEC, 2009). However this decrease tends towards a limiting value and furthermore the data shows that the difference between the most and least efficient appliances constantly falls. Thus with the passage of time as appliance marginal unit energy consumption (UEC) approaches a minimum, the effect of the cost of electricity reduces as the cost for marginal improvements rises. Due to delays in stock turnover the effect by 2030 is even more suppressed. Thus the total effect of climate policy on appliance UEC on an aggregate level is minimal.

Despite all this, climate policy does meet its overall goal since total emissions under strict climate policy do fall significantly. Yet this is not due to behavioural changes in the residential sector brought on by economic incentives, but rather an effect of the de-carbonization of the electricity supply. Similar conclusions have been made for the buildings sector of developed countries (Kyle *et al.*, 2010). This conclusion also reinforces the hypothesis that regulation rather than economic incentives are more effective at reducing energy use in the residential sector (Hui, 2000; Iwaro *et al.*, 2010). Studies have shown that climate policy aimed at reducing carbon intensity often gives many co-benefits (He *et al.*, 2010). However, we have shown that problems may arise as well.

3.3 *Access to Clean Cooking Fuels*

In this experiment we applied fuel subsidies in order to promote fuel switching. Furthermore the effect of micro financing is studied by reducing the consumer discount rate which acts as a significant barrier to poor households.

Data concerning the level of fuel subsidies as a percentage of fuel price is scarce and with the little data available it seems that these subsidies hover around 50% (Jannuzzi *et al.*, 2004; Indiastat.com, 2007). It is generally accepted that offering blanket subsidies to the population with the aim of promoting fuel switching is wasteful and leads to inefficient use, smuggling and ‘freeriders’; thus direct financial assistance to poor families is more efficient and cost effective (IEA, 2010).

With this in mind, the subsidies introduced in this experiment are aimed at reducing the urban and rural average use of solid fuels for cooking to 10%. If these population classes to not meet this goal by 2030 under the baselines, subsidies are provided to the quintiles which pull down the average; in this sense a targeted subsidy scheme is adopted in order to avoid free riders. The subsidies are given to the cheapest (annualized capital and fuel costs) clean fuel for each region. In rural households subsidies for natural gas are not given since vast network expansion would be necessary to provide natural gas to rural areas. Fuel subsidies are phased out as the goal is approached so that other clean fuels can also become competitive.

Furthermore, as already mentioned the high consumer discount rates that low-income households have pose a significant barrier towards fuel switching. It has been proposed that in order to alleviate this problem, micro-financial institutions can provide loans to the poor in developing countries at more attractive interest rates than are otherwise available to them (Robinson, 1996). This has been implemented in this experiment by setting the consumer discount rate for subsidized fuels at 10% irrespective of household expenditures

It is implicitly assumed that when subsidies are given, an active effort is made to improve the accessibility towards these fuels. Furthermore in order to overcome cultural and educational issues an information campaign is waged highlighting the benefits of cleaner fuels. This ensures that fuel choices are made on a purely economic basis and thus the perceived costs are eliminated. Furthermore it is implicit that at least 90% electrification rate by 2030 is available for all income quintiles.

The 2030 results of the access scenarios compared to 2007 and the baselines are highlighted in sections 3.3.1 to 3.3.5. The results presented include the percentage of population relying on solid fuels, the annual per capita final energy use, the annual per capita carbon emissions, the cumulative subsidies and the subsidy effectiveness. These measures have been chosen in order to see the effect the subsidy scheme has on a number of fronts.

The subsidy effectiveness is a measure of how successful the subsidy is at making people switch towards clean cooking fuels by 2030 and is measured in ‘dollars per (fuel)switched-person-years’. It is calculated according to Equation 10.

$$Eff_{p,2030} = \frac{\sum_{t}^{2030} ASub}{\sum_{t}^{2030}\left[\left(PTrad_{(t-1)} - PTrad_{(t)}\right)\times(2030-t)\right]_{Access} - \sum_{t}^{2030}\left[\left(PTrad_{(t-1)} - PTrad_{(t)}\right)\times(2030-t)\right]_{Baseline}}$$

Equation 10

Where:
$2015 \le t \le 2030$
Eff = Effectiveness ($\$_{2005}$/person-switch.year)
$ASub$ = The annual subsidies given
$PTrad$ = Persons using traditional fuels for cooking, per year per demographic

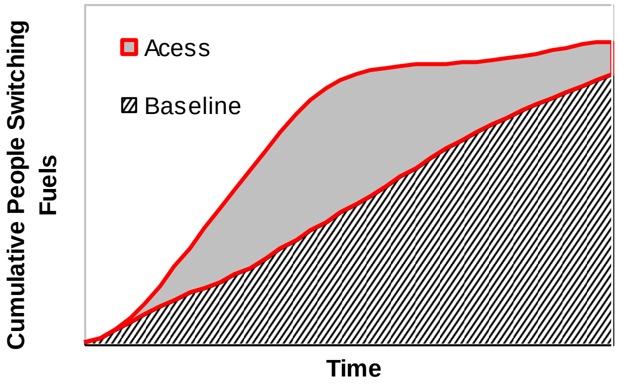

Figure 30. Difference between cumulative people switching fuels between Access and Baseline storylines.

The measure we use has been specifically designed in order to determine how good a subsidy is at promoting clean cooking fuels with the evaluation date being 2030. The annual subsidies are determined through the annual use of the particular fuel. The denominator determines the switched person years and the second term of the denominator corrects for people switching fuels under the baseline. Thus the effectiveness accounts only for the grey area in Figure 30. This measure assumes that once a household switched to a clean fuel, it does not switch back to solid fuels under any circumstances. According to Equation 10 the following effects are considered subsidy failures:

- Moving from clean fuels towards the subsidised fuel.
- Use of subsidy from households already using the subsidised fuel or those who would have switched anyway before 2030 but after 2015 (freeriders).
- Using the subsidised fuel for heating.

There is an inconvenient consequence of the last point. The purpose of the subsidy is to promote cleaner cooking since cooking has been identified as the main end use function of poor households as well as the main focus of the MDG's (Modi *et al.*, 2005). Yet there is nothing stopping households from using subsidised fuels for heating. Strictly speaking this is not a problem since the use of clean fuels for heating is important as well, but as far as the effectiveness is concerned, it has a confusing effect.

It is important to note the difference between access rate and percentage of population using solid fuel. Even though the access rate (on a household level) to modern fuels may be 90%, the percentage of population using modern fuels will be slightly lower since poorer households, which are dependent on traditional fuels, tend to be larger.

3.3.1 India

Indian households are given a 50% subsidy on LPG price. Under the GEA-L baseline only the lowest urban quintile does not meet the objective but since the urban average has an overall population depending on solid fuels less than 10%, no subsidies are given to urban households. None of the rural quintiles are predicted to meet the goal (Figure 10) and thus get complete access to subsidies and micro-financing services. Under the GEA-H baseline the two lowest urban quintiles and all the rural quintiles fail to meet the goal. Yet once again the urban average has met the goal (8% relying on solid fuels) and so again only rural households have access to the subsidies.

Figure 31 (top panel) shows the breakdown of cooking capital used per quintile under the GEA-L in 2030 with financial aid. The 10% goal is reached by rural households in 2047. A comparison with Figure 10 (middle panel) shows that the situation is much better (especially for rural houses all of which enjoy the subsidy scheme), however it can also be seen that the use of electricity and kerosene has been reduced when compared to the baseline. This in effect is a loss of the subsidy since households already cooking with clean fuels, or which would have switched anyway, take advantage of the subsidized LPG.

For the GEA-H case, urban households again reach the goal in 2024 while for rural households only 24% of the population still depend on solid fuels in 2030 and 11% do so in 2050. This still is a substantial increase compared to the 84% in 2007 and 55% in 2030 under the GEA-H baseline. The improvement can be seen by comparing Figure 31 (bottom panel) with Figure 10 (bottom panel). As with the GEA-L case electricity loses part of its share.

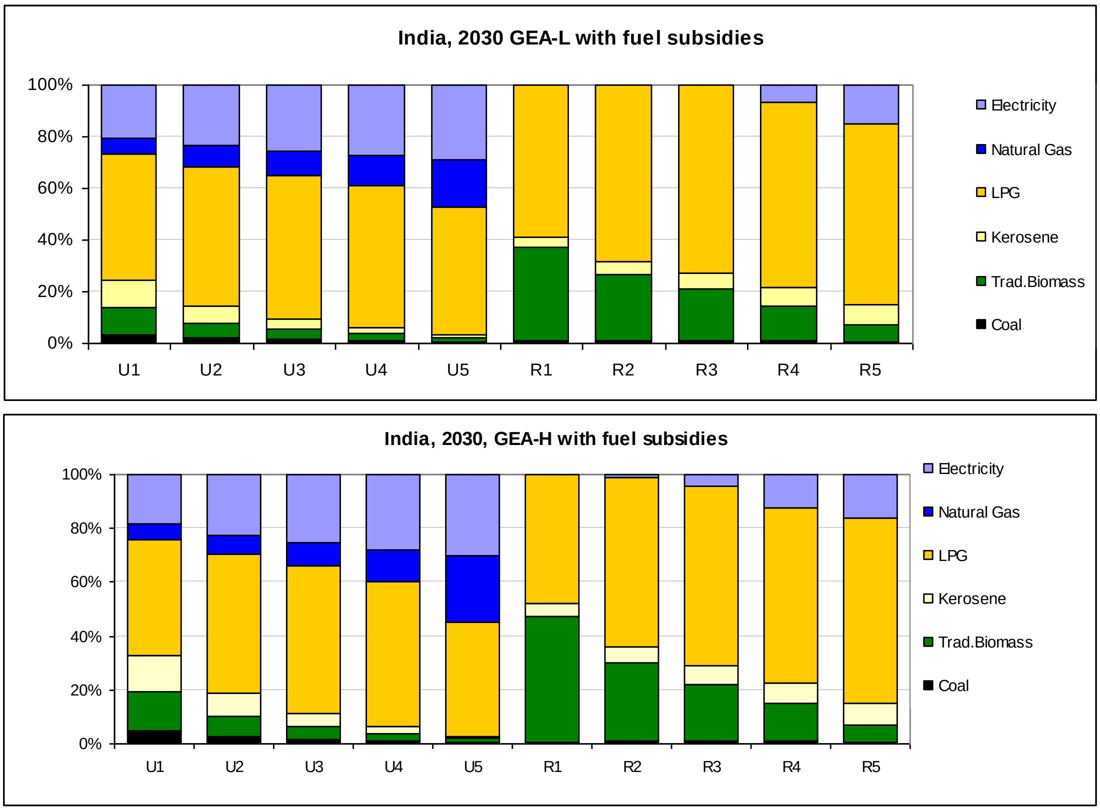

Figure 31. Shares of cooking capital in 2030 under GEA-L and GEA-H with 50% fuel subsidies and micro financing.

Table 4 and Table 5 summarize the projected values for India under the baseline and access scenarios and thus give a good overall view of the results of the storylines. Obviously there is no difference for urban households between the baselines and the access scenarios since these households do not gain from any subsidy scheme.

Table 4. Summary of results for 2007, baseline and access scenarios in 2030, GEA-L.

	2007		GEA-L		GEA-L access	
	Urban	**Rural**	**Urban**	**Rural**	**Urban**	**Rural**
% Population using solid fuels	19	84	7	50	7	21
Annual Energy Use (GJ$_{SE}$/cap)	3.3	6.1	3.8	5.1	3.8	3.7
Annual Emissions (kgC/cap)[2]	69.6 (86.0)	30.3 (113.3)	111.1 (120.8)	68.7 (115.4)	111.1 (120.8)	65.9 (88.7)
Cumulative Subsidies (Billion $$_{2005}$)	N/A	N/A	N/A	N/A	0	73.45
Subsidy Effectiveness ($$_{2005}$/person-switch.year)	N/A	N/A	N/A	N/A	0	10.49

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[2] Number in brackets is value includes emissions from fuel wood.

Table 5. Summary of results for 2007, baseline and access scenarios in 2030, GEA-H

	2007		**GEA-H**		**GEA-H access**	
	Urban	**Rural**	**Urban**	**Rural**	**Urban**	**Rural**
% Population using solid fuels	19	84	8	56	8	24
Annual Energy Use (GJ_{SE}/cap)	3.3	6.1	4.0	5.3	4.0	3.9
Annual Emissions (kgC/cap)	69.6 (86.0)	30.3 (113.3)	118.3 (128.2)	65.3 (117.2)	118.3 (128.2)	69.8 (95.1)
Cumulative Subsidies (Billion $\$_{2005}$)	N/A	N/A	N/A	N/A	0	64.66
Subsidy Effectiveness ($\$_{2005}$/person-switch.year)	N/A	N/A	N/A	N/A	0	40.40

Providing subsidies provides a serious incentive for fuel switching as the rural population reliant on solid fuels more than halves in the access cases. It can also be an effective method of reducing the emissions (when emissions from fuel wood are included) since for poor households a significant fraction of emissions comes from cooking with traditional biomass. As can be seen, for rural households it possible to reduce total emissions even below the 2007 values simply by replacing cooking fuels according to our calculations. However it is important to realize that these emissions will grow again in the future as the households seek to meet their heating and appliance energy functions which still remain unsatisfied. This explains the lower emissions of rural households (under the access scenario) compared to urban households since they are poorer and perform fewer energy functions.

It is also interesting to compare the differences between the GEA-L and GEA-H situations. The fraction of population which uses solid fuels is higher in the GEA-H case and this is a result of increased inequality since the poor are forced to still cook with dirty fuels. The difference between the two baselines concerning annual energy use and emissions is mainly driven by efficiency differences. However inequality also means that urban households are slightly better off than rural households and thus also take advantage of other energy functions in the GEA-H case.

The cumulative subsidies for rural households shown in the above tables should be treated with caution, since at first it seems the cumulative subsidies are less for the GEA-H case. It is worth though checking the subsidy effectiveness which shows that fuel switching is more expensive in the GEA-H case and also keeping in mind for how much longer the subsidy scheme has to be in place under each scenario to reach the 10% goal. Due to extreme poverty, in the GEA-H the fuel subsidy given and the effect of micro financing still do not make fuel switching an attractive option for the poorest households. Thus in the long run the GEA-H case is significantly more expensive than the GEA-L case assuming the subsidies are in place in order to meet a goal. This is due to increased inequality and thus greater requirement for households to use the subsidy, but also decreased efficiency means larger volumes of fuel have to be subsidized.

3.3.2 China

Rural Chinese households are given a 50% subsidy on LPG. This subsidy is directed towards the rural quintiles in both GEA-L and GEA-H cases. It is predicted that urban households will not require the subsidies in either baseline. In the GEA-L Access with financial aid case 20% of the rural population depends on solid fuels while in 2050 this has been reduced to 11.2%. For GEA-H Access case the numbers are 29% and 17% respectively. The results in 2030 are summarized in Figure 32. Marginalization of electricity use due to the subsidization of LPG can be seen when comparing the access scenario with the baselines (Figure 11). There is no difference between the baselines and the access scenarios for urban households since they do not have access to the subsidy scheme.

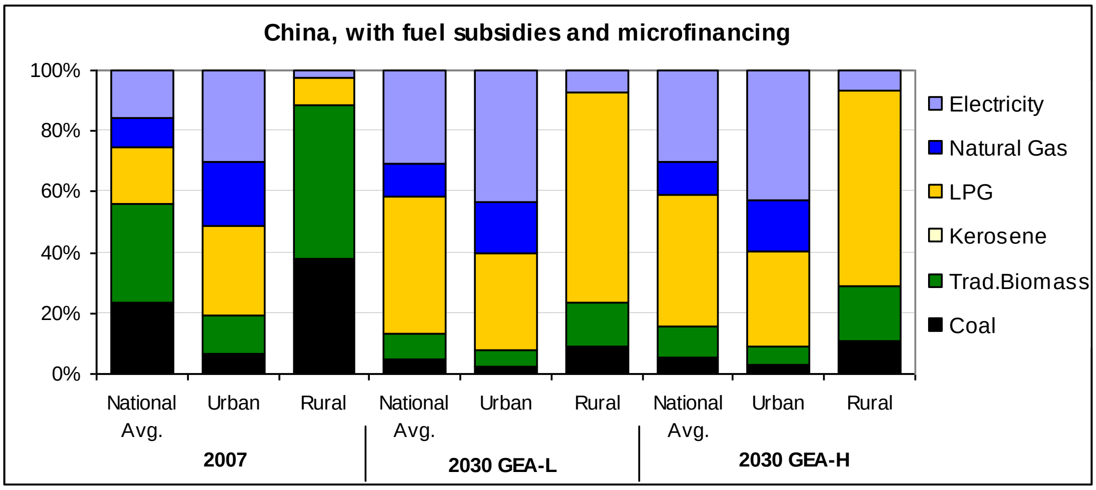

Figure 32. Shares of cooking capital in 2030 under 50% fuel subsidies and micro financing, GEA-L and GEA-H.

Table 6. Summary of results for 2007, baseline and access scenarios in 2030, China, GEA-L.

	2007		GEA-L		GEA-L access	
	Urban	**Rural**	**Urban**	**Rural**	**Urban**	**Rural**
% Population using solid fuels	19	89	8	53	8	23
Annual Energy Use (GJ_{SE}/cap)	8.1	11.5	10.8	14.2	10.8	11.4
Annual Emissions (kgC/cap)	249.3 (291.2)	186.9 (297.3)	321.3 (335.2)	248.2 (367.5)	321.3 (335.2)	238.7 (308.2)
Cumulative Subsidies (Billion $\$_{2005}$)	N/A	N/A	N/A	N/A	0	102.52
Subsidy Effectiveness ($\$_{2005}$/person-switch.year)	N/A	N/A	N/A	N/A	0	111.01

Table 7. Summary of results for 2007, baseline and access scenarios in 2030, China, GEA-H.

	2007		GEA-H		GEA-H access	
	Urban	**Rural**	**Urban**	**Rural**	**Urban**	**Rural**
% Population using solid fuels	19	89	9	61	9	29
Annual Energy Use (GJ_{SE}/cap)	8.1	11.5	11.0	14.4	11.1	11.4
Annual Emissions (kgC/cap)	249.3 (291.2)	186.9 (297.3)	340.7 (355.5)	247.5 (370.3)	340.7 (355.5)	239.7 (309.9)
Cumulative Subsidies (Billion $\$_{2005}$)	N/A	N/A	N/A	N/A	0	94.1
Subsidy Effectiveness ($\$_{2005}$/person-switch.year)	N/A	N/A	N/A	N/A	0	100.28

In this case the cumulative subsidies are higher than India due to the much larger Chinese population. Subsidies are also less effective since a significant fraction of the fuel subsidised goes towards heating, which is not the goal of the subsidy scheme. It is also worth comparing the emissions of Chinese urban households with those of India, since both have similar penetration rates of clean cooking fuels (LPG). Chinese households have higher per capita emissions since household expenditures are higher than in India and thus total energy use increases due to increased use of heating and increased use of appliances. This is evident in Figure 4.

3.3.3 Pacific Asia

In this region subsidized fuels differ between urban and rural households. Urban households are given a subsidy on natural gas while in rural households LPG is subsidized. In the GEA-L access case urban households reach the goal in 2028 while in the GEA-H Access they meet it one year later in 2029. The rural population does not meet the goal in either GEA-L or GEA-H Access scenarios. In 2030 21% and 25% depend on solid fuels for GEA-L and GEA-H respectively while by 2050 the dependence has been reduced to 14% and 18%. The situation in 2030 is shown in Figure 33.

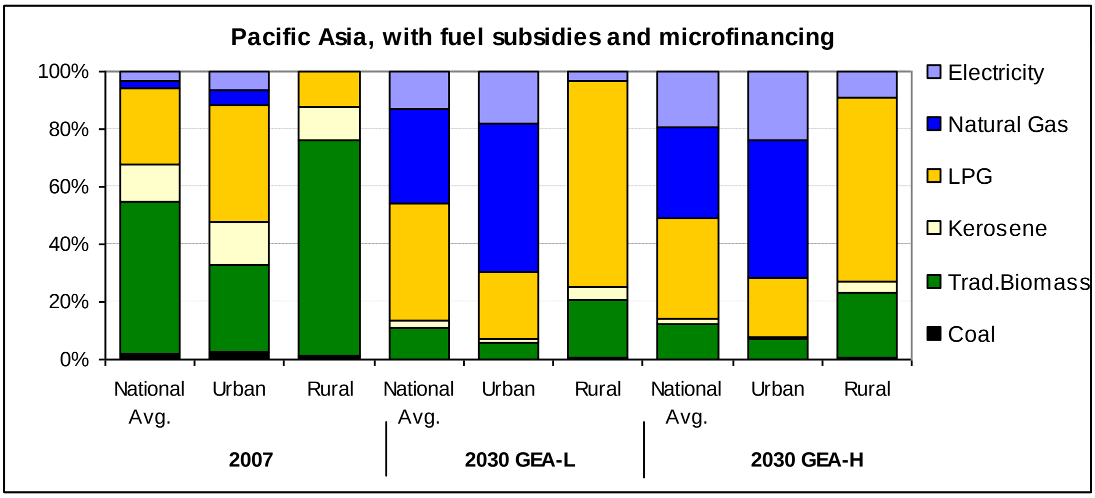

Figure 33. Shares of cooking capital in 2030 under 50% fuel subsidies and micro financing, GEA-L and GEA-H.

Table 8. Summary of results for 2007, baseline and access scenarios in 2030, Pacific Asia, GEA-L.

	2007		**GEA-L**		**GEA-L access**	
	Urban	**Rural**	**Urban**	**Rural**	**Urban**	**Rural**
% Population using solid fuels	34	78	14	47	6	21
Annual Energy Use (GJ$_{SE}$/cap)	6.2	9.6	6.4	8	5.7	5.8
Annual Emissions (kgC/cap)	83.9 (138.4)	42.7 (170.0)	156.8 (186.7)	89.2 (169.8)	151.5 (169.3)	91.4 (133.3)
Cumulative Subsidies (Billion \$$_{2005}$)	N/A	N/A	N/A	N/A	7.07	27
Subsidy Effectiveness (\$$_{2005}$/person-switch.year)	N/A	N/A	N/A	N/A	56.95	57.19

Table 9. Summary of results for 2007, baseline and access scenarios in 2030, Pacific Asia, GEA-H.

	2007		**GEA-H**		**GEA-H access**	
	Urban	**Rural**	**Urban**	**Rural**	**Urban**	**Rural**
% Population using solid fuels	34	78	17	54	7.8	25
Annual Energy Use (GJ$_{SE}$/cap)	6.2	9.6	6.8	8.6	6.1	6.3
Annual Emissions (kgC/cap)	83.9 (138.4)	42.7 (170.0)	168.0 (201.0)	86.8 (176.8)	163.5 (182.3)	101.8 (148.1)
Cumulative Subsidies (Billion \$$_{2005}$)	N/A	N/A	N/A	N/A	7.02	23.5
Subsidy Effectiveness (\$$_{2005}$/person-switch.year)	N/A	N/A	N/A	N/A	48.55	49.68

In this region urban households also benefit from the subsidy scheme leading to an urban as well as a rural reduction in annual energy use and emissions per capita. An interesting insight can be provided from this region since the subsidy scheme is effective at meeting the goal for urban households by 2030 and thus this indicator can be used to assess the policy. As can be seen, the cumulative subsidies in 2030 are lower for the GEA-H case than the GEA-L case. This is counter intuitive since the higher inequality and lower efficiency of the GEA-H case would lead us to expect that greater volumes of fuel would have to be subsidized. However, since in the GEA-L case more households switch under the baseline, more households take advantage of the subsidy scheme in the early years increasing the costs.

Even though the welfare levels are comparable with that of China, due to climatic conditions there is a very low heating demand and so this regions’ energy use and emissions are lower. For this reason the subsidies are also more effective than in the Chinese case. Furthermore, the cumulative subsidies are significantly smaller than India and China due to the smaller population.

3.3.4 South Africa

In South Africa subsidies are given on electricity, mainly because it is already widely used and so giving subsidies on any other fuel would lead to electricity users switching away. However the number of freeriders is also increased by subsidizing electricity. In this region under the both baselines urban households do not require a subsidy. For rural households when the financial aid is given under the GEA-L and GEA-H cases 13% and 25% of the population depend on solid fuels in 2030 respectively. In 2050 these numbers are 9% and 15% where once again inequality is detrimental in the GEA-H access scenario. The 2030 situation is displayed in Figure 34.

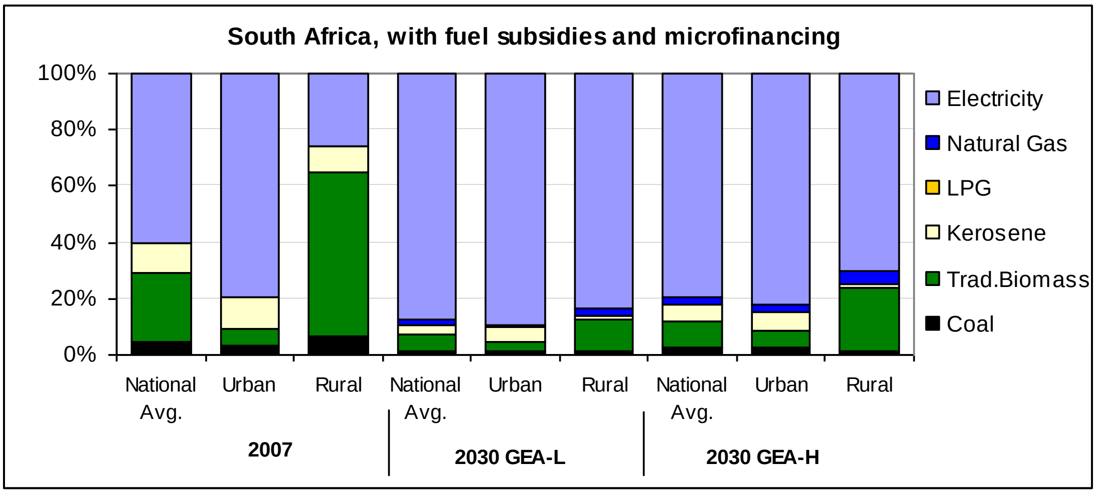

Figure 34. Shares of cooking capital in 2030 under 50% fuel subsidies and micro financing GEA-L and GEA-H.

Obviously electricity remains as the dominant fuel, but while in the baselines natural gas had started to penetrate the market, under the access scenarios it gets marginalized.

Table 10. Summary of results for 2007, baseline and access scenarios in 2030, South Africa, GEA-L.

	2007		GEA-L		GEA-L access	
	Urban	Rural	Urban	Rural	Urban	Rural
% Population using solid fuels	10	68	5	37	5	13
Annual Energy Use (GJ_{SE}/cap)	7.1	13.6	8.1	11.3	8.1	7.5
Annual Emissions (kgC/cap)	252.0 (286.0)	113.5 (279.0)	328.6 (355.5)	200.7 (297.8)	328.6 (355.5)	245.2 (288.4)
Cumulative Subsidies (Billion $\$_{2005}$)	N/A	N/A	N/A	N/A	0	4.72
Subsidy Effectiveness ($\$_{2005}$/person-switch.year)	N/A	N/A	N/A	N/A	N/A	188.89

Table 11. Summary of results for 2007, baseline and access scenarios in 2030, South Africa, GEA-H.

	2007		GEA-H		GEA-H access	
	Urban	**Rural**	**Urban**	**Rural**	**Urban**	**Rural**
% Population using solid fuels	10	68	9	51	9	25
Annual Energy Use (GJ$_{SE}$/cap)	7.1	13.6	8.1	12.5	8.1	8.7
Annual Emissions (kgC/cap)	252.0 (286.0)	113.5 (279.0)	314.8 (343.2)	168.2 (296.9)	314.8 (343.2)	220.6 (288.0)
Cumulative Subsidies (Billion \$$_{2005}$)	N/A	N/A	N/A	N/A	0	3.89
Subsidy Effectiveness (\$$_{2005}$/person-switch.year)	N/A	N/A	N/A	N/A	N/A	168.98

In South Africa even though the rural population is most in need of the financial aid and it also receives it for a very long time, the cumulative subsidies are rather low. This is because it is projected that South Africa has a small and decreasing rural population, being only a minor fraction of the total. Also due to the high baseline penetration of electricity and the high heating loads much of this subsidy goes much of this subsidy is not used just for fuel switching, making the subsidy scheme extremely ineffective according to the effectiveness indicator.

3.3.5 Brazil

In Brazil subsidies are given for LPG to both urban and rural households. Since there is already a high use of LPG it is the most appropriate fuel to subsidize in order to avoid clean-to-clean switching. Urban households are projected to meet the goal in 2028 under the GEA-L baseline but do not meet it by 2030 under the GEA-H baseline, so urban households gain access to the subsidy scheme under this baseline. Under GEA-H Access scenario urban households do not meet the goal in 2030 according to our model even though the majority of quintiles have sufficient access to modern fuels. Due to very high levels of inequality the lowest urban quintile drags down the class average. The goal is finally met in 2036. Rural households gain access to the subsidy scheme in both cases. Under GEA-L Access the goal is met in 2042 but under GEA-H Access by 2050 15% of the rural population still depend on solid fuels.

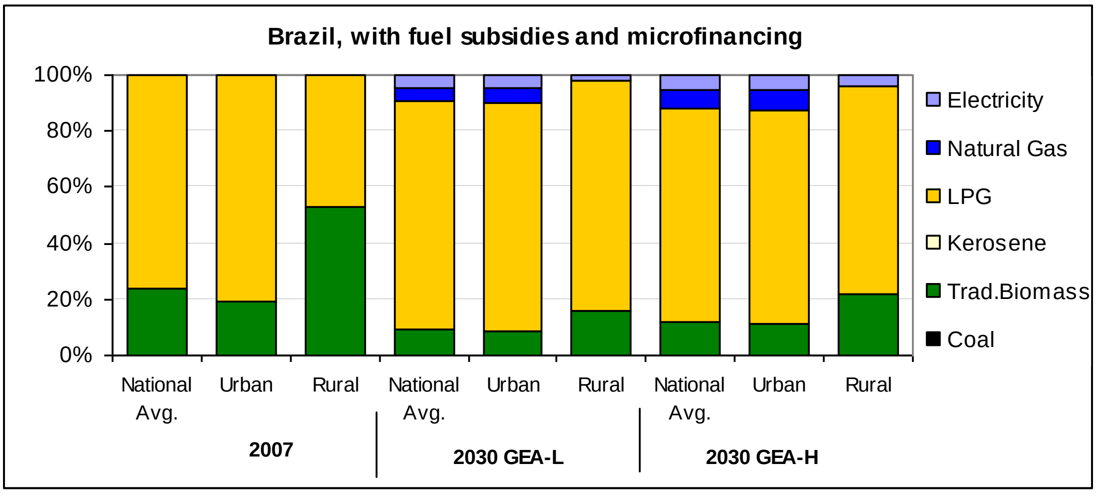

Figure 35. Shares of cooking capital in 2030 under 50% fuel subsidies and micro financing GEA-L and GEA-H.

Table 12. Summary of results for 2007, baseline and access scenarios in 2030, Brazil, GEA-L.

	2007		**GEA-L**		**GEA-L access**	
	Urban	**Rural**	**Urban**	**Rural**	**Urban**	**Rural**
% Population using solid fuels	20	56	9	27	9	16
Annual Energy Use (GJ$_{SE}$/cap)	6.2	7.9	7.0	6.9	7.0	5.8
Annual Emissions (kgC/cap)	55.4 (90.3)	30.0 (117.8)	75.2 (99.2)	50.8 (101.7)	75.2 (99.2)	56.4 (87.5)
Cumulative Subsidies (Billion \$$_{2005}$)	N/A	N/A	N/A	N/A	0	2.53
Subsidy Effectiveness (\$$_{2005}$/person-switch.year)	N/A	N/A	N/A	N/A	N/A	85.6

Table 13. Summary of results for 2007, baseline and access scenarios in 2030, Brazil GEA-H.

	2007		**GEA-H**		**GEA-H access**	
	Urban	**Rural**	**Urban**	**Rural**	**Urban**	**Rural**
% Population using solid fuels	20	56	16	40	12	22
Annual Energy Use (GJ$_{SE}$/cap)	6.2	7.9	7.5	7.7	7.1	6.2
Annual Emissions (kgC/cap)	55.4 (90.3)	30.0 (117.8)	71.8 (103.4)	46.0 (112.1)	73.6 (98.0)	53.3 (92.0)
Cumulative Subsidies (Billion \$$_{2005}$)	N/A	N/A	N/A	N/A	11.85	2.43
Subsidy Effectiveness (\$$_{2005}$/person-switch.year)	N/A	N/A	N/A	N/A	94.1	69.69

As with South Africa, due to a small and declining rural population the cumulative subsidies for rural households are lower than urban households. Though Brazil also suffers from inequality levels similar to those of South Africa, the subsidies are much more effective. This is because there are fewer freeriders and so the subsidy does actually promote cleaner cooking.

3.3.6 Overall Effects of Access Policy

Within this research, subsidies are handed out with a clear goal in mind: Promote clean fuels for cooking. However some side effects are unavoidable such as fuel switching for heating also taking place. Thus in countries where heating demand is high (due to climate or affluence) a portion of this subsidy (approximately 50%) is "lost" towards that end use. This however is merely a framing issue since clean heating fuels are also a precursor towards development, only secondary to clean cooking fuels.

A more unfavourable side-effect of the subsidies which our projections show is the inevitable switching from clean fuels towards the subsidized fuel in households which do not use traditional fuels. This in essence is a complete loss of the subsidy. This effect can be limited by targeting the subsidies to those households which would not use the fuel otherwise. Determining this in real life is very difficult but income levels are a good starting point. Within this research subsidies have been targeted to those quintiles which do not meet a given goal however still a significant portion of the subsidy is lost. Further disaggregating population into deciles or vintiles would make the schemes more effective. It has been shown that under conditions of economic equality, subsidy schemes tend to be less effective due to the increased prevalence of free riders, but also on the other hand a greater portion of the population requires the subsidies for a longer period under economic inequality. Thus the complex relationship between fuel switching cost and economic inequality becomes apparent. Yet, the social cost of inequality and the effects on development within the household sector outlined earlier should not be ignored. The total cost of subsidies is also dependent on how much of the fuel has to be subsidised. This not only depends on how many people have access to the subsidy (inequality), but also how efficiently this fuel is being used. Thus the volumes of subsidised fuel (and thus the cost) can be significantly reduced together with policies promoting energy efficiency.

It has been shown that providing access to modern cooking fuels can lower energy demand and emissions, but these are only temporary decreases since emissions from energy demand of other functions are only set to grow with affluence. Also further reducing heating demand via improving building shells can play a very big role especially in cold climates. Efficiency improvements of cooking stoves also influence possible emission trajectories of poor households. Even though emissions are bound to increase with affluence the importance of cumulative emissions should not be overlooked.

An adverse effect in long term subsidies is that other fuels which may become cheaper in the future are marginalized. This hinders the growth of new energy industries in the region and affects energy diversity and security since households become heavily dependent on a single fuel. In this respect electricity may be a favoured carrier since it allows for diversity in generation.

Tools such as micro financing can be employed in order to aid poor households with the upfront costs of switching fuels. According to our analysis the rate of fuel switching does not increase dramatically compared to a subsidy only case (access of a given percentage happens 3-5 years earlier). In the current set-up of REMG the annualized fuel prices are much higher (by a factor of 10) than the annualized capital costs which makes capital subsidies ineffective and micro financing effective only in combination with fuel subsidies. Interestingly, when micro financing is used together with fuel subsidies, the annual subsidies are significantly higher since penetration of clean technologies happens faster and thus a larger volume of fuel has to be subsidized. Even though the annual subsidies are higher, once a certain goal is met the cumulative subsidies are lower when micro financing is involved.

When subsidies are removed it was witnessed that the poorest households may move down the energy ladder. This is an effect which has not been studied much but has been implied in previous studies (Jannuzzi *et al.*, 2004; Maconachie *et al.*, 2009). A counter argument is that by subsidizing fuels labour productivity can increase leading to an overall increase in welfare, rendering subsidies unnecessary (Ekholm *et al.*, 2010). Whatever the case subsidy removal should be gradual in order to avoid this effect and also promote the use of more fuels. Also, volatility of fuel prices affects movements along the energy ladder but also level of subsidies. With this in mind it may be wiser to subsidize a local fuel which has greater price stability, or electricity which can be generated through a number of means.

4 The Energy Development Index

In order to better understand the role that energy plays in human development, the *International Energy Agency* has developed and parameterized energy development in the form of the *Energy Development Index* (EDI) (IEA, 2004b; IEA, 2010). The EDI is calculated in such a way so as to make it congruent to the *United Nations Development Program*'s *Human Development Index* and it is explicitly stated that it "seeks to capture the quality of energy services as well as their quantity". For the residential EDI, Four indicators are chosen, each of which captures a specific aspect of potential energy poverty:

1. *Per capita commercial energy consumption, all sectors (toe)*
2. *Per capita electricity consumption in the residential sector (toe)*
3. *Share of modern fuels in total residential sector energy use (%)*
4. *Share of population with access to electricity (%)*

An index is created by comparing the values of the above to the actual minimum and maximum values for developing countries. Each indicator is expressed as a value between 0 and 1 based on Equation 11. Subsequently the EDI is calculated as the arithmetic mean of the four indicators.

$$Indicator = \frac{Actual\ Value - Minimum\ Value}{Maximum\ Value - Minimum\ Value}$$

Equation 11

The minimum and maximum values for each of the indicators given by the IEA based on 2009 data are shown in Table 14. Note that these values are for developing countries so this indicator should be treated as a comparison between developing countries.

Table 14. The minimum and maximum values used for the calculation of the 2010 Energy Development Index.

	Minimum (country)	Maximum (country)
Commercial Energy Consumption	0.03 (Eritrea)	2.88 (Libya)
Electricity Consumption	0.001 (Haiti)	0.08 (Venezuela)
Share of modern fuels	1.4 (Ethiopia)	100 (Yemen, Lebanon, Syria, Iran)
Share of pop. With access to electricity	11.1 (Dem. Rep. of Congo)	100 (Jordan, Lebanon)

It was attempted to compare the REMG results for EDI with the IEA values for 2010 and also see how the EDI changes according to each scenario. REMG can provide the data for indicators 2-4 while the first indicator was provided from IEA data. The minimum and maximum values remain as in Table 14; so the results are a comparison of how each of the regions progresses based on the 2010 standard of developing countries. The results are summarized in Table 15.

Table 15. EDI values for 2010 (REMG & IEA) and scenarios on a 2010 base.

	2010		2030			
Region	**REMG**	**IEA**[3]	**GEA-L**	**GEA-H**	**GEA-L Access**	**GEA-H Access**
India	0.25	0.26	0.42	0.42	0.46	0.49
China	0.59	0.56	0.78	0.79	0.79	0.81
Pacific Asia	0.33	0.31[4]	0.54	0.55	0.57	0.62
South Africa	0.58	0.72	0.78	0.75	0.88	0.82
Brazil	0.58	0.62	0.71	0.71	0.71	0.73

REMG generally reproduces the 2010 IEA values quite well. The largest deviation is from the South African value with REMG providing a figure 20% less than the IEA one. As expected, since all regions are projected to increase their affluence by 2030 under all scenarios the energy development index increases for all regions. Little difference is witnessed between the GEA-L and GEA-H baselines. This is because the first two indicators are higher for the GEA-H case since due to inefficiencies the absolute amount of (modern) energy consumed is higher. GEA-L on the other hand has an advantage concerning the share of modern fuels.

India fails to increase its EDI significantly mainly due to the limited growth of the first and second indicators. China grows significantly due to increased consumption of electricity and total share of modern fuels. The EDI for Pacific Asia is limited due to the limited share of modern fuels as well as a very low per capita commercial energy consumption (all sectors). For South Africa, the very high use of electricity contributes to its high value as well as very high electrifications rates. The access scenarios seem to be most beneficial for South Africa. This is because the subsidy scheme given to South Africa was based on electricity which gives it an extra advantage on the second indicator while for the other regions this indicator suffered. The only reason Brazil is lower than South Africa and China is due to its lower electricity consumption.

With this in mind a critique of the EDI can be offered. As an indicator of energy development it mainly focuses on the ability to consume modern fuels. However in a more “Sustainability” context the rate of consumption of these fuels is also important; in this view the efficiency with which fuels are consumed should also be accounted for. Also considering efficiency, wasteful use of modern energy inflates the value of the first two indicators leading to misleading results. It is primarily because of this reason that middle eastern countries have the highest EDI (IEA, 2004b; IEA, 2010). Within the EDI, electricity gets a clear bias which together with the lack of attention towards energy functions creates a significant problem. As households get richer, the main energy function shifts from cooking towards heating (for cold climates) or appliances (of which air conditioning is a very significant contributor). Heating demand can be met by all fuels while appliances are dependent solely on electricity. By focusing on the per capita electricity consumption rather than the per capita modern fuel consumption for the residential sector, the outlook is biased. Especially

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[3] Approximate, values read off a bar-chart.

[4] For individual countries values ranged from 0.8 (Malaysia) to <0.5 (Myanmar). Indonesian value picked since it is the most populous country in the region.

from an emissions perspective since electricity may be a very dirty fuel for household use in developing countries.

The fact that energy functions and their drivers are not accounted for explicitly limits the usefulness of the indicator. Taking South Africa and Brazil as examples, Brazil has a higher share of modern fuel use in households, a higher electrification rate and as is visible in Figure 4 have a higher use of appliances and more efficient use of fuels for cooking. Also evident in Figure 4 is the increased demand for space and water heating for South Africa, something which is directly related to climatic conditions. As shown in sections 3.3.4 and 3.3.5, Brazil generally fares better concerning the portion of the populations depending on solid fuels. South Africa also has a very high use of electricity for all end use functions while for Brazil liquid fuels are primarily used. Simply because South Africa has a higher heating demand and it meets this demand with electricity, its EDI is higher, even though basic amenities such as appliance ownership and use of modern fuels are greater in Brazil while emissions are also much lower.

5 Discussion and Conclusions

From the above results a number of limitations of the model and the analysis become apparent. Furthermore a number of observations and conclusions can be made concerning the facets of residential energy use in developing countries. These are addressed one by one.

5.1 *Model and Methodology Limitations*

Concerning our methodology, certain aspects of the model have to be taken into account when looking at the results. The most important of these are listed below:

- *Limitation of disaggregated data:* Historically the model has been calibrated to available data. However, since the model disaggregates between urban and rural classes and the respective income groups, data with similar disaggregation levels is required in order to ensure accuracy. This became a significant problem especially in the Pacific Asia and Brazil regions where very little data at this level is available. For these regions it was assumed that the difference between quintiles follows similar patterns to those in other regions given the household expenditures. Despite these limitations final energy use has been made to be as consistent as possible with IEA data.

- *The effect of household expenditures:* The model is built in such a way that the demand of energy services is directly related to household expenditures. It could be argued that a more appropriate approach would be to relate this demand with the share of income spent on energy. Thus the model would become more dynamic with respect to fuel prices. However, given lack of accurate data needed to pursue this method, this approach could not be taken.

- *Perceived costs:* The drivers of fuel choice within the residential sector are only partly understood and it is evident that economic drivers have a limited importance. Issues such as social standing, perception of the fuel, cultural aspects and cooking habits play a more important role; quantification of these costs is not easy and have been set as calibration factors. The use of perceived costs also makes the model inelastic when it comes to fuel choices under the climate policy.

- *Hidden costs:* The access storyline assumes the perceived costs are removed via widespread information campaigns and positive efforts to increasing accessibility. These actions carry costs which have to be paid for by the government. These costs are not included in our calculations. Also costs in order to increase the electrification rate which is implicit in the access scenarios are not included.

- *Limitation in fuel price data:* The accuracy of fuel prices is quite important for the access scenario. Fuel prices affect the absolute value of the cumulative subsidies, their effectiveness and the helpfulness of micro-financing which in turn affects the levels of subsidies. Unfortunately it is notoriously difficult to get accurate fuel costs for residential use.

5.2 *Conclusions*

This paper started out with the aim of determining what the future trends of residential energy use may be. Furthermore, in order to further understand residential energy use, human development, pollution, sustainability and the relationship amongst these. A number of inferences can be made from the analysis:

- The first research question this paper sought to answer concerned the future trends for residential energy use in five major developing regions. More specifically we set out to study what dictates these trends. As stated in the beginning of this paper, residential energy use depends on a number of domains:

    - Economic: Household expenditures, welfare
    - Human: Behaviour, culture, requirements of energy services
    - Physical: Urban/rural demographics, access, climate

  We have demonstrated how final energy demand increases with increased affluence. This increase is due to greater satisfaction in energy needs within a household. We have also shown how factors such as inequality can affect final energy demand through satisfaction of energy functions. Furthermore we have shown how both inequality and efficiency affect fuel choice and thus emissions and final energy use. Furthermore, it has been shown that these factors are very much affected by region specific traits such as climatic conditions, accessibility to fuels and cultural traits such as an affinity towards appliance use or preference of certain fuels. For all the regions analyzed, the energy use per capita in 2030 is still well below that of the western world today. Further into the future the energy use of all the analyzed regions is expected to increase mainly due to the further use of air conditioning (especially in warmer regions) which by 2030 is still limited.

- The second part of this study focused on the effects of specific policies on the residential sector of developing countries. The first policy which was analyzed was climate policy. The main goal of climate policy is to reduce emissions; however it has some perverse effects when considering development. This is because poor households struggle to meet their primary energy needs and imposing further costs hinders this progress. The households most affected by this are the poorest households.

  Setting fuel prices based on carbon content does not necessarily lead towards fuel switching towards cleaner fuels and thus lower emissions. This rationalist approach perhaps is not appropriate for the residential sector, since, as witnessed in the results fuel switching is limited primarily because fuel choices in households apparently do not depend on economic factors but more on subjective choice. In this aspect climate policy is ineffective. On the other hand, the overall emissions do reduce due to de-carbonization of electricity supply.

- The second policy which we looked into was the provision of financial aid in order to promote fuel switching away from solid (traditional) fuels. Since the affluence of a household plays a significant role in fuel choice, how the wealth of a region is spread greatly determines the accessibility rate of clean fuels. It has been shown that inequality lowers access to cooking fuels, increases emissions and also makes subsidy schemes more expensive (to reach a given goal). The poorer a household is, the harder it is to promote fuel switching making subsidy schemes progressively more expensive with rising inequality. The cheapest method to promote clean cooking is to spread wealth more equally.

5.3 *Final Thoughts*

In a development context, an important first step is to ensure the provision of clean cooking fuels to households. This helps with improving health via the reduction of indoor air pollution, promoting gender equality, education, employment and stops environmental degradation. Studies suggest that even though poverty does play a significant role in fuel choice, other subjective factors are perhaps more important when it comes to fuel choice such as the ability to cook for large groups or maintenance of traditions (Masera *et al.*, 2000; Farsi *et al.*, 2007; Maconachie *et al.*, 2009). A solution to this is no simple matter as it is uncertain if the route of the problem is lack of information, lack of access or purely behavioural.

Very few attempts have been made in order to come up with a quantitative description of residential energy use and development. The *Energy Development Index* of the *International Energy Agency* is a step in the right direction however it ignores certain of the diverse facets of residential energy use and does not fare well considering efficiency of use and multiple aspects of electricity use.

In this context importance of electricity cannot be overlooked. Electricity is the cleanest possible (at end use level) fuel and also is very attractive since it can be generated from a host of primary energy carriers, including renewable sources, thus being favorable concerning energy security. Also it is easily delivered once a grid is set up giving added freedom to the users to pursue other activities such as education and employment, further aiding development. Furthermore electricity use inevitably increases since it is the only energy carrier which can provide energy use for appliances and cooling, the first of which becomes a very important end use function regardless of climate. With this in mind, emissions from electricity generation are of paramount importance. However, in developing countries it is notoriously polluting, and many time switching towards it may bring down energy use (since it is efficient), but has the opposite effect for emissions. Making electricity supply cleaner though, will probably increase its cost making it less accessible to poor households.

In conclusion, residential energy use is complex and this study has attempted to understand the main facets of this sector. The dynamics and tradeoffs of changing variables have been demonstrated with environmental and developmental goals in mind. Positive movements for the residential sector would include economic growth with reduced inequality, promoting use of clean fuels for cooking for the poor via increasing accessibility, providing capital which allows efficient use and eventually increasing accessibility to clean electricity.

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PART II - DATA AND TECHNICAL REPORT

1 Introduction

This report outlines the data availability and analysis and some technical aspects of the Global Residential Energy Demand Model (REMG). The model is based on the previous Residential Energy Demand Model for India (REMI) which was made by Bas Van Ruijven (van Ruijven, 2008). The aim of REMG is to adapt REMI so that it becomes representative of other regions as well. For a full explanation of the REMI (and thus REMG) models, consult the technical documentation of the REMI model. This paper explains how REMI was changed based on available data in order to make it appropriate for global analysis.

The first step in creating a global residential energy model was to determine which aspects of REMI can remain, which aspects have to be edited and finally, what has to be added which was not necessary for India. In order to find answers to these questions a very thorough literature review of residential energy was conducted as well as significant volumes of data were gathered and analyzed. This literature review and data gathering was done on a global level.

This document first outlines the REMI and REMG models (Chapter 2). Following, each chapter is dedicated to a certain function of the model where the following are described (Chapters 3 to 8): Availability and quality of data (*Remarks)*, context related observations based on the available data (*Inferences)* and how the data was used to adapt REMI to REMG (*Analysis*). Chapter 9 describes other aspects and dynamics of the model which are important and finally Chapter 10 suggests areas where further work may be performed.

2 REMI and REMG

The REMI model was developed in order to model residential energy demand in a bottom up fashion. It focused solely on India due to the large amount of available data from the Indian National Sample Survey Organization (NSSO, 1997; NSSO, 2004). One of the crucial aspects of REMI was that it accounts for heterogeneity of the residential sector. It does this by segregating households into a number of classes (demographics). These include *Urban* and *Rural* households, the income quintiles of each *Urban* and *Rural* demographics respectively, and finally a *Total* for the entire region. Thus all results (and intermediate calculations) are divided amongst these thirteen classes.

The basic outline of the REMI model is the following. First a number of drivers determine the useful energy demand for key end-use functions within the residential sector. Following that the final energy demand is determined by allocating fuels to meet this energy demand. This fuel allocation is based on providing market shares to fuels based on total costs. These total costs include monetized and non-monetized costs. This conceptual model will be retained for REMG. However, significant changes have to be made concerning the useful energy demand for end-use functions since this demand varies amongst regions and as households become richer, thus the REMI set-up cannot be retained. The conceptual model of both REMI and REMG is shown in Figure 36.

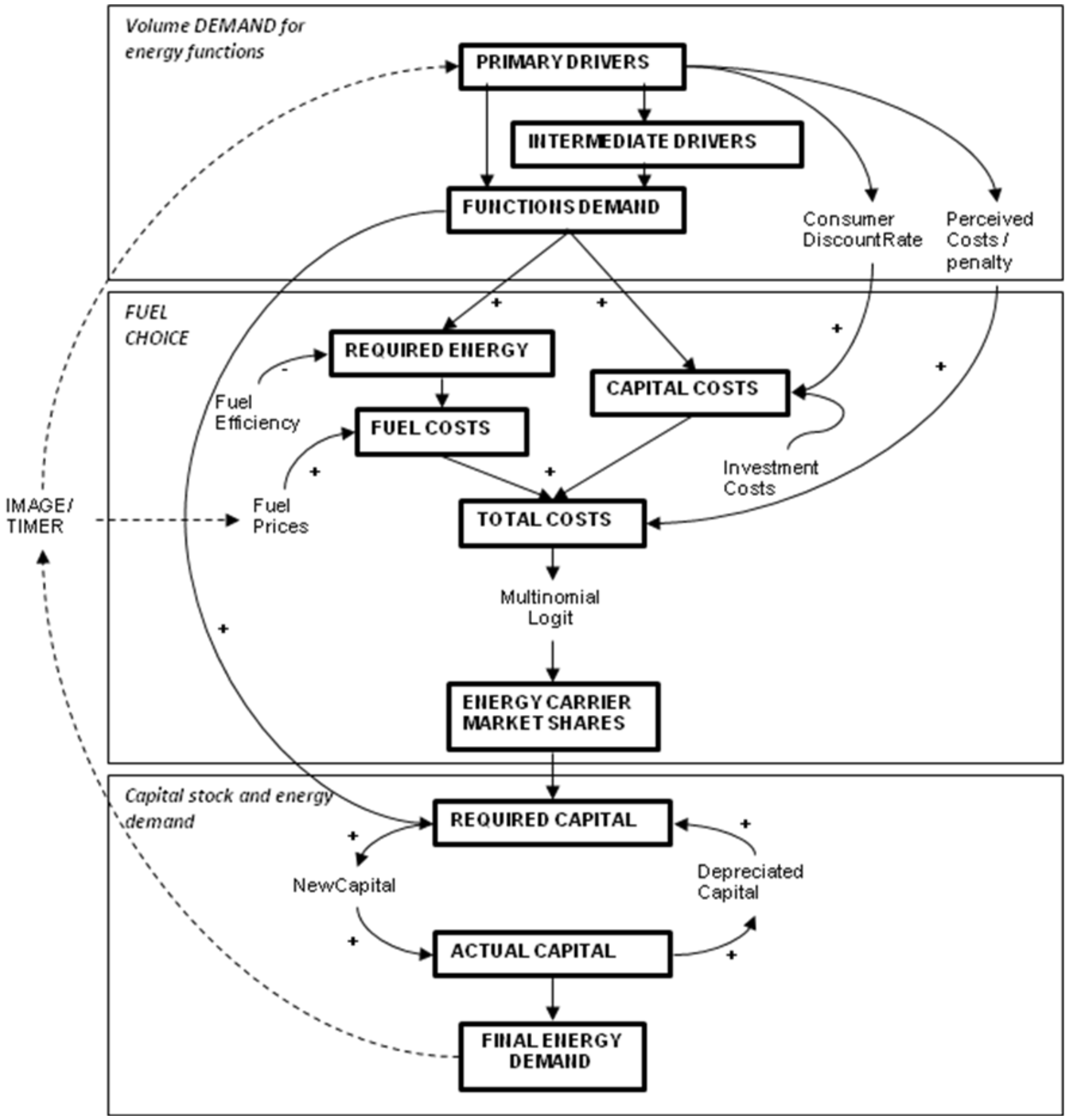

Figure 36. Causal relation diagram of main indicators of REMI and REMG

The energy functions which are considered important for the residential sector have been identified as:

1) Cooking
2) Water Heating
3) Space Heating
4) Space cooling
5) Appliances
6) Lighting

The energy demand of each of these end use categories is based on a set of drivers. These drivers are either completely exogenous, or they are derived within the model. The drivers are:

1) Exogenous Drivers
    a) Population
    b) Household Expenditure
    c) Household Size
2) Intermediate Drivers
    a) Floor Space
    b) Electrification

For the development of the REMI model, there was a plethora of data down the Urban/Rural Quintile level which made it possible to run the model on the level and then the Urban/Rural and Total levels was determined for the quintile results.

2.1 *From REMI to REMG*

The purpose of REMG is to adapt REMI to a global level, i.e. to expand it to all TIMER regions (see Appendix I) so that the model can ultimately be coupled to the TIMER/IMAGE modeling framework (de Vries *et al.*, 2001; van Vuuren *et al.*, 2006). It was decided early on the same structure and the division of the population into demographics would remain. Yet many aspects of the model have to be adapted or changed completely simply because what modeling techniques were appropriate for India, may not be appropriate for other regions.

REMI focused heavily on modeling poor populations, thus many energy needs and dynamics of richer populations are completely ignored within REMI. This had to change. This includes modeling more appliances in a bottom up fashion, fuel choices for cooking and water/space heating, discount rates across income levels, different behavior of different cultures, and many other aspects of REMI which needed revision or adaptation. Furthermore some original work has been conducted concerning appliance ownership rates and energy use in order to make the model more dynamic. All the changes which have been made are outlined throughout this report.

As already mentioned, the detailed bottom up REMI model could be made due to vast volumes of data available for India. The data which was used was available down to the urban/rural quintile level. Assuming this same data and data resolution was available for the rest of the regions, in principle the same (or very similar) model could be used by only changing certain coefficients in each region. Unfortunately this was not so. Thus the thinking which was employed in the development of REMG was the all the available data would be combined to come up with 'generic' global equations, and where more precise data exists for a region, this generic equation is adapted to describe this particular region better. Throughout this report, unless otherwise stated, any quoted coefficients represent the 'generic' form.

Also, a significant departure from REMI is that the drivers and ownership curves are not modeled from quintile level upwards, but rather the other way around. Urban and rural are determined, and then these are distributed amongst quintiles and averaged (weighted by urbanization) in order to get the regional total. Thus a significant amount of the modeling work performed focused on how this division is going to done by examining the differences between urban/rural rich and poor.

Table 16 lists how the use functions are further broken down in order to determine their demand in a bottom-up fashion for both REMI and the adapted REMG models:

Table 16. Break down of end-use functions in the REMI and REMG models.

REMI	REMG
1. Cooking and Water Heating 2. Appliances a. Cooling Appliances i. Fan ii. Air Cooler iii. Air Conditioner b. Food Storage and Processing i. Refrigerator c. Washing and Cleaning i. Washing Machine d. Entertainment i. Television 3. Lighting a. Non Electrified Households i. Kerosene b. Electrified i. Standard ii. Efficient 4. Space Heating	1. Cooking 2. Appliances a. Cooling Appliances i. Fan ii. Air Cooler iii. Air Conditioner b. Food Storage and Processing i. Refrigerator ii. Microwave Oven c. Washing and Cleaning i. Washing Machine ii. Dish Washer iii. Dryer d. Entertainment i. Television ii. DVD/VCR iii. Personal Computer 3. Space/Water Heating 4. Lighting a. Non Electrified Households i. Kerosene b. Electrified Households i. Standard ii. Efficient

It should be noted that even though cooling appliances are listed under appliance energy use above, their energy use is calculated in a similar manner to space heating.

2.2 *Data Requirement for REMG*

Based on what is mentioned above, it becomes obvious that the REMI and REMG models require a number of different data inputs in order to perform an adequate analysis. The data which was gathered is outlined in Table 17.

Table 17. Data requirement for the REMI/REMG models.

Data Cluster	Data Gathered
Household Characteristics and drivers	• Household size • Floor Space per Capita • Population Density • Household Expenditures • GINI coefficients • Urban/Rural shares of GDP • Cooling/Heating degree days • Consumer Discount Rates
Cooking	• Useful Energy for cooking • Fuels Used for cooking (shares) • Efficiency of cooking fuels and capital • Prices of cooking capital
Appliances	• Ownership Levels • Unit energy consumption (aggregate and marginal) • Prices of major appliances
Water Heating	• Useful energy for water heating • Fuels used for water heating (shares) • Efficiency of water heating fuels and capital • Prices of water heating capital
Space Heating	• Useful energy for space heating • Fuels used for space heating (shares) • Efficiency of space heating fuels and capital • Prices of space heating capital
Lighting	• Fuels used for lighting • Energy use for lighting • Prices of CFL and incandescent lamps

Also note, that for all the above ideally they also be split up between Total, Urban, Rural, amongst income levels and across time.

All of the data has to be gathered on a global level (i.e. for all TIMER regions). It was collected via national statistical services, demographic censuses, household budget surveys, scientific papers[5] and reports of various kinds and the *World Development Indicators* Database of 2009 (WDI).

Generally, data exists to some extent for all regions. For Central America, Northern Africa, Western Africa, Turkey, Russia, Middle East, and Indonesia limited data is available. For the rest of the regions, most or all of the required data has been gathered. However, due to the multitude of sources used, many times, even within the same country, the data does not agree. Thus the data should be used carefully.

The following chapters offer a description of each of the data clusters and how they were acquired. Countries where the data should be used with care have been elaborated on. Furthermore, for each data cluster, inferences and conclusions have been drawn out. Finally, how REMI was adapted to make it more appropriate for a global analysis is outlines.

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[5] Especially for “energy for cooking” and “Unit Energy Consumption”

3 Household characteristics

3.1 *Household Size*

This information was gathered from the census bureaus of each individual country.

3.1.1 Remarks

Bolivia & Cambodia: The data is unusual in these countries as the household size is larger for urban areas compared to rural areas. For both cases data was calculated from population and household numbers.

Gambia: The Central Statistics Department of Gambia gives the Total population and the total number of households for 2003 and 2004, thus household sizes can be derived. Yet the values of 8.95 and 8.61 (1993 and 2003 respectively) are suspiciously high.

3.1.2 Inferences

The data confirms the hypothesis that household sizes fall as welfare (measured in per capita expenditures) increases, as shown in Figure 37. Figure 38 shows that the rate at which household sizes decrease is region specific, yet all regions tend towards a level of about 2 persons per household. While Figure 37 and Figure 38 show household sizes for entire populations, Figure 39 shows the difference between urban and rural household sizes (for East Asia). As can be inferred from the plot and is witnessed in other regions, the difference between urban and rural household sizes diminishes with rising welfare.

An interesting observation is that in some regions, household sizes increase amongst income levels of a given year (though the average falls with time). This is witnessed in Eastern Africa, Western Europe, Japan and Oceania. The opposite, which is what is expected, is seen in regions Ukraine region, Middle East, Southeast Asia and Rest of South Asia. Thus quintile data should **not** be used to determine *Household size vs. Expenditure* relationships.

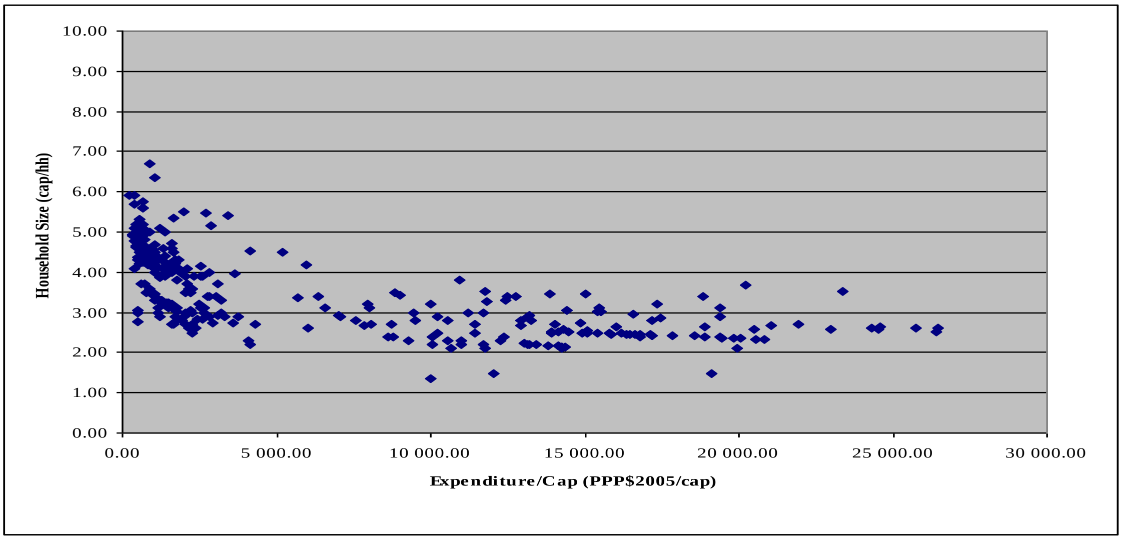

Figure 37. Household Size vs. Expenditure (Global)

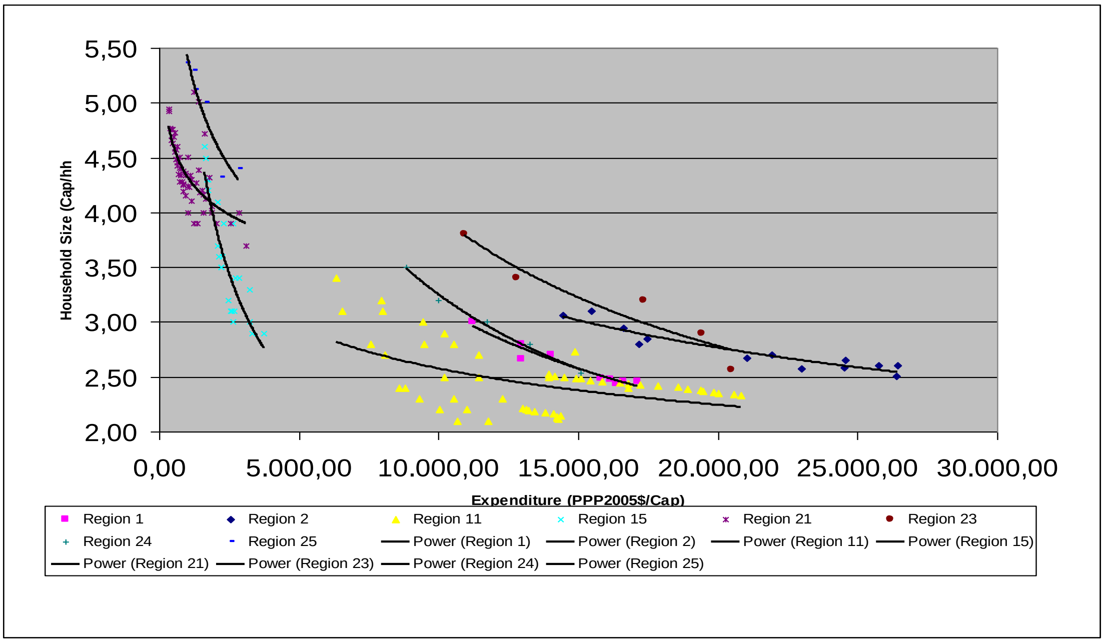

Figure 38. Household Size vs. Expenditure (Various Regions)

3.1.3 Analysis

Household size is directly input in the REMI model as data and future projections are scaled according the UN habitat projections. This same methodology will remain in the global model. Unfortunately this mean that household sizes are required for 1970-present for total, urban, rural, urban quintiles and rural quintiles, in other words: 13 dimensions over 40 years for 26 regions. All of this data simply does not exist so some generalizations will have to be made. It has been decided to use the regional *Total* values which are derived from the PHOENIX model and then urban, rural and quintile values will be derived from this (sections below). Since there may be inherent errors in the PHOENIX values, for calibration purposes a constant value can be added or subtracted from the PHOENIX values to make Total household size more realistic (see Appendix II).

3.1.3.1 Urban/Rural Allocation

Concerning urban and rural household sizes, it is important to keep in mind that when allocating, the urbanization rate is very important. Thus the allocation must be dynamic with urbanization rate in order to ensure that the urban and rural household sizes average out to the national (which is what we are starting from).

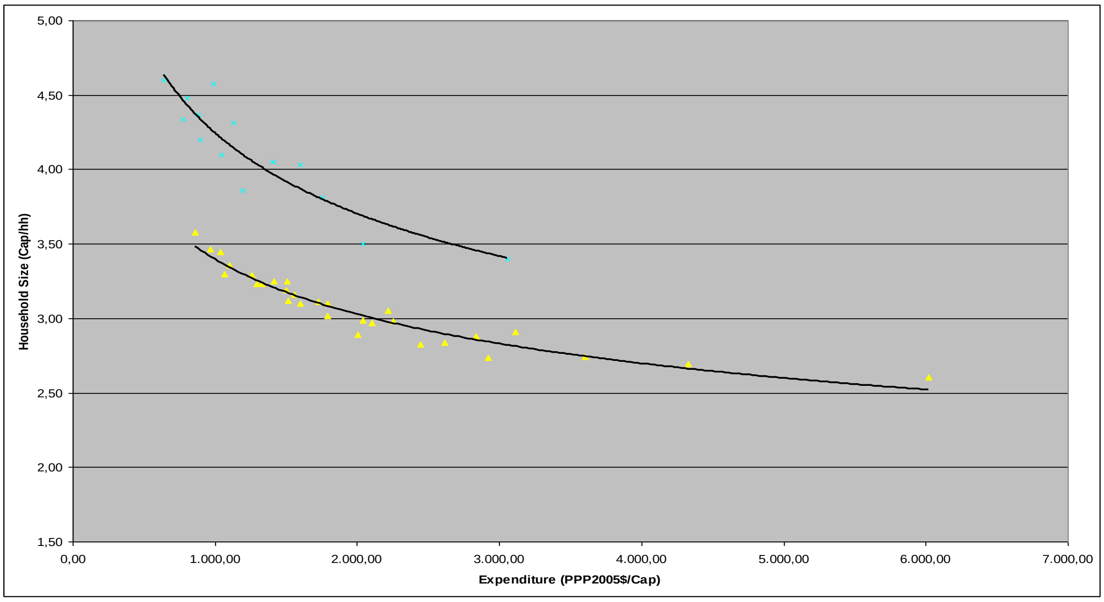

Figure 39. Household Size vs. Expenditure, Urban/Rural Difference (East Asia)

Urban households tend to be smaller than the national average, thus is the national average can be multiplied by a certain factor (UrbFac) which is less than 1 in order to get the urban household size. Subsequently, once the urban and total household sizes are known, the rural value can be determined by weighing with urbanization. Obviously, UrbFac = 1 for Urbanization = 1, since then national average and urban household sizes are identical. The available data does suggest this, since when the UrbFac of the available data (71 data points, 15 regions) is plotted against urbanization (determined from the RURPOP27.dat file used in REMI) a straight line relationship leading to (1, 1) is seen. With aid from the data the following equation is derived:

$$\text{UrbFac} = 0.174078 \cdot \text{Urbanization} + 0.825922$$

This equation, when used with the observed data offers and R^2 value of 0.59088.

3.1.3.2 Quintile Allocation

For the allocation of household sizes across quintiles an entirely new method has been set up. In order to avoid bizarre results where a household is reduced to a household size of less than 1 because the urban/rural household sizes have fallen, the variance across quintiles is dynamically linked with the average (urban/rural) household sizes. The *Global Income Distribution Dynamics* (GIDD) dataset of the World Bank gives household sizes across income *vintiles* for almost all regions (World-Bank, 2009).

With this data it is possible to see how household sizes vary across income levels. Using this available data, and the assumption that once average household sizes fall to 2 the difference across income levels ceases to exist, the gradient of the line describing the variance across quintiles can be computed via:

$\text{Gradient} = -0.0383 \cdot \text{HHSize}_{U,R} + 0.0766$

Then, to get the factor for each quintile by which the average household size has to be multiplied:

$\text{HHSizeQFac}_{Q} = 1 + (\text{Gradient} \cdot (3\text{-Quintile}))$

Where
Quintile = 1, 2, 3, 4, 5

And thus quintile household size:

$\text{HHSize}_{UR,Q} = \text{HHSizeQFac}_{Q} \cdot \text{HHSize}_{UR}$

3.1.3.3 Final Setup

Following the above analysis, the final calculation for household size will follow the following path:

Input:
HHSizeTOT_{R} = Average household size from PHOENIX (converted to TIMER regions), 27 regions.
RURPOP27_{R} = Fraction of rural population from, 27 Regions

Urban/Rural
$\text{Urbanization}_{R} = 1 – \text{RURPOP27}$
$\text{UrbFac}_{R} = 0.174078 \cdot \text{Urbanization}_{R} + 0.825922$
$\text{HHSizeURB}_{R} = \text{HHSizeTOT}_{R} \cdot \text{UrbFac}_{R}$
$\text{HHSizeRUR}_{R} = (\text{HHSizeTOT}_{R} – (\text{HHSizeURB}_{R} \cdot \text{Urbanization}_{R}))/\text{RURPOP27}_{R}$

Quintile
$\text{Gradient}_{U,R} = -0.03083 \cdot \text{HHSize}_{U,R} + 0.0766$
$\text{HHSizeQFac} = 1+ (\text{Gradient}_{U,R} \cdot (3\text{-Quintile}))$
$\text{HHSize}_{UR,Q,R} = \text{HHSizeQFac}_{Q} \cdot \text{HHSize}_{UR,R}$

An inherent problem with this set up is that it depends greatly on the accuracy of the input data, especially HHSizeTOT, which depends on the accuracy of the PHOENIX model. When tested with available data for the USA, the predictions were wrong since the PHOENIX data was incorrect (did not agree with Data). For this reason a correction factor has been introduced as a calibration factor in order to account for this error (see Appendix II). A basic assumption of this method is that the variation across quintiles is the same for urban and rural settings.

3.2 *Floor space*

This information was gathered the census bureaus of each individual country. Floor space in residential buildings was determined in m^2/cap.

Population density was also looked into. This was in order to determine if there is a strong relationship between floorspace and population density. This would also aid in determining rural/urban differences in countries where the urban/rural data does not exist. Population densities were taken from the data collected by Morna Isaac, which provides national population densities for many countries from 1970-2005 (WDI, 2009). When data for other years was necessary, the population of the current year was divided by the total area of the country.

3.2.1 Remarks

Japan: In the quintile data available for 2004, it seems that floorspace **decreases** at the higher quintiles. This is because even though the total floorspace increases, the household size also increases (see section 3.1), thus floorspace per capita decreases.

Jordan: The 2004 Population and housing census gives a count of houses (total/urban/rural) within a given floor-area range. The middle value of this range was taken and multiplied iteratively with the number of houses within that range in order to get the total household area. This was then divided by the total number of houses in order to determine household area. Together with the household size (given in the census), floor space/capita could be determined.

Kazakhstan: Floorspace is lower for rural households than urban households!

Sri Lanka: The 2006 Household income and Expenditure Survey gave floorspace ranges and proportion of houses falling in that range. A similar procedure to that done for Jordan was followed.

Vietnam: Floorspace is lower for rural households than urban households!

3.2.2 Inferences

For regions where multiple sources are available (data sources or countries) a large variation within the region is witnessed. This is particularly true for Western Europe. Figure 40 demonstrates the expected trend that floorspace increases with welfare levels, with no tendency to stabilize. Figure 41 shows the trends for specific regions where consistent data was available. It can be seen that generally the same trend is followed except for Region 23 (Japan) where floorspace is significantly lower. This leads to the hypothesis that population density or urbanization are critical factors. The last Data point for region 23 which is significantly higher than the rest is from a different reference.

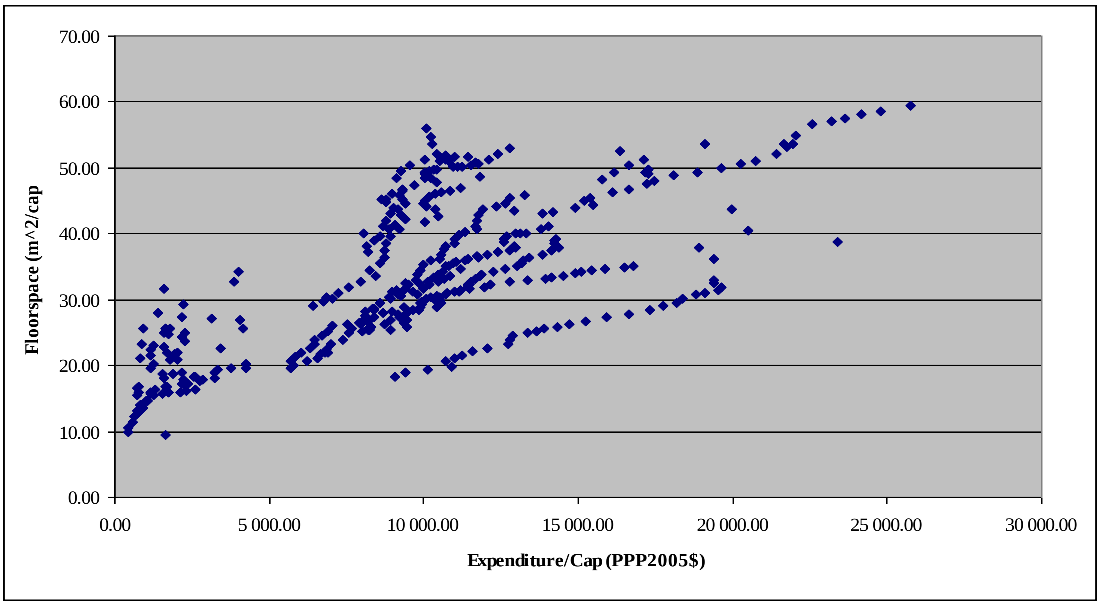

Figure 40. Floorspace vs. Expenditure (Global)

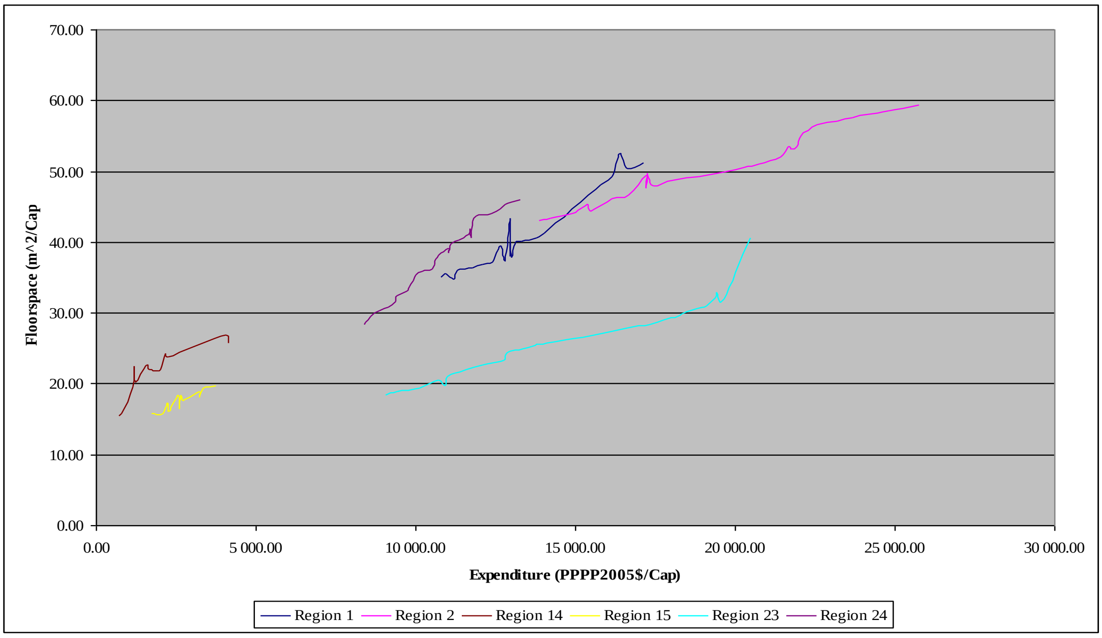

Figure 41. Floorspace vs. Expenditure (Various Regions)

Figure 42 shows the difference between urban and rural households for the Ukraine Region. Similar graphs can be drawn for East Asia however the higher floorspace in rural households is only witnessed in these two regions with Kazakhstan and Indonesia showing smaller rural households. Unfortunately urban/rural data is limited to these regions and does not exist for developed regions.

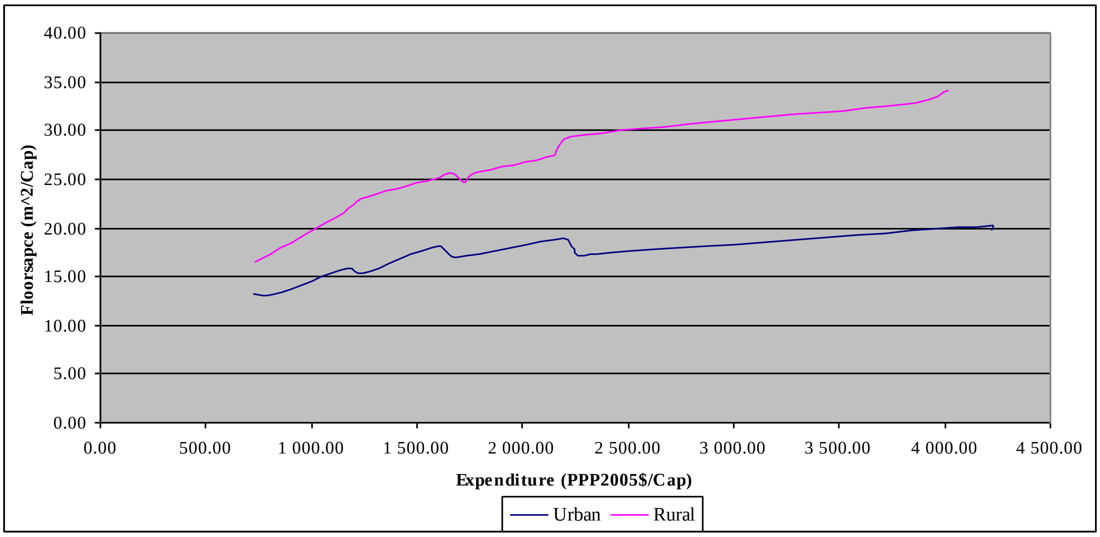

Figure 42. Floorspace vs. Expenditure, Urban/Rural Difference (Ukraine Region)

Figure 43 shows the factor by which the floorspace of each quintile deviates from the average (i.e. Floorspace for each quintile = $FS\_Fac_{Quintile}$ × Average). As expected, lower income houses have less floorspace, and this increases proportionally at higher income classes. It can be argued that in areas where there is high income inequality, the variation of floor space across income quintiles is going to be larger. Unfortunately there is not enough data to reaffirm this hypothesis.

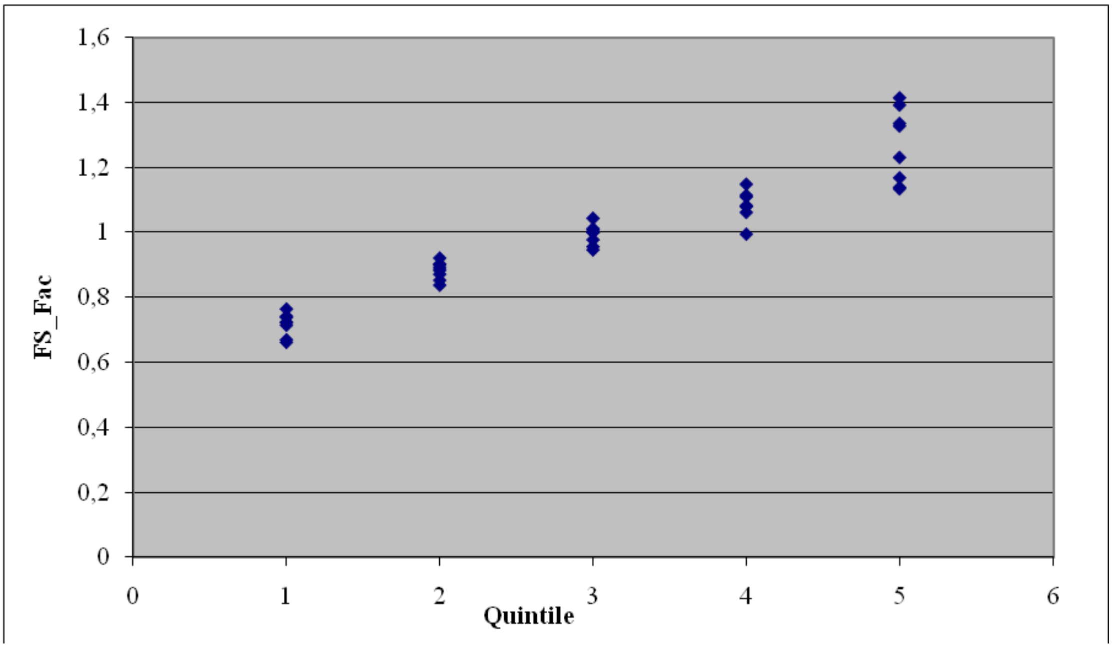

Figure 43. Factor by which each quintile deviates from the average

3.2.3 Analysis

In REMI, floorspace is determined purely as a function of household expenditures and behaves as an asymmetrical logistic growth, a Gompertz curve.

$$FS = \varphi_1 \cdot EXP(-\varphi_2 \cdot EXP(-(\varphi_3/1000) \cdot HHExp))$$

Equation 12. Gompertz Equation

Where:
FS = Floor Space
HHExp = Household Expenditures
φ_1, φ_2, φ_3 = Gompertz curve parameters

For the global model it would be possible to simply determine the parameters for different regions, albeit with a number of assumptions. It was instead attempted to determine if population density has an effect on floorspace and if this effect could be modeled. This approach allows for a more dynamic model.

The available data confirmed the hypothesis that population density ultimately affects floor space. When the data was separated into population density classes, at equal incomes, an increase in floorspace was witnessed with decreasing population density. To model this it was assumed that population density affects the φ_1, or the 'cap' of the logistic growth. Additional to this, the gompertz curve limits itself to φ_1, while in reality household sizes ten to grow indefinitely with income (a phenomenon visible in Figure 40 to Figure 42) albeit at a reduced rate. Taking this into account it can be seen that φ_1 has two components to it:

1. A linear increase with time
2. A logarithmic decrease with population density

Thus φ_1 is now modeled as:

$$\varphi_1 = (x_1 \cdot \ln(PD) + x_2) \cdot (1 + (\alpha \cdot HHExp)/35000)$$

Where PD is the Population density (per region, time). This φ_1 is substituted in Equation 12 in order to determine floorspace. The coefficients are shown in Table 18.

Table 18. Floorspace function coefficients

x_1	x_2	α	φ_2	φ_3
-2.964	60.577	0.125	1.341	0.125

Japan is a special case where the floorspace is surprisingly low for their household expenditures (even taking into account the increased population density). For all the Japanese data points, the modeled values are consistently ~10m^2/cap higher. Thus in the model, the calculated Japanese floorspace values are reduced by this much.

3.2.3.1 Urban/Rural Difference

For the urban/rural difference, since floorspace is dependent on income rural households tend to be smaller than urban according to the model. As shown in section 3.2.2, this is not true since it is generally expected that rural houses are larger than urban houses due to larger plots of land. This can be corrected by not determining Urban/Rural floorspace directly from a curve, but by adding an urban/rural multiplier to the total factor.

An important aspect of the model is that the urban and rural households, when weighted by urbanization level, should add up to the national average. If these factors are constant, then this criterion is not fulfilled. Ideally, as urbanization →1, the urban factor → 1. Data for China which is the only time series country available confirms this. Thus the Urban factor is going to be modeled as a linear relationship with urbanization. Then the rural floorspace can be determined. This linear relationship has to pass through the points (1,1) and (0.556, 0.872), the second point being the averages of the available data.

When the model is adapted in this fashion, the R^2 (urban and rural only) increases to 0.6779332, which shows that the improvement is quantitative as well as qualitative.

So the final Formulation for floorspace now is:

$FS_{Tot,,R} = (x_1 \cdot \ln(PD_R) + x_2) \cdot (1 + (\alpha \cdot HHExp_{R,Q})/35000) \cdot EXP(-\varphi_2 \cdot EXP(-(\varphi_3/1000) \cdot HHExp_{R,Q}))$

$UrbFac_R = 0.28925 \cdot Urbanization_R + 0.71705$

$FS_{Urban,,R} = UrbFac_R \cdot FS_{Tot,Q,R}$

$FS_{Rural,,R} = (FS_{Tot,Q,R} - (Urbanization_R \cdot FS_{Urban,Q,R}))/(1 - Urbanization_R)$

3.2.3.2 Quintile Allocation

In determining the distribution of floorspace amongst different income classes, the key assumption made is that the floorspace of higher income classes tend to be larger. This follows directly from the hypothesis that richer households tend to be bigger. The data reinforces this hypothesis. Since within the model, floorspace is a driver of a number of important end use functions (lighting, air cooling, air heating), how it varies amongst income classes (and is thus also dependent on inequality between these income classes) is important. However, there is not enough data to determine such a detailed relationship, so currently in the model, level of inequality is not taken into account, and instead each quintile is multiplied by a given factor. This is done by primarily assuming that the middle income class (Quintile 3) is the reference from which the others deviate (Q4 and Q5 being higher, and Q2 and Q1 being lower).

Having already calculated the Urban and Rural average floorspace (section 3.2.3.1), this is divided amongst the income classes based on a Floorspace Quintile Factor (FSQFac) which acts as a multiplier upon the urban and rural values. Based on the available data, this was formulated as:

$FSQFac_{R,URQ} = 1 + (0.131 \times (Quintile_{R,UR} - 3))$

This results in the following Factors:
Q1 = 0.738, Q2 = 0.869, Q3 = 1, Q4 = 1.131, Q5 = 1.262.

3.3 *Household Expenditure and Inequality*

This was determined to a large extent from the WDI database which can give for all countries time-based values of ‘*Household Final Consumption Expenditure per capita (constant 2000 US$)*. It was chosen to present the data in *constant* **PPP2005US$/*Cap.*** In order to do this, first the value was converted from the local currency unit to US$, then a deflator was used to convert to constant 2005US$. The *‘PPP conversion factor (GDP) to market exchange rate ratio’* from the WDI database was used then to convert the values to PPP. The 2005 PPP value was used to avoid errors rising from fluctuating PPP conversion factors.

Since the currencies are first converted to US$ and then deflated, an inaccuracy arises since it assumes that the inflation rates of the US are similar to those of the local currency. Especially for developing countries, where available, the local Consumer Price Indices were used.

The WDI Database does not breakdown household expenditures into the income quintiles, or amongst urban and rural households. Thus when this data was available from other sources, it was used. Regarding the use of other sources, certain points have to be made:

- Household Expenditures were used, in case only incomes were available, then the *Private Consumption* was divided by the *GDP per Capita* (both acquired from the WDI) in order to determine the savings rate plus taxes (i.e. the difference between incomes and expenditures).
- Currencies were converted using the www.oanda.com, historical exchange rates, averaging out the exchange rate for the entire year in question.
- US$ Deflators were acquired from the GPOaccess database at: http://www.gpoaccess.gov/usbudget/fy09/hist.html, specifically table 10.1 which lists the historical deflators.

Some cells remain blank. These include Urban/Rural areas where local authorities did not report expenditures (and the WDI2009 database does not differentiate between urban/rural). National values which remain blank include Burma, Gambia, Rwanda, Saint Lucia, Sierra Leone and the Turks and Caicos Islands. This is because the WDI database does not report values for these countries.

3.3.1 Remarks

IEA: Lots of data was extracted from the *30 years of energy use in IEA countries* report of the IEA. This data included per capita expenditures, however these per capita expenditures did not always agree with other sources (see Australia, Japan, United Kingdom and USA below). The IEA expenditures generally seemed to be consistently higher than other sources, thus its expenditure data was ignored and the WDI was used instead (except for the UK and USA, see below).

Australia: The Australian Bureau of Statistics (ABS) does provide a detailed household expenditure survey. The results here were presented as '*Total Goods and Services Expenditures'* per household per week per quintile in AU$. The same database also gives quintile households and populations (estimates based on sample), thus it was easy to convert the data into the useful unit. Unfortunately, these expenditure values do not agree with the IEA data. Since the values given from the ABS are relatively low (~$12,700/cap/yr) it is assumed that not all household expenditures are incorporated, thus they are ignored and WDI data is used instead. However, the distribution amongst quintiles which is witnessed is used with the WDI data.

A peculiarity with Australia was that even though the household income (presented per household) increased across the quintiles, between Q1 and Q2 there is a large increase in Cap/HH (1.47 to 2.20). This means the expenditure *per Capita* between Q1 and Q2 actually decreases!

Germany: The household expenditure data was retrieved from the WDI2009 database. It is interesting to note that from 1995-2005, there is a peak in 2001. Thus when analyzing the Germany data (especially in Cooking, Water Heating and Space heating) it may be more useful to view the data in chronology rather than expenditure.

Japan: The 2004 National survey of Family income and Expenditures give Household monthly total *Living expenditures* per quintile group. It is not clear if these living expenditures cover all household consumption expenditures, it is assumed that it does not as it produces an annual per capita expenditure of ~PPP2005$10.000 for 2004 while the WDI gives ~PPP2005$20.000, and the IEA data (value not available for 2004) gives results comparable to the WDI. Thus the WDI data is used. The WDI data was also split up per quintile as was done with Australia.

Malaysia: The 2007 yearbook of statistics gives monthly household expenditures for Total/Urban/Rural; however the values are *per household.* Household sizes cannot be determined anywhere, and the data from the Population and Housing Census (which would have the appropriate data) has to be bought.

Rwanda: Household expenditure data for Rwanda is not available either in the *Domestic and Health survey* or in the WDI database.

South Korea: 'Statistics Korea' gives detailed quarterly tables of incomes and expenditures, as well as incomes per quintile, however only for National and Urban levels. To convert the incomes per quintile to Expenditures per Quintile, the National average income was divided by the national average expenditures, and this factor was multiplied by the income quintile data.

Tanzania: The 2000 Household Budget survey gives household expenditures for Dar es Salaam, Other Urban, Rural and Total. Since Dar Es Salaam accounts for less than half of the urban population, only the urban data is used to represent the urban setting. Ideally weighing of the two should be done.

Turkey: Consumption expenditures by income quintile and by urban/rural/total are given in percentage of end use consumptions, not absolute monetary values. The household budget survey perhaps gives the monetary values but it has to be bought.

United Kingdom: The sources for expenditures were data from the Department of Energy and Climate Change (DoECC, 2009) (1970-2008, disposable income), the WDI database and the IEA (1970-1999). The IEA and DoECC data agreed while the WDI data was consistently about $2000 less. The DoECC data was used since it was available for most years.

USA: The Current Population Survey results give the mean household incomes for 1994 to 2008 for Total, Urban and Rural. These were converted to expenditures by the method mentioned above. For the quintile data, the *Historical Income Inequality tables* were used, converting the values to 2005$, per capita expenditures (from 2008$ per household income). Even though the data from these sources agreed with each other, the IEA expenditures did not, and WDI household expenditures are not available for the USA. This poses a problem as it is not known which sources should be used as the IEA does not differentiate between urban, rural and quintiles while US government data is not available for the years where useful information from the IEA can be gathered. If the GDP/Expenditures factor is ignored (i.e. capita = Income), then the data from all sources levels out. This is justified since in the USA tax rates are relatively low and the last few years have not witnessed many savings. The IEA values are used with the IEA data.

Zambia: The WDI2009 database was used to get the household final consumption expenditure per capita for 1980, 1990, 2000 and 2007 (in these years the *2000 Census of population and housing* gave the household sizes). It should be noted that the final consumption expenditure **falls** for Zambia.

Concerning the inequality between household expenditures between regions and urban/rural households, GINI coefficients are the determining factor. When GINIs were reported by the national census bureau they were used (based on income). Otherwise they were collected appropriately from the *UNU-WIDER World Income Inequality Database* (UNU-WIDER, 2008) the WDI database, or the GIDD dataset.

3.3.2 Inferences

The development of household expenditure is extremely important for the model to work as it is used one of the key drivers. The WDI database provides time series for Household per Capita expenditure for almost every nation; however it does not segregate between urban and rural regions, something which is important for the residential model. No expenditure information could be found for the Urban/Rural areas of Canada, Mexico, Central America, Brazil, Northern Africa, Western Africa, South Africa, Turkey, Middle East, Indonesia, Japan and Oceania. In all the regions where data exists, urban expenditures are consistently higher than rural expenditures, as expected, since there are generally more economic opportunities in urban areas.

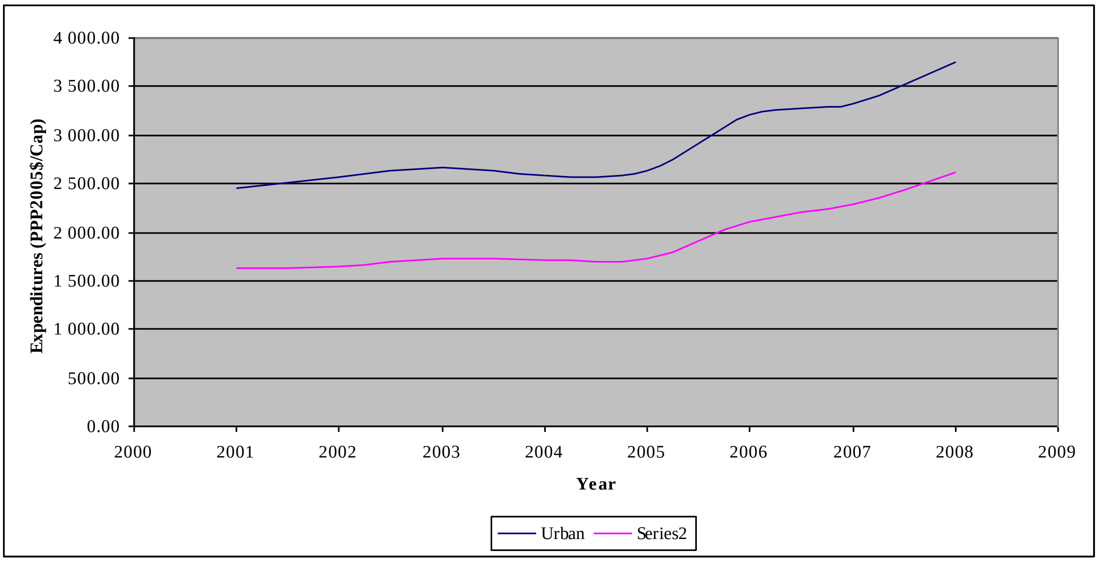

Figure 44. Expenditures vs. Year, Urban/Rural difference (Kazakhstan Region)

This urban/rural difference does not diminish with welfare (as demonstrated in Figure 44). In East Asia and the USA the difference between urban and rural expenditures has in fact increased with time as seen in the available data.

3.3.3 Analysis

In the REMI model, national expenditures are determined by calibrating WDI data to future TIMER household expenditure developments (per capita). There is also a RatioToAvg component which determines how urban and rural household expenditures are related to the national average. Following this, the national, urban and rural GINIS are used in order to determine the per quintile (urban and rural) per capita household expenditures.

In the global model it was decided to use a similar methodology. As explained in the previous sections, it was attempted to determine time series household expenditures from data sources, be that national accounts or international databases. However (as stated) there are difficulties and inconsistencies in the data, and additional to this,. The data has to be aggregated into 27 regions. All of these produce considerable difficulties in creating a new data set. Thus it was finally decided not to create a new household expenditure data asset but rather to use household expenditures calculated from the TIMER model which already exist for certain scenarios.

A number of sources exist to determine GINIs, primarily from the world bank, such as the GIDD database and the PovcalNet database which also offers time series (World-Bank, 2009; World-Bank, 2010). However a difficulty arises due to the fact that the model requires total, urban *and* rural GINIs, while these databases primarily give the total GINI only. Thus in the model, urban and rural GINIs **are kept constant**[6].

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[6] PovcalNet gives urban and rural data for China, India and Indonesia, as time series and these have been incorporated. Thus also the Urban/Rural GIDD calculated GINIs have been ignored.

A further important factor in REMI and REMG is the r*atio to average* (RatioToAvg) which describes the ratio of the expenditures of the urban and rural persons to the average expenditures of the region (on a per capita basis). The RatioToAvg and GINI for all regions for 2005 were calculated using the GIDD database. Following, it was assumed that the RatioToAvg is a function of $\mathrm{GINI}_{\mathrm{Tot}}$, and as $\mathrm{GINI}_{\mathrm{Tot}} \rightarrow 0$, RatioToAvg → 1. Thus using the PovcalNet GINI time series, a time series for RatioToAvg could also be determined.

4 Appliances

On average, electricity consumption of households account for over 25% of total electricity consumption, with traditional large appliances accounting for most of this, with home entertainment and communication appliances getting an increasing share. Furthermore, due to increased use of household appliances, there is an observed increase in residential electricity use in the order of 2% per year (Tyler *et al.*, 1990; Waide *et al.*, 1997; Ghisi *et al.*, 2007; Bogdan *et al.*, 2008; Firth *et al.*, 2008; IEA, 2008). Thus data concerning ownership rates and unit energy consumptions of appliances was sought. Both ownership rates and unit energy consumptions are to be modeled as a function of household expenditures per capita.

The appliances sector has expanded compared to REMI in order to cater for developed countries. In the REMG model appliances are aggregated into four groups, with one major energy consuming technology as the representative item for this cluster:

1. Space cooling. Represented by fans, air coolers and air conditioners.
2. Food storage and processing. Represented by refrigerators and microwaves.
3. Washing and cleaning. Represented by washing machines, clothes dryers and dish washers.
4. Entertainment and communication. Represented by televisions, VCR/DVD players and Personal computers.

Additional to these clusters there is a ‘miscellaneous’ appliance energy use which accounts for other appliance energy use which cannot be attributed to the eleven appliances listed above. In sections 4.1.1 and 4.1.2, data concerning clusters 2, 3 and 4 will be discussed. Data for cluster 1 was not gathered as the methodology used has been kept the same with REMI and is based on the work of Isaac and van Vuuren (Isaac *et al.*, 2009).

4.1 *Ownership Rates*

In the initial search for data, ownership rates of certain appliances were sought. This was broken down to ownership rates (units/hh) of: Fans, Air conditioners, Refrigerators, Microwaves, Washing Machines, Clothes Dryers, Dish Washers, Televisions, DVD/VCR players, Personal Computers and Mobile Phones. Ownership rates were primarily determined from Household Budget Surveys, though some data was acquired from scientific papers and reports. In many cases, ownership as a percentage of houses who own the appliance is given, rather than number of appliances in the household. This is not useful for developed countries as a 99% ownership rate does not necessarily mean that there are 99 units in 100 houses. However, when such ownership rates were low, or for developing countries, it is assumed that on average there would be 1 unit per household, thus these rates would be used.

For countries where electrification rates are below saturation, appliance ownership has to be corrected for electrification. Reported values of appliance ownership are absolute, yet houses with no access to electricity cannot possibly have these appliances. In this analysis the absolute ownership rates as well as the electrification rater determined by an existing electrification model (Schers, 2009) are used. All analysis done in section 4.1.3 is done with ownership corrected for electrification.

4.1.1 Remarks

Brazil: The household residential surveys give ownership rates for many appliances for urban households (**not** rural). Also, data comes from a number of sources, which show big variance in observations. This data should be used with caution.

Moldova: Washing machines are reported as “Mechanical” and “Automatic”, these two have been summed together.

Mexico: Urban/Rural ownership rates exist for a number of appliances (Scheinbaum *et al.*, 1996; Rosas-Flores *et al.*, 2010), but the household expenditures for urban/rural are missing.

Poland: The *2008 Household Budget Survey* (CSO-Poland, 2009a), gives National ownership rates for various appliances per income quintile (Table 40) and the *2008 Incomes and Living Conditions of the Population Report* (CSO-Poland, 2009b) has ownership rate per urban/rural. Yet these two sources do not agree with each other.

Televisions: The *World Resources Institute* has a number of databases on variables for human well being, amongst those a database for ownership of televisions per 1000 persons for almost all countries with data points between 2000 and 2007 (WRI, 2007). When household sizes were available for the available country/year this data was converted to TVs/household.

4.1.2 Inferences

Appliance ownership is very important in the residential model. Ownership rates multiplied by unit energy consumptions (UEC), see section 4.2, gives the electricity use of these appliances. Ownership rates for major appliances have been found for a number of appliances and regions. Appliances looked into were: Fans, air-conditioners, refrigerators, microwaves, washing machines, clothes dryers, dish washers, televisions, DVD/VCR players, personal computers and mobile phones. Figure 45 to Figure 48 show the ownership rates vs. expenditures for refrigerators, washing machines, dish washers and televisions. It can be seen that refrigerators tend to settle at just over one unit per household, washing machines and dish washers just under one/hh, and televisions at around three/hh. Yet the expenditure level and the (saturated) ownership rate vary per region and appliance.

A tricky aspect of appliance ownership and time series is that appliances become more and more popular with time. Thus relationships with income should be treated cautiously. For instance at an expenditure level of approximately 7000$/yr, in the UK microwave ownership was at 0.3Units/HH, while in Central Europe it was about 1. This does not mean that central Europeans enjoy microwaves more, but that when the UK had those income levels, microwaves had not broken into the market.

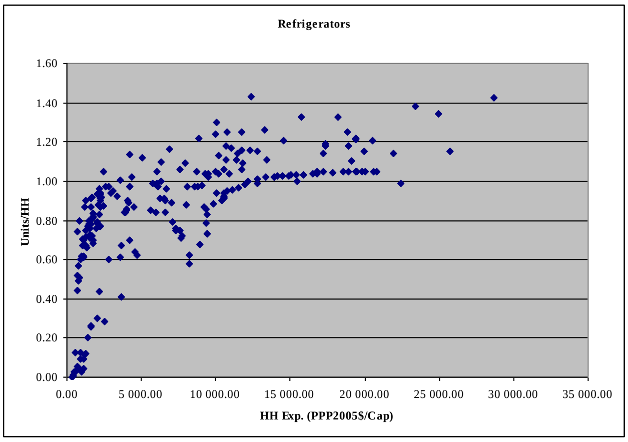

Figure 45. Refrigerators

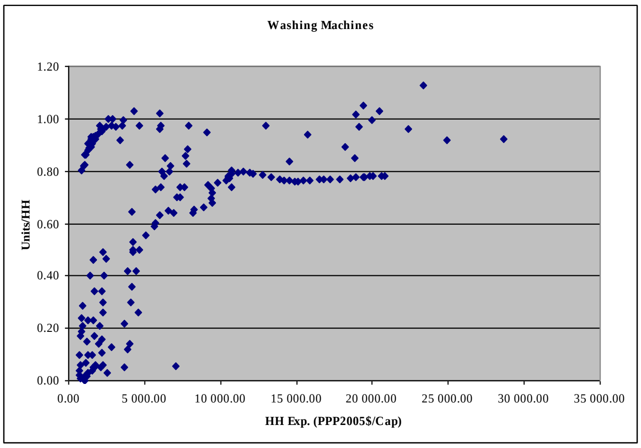

Figure 46. Washing Machines

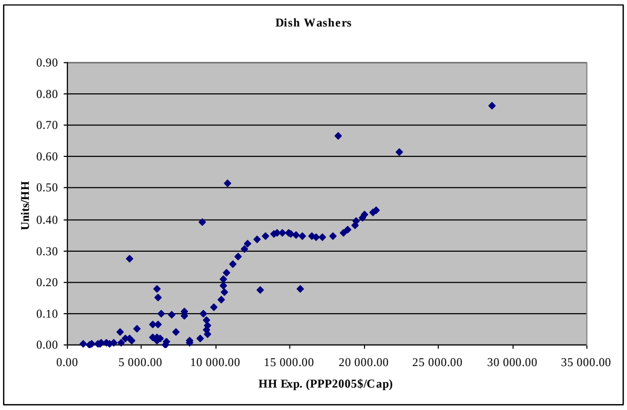

Figure 47. Dish Washers

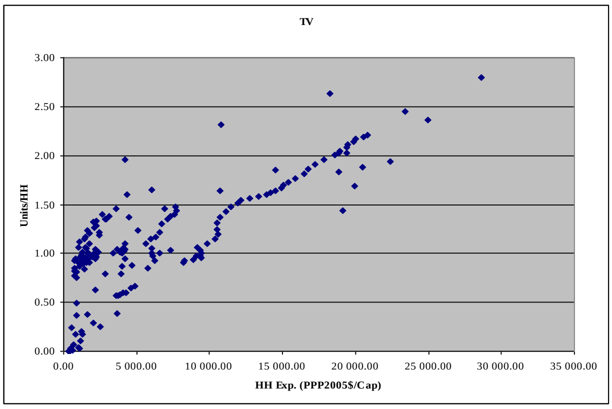

Figure 48. Televisions

4.1.2.1 Urban/Rural Difference

An important characteristic is the difference in ownership rates of various appliances between urban and rural households. It is assumed that especially at low expenditure regions, rural households will have fewer appliances than urban households, with this difference diminishing with increasing welfare. The availability of data (at least one data point) in order to study this hypothesis is summarized in Table 19. It should be noted that an Urban/Rural difference is not always observed, and is region specific.

Table 19. Data availability concerning appliance ownership per urban-rural

Appliance	**Region**
Fans	W. Africa, E. Asia, Rest of SE. Asia, Rest of S. Africa
Air Conditioners	Mexico, W. Africa, E. Asia, Rest S. Africa
Refrigerators	Mexico, Brazil, Rest S. America, W. Africa, E. Africa, Ukraine, E. Asia, Rest S. Asia, Rest S. Africa
Microwaves	Rest S. America, C. Europe, Ukraine, Rest S. Asia, Rest S. Africa
Washing Machines	Mexico, Brazil, Rest S. America, W. Africa, C. Europe, Ukraine, East Asia, Rest S. Asia, Rest S. Africa
Dish Washers	C. Europe
Televisions	Mexico, Rest S. America, W. Africa, E. Africa, Ukraine, E. Asia, Rest S. Asia, Rest S. Africa
DVD/VCR Players	Rest S. America, W. Africa, E. Africa, Ukraine, Rest S. Asia, Rest S. Africa
Personal Computers	Rest S. America, E. Africa, C. Europe, Ukraine, Rest S. Asia, Rest S. Africa

Curves for urban rural difference for some appliances are shown in Figure 49 to Figure 51. These curves are based on data from the Ukraine Region and East Asia where most data points are available. They show that the expenditure levels at which the urban/rural difference diminishes varies for each appliance, with televisions reaching similar levels at very low expenditure levels (~$1,500), but washing machines, refrigerators and air conditioners at much higher (>$3,000). It is also worth noting that the expenditure level at which appliances saturate, and the level at which they saturate varies for each region, this is obvious in Figure 49 and Figure 50 where both regions have been superimposed. Televisions seem to be more popular in East Asia than Ukraine. This does not hold true for more utility-based appliances such as refrigerators where both regions seem to saturate at more comparable levels.

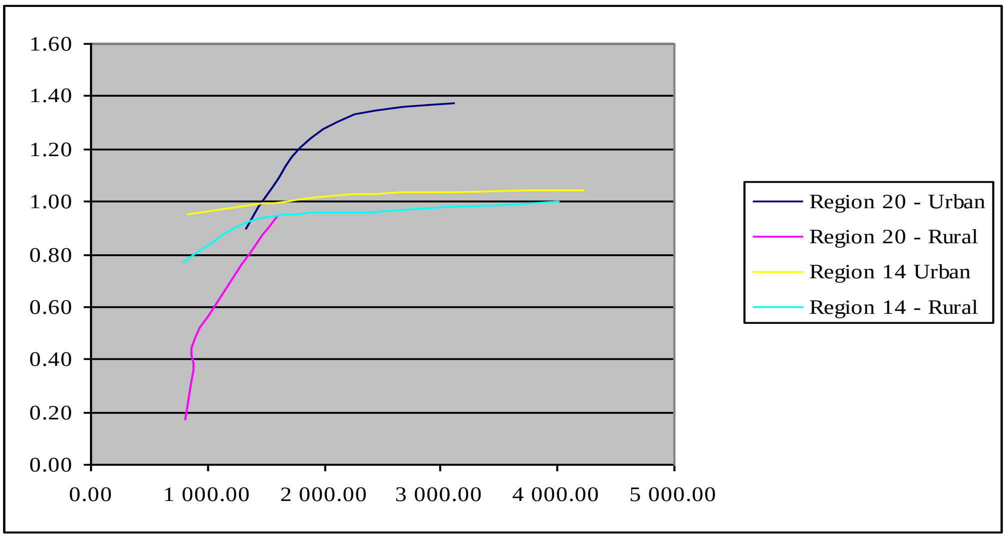

Figure 49. Urban/Rural Televisions for regions 20 (E. Asia) and 14 (Ukraine)

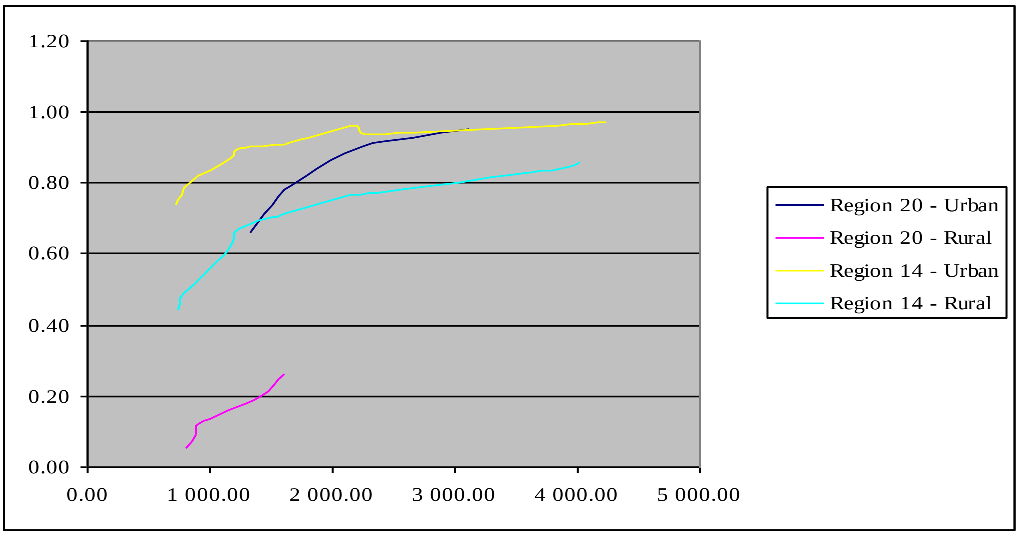

Figure 50. Urban/Rural Refrigerators for regions 20 (E. Asia) and 14 (Ukraine)

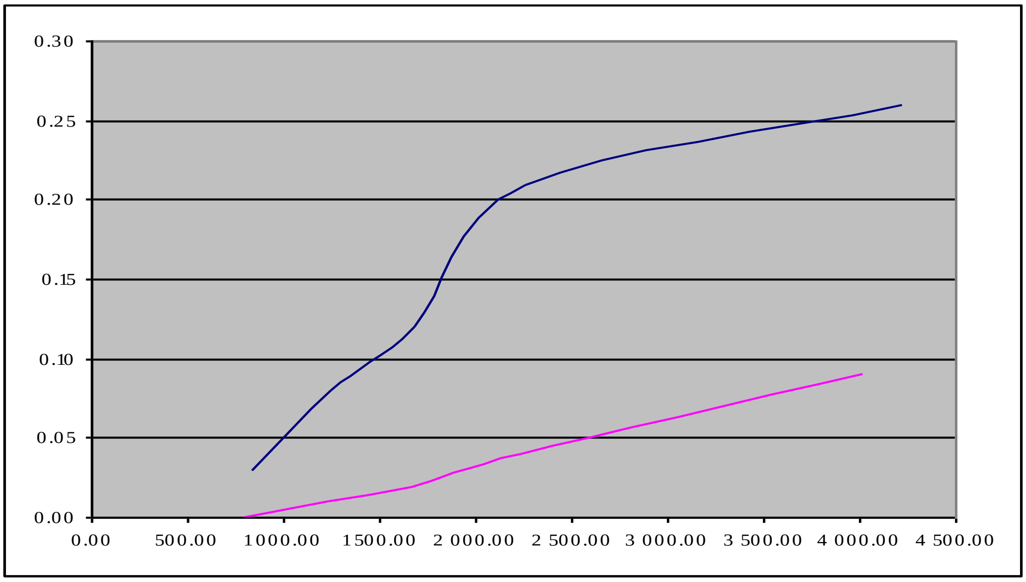

Figure 51. Urban/Rural Personal Computers (Ukraine)

4.1.3 Analysis

First and foremost, before analyzing the data, it has to be corrected for electrification levels. Since the data exists over a wide range of regions, demographics and time, electrification levels across all of these dimensions are also required. Thus the results of the previously developed electrification model (Schers, 2009) were used to get the required electrification levels. At this stage, difference in electrification levels amongst income groups was assumed to be zero.

For Fans, Air Conditioners and Air Coolers (section 4.1.3.1), the exact same methodology as in REMI was kept except for adjusting some coefficients. In REMG, more appliances have been modeled since as households become richer, there is a larger variety of appliances which are important. Thus additional to Fans, Air Conditioners, Air Coolers, Refrigerators, Washing Machines and Televisions (water heaters are not modeled in REMG, see section 6.3.2), in REMG the diffusion and energy consumption of Microwaves, Clothes Washers, Clothes Dryers, VCR/DVD players and Personal Computers has also been modeled. Additional to these, there is also an extra ‘Other/Miscellaneous’ which accounts for the extra electricity demand of rich households due to gadgets, peripherals and other small electric appliances which cannot be modeled bottom up due to data constraints .

Appliance diffusion is dictated by a number of dynamics. The cornerstone is that as households get richer, the aggregate ownership of appliances per household increases (*Diffusion*). Furthermore, on an aggregate level, there is a maximum amount of certain appliance a household will have (*Saturation*). Within REMI and REMG, the diffusion rate is assumed to follow a gompertz curve, i.e. an asymmetric logistic growth.

$$Diff = \varphi_1 \cdot \mathrm{EXP}(-\varphi_2 \cdot \mathrm{EXP}(-(\varphi_3/1000) \cdot \mathrm{Y}))$$

Equation 13. Simple Gompertz function

Where:
Diff: The diffusion of the appliances, units/hh
φ_1, φ_2, and φ_3: coefficients, to be determined from a regression

Y: Household expenditures in 2005$ppp/cap.yr.

The existence of household expenditures for urban, rural and respective quintile demographics (as explained in section 3.3) means diffusion of appliances can also be determined for these demographics, though as explained later the coefficients for urban and rural households may differ.

Though the gompertz function adequately describes the slow initial diffusion from 0 ownership and subsequent rapid growth, it does not describe certain other dynamics which a global model should take into account. As appliances get cheaper, both D*iffusion Rates* and *Saturation Levels* should be adjusted. Refrigerators (or all appliances for that matter) today are cheaper than what they were thirty years ago, so the poor of today tend to have refrigerators, while thirty years ago in was only the richest. Also, with time, the saturation levels tend to increase, so this has to be accounted for as well.

To account for these, a number of modeling techniques have been used in REMG, depending on the properties and data availability of the appliances. The choice of which method was to be used for each appliance is based completely on if the available data indicated towards that dynamic. These diffusion dynamics include:

1) *Sat Price*: The saturation level increases with time based on the price development. This is what was used in REMI, and in REMG it is used for **Fans**, **Air Conditioners** and **Air Coolers** (see section 4.1.3.1). For a critique on the use of this method see section 10.3.2.

2) *Simple Gompertz function*: This assumes that the diffusion is dependant only on the income level and Equation 13 is used directly. This tends to be true for expensive non-necessary appliances such as **clothes dryers** and **dish washers** (section 4.1.3.2). Even though the simple gompertz function may not be completely appropriate, it was used if the data did not point towards greater appropriateness of the other methods.

3) *Varying diffusion rate and Saturation level*. This method was used to describe **refrigerators**, **washing machines** and **televisions** (section 4.1.3.3), and attempts to model within a single equation a time-based variation in diffusion rate and saturation level. So even though the diffusion is determined on household expenditures, the diffusion at a given expenditure will vary over time. This has only been done for these three appliances because setting up this equation requires a vast amount of data across many regions and over large time spans. The formulation is based on the gompertz function but with a variable saturation point and growth rate (coefficients φ_1 and φ_3 respectively in Equation 13).

$$Diff_{R,App} = (m_{App}(t\text{-}1970)+c_{App}) \cdot \mathrm{EXP}(-\varphi_2 \cdot \mathrm{EXP}(-((\alpha \cdot \ln(t) + \beta_{App})/1000) \cdot Y_R))$$

Equation 14. Adapted Gompertz function for time dependent saturation and growth rate

4) *Income Delay:* This method was set up to model new appliances which in the past were very expensive and thus rarely in use, while today play a significant role in appliance electricity consumption. These include **DVD/VCR Players** and

Personal Computers (section 4.1.3.4). There is an added factor to the gompertz function which describes at what household expenditures diffusion of this appliance commences (*Income Delay)*. This income delay decreases with time as these appliances became more and more mainstream. To an extent, this method is a simplification of Equation 14, where the logarithmic function dictating the saturation rate has been replaced with a simple linear decrease. Note that in this method the *Diffusion Rate* and *Saturation Level* do not change with time, only the expenditure level at which diffusion **begins** changes, and that decreases with time reaching a minimum of 700US$_{2005PPP}$.

$$\mathit{Diff} = \varphi_1 \cdot \mathrm{EXP}(-\varphi_2 \cdot \mathrm{EXP}(-(\varphi_3/1000) \cdot (Y - \mathit{Income\ Delay})))$$

Equation 15. Adapted Gompertz function to allow for income based delay

As stated, the choice of which of these methods is used for each appliance depends on if the data shows that this dynamic is valid. In many cases, there simply was not enough data to test the underlying hypotheses of each method, and so a method which could not be validated, could not be used. Furthermore, as mentioned the third method required huge amounts of data in order to come up with meaningful coefficients, something which simply did not exist for many appliances. For instance the fourth method was created because there was not enough data to confirm that the third method was appropriate, or even to determine the coefficients, for DVD/VCR Players and Personal Computers. How exactly each method was used in REMG is explained in the following sections.

Coming up with individual coefficients for each region is almost impossible. That would require data for each appliance, over a significant amount of time, for urban and rural households, and covering the growth of each appliance towards saturation, something which obviously does not exist for countries which are not saturated, but also lacks even for developed countries. Thus, in determining the coefficients, all the global data was put together and a regression was performed using the SPSS statistical analysis program. These coefficients are treated as *global generic'*. In performing model calibration (see Appendix II) these coefficients were tweaked for each region in order to make the curves pass through whatever data points already exist. Since the data presented earlier shows that urban and rural households follow different patters, these coefficients are demographic specific.

4.1.3.1 Fans, Air Conditioners and Air Coolers

In REMI, a variable called the *Saturation Price* is defined. This saturation price has a value between 0 and 1 and dictates the highest possible saturation. In REMI this is based on the price development (CPI) of fans and the deflator:

$$\mathit{SatPrice} = \mathrm{EXP}(-0.15 \times \mathrm{CPI}_{\mathrm{Fans}} / \mathrm{Deflator}_{2000})$$

Equation 16. SatPrice in REMI

It was decided to follow the same method on a global scale, since the energy consumption for these appliances is determined not on ownership rates, but rather on a saturation point and then UEC is climate and income dependant (thus saturation **should not** exceed 1).

The first step was to confirm that the dynamic adopted for India makes sense on a global scale. The CPI for *non-food* and *non-energy* products (and thus to a large extent a proxy to household appliance expenditures) for 1970 to 2006 were downloaded from the online OECD database, and the GDP deflators of the US were used. When used with Equation 16, the expected result of a constant *SatPrice* ≈ 1 resulted. This simply means that in OECD countries price changes have not dictated the saturation points (as is true for poor countries).

Initially, it was decided to use the India dynamic, as well as the fact that as countries get richer *SatPrice* → 1, to describe developing countries. Thus the REMI development of *SatPrice* was modeled as a function of household expenditures. This resulted in:

$$SatPrice_{R,T} = 0.054/(0.053839 + \mathrm{EXP}(-(3.187/1000) \times (\mathrm{HHExp\_ppp}_{R,T} - 250)))$$

Which has the limits of 0.024 at HHExp_ppp = 0 and 1 at HHExp_ppp = 3000. Unfortunately, when the model was run with this development for SatPrice, problematic results came out for very poor regions. This is because an income based approach for SatPrice ignores that certain appliances get cheaper and thus across time ownership of at the same income level increases. This resulted in very low ownership rates for very poor regions for a very long time to come. Thus SatPrice has been kept the same as REMI, something which has to be corrected (see section 10.3.2).

4.1.3.2 Clothes Dryers and Dish Washers

Though some data concerning the ownership levels of these appliances does exist, it was not plentiful enough to assess time/price based dynamics. Figure 52 and Figure 53 show the available data points for clothes dryers and dish washers respectively. The appropriateness of the gompertz function is apparent, especially for dish washers.

The generic regression coefficients for Equation 13 are shown in Table 20.

Table 20. Generic coefficients for gompertz equation, Clothes dryers and Dish washers

	Clothes Dryer	Dish Washer
φ_1	0.7	0.802
φ_2	4	9
φ_3	0.15	0.15

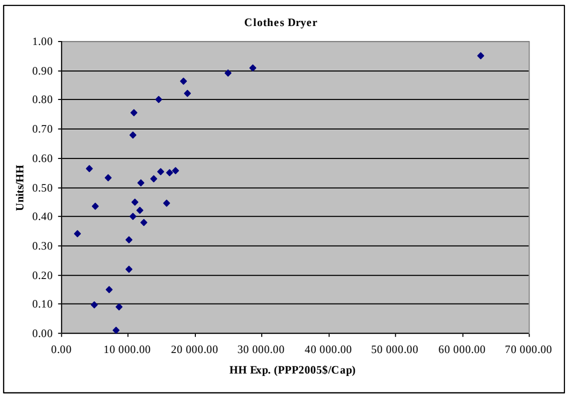

Figure 52. Clothes Dryers

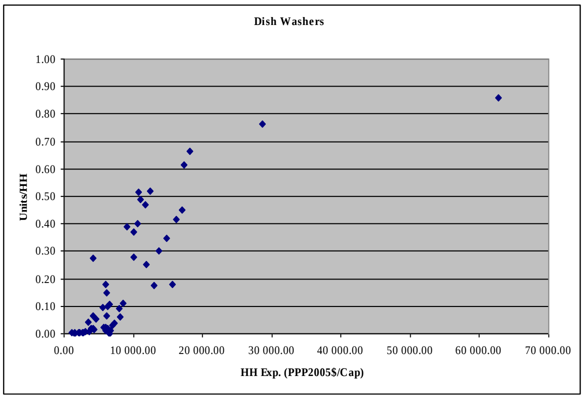

Figure 53. Dish Washers

4.1.3.3 Refrigerators, Washing Machines and Televisions

These three appliances provided the most data points, with ownership rates available for a multitude of regions covering urban and rural households and even quintiles. A number of observations could be made. First and foremost, the basic hypothesis that as household expenditures increase, appliance ownership goes up is clearly visible in the data. However, a further observation can be made as well concerning the rate at which diffusion takes place and its dependence on which point in time we are located. Since the real price of appliances tends to go down with time (Weiss *et al.*, 2010), the diffusion rate depends on *when* appliance uptake commences. This hypothesis is validated when comparing the UK data with other poorer regions. The UK data displays that certain appliances where purchased at higher expenditures (compared to other regions), simply because it was more expensive for them to buy these appliances when their expenditures where lower. The conclusion is that the rate of diffusion increases with time, which is particularly important when analyzing the difference between the poor and the rich within a single region. Thus no single curve (per region) can illustrate appliance diffusion, but rather a time based surface would probably explain the phenomenon better. Since for these appliances there is no evident saturation point (ownership goes well beyond 1) and since energy consumption is calculated via *ownership rate* multiplied by *unit energy consumption*, the same method used in the previous appliances outlined could not be employed.

An attempt was made in order to determine such a surface. Global ownership rates were broken down into time classes and the individual Gompertz curves were determined. The hypothesis is verified as shown in Figure 54, which also shows that there is a limiting diffusion rate.

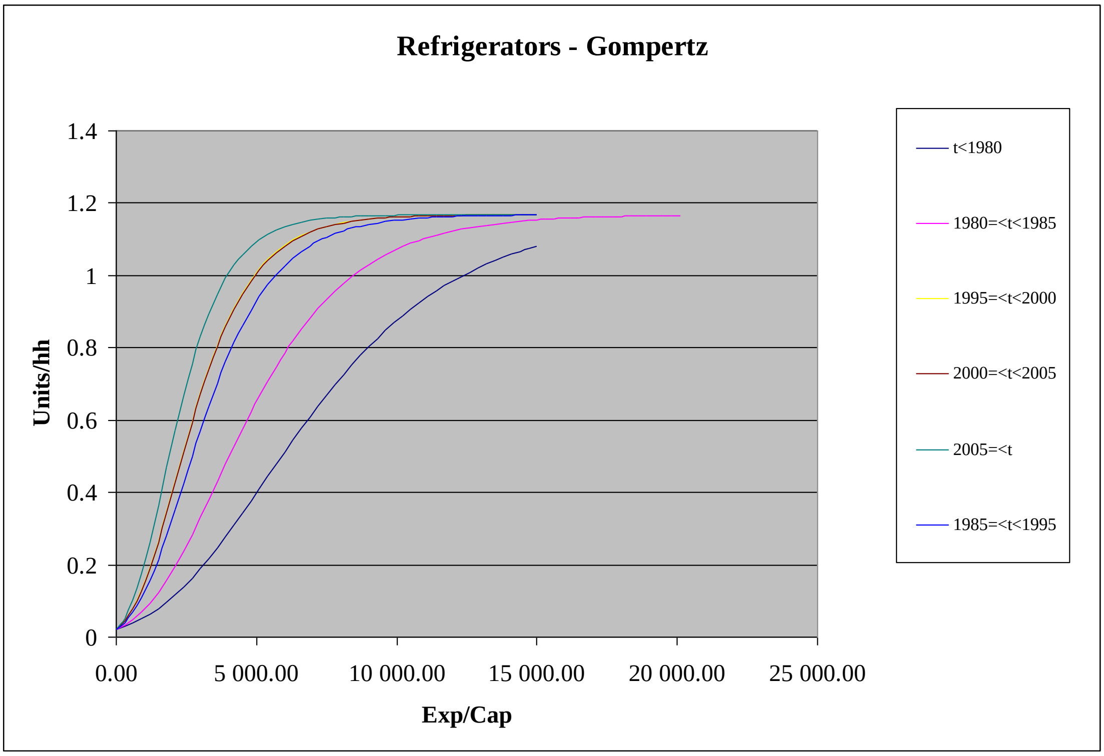

Figure 54. Gompertz curves for refrigerator diffusion in different time periods[7]

This increased diffusion rate with time means that the φ_3 of the Gompertz curve is a function of time. This has been modeled as a logarithmic function in the form:

$$\varphi_3 = \alpha \cdot \ln(t) + \beta$$

Equation 17

A logarithmic description for φ_3 was chosen since as can be seen in Figure 54, there is a saturation of the time (price) influence on diffusion rates.

Additional to this, a saturation cap is unlikely since observed data shows that even though a sigmoid curve is followed, diffusion still increases with income (or time), albeit at a much slower rate, thus an extra function has to be added to the gompertz curve which increases φ_1 with time. The hypothesis is that increased appliance purchase after the saturation point does not depend on expenditures but only on the fact that the appliances get cheaper, thus this ‘inflation’ of saturation point is a function of time. This was modeled as a linear function in the form:

$$\varphi_1 = Sat = \mathrm{m}(t\text{-}1970)+\mathrm{c}$$

Equation 18

Where ‘m’ is the rate of increase, t is the year and ‘c’ is a constant. Thus the final form of the diffusion curve has now changed to:

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[7] In making these curves it has to be noted that a constraint was put for the saturation value (φ_1=1.168), and the *x* positioning of the curve (φ_2=4). Though these constraints affect the shape of the curves, they do not affect the hypothesis that rate of diffusion increases with time.

$$\mathit{Diff}_{R,App} = (m_{App}(t\text{-}1970)+c_{App}) \cdot EXP(-\varphi_2 \cdot EXP(-((\alpha \cdot \ln(t) + \beta_{App})/1000)\cdot Y_R))$$

Equation 19. New diffusion relationship for refrigerators and washing machines

The coefficients of Equation 19 are shown in Table 21 ($\varphi 2 = 5$ in all cases). Note that these are generic patterns to generally describe the behavior, and during calibration these coefficients are refined so that each region is represented according to its data (Appendix II).

Table 21. Coefficients for refrigerator and washing machine diffusion rates

	Refrigerators	*Washing Machines*
m	0.007	0.003
c	0.9	0.8
α	30.559	17.719
β	-231.6	-134.2

This approach was used for refrigerators and washing machines which displayed such time based diffusion rate behavior (Figure 55 and Figure 56). However, this was not noticed with television data. In fact television diffusion barely showed any relationship with time but was rather more dependant on regions. Some regions displayed very high diffusion at low incomes while others showed relatively low diffusions at high incomes. Thus televisions, unlike refrigerators which are more utility based, are based more on preference. The lack of observable time difference could be because the price-dependency of diffusion could have already saturated (as Figure 54 shows happened for refrigerators in the 1990's) prior to the dates for which data is available (detailed data exists only post-1995). Whatever the case, it is assumed that currently diffusion of televisions depends more on preference rather than price.

To model this, two different curves were set as *high* and *low* preference (regions are allocated as either *Low* or *High Preference* based on available income series data and summarized in Table 22). Another methodological problem with televisions was that there doesn't seem to be any saturation level, with quintile data from the USA and Moldova displaying that any saturation level simply inflates with time. Thus the two curves were initially made with a saturation level of $\varphi_1 = 1.5$. Determining a linear relation ship for the increase in saturation level as was done for refrigerators and washing machines would result in a very high ownership rate since the gradient (*m* in Equation 18) is significantly higher for televisions. Thus it was chosen to use a logarithmic function which would show an initial large increase in saturation level with that leveling out with time.

$$\mathit{Diff}_{TV} = (\alpha_{Pref}\cdot\ln(t\text{-}1970) + \beta_{Pref}) \cdot EXP(-\varphi_2 \cdot EXP(-(\varphi_{3Pref}/1000)\cdot Y_R))$$

Equation 20. New diffusion equation for televisions+

The coefficients of Equation 20 for the *Low* and *High* preference curves are shown in Table 23. Also shown is the R^2 value of the predicted diffusion rates compared with the existing data. Note that the only parameter which changes is the φ_3.

Table 22. Allocation of regions to Low or High TV preference based on data

	Regions
Low Preference	Mexico, C. America, Rest S. America, S. Africa, W. Europe, C. Europe, Oceania, Rest S. Africa
High Preference	Canada, USA, E. Africa, Ukraine, Kazakhstan, S. Asia, Korea, E. Asia, SE. Asia, Japan, Rest S. Asia

Table 23. Coefficients for television diffusion rates

	Low Preference	*High Preference*
α	0.292	0.292
β	1.148	1.148
φ_2	3	3
φ_3	0.212	0.808
R^2	0.812212057	0.99156502

Figure 55 to Figure 58 display the surfaces created for the appliances.

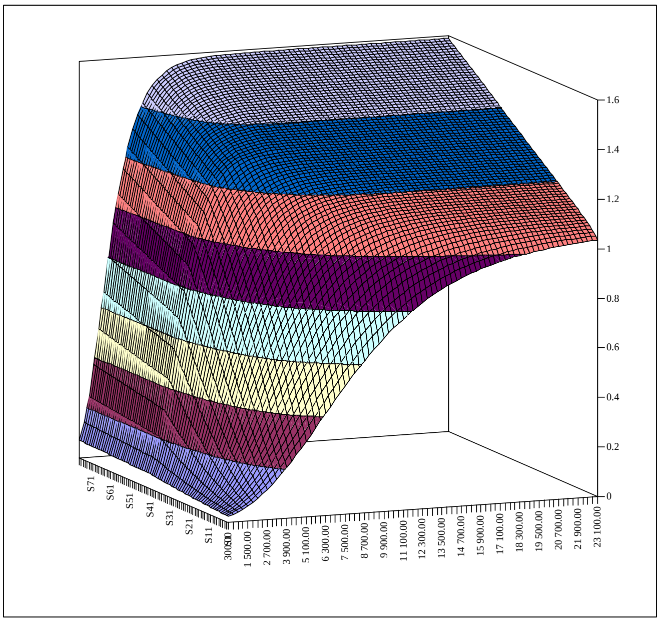

Figure 55. Refrigerator Surface

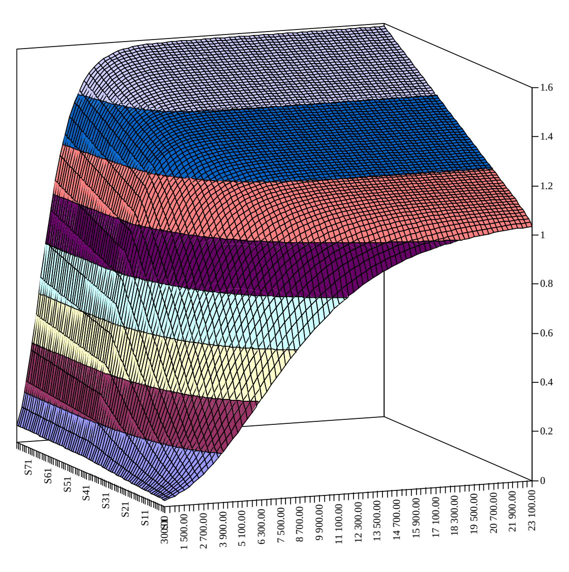

Figure 56. Washing Machine Surface

Once again, the coefficients are adapted during calibration. For regions where data does not exist in order to determine if the region follows a *high* or *low* TV preference, an assumption is made that they will follow the low preference.

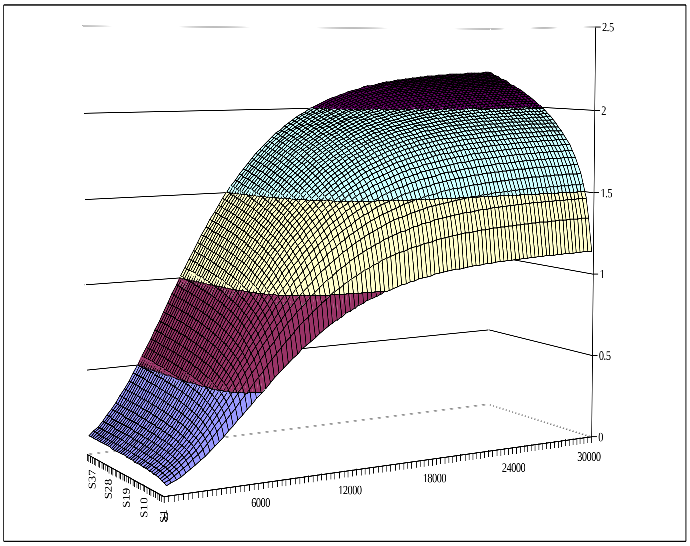

Figure 57. Television Low Preference Surface

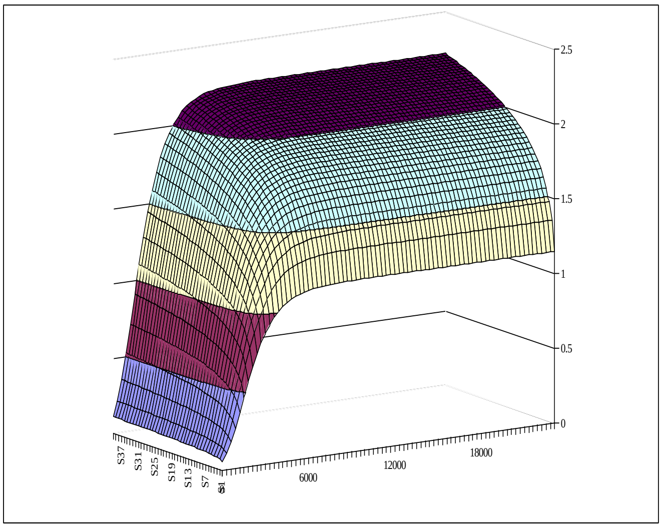

Figure 58. Television High Preference Surface

4.1.3.4 Microwave ovens, VCR/DVD players and Personal Computers

Technological progression as well as increased leisure has led new non-necessary appliances enter households and thus increase household electricity consumption. Many of these appliances did not exist thirty years ago except for in the richest households where they were seen as somewhat of a status symbol. Due to reduction in their prices and recognition of their utility within modern society, today they have become almost standard within households of medium income. Since, for validation purposes, REMG is to reproduce data from 1971-2007, this dynamic of appliances gradually entering lower and lower income households has to be included.

Figure 59 shows the diffusion of microwave ovens versus household expenditures for the UK and a host of developing and transition countries (including urban and rural households). As can be clearly seen, in the UK microwave oven uptake started at high expenditures, but note that the UK data starts in 1981, when the UK was significantly richer than the other countries (who still have not reached that affluence). It can also be seen that the later data points for the UK coincide with possible curves extrapolated from the ‘later’ developing country data points. This indicated a reduction in microwave oven price with time.

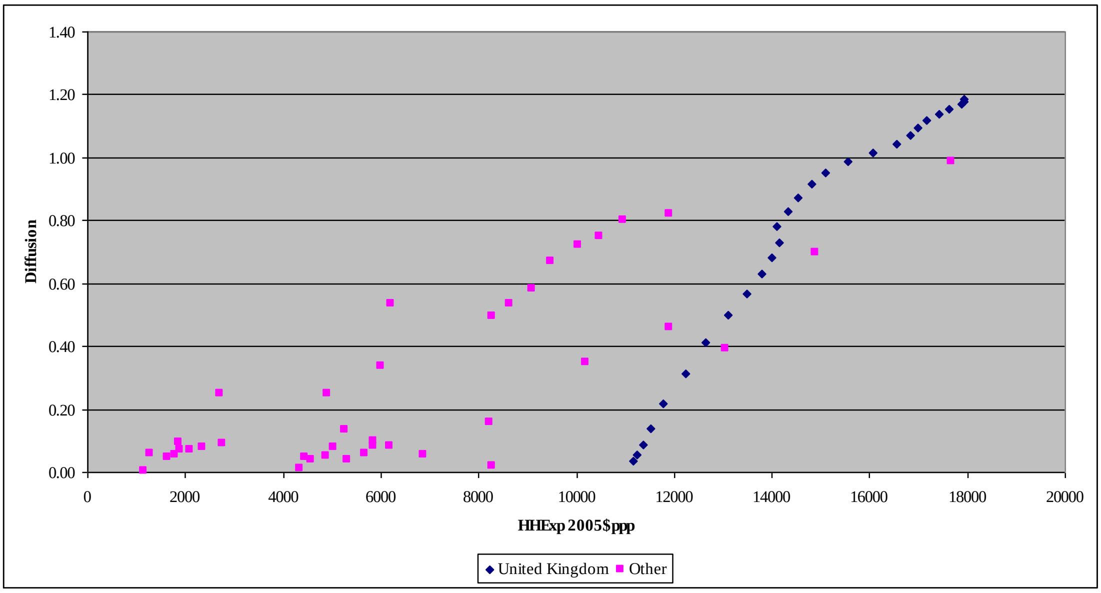

Figure 59. Diffusion of microwave ovens for the UK and developing countries

Since detailed enough data is not available to repeat the process employed for refrigerators, washing machines and televisions, a simpler more arbitrary method was used. The gompertz function was adapted simply so that the household expenditure at which diffusion takes place decreases linearly with time. This is represented in Equation 21 by the *Income Delay.*

$$\mathit{Diff} = \varphi_1 \cdot \mathrm{EXP}(-\varphi_2 \cdot \mathrm{EXP}(-(\varphi_3/1000) \cdot (Y - \mathit{Income\ Delay})))$$

Equation 21. Adapted Gompertz function to allow for income based delay

This income delay starts at 10 000$\$_{2005}$ppp in 1970 and linearly falls to 700$\$_{2005}$ppp in 2000, where it remains.

4.1.3.5 Demographic Allocation

The mathematical techniques described in the previous paragraphs explain how each appliance is managed as a function of household expenditure (and in most cases time as well). As explained in section 3.3, household expenditure is modeled for total, urban, rural, urban quintiles and rural quintiles. In REMI, diffusion is modeled on a quintile level (urban and rural). Then the urban and rural averages are determined from their respective quintiles, and then urban and rural are used to determine the total. This was possible in REMI due to a plethora of quintile data available for India. In the case of REMG, this was not true so a different method had to be chosen. This could either be done via modeling the total and then disaggregate it to urban/rural and then quintile levels, or determine on an urban/rural basis, from there determine the total and quintile values. Due to the availability of urban and rural data and the very region specific urban/rural difference (meaning that a generic desegregation from total was impossible), the latter was chosen[8].

---

[8] Concerning Fans, Air Coolers and Air conditioners, the REMI method was retained as discussed in section 10.3.

So diffusion rates of each appliance are determined on an urban rural basis by changing the φ_1, φ_2 and φ_3 of each equation during the calibration process. Once the urban and rural diffusions are known, it is easy to determine to total ownership rate by using the urbanization level.

Concerning quintile differences, it is not possible to directly determine them using the abovementioned equations and the quintile expenditures (as was done for urban/rural) as appliance diffusion depends more on the national expenditures rather than the absolute expenditures. In order to overcome this problem it is proposed to multiply the urban/rural average by a certain factor in order to correct for quintile.

Ideally this factor would be related to GINI so that areas with high income inequalities would have a higher variance in appliance ownership between the rich and the poor. Relating directly to GINI is a difficult task due to data problems; however the variance in household expenditures between income classes can be used as a proxy for the GINI.

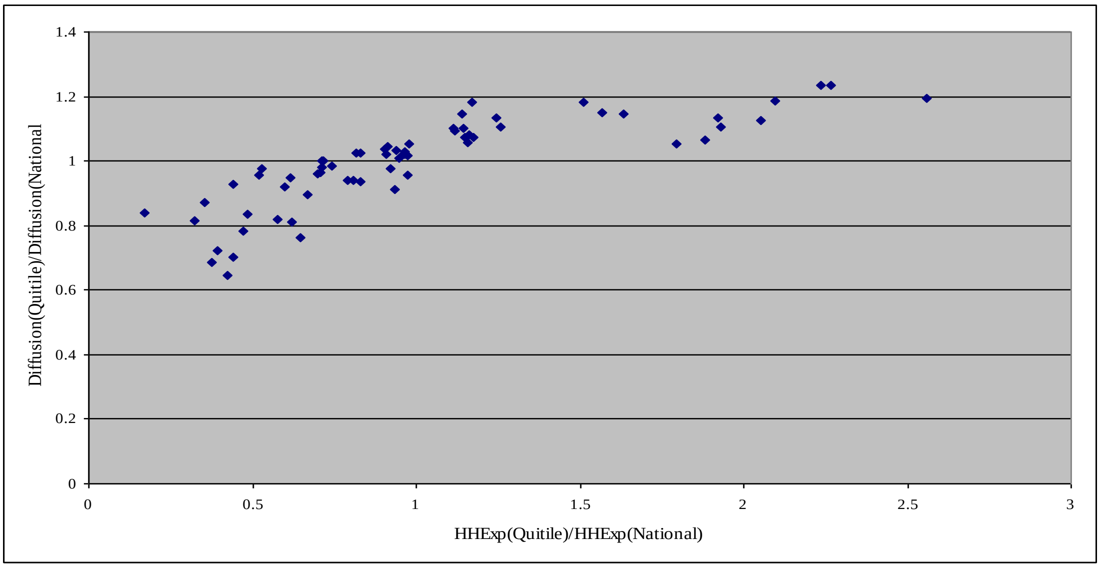

Figure 60. Factor of appliance ownership vs. Factor of household expenditures (refrigerators)

Figure 60 is a plot of appliance ownership ratio versus household expenditure ratio (income class to national average in both cases) for all available income class data. The particular data is for refrigerators but similar plots also can be made for other appliances wherever data is available. It displays expected behavior as households with expenditures below average have a lower ownership of appliances while richer households have more, however the curve tends to flatten out, meaning that ownership rates of richer households do not shoot up. Also the curve passes through the point (1,1) as expected (household with the average expenditure have the average ownership). The equation describing the relationship is set as:

$$QFac_{URQ} = \alpha_{App} \cdot \ln(HHExpFac_{URQ})+1$$

Equation 22. Appliance diffusion factor as a function of quintile expenditure factor

Where:
A_{App} = Constant
$QFac_{URQ} = Diffusion_{URQ}/Diffusion_{UR}$

$HHExpFac_{URQ} = HHExp_{URQ}/HHExp_{UR}$

An interesting feature is that as HHExp(Average)→∞, HHExpFac→1 (since $HHExp_{Quintile}$ inevitably also increases) , so as a country becomes richer the difference between households reduces. Since REMI calculates household expenditures for each urban/rural quintile via the GINI, this formula can easily be incorporated, and has the benefit that income inequalities are directly reflected in appliance ownership discrepancies between rich and poor households. The values of α of this model are shown in Table 24.

Table 24. Coefficients for appliance quintile allocation

	Refrigerators, Microwave Ovens	*Washing Machines, Clothes Dryers, Dish Washers*	*Televisions, VCR/DVD Players, Personal Computers*
α	0.206	0.238	0.144

It should be noted, that the data used to determine the deviation between quintiles, came from cases where electrification was 100%. Thus the possible effects of non-saturated electrification are **not** captured.

4.2 *Unit Energy Consumption*

In order to determine the total energy use by household appliances, the ownership levels will be multiplied by the unit energy consumption (*UEC*) of the specific appliance and corrected for electrification. Thus unit energy consumption for the eleven appliances listed above (preferably per region as well) is required. This unit energy consumption must be in the form of kWh/yr, and thus including standby power consumption which accounts for a significant amount of total annual energy consumption (between 20 and 95% depending on appliance) (Rosen *et al.*, 2000; Loveday *et al.*, 2008; Ajay-D-Vimal Raj *et al.*, 2009).

Data for unit energy consumption was extremely limited came primarily from academic papers, reports and databases focusing on this issue. Concerning marginal appliances (appliances on the market) websites of retailers and producers were also consulted as well as databases and reports focusing on marginal appliances (Weiss *et al.*, 2008; CEC, 2009). For the eleven appliances for which saturation levels have been determined, it is important to also determine unit energy consumption (in kWh/unit/yr), preferably in urban and rural settings, for each region. Unit energy consumption is the energy consumed by one appliance unit in one year, accounting for all operation modes (active, standby, off). Since unit energy consumption depends a lot on behavioral aspects, determining unit energy consumption depends a lot on assumptions made. Air-conditioning UEC was not looked into since space-heating and cooling energy consumptions are going to be derived via another methodology (Isaac *et al.*, 2009).

It is important to clarify a distinction which is prominent in the following sections. Unit energy consumption can be described in two different forms: *aggregate* and *marginal*. Aggregate concerns the UEC of the appliances currently in households, while marginal is based on appliances in the market. The distinction is important since if a new (marginal) appliance is more energy efficient then its predecessors, it is not necessary that the aggregate UEC is going to be equal to it. This would be so only if **all** households used this new appliance (and all subsequent new appliances with corresponding energy improvements). Thus, since household appliances tend to have a certain lifetime (taken as 15 years in REMI/REMG) the aggregate UEC always lags behind marginal UEC, and the rate of change depends on the stock turnover.

4.2.1 Remarks

Dish and clothes Washers: Concerning washing machines there is a further methodological problem additional to the measuring techniques mentioned at the beginning of this section. Washers use electricity for two purposes, to heat water and to operate the motor. If the water heating energy is subtracted the UEC falls considerably (to about 10%) (Wenzel *et al.*, 1997). Unfortunately, it is seldom reported if the water heating energy is accounted for in the available data.

United Kingdom: The DoECC gives national energy consumption of various appliances for the years 1970 to 2008, as well as an estimate for how many such appliances exist. Thus UEC could be determined.

United States: Significant data concerning refrigerators on the American market (thus *marginal*) is provided from an online database of the California Energy Commission (CEC, 2009). The database is especially useful for refrigerators where UEC and volume for all refrigerators on the market are given for the time period 1978 to 2009.

Netherlands: The Dutch consumer organization 'Consumentenbond' provides data fro refrigerator UEC, volume and price for all Dutch market refrigerators for the period 1964-2007 (Consumentenbond, 1964-2008).

4.2.2 Inferences (Aggregate)

Data for unit energy consumption is extremely limited and no difference between urban and rural households could be determined. Thus it is assumed that unit energy consumption remains the same, i.e. behavioral patterns do not depend on urban or rural settings.

Since data comes from a number of different sources whose estimates are based on diverse methodologies, consistent data is not available. Also, the data is not plentiful region-wise with very few regions represented, and rarely with more than 1 data point. Due to all of these inaccuracies, there is quite a spread in UEC values as shown in Figure 61 to Figure 64 (all graphs show global data).

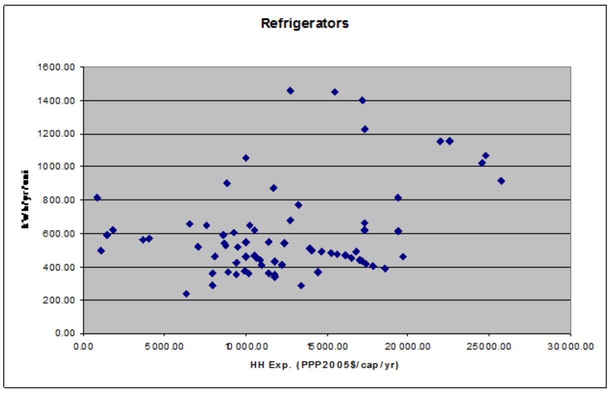

Figure 61. Refrigerators

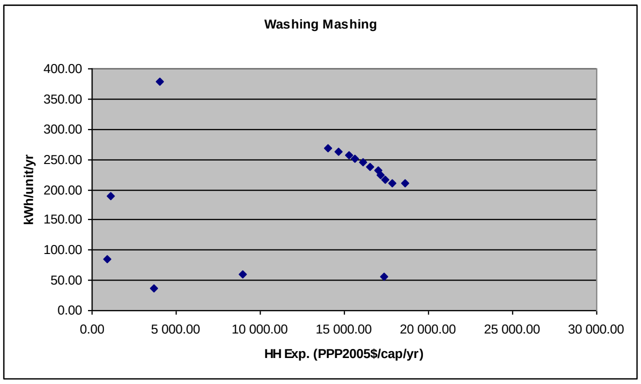

Figure 62. Washing Machines

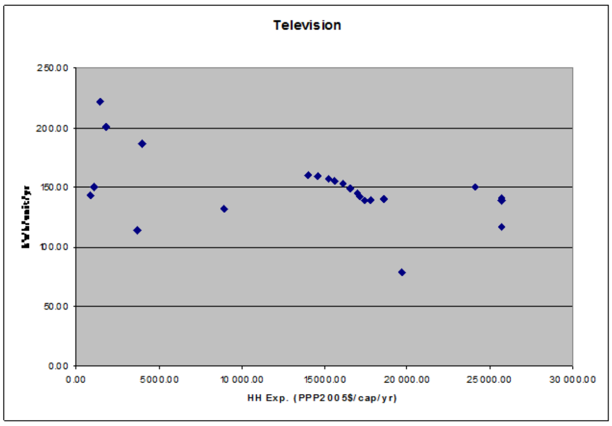

Figure 63. Televisions

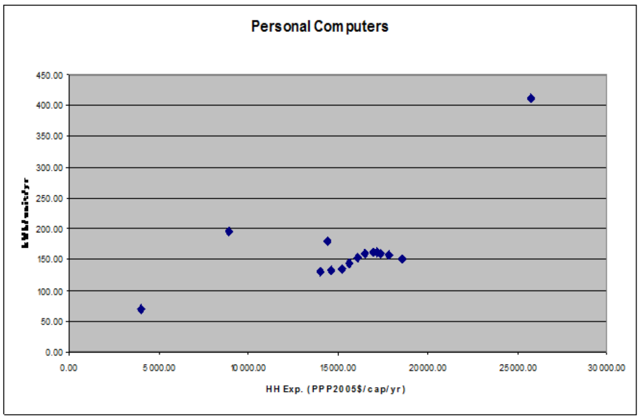

Figure 64. Personal Computers

Table 25 summarizes the regions for which there is at least one data point for each appliance. The following paragraphs summarize the findings and some conclusions per appliance.

Table 25. Data availability concerning UEC

Appliance	**Region**
Fans	USA, S. Asia, SE. Asia
Refrigerators	Canada, USA, Brazil, W. Europe, S. Asia, E. Asia, SE. Asia, Japan, Oceania
Washing Machines	Canada, USA, Brazil, W. Europe, S. Asia, SE. Asia, Oceania
Clothes Dryers	USA, W. Europe
Dish Washers	USA, W. Europe
Televisions	USA, Brazil, W. Europe, S. Asia, E. Asia, SE. Asia, Japan, Oceania
Personal Computers	Canada, USA, W. Europe, SE. Asia, Oceania

4.2.2.1 Air Cooling

The energy consumption of air cooling devices cannot be calculated via the UEC methodology. This is because the absolute number of appliances is not relevant since cooling (by air condition) could be done via multiple stand alone units, or via a central unit, and also climate aspects are the major factor for the energy consumption of these appliances. Furthermore, the method by which ownership of cooling appliances is modeled, does not explicitly determine the absolute number of these appliances (see section 4.1.3.1). For these reasons the method by which UEC of fans is calculated in REMG will remain the same as in REMI.

4.2.2.2 Refrigerators

There are enough data points for the UEC of refrigerators in order to derive certain conclusions. This is quite fortunate since refrigerators are the most energy intensive household appliance. For a number of regions decreasing trends have been witnessed. Additional to this, the households expenditure level at which the "maximum" UEC was observed can be seen.

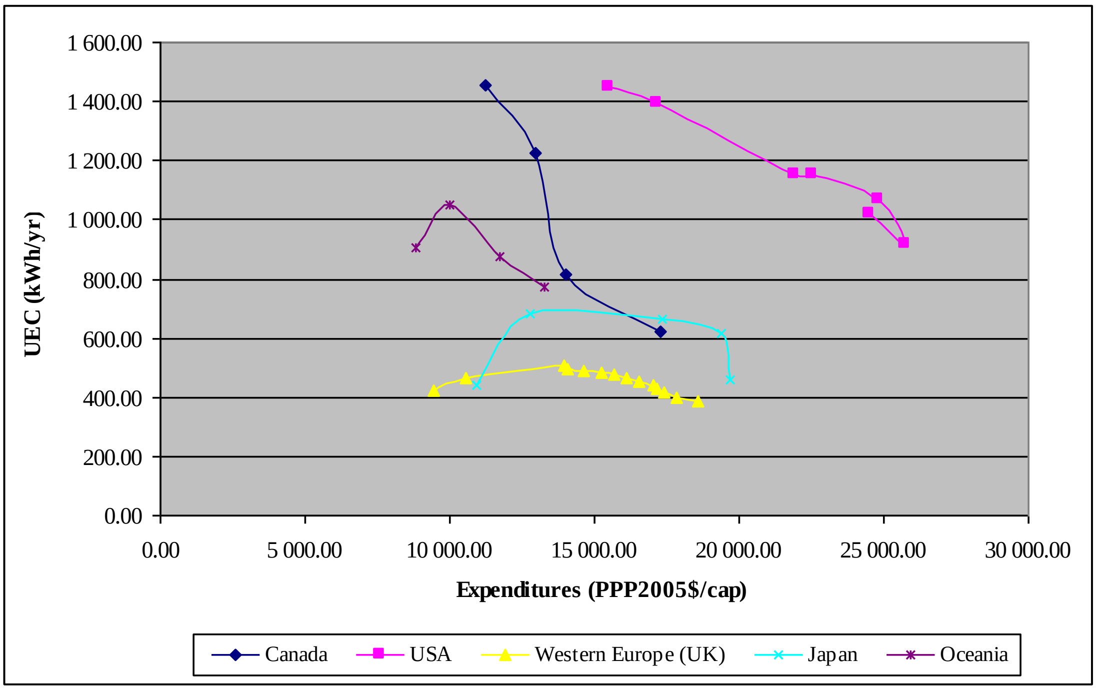

Figure 65. Refrigerator UEC vs. Expenditures for some regions[9]

Some observations can be made from Figure 65. First of all, different UEC's exist for different regions. Canada, USA and Australia have higher UEC's Japan and Western Europe. This is probably due to cultural aspects with certain regions preferring larger and more extravagant refrigerators than others. Furthermore, it can be inferred that there is a definite peaking point for the UEC, after which it declines. This peaking point varies from region to region, as does the UEC_{peak} and the $Expenditure_{peak}$.

For poorer regions, the picture is less clear. Figure 66 shows the available data points for Brazil, South Asia, East Asia and Southeast Asia. Due to the scarcity of data, no per-region conclusions can be made, and with the presented data points nothing much can be said except that refrigerator UEC is ~600kWh/yr (with one outlier[10]). It has been suggested that energy use of refrigerators in developing countries, especially Africa, may be higher than in developed regions. This may occur due to a number of factors: 1) Higher ambient temperatures and humidity, 2) Use of old and badly maintained equipment, 3) Voltage and power supply fluctuations and inefficient use patterns that respond to these fluctuations (van Buskirk *et al.*, 2007).

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[9] UK data was used for region 11. This is because there are many data points in that region and this pattern could not be displayed if they were all included.

[10] The point at ≈800kWh/yr is for India, and does not agree with other India data points.

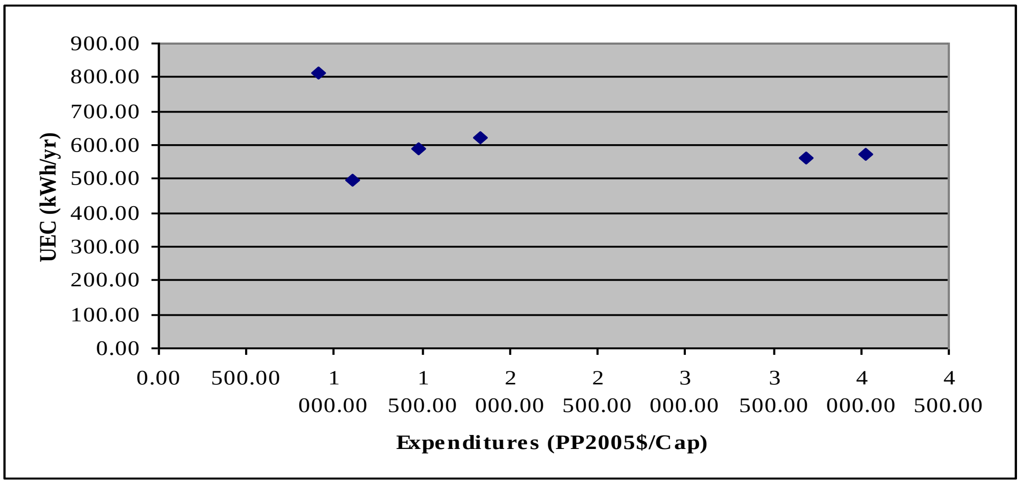

Figure 66. Refrigerator UEC vs. Expenditures, developing regions

For the purposes of the model, it is also useful to look at the data in a time base. Figure 67 and Figure 68 show the same data as above but in time.

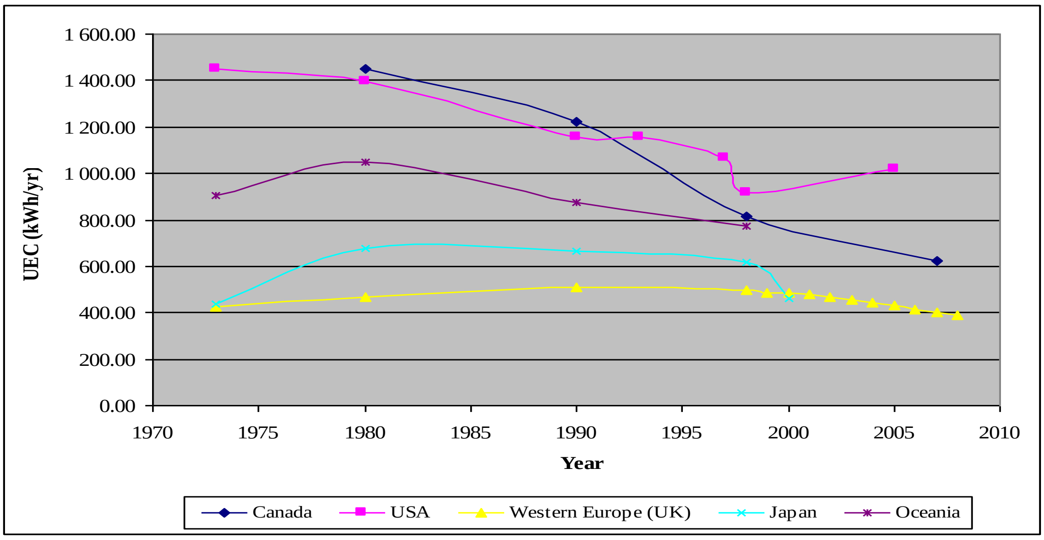

Figure 67. Refrigerator UEC vs. Year for some regions

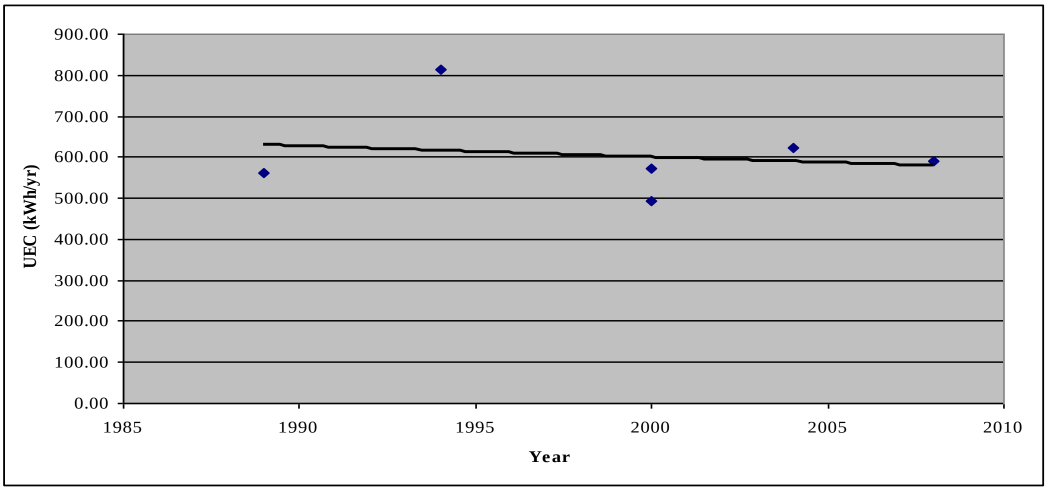

Figure 68. Refrigerator UEC vs. Year, developing regions

4.2.2.3 Washing Machines

As already mentioned, concerning washing machines there is a further methodological problem since washers use electricity for two purposes, to heat water and to operate the motor. According to the LBNL Energy data sourcebook the annual motor energy usage is 103kWh and 1148kWh for the total.

Figure 69 shows the available data. Unfortunately not much can be concluded due to the many data sources (only region 11, Western Europe, had a consistent source), and the methodological problems described above. A hypothesis can be made that as households get more affluent, the UEC increases due to increased use of washing machines, however generally with time this UEC tends to fall due to improvements in energy efficiency (as shown in region 11).

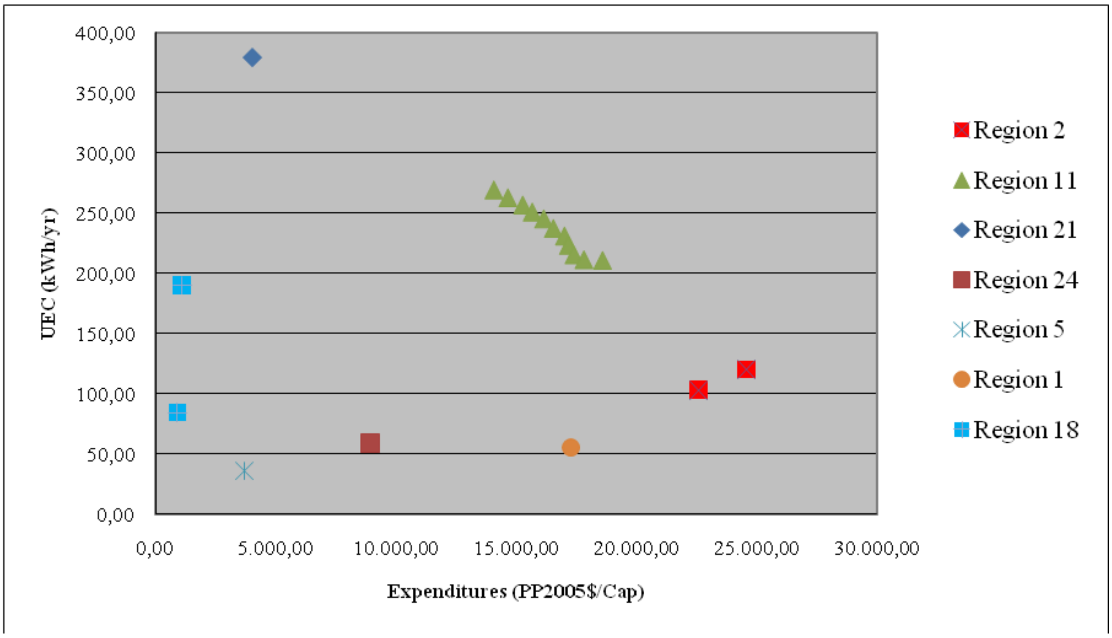

Figure 69. Washing Machine UEC vs. Expenditures

4.2.2.4 Clothes Dryers and Dish Washers

For clothes dryers and dish washers very few sources provided data over a limited number of countries (Schipper *et al.*, 1996; Wenzel *et al.*, 1997; O'Doherty *et al.*, 2008). Unfortunately these sources disagree with each other; this could be due to behavioral differences as well as measuring techniques since what exactly is included in the energy measurement is crucial. For dishwashers, the UEC is about 170kWh/yr while in Western Europe it is 400 kWh/yr. The USA Dishwasher UEC presented here does **not** include water heating. For Western Europe it is unclear if this is included. For clothes dryers, the value for the USA I about 950kWh/yr, for Western Europe and Japan about 370kWh/yr. There is no evident reduction with time over the past four decades.

4.2.2.5 Televisions

Television energies depend on television technologies. With the current breakthrough of Plasma televisions the unit energy consumption has increased very rapidly. The data presented does not have this included as standard color televisions are what have been listed. Figure 63 (page 96) shows the available data points for televisions, which include values from a number of regions (Table 25, page 96). No direct conclusions can be made except that television UEC ~150kWh/yr and reducing due to improvements in efficiency. However due to the aforementioned breakthrough of more energy intensive technologies, this improvement should perhaps not be accounted for.

4.2.2.6 Personal Computers

Determining the UEC for personal computers is especially tricky since peripherals play a major role here. In the data collected, it was attempted as much as possible to reflect the energy consumption of a desktop PC with a standard monitor, yet due to ambiguities in the reported data, some of the points may not reflect this. Figure 70 shows than generally PC UEC is ~180kWh/yr, and may increase with expenditure due to this increased use of IT and internet services at higher welfare levels.

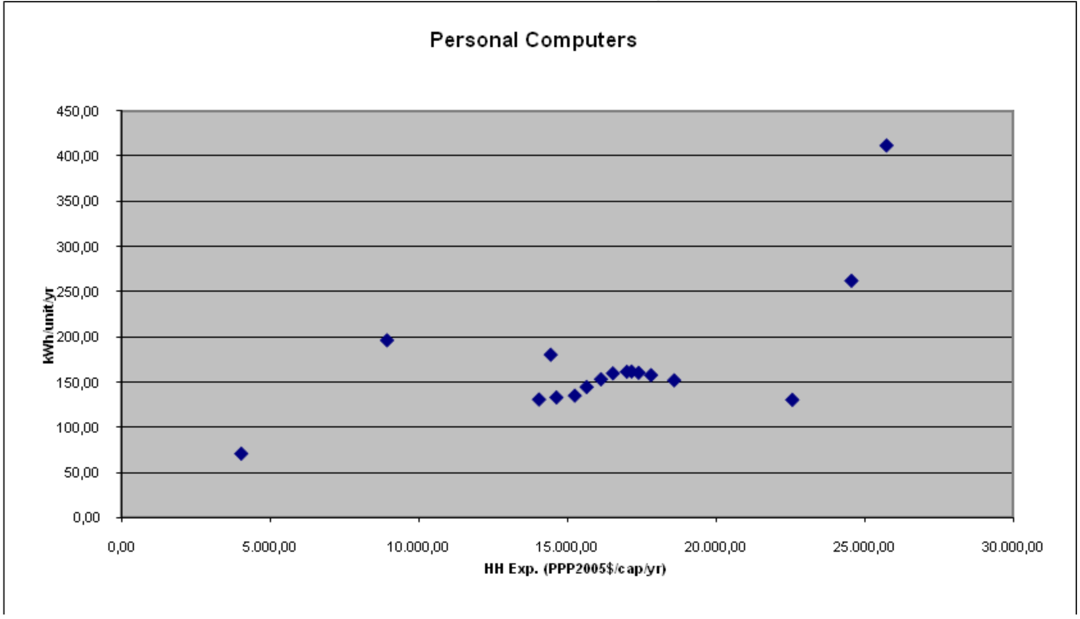

Figure 70. Personal Computers UEC vs. Expenditures

4.2.3 Inferences (Marginal)

UEC does not only depend on appliances entering the market today. Since many appliances (especially refrigerators and washing machines) have a long life time, new models are not representative of current energy consumptions. Additional to the current UEC, a database from the California Energy Commission (CEC, 2009) and some studies (Bogdan *et al.*, 2008; Cardoso *et al.*, 2010) gave UEC information for new refrigerators (Figure 71) and washing machines. A report by Weiss (Weiss *et al.*, 2008) has data for electricity consumption of new refrigerators in the Netherlands from 1964 to 2007 compiled from the Dutch consumer organization Consumentenbond, corrected for 100 liter volume (Figure 72). Their data is in agreement with other studies once the increase in refrigerator volume (to volumes well over 300 liters in 2010) is considered. This data is important in determining how UEC may change as household stock changes and modernizes.

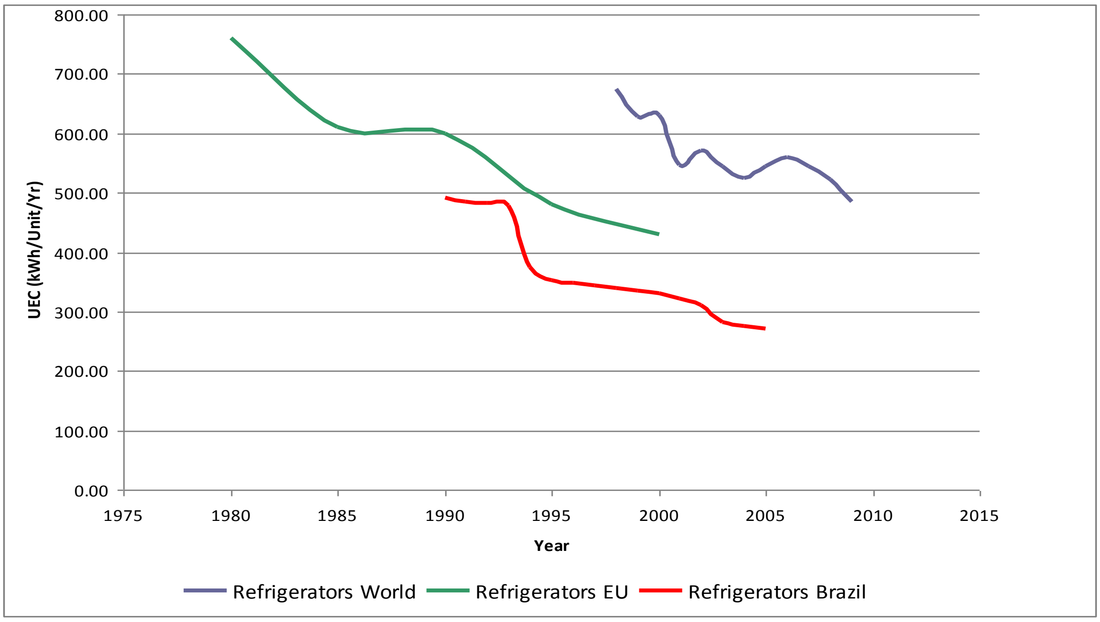

Figure 71. UEC of New Refrigerators

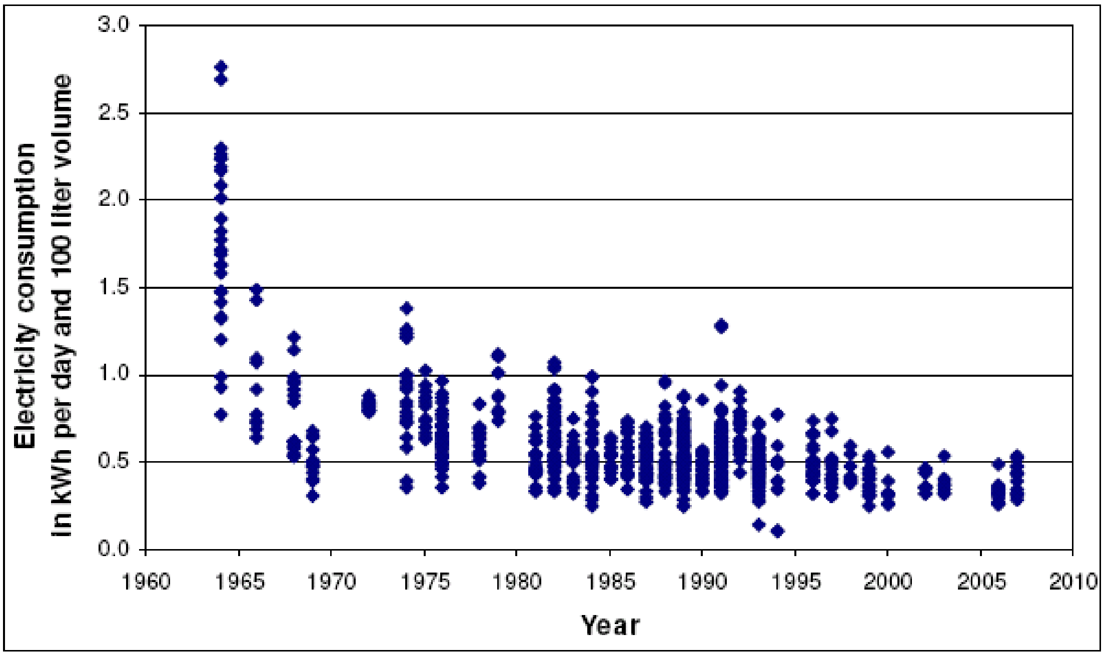

Figure 72. Energy Consumption of Refrigerators (per day, per 100L) in the Netherlands (Taken from (Weiss *et al.*, 2008))

Using the data from the California energy commission, it is possible to plot the UEC/L vs. year for the marginal refrigerator market in the United States. This produces a graph identical to that in Figure 72. Thus the energy intensity (kWh/L) as well as its reduction is constant across these regions. This makes sense since technological advances cross borders quickly. Yet the absolute energy consumption of

American refrigerators is much higher than European refrigerators because they are much larger. Historic development of average fridge capacity is shown in Figure 73.

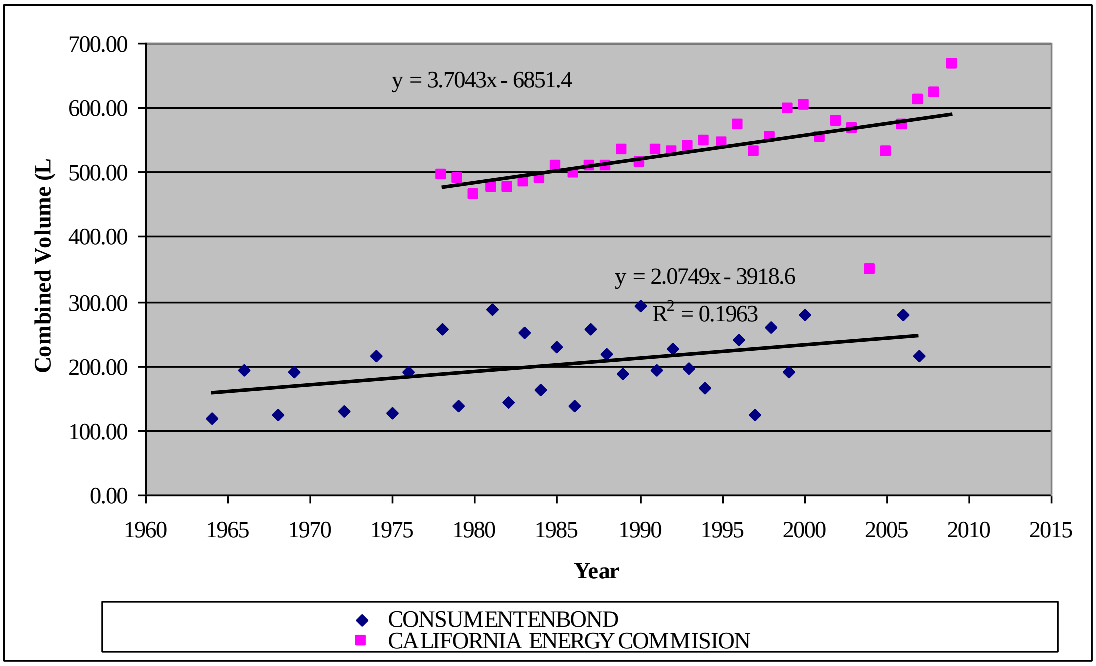

Figure 73. Development of average total volume of refrigerators in the USA and the Netherlands

It is also possible to see the difference between the average refrigerator and the most/least efficient ones as shown in Figure 74. For instance if all new refrigerators bought were of the top of the line, with the complete replacement of all current refrigerators, refrigerator UEC could fall to ~300kWh/yr (compare this to Figure 65 and Figure 67), even though this hypothesis ignores consumer preferences.

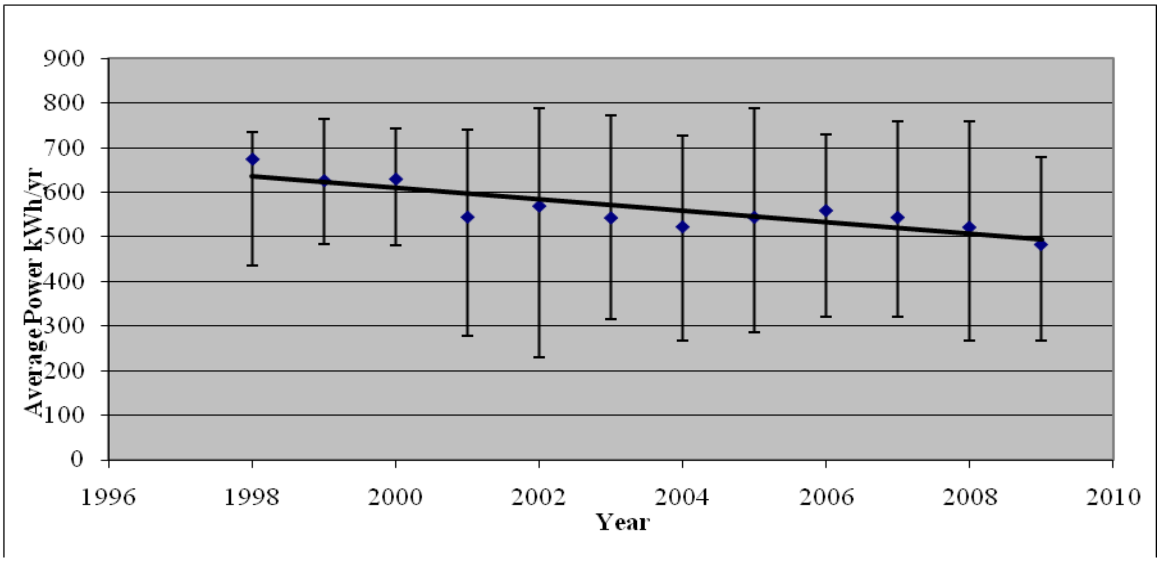

Figure 74. Average and range of UEC of new refrigerators

The California Energy commission gives such data for dish washers and clothes washers as well, however not as annual UEC but rather as UEC/cycle.

4.2.4 Analysis

In the REMI model unit energy consumption is not modeled. Instead, a current (2000) and assumed future (2030) value are inserted. In the global version it is going to be attempted to model Unit energy consumption so that various scenarios can be run.

In the TIMER model, efficiency is modeled with two components:

1. Autonomous Energy Efficiency Improvement (AEEI) via technological breakthroughs
2. Price Induced Energy Efficiency Improvement (PIEEI) via cost supply curve of more efficient appliances

A further driver for energy efficiency improvements includes regulations as well as elasticity of UEC with the price of energy. Yet UEC does not only depend on efficiency, but also on behavior, usage patterns and consumer preference (which may be region or welfare dependant). Thus, as can be seen in the data, the UEC development is unclear and varies a lot, thus assumptions have to be made since the data cannot be used on its own.

Since REMG is to be used to perform analysis on possible policies to reduce appliance energy consumption, it should be able to perform the following tasks concerning the development of unit energy consumption

1. Display the autonomous energy efficiency improvement
2. Have marginal unit energy consumption of appliances vary according to the cost of electricity
3. Have the ability to enforce regulation on energy consumption

In order to accommodate all of these, the REMI method has to change significantly. The most important change is that now UEC is going to be calculated on a marginal basis, since regulation on UEC can only be modeled like that. Additional to this, energy consumption is to be modeled on a base unit (kWh/L,, kwh/kg, etc.) which will be constant across regions (they all use the same technology), but the unit changes according to region based on behavior. Due to limits on data availability, differences amongst urban and rural localities and income levels will not be accounted for in UEC development.

The base units used are the following:
Refrigerators: kWh/Liters capacity (total), unit
Microwave ovens: kWh/unit
Washing Machines: kWh/Liters capacity, unit
Clothes Dryers: kWh/kg of load, unit
i kWh/cycles per wash, unit
Microwave ovens, Televisions, VDR/DVD players and Personal Computers: kWh/unit

The following pages describe how each of the abovementioned objectives are met.

4.2.4.1 Autonomous Energy Efficiency Improvement

As the data shows, for **refrigerators** and **washing machines** there is an autonomous energy efficiency improvement of the UEC per base unit (kWh/L for both refrigerators and washing machines). Obviously, this energy efficiency improvement must have limit dependent on thermodynamic considerations, as well as a rate of reduction. It was chosen to model energy efficiency improvement according to the following.

$$UEC = A \cdot b_{base}\text{^}(t-1970)+c\ ,\ for\ t \leq t_{scen}$$
$$UEC_{scen} = (UEC_{tscen} - c) \cdot b_{scen}\text{^}(t-t_{scen})+c\ ,\ for\ t > t_{scen}$$

Equation 23. UEC description

Where:
A = Constant (determined by historical UEC)
b = Rate of reduction of UEC ($0<b<1$, or $b>1$ in the case that UEC increases)
c = Constant (Minimum possible UEC)
t_{scen} = Date of UEC "shock"

As can be seen this formulation is broken in two bits, namely pre-shock and post-shock. *A*, *b* and *c* are appliance specific (with a possibility be region specific as well). '*b*' determines the rate of reduction and has been set as 0.959 for refrigerators and 0.96 for washing machines which represent a annual reduction of approximately 3% per year (1971-2010), which is in agreement with a number of other studies (Schiellerup, 2001; Dale *et al.*, 2002; Laitner *et al.*, 2004; EES, 2006; Weiss *et al.*, 2008).

Figure 75 shows the behavior of this equation under two different values for *b* under a '*no scenario'* case and when t_{scen} = 2008 (note that the y-axis is in kWh/unit, **not** kWh/L, though this is unimportant for our current purposes).

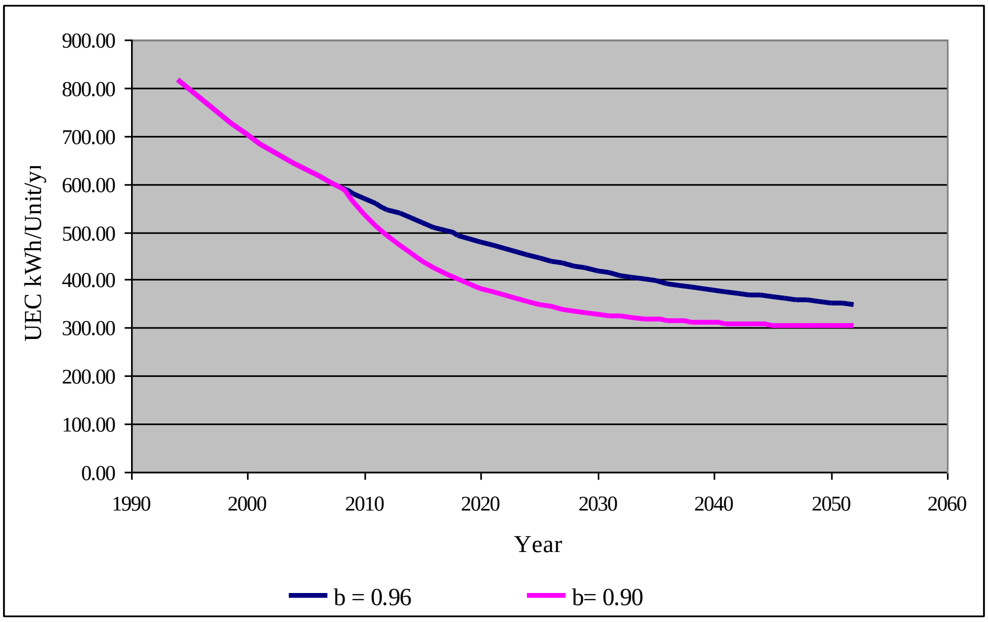

Figure 75. Behavior of UEC equation

But, what exactly is a change in *b*? ‘*b’* exists because technological innovation and learning by doing means that absent from external forces, these appliances autonomously get more efficient. A change in *b* would mean that this autonomous decline is expedited via increased research and incentive to do so. The ability to change *b* has been included in REMG to make it possible to run scenarios under various world views concerning industry’s willingness to create more efficient appliances or not. Yet, to what value *b* is to be changed to under various scenarios is arbitrary.

As already mentioned, Equation 23 is used to determine the UEC/L, but what we require is the total UEC. Historic data on fridge sizes exist for the United states and for the Netherlands. Also the analysis in section 4.2.2.2 shows that there are essentially two distinct refrigerator types, high consumption and low consumption, with the USA and Europe representing either one. Thus the *large fridge* case is given to Canada, the USA, and Australia while the *small fridge* case is given to the rest of the world[11]. The inherent assumption here is that the developing world will not have an American type consumer preference of huge fridges.

The value for ‘c’ has been assumed. Ideally this would be determined from a ‘minimum possible energy use’ (*Technical potential*) based on an engineering analysis or the *theoretical potential* of the devices based on an exergy analysis. A literature review into this did not yield any results.

In the baseline setup of REMG, autonomous energy efficiency improvement is only set for refrigerators and washing machines, and those are the appliances where the data demonstrates it. Data presented in (Weiss *et al.*, 2008) suggests that a slight decline also for clothes dryers but unfortunately it was not possible to acquire the data to do the required analysis.

4.2.4.2 Price Induced Energy Efficiency Improvement

REMG is to be used in order to see what the effect of rising costs of electricity is on appliance energy use. The basic premise is that if the cost of electricity rises significantly (by, say, the introduction of a carbon tax), consumers will become more UEC conscious and thus the marginal UEC of appliances purchased will drop, leading to an earlier drop in the aggregate UEC which would not have been witnessed otherwise.

The previous section describes an autonomous decline of UEC (base) with time. What is being proposed now is that in any given year, the base UEC can shift upwards or downwards depending on changes in cost of electricity (*coe*). In other words an attempt is being made to add a UEC elasticity of coe. An experiment was set up to determine this by looking at available appliances on the market today see how purchase of these appliances depends on the cost of electricity.

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[11] Using the Dutch refrigerator sizes actually led to an underestimation of European fridge UEC. This is justified by the fact that Dutch fridges tend to be smaller than the average in the European market, and thus for Western Europe the volume was set slightly higher, but still well below the American.

Data from the appliances was provided from online retailers amana.com, whirlpool.com and dixons.co.uk. The test was performed for refrigerators (70 units), washing machines (26 units), dish washers (18 units) and clothes dryers (35 units). The experiments were performed for *a coe* ranging from $0.05\$_{2005ppp}$/kWh to $2\$_{2005ppp}$/kWh and for different levels of poverty by adjusting the annuity factor from 0.01 to 5. As described in section 9.1 the consumer discount rate (CDR) of appliances is set by default to 40% which leads to an annuity factor of 0.53, however the significantly lower value for which tests were run was done to represent cases where households start acting like businesses where discount rates are much lower.

For each refrigerator the capital costs and the fuel costs (determined at various coe) are summed to give the total cost. Thus, at each coe the 25th percentile (25% cheapest options) UEC/unit is determined. The 25th percentile is used since consumers tend to be less than rational so using the cheapest would be a misrepresentation. From this it is possible to draw the UEC preference as a function of coe as shown in Figure 76. This function is described in the form:

$$\mathrm{UEC}_{\mathrm{TURQ}} = -coeff1_{TURQ} \cdot Ln(coe) + coeff2_{TURQ}$$

Equation 24. UEC as a function of coe

The two coefficients of this equation (and thus the shape of the curve) change according to the annuity factor, and thus according to household expenditures. At higher annuity factors (poorer households), capital costs are the biggest barrier for purchasing a new appliance and so potential fuel savings are heavily discounted, thus the curve is significantly shallower. This is demonstrated in Figure 77 where the path *coeff1* follows is shown as a function of annuity factor.

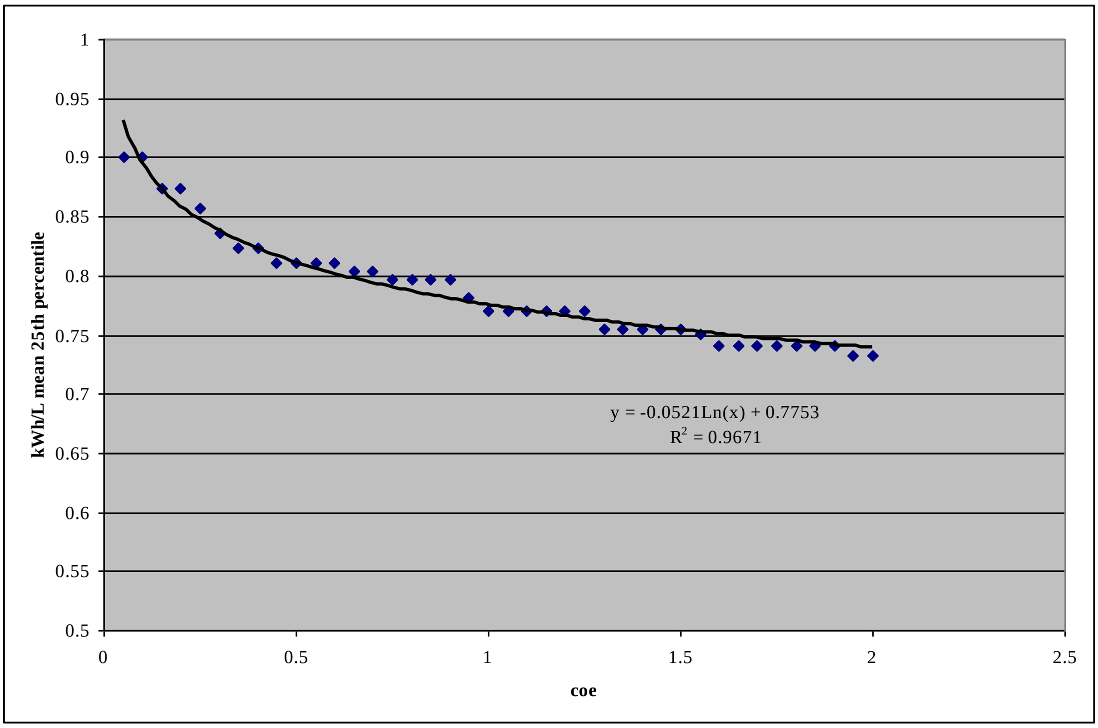

Figure 76. UEC vs. coe for refrigerators, Annuity factor = 0.53

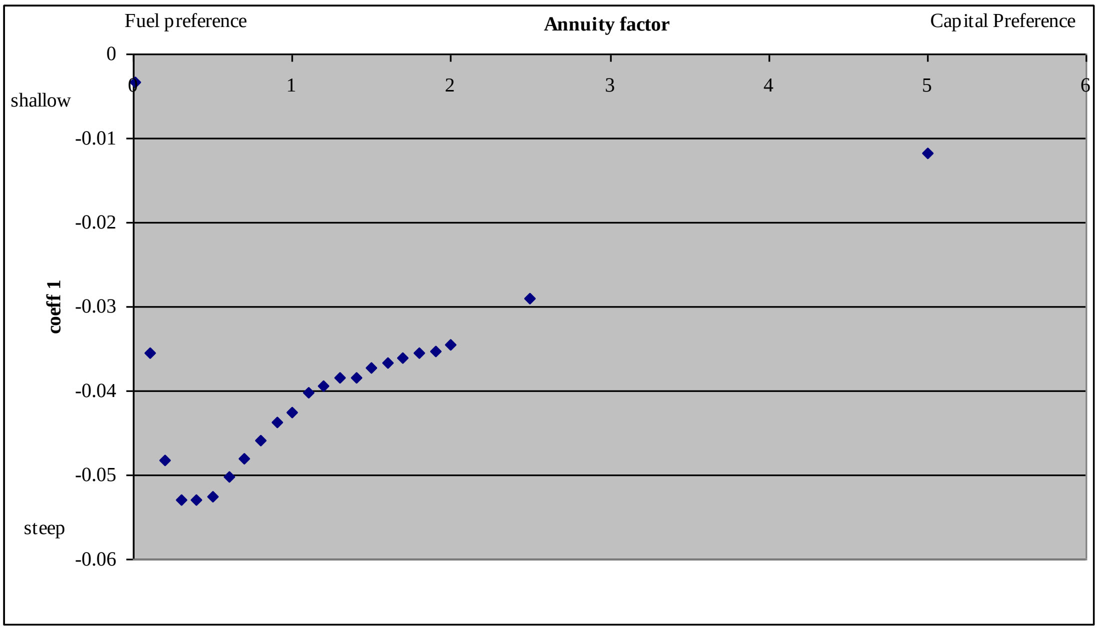

Figure 77. Coeff1 for refrigerators as a function of annuity factor

It is clear that poorer households (higher annuity factor) have a shallower UEC vs. coe 'choice' since they only care about refrigerators with the lowest capital cost. This is also true for extremely low annuity factors (<0.5, which is unlikely) where again choice is limited to the options with the lowest fuel costs. In the intermediate region there is a large array of options. Similar curves can be drawn for other appliances, however since the magnitudes and dynamics of *coeff1* and *coeff2* are unique for each appliance (because of the range of options, range of UEC's and the ratio of fuel costs to capital costs), this method has on been applied to appliances where the relevant data could be found (refrigerators, washing machines, clothes dryers and dish washers). These also happen to be the major energy consuming appliances where it is most relevant since in minor energy consuming appliances these dynamics are irrelevant since fuel costs are low.

A drawback of this method is that it has been based on 2010 market data. Obviously there is a time element in how these choices change. For instance Figure 72 shows that the difference between the most and least efficient refrigerators has decreased with time. This in turn affects the effectiveness of price induced energy efficiency improvements since the possible reduction in UEC is constantly diminishing. However, to model this effectively, huge amounts of data are required on order to model this in detail.

4.2.4.3 Energy Regulations

The final requirement of REMG is to be able to simulate the possibility where appliance energy use regulations come into effect. In other words, what happens if all refrigerators sold after *year-t* have a UEC of x kWh/L? As already mentioned, stock turnover is very important. Even though the "shock" takes place in t_{scen}, this does not mean that the UEC reduction takes place instantly, due to delays in capital stock turnover.

The REMI model the absolute number of each appliance (determined from the diffusion rate and number of households) is multiplied by the given UEC in order to determine energy consumption. Thus if the new UEC formulation is simply inserted in the existing REMI code, ALL appliances will have the marginal UEC (i.e. the reduced UEC_{scen}). This has to be amended so that only **new** appliances have the UEC_{scen} by creating an *Energy Stock Model* where the energy use of new and depreciated appliances are stocked in order to determine aggregate UECs.

Together with the new energy stock model, if energy regulations are put in some year-t, the methods described in sections 4.2.4.1 and 4.2.4.2 are handicapped and all new appliances are assigned the regulation UEC.

4.2.5 Miscellaneous Appliances

The 11 appliances specifically modeled represent the key large energy consuming appliances, and are characteristic of the increase in energy electricity consumption of households as they get richer. Yet, there is a whole legion of other smaller appliances which consume electricity which are not worth modeling from a bottom up perspective because they vary from household to household with no clear indicators. These include computer peripherals, television peripherals, mobile communication and audio devices, small kitchen devices, radio/stereo systems, cleaning devices and many other small devices. Thus what is required is a *miscellaneous appliances* section.

Since modeling them in a bottom up fashion is difficult, their consumption level was determined from the remainder of electricity after deducting electricity use of the main (11) appliances from electricity for appliance use data from the IEA. This data exists for Canada, the USA, Japan, Australia and Western Europe. Fortunately, these countries also represent the most affluent regions and thus the regions where this “miscellaneous” appliance use is most relevant. It is important to note that since this exercise is a direct comparison of REMG’s output to IEA data, that this “other” factor also includes errors in the modeling, errors in UEC and possible errors in the IEA data. Eliminating all of these and accounting only for “other appliances” is impossible at this point.

As expected, REMG (11 appliances) underestimated the electricity use for appliances, and a linear relationship could be determined between the absolute underestimation and the household expenditures, with richer households having a larger difference. This is visible in Figure 78, and it can be seen that at household expenditures of ≈ $10000\$_{2005PPP}$ appliances beyond the “11” start to become important. What is also seen is that the increase of energy use for miscellaneous appliances is smaller for Europe and Australia than the other three countries. This can lead to a segregation of gadget countries and non-gadget countries, the USA, Canada and Japan falling in the former and the rest of the world in the latter.

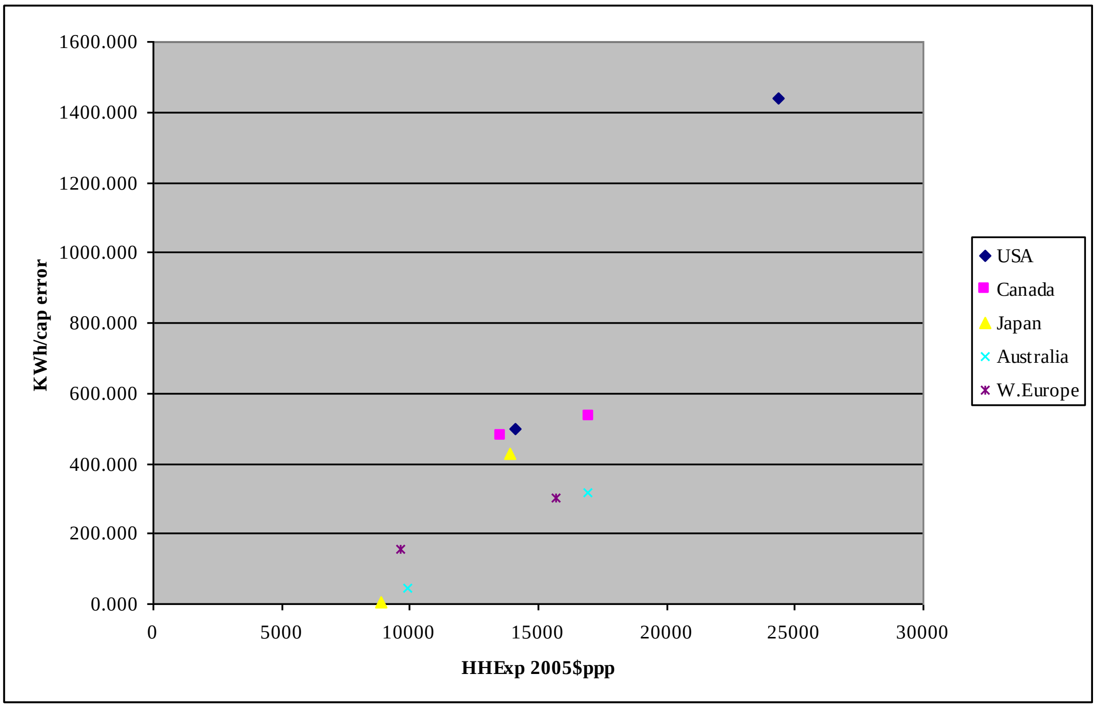

Figure 78. Difference between IEA (IEA, 2004) data and REMG output for appliance electricity use.

Describing miscellaneous appliances via a linear relationship with this data would lead to extremely high electricity consumptions for small appliances in the future (>50% of total electricity consumption). It is assumed that small appliances will never have such a share of electricity consumption, and thus instead a logarithmic relationship is used.

Thus the final formulation for miscellaneous appliances has the form:

$$Miscelaneous_{R,URQ} = \alpha \cdot Ln(HHExp_{URQ}) - \beta$$

Figure 79. Energy consumption of miscellaneous appliances

The α = 597.63 and 133.45 and the β = 5397.6 and 1187.6 for gadget-friendly and non-gadget-friendly regions respectively.

5 Cooking

Energy for cooking is very significant in developing countries; especially in poor households it forms the lion's share of energy demand (Hosier *et al.*, 1987; Clancy, 2006). Thus it was attempted to determine how energy use for cooking develops with increasing affluence. Energy required for cooking (in MJ/cap/yr) data is sparse, but still via some national accounts and some academic papers information could be extracted.

It was chosen to maintain the eight fuels used in the REMI model (Coal, Tradition Fuel wood, Improved Fuel wood, Kerosene, LPG, Natural Gas, Biogas and Electricity). Yet, when energy use per fuel was reported, in the various sources different fuels are named. In this case they were appropriately placed in one of the eight existing categories. Also, most of the data sources list minor fuels used as "Other". It is not known what these "Other" fuels are, and they vary among sources, and may be amongst the eight listed. All data has been corrected for efficiency (i.e. useful energy is listed). The Data provided from the IEA was assumed to be useful since the values were already fairly low, and correcting them for efficiency would yield very low numbers.

For the cooking energy shares, shares of fuel in useful energy have been assembled by dividing the Energy values by Total Cooking energy. Yet, considerably more data is available, especially for developing countries (in the form of *primary source of fuel for cooking*). However, these values are percentages of households, and **not** useful energy. However, since in most of the cases the vast majority of household use fuel wood (>80%), this error is considered small. For developing countries "Fuel wood" is treated as "Traditional Fuel Wood".

5.1 *Remarks*

Germany: The *Economy and Use of Environmental Resources* (FSO, 2010) reports energy use reports energy use fuel for space heating, hot water heating and *other process heat*. Other process heat is footnoted as "Particularly for cooking". *Mineral Oil* is treated as Kerosene.

Ghana: The Ghana statistical service lumps Gas, Electricity and Kerosene together. Kerosene is given half the share and Gas and Electricity the other half.

IEA Countries: The data used in the IEA report *30 Years of Energy use in IEA countries* is available and gives total energy use for cooking in a number of IEA countries. It is assumed the reported numbers are the useful energy as otherwise they would be too low. Yet the values for the United Kingdom are not comparable with the DoECC values (On the other hand, Japan compares quite well with other sources). The values given for Australia are suspiciously low.

India: (D'Sa *et al.*, 2004), report cooking energy use shares for crop residue and dung. Crop residue has been put under Traditional Fuel wood, and dung under Other.

Malawi, Zambia: Paraffin has been classed under Kerosene, Crop Residue under Tradition Fuel wood, and Cow dung under Other.

Mexico: Data for 1989 and 1990 (Scheinbaum *et al.*, 1996) group LPG and Kerosene together, however it is stated that LPG replaces kerosene with time. In a similar study (Rosas-Flores *et al.*, 2010) kerosene is not mentioned, only LPG. Thus kerosene was ignored in the Scheinbaum data and placed under LPG.

Peru: "Gas" has been put under "LPG" so as to be similar to Bolivian Data.

Sri Lanka: "Gas" has been put under "LPG". This is validated by the fact that under the household expenditure data, expenditures for fuels include L.P Gas only.

Tanzania: "Gas" is used for cooking. This is placed under LPG as in other countries of that region.

Turkey: (Utlu *et al.*, 2005) mention the use of a stove. It is assumed that improved fuel wood is used in this stove.

United Kingdom: The DoECC tables report energy use for cooking with electricity, oil and solid fuel. *Oil* was put in the *Kerosene* category and *solid* in the *coal category* (in order to agree with IEA data).

Capital Costs: The model requires the capital costs of cooking options in order for the multinomial logit function to work. Capital costs for cooking were determined from various consumer organizations (Consumentenbond, 2010; Consumer Reports, 2010; Which? , 2010). However unfortunately such organized data only exists for developed countries and thus only covers electricity and gas (while costs are ideally required for all 8 fuel types). The capital costs are converted to 2005$MER (**not** PPP).

5.2 *Useful Energy for Cooking*

As can be seen in Figure 80, no real relationship between energy for cooking and expenditures can be determined on a global scale. But even on a regional scale nothing definite can be said since there is not a plethora of available data, and even within the same region different sources give conflicting data (especially for the USA). Furthermore no concrete time or income based statements can be made since time-based series available for the United Kingdom and Germany show a small decrease and a small increase respectively.

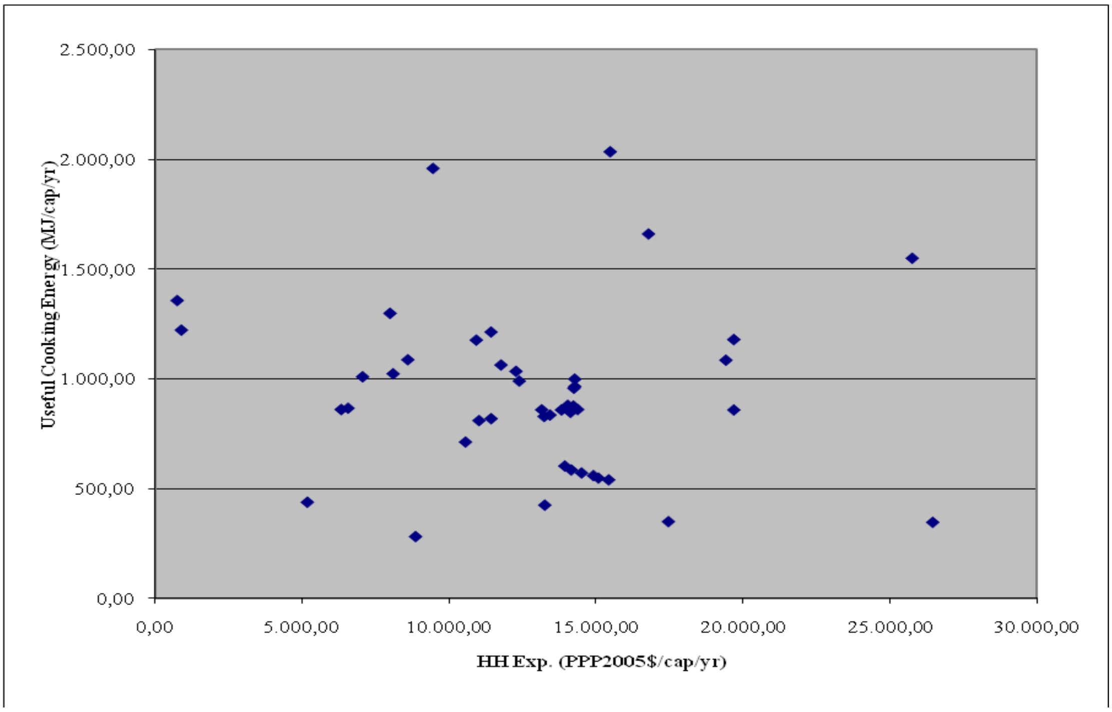

Figure 80. Energy for cooking vs. Expenditures (Global)

It was hoped that a definite decline would be observed which would confirm the hypothesis that cooking energy decreases with affluence due to the increase of meals eaten outside the household (Clancy, 2006). The average annual energy use of all data points is 930MJue/cap/yr.

5.2.1 Analysis

Since no direct pattern can be determined, energy use for cooking will not be modeled, retaining the same form as in REMI. REMI used a value of $2MJ_{UE}$/capita/day for cooking for India. Since more data is available now, this value will be revised to $3MJ_{UE}$/capita/day. A histogram displaying the frequency of data values for useful cooking energy is shown in Figure 81.

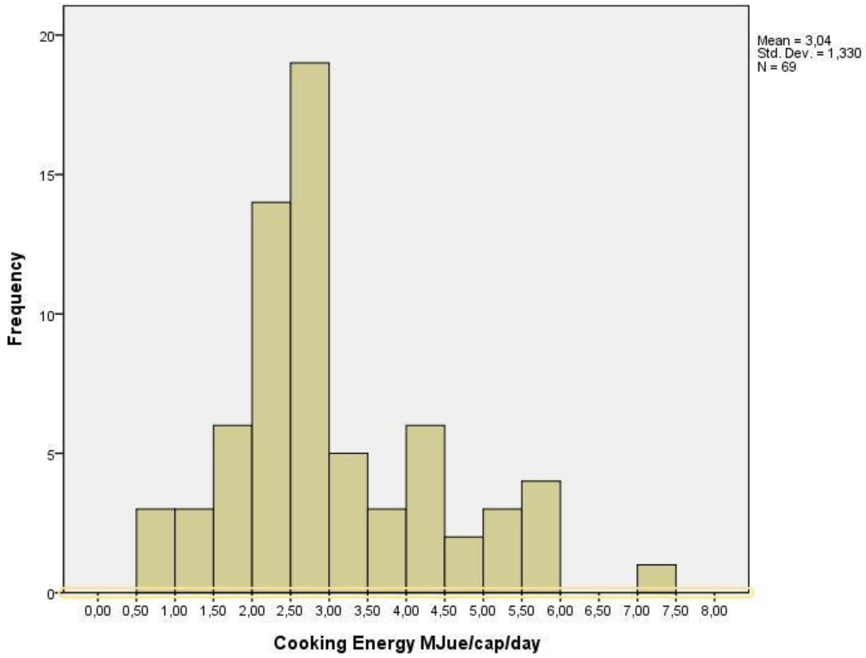

Figure 81. Histogram of Useful Energy for Cooking data points

5.3 *Shares of Cooking Fuels*

What fuels are used for cooking depends on welfare levels (the energy ladder) as well as regional variations. It has been attempted to get enough data to display both of these characteristics. Data on shares of cooking fuels were available for regions Mexico, Rest of South America, Western Africa, Eastern Africa, South Africa, Western Europe, Turkey, Southeast Asia, Rest of South Asia and Rest of Southern Africa. Urban/Rural differences could be gathered for regions Mexico, Rest of South America, Eastern Africa, South Asia, East Asia, Southeast Asia, Rest of South Asia, and Rest of Southern Africa.

5.3.1 Energy Ladder

The available data confirms the energy ladder for poor households as shown in Figure 82 (presents data for Western Africa, Eastern Africa and Rest of South Africa). It can be clearly seen the poorest households use traditional fuel wood, which is replaced by coal then LPG and finally electricity (in richer regions Natural gas also plays an important role as shown later). Kerosene is always a secondary cooking option.

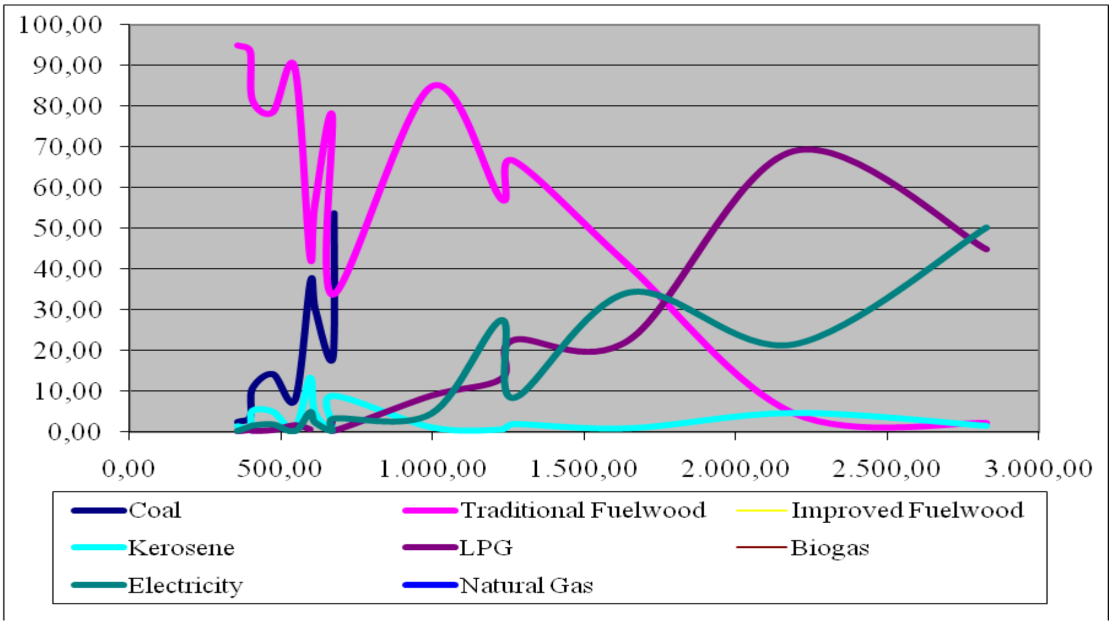

Figure 82. Fuel Shares vs. Expenditures

5.3.2 Regional Variations

Regional variation can be seen between and even within regions as shown in Figure 83 to Figure 85. Figure 83 shows that in equatorial Africa (which has the lowest expenditure levels) fuel wood is replaced by coal as expenditures increase with kerosene used in few households and extremely small amounts of electricity and LPG.

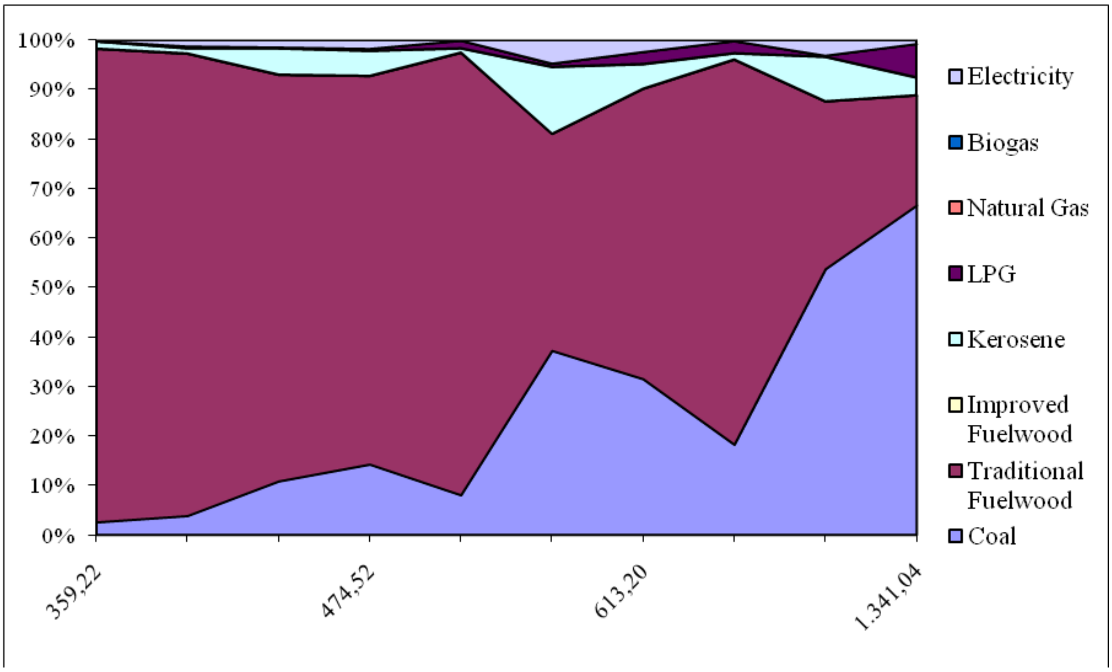

Figure 83. Fuel Shares vs. Expenditures (Western and Eastern Africa)

In South Asia, traditional fuel wood is replaced primarily by LPG and kerosene with coal never gaining the popularity of the African regions.

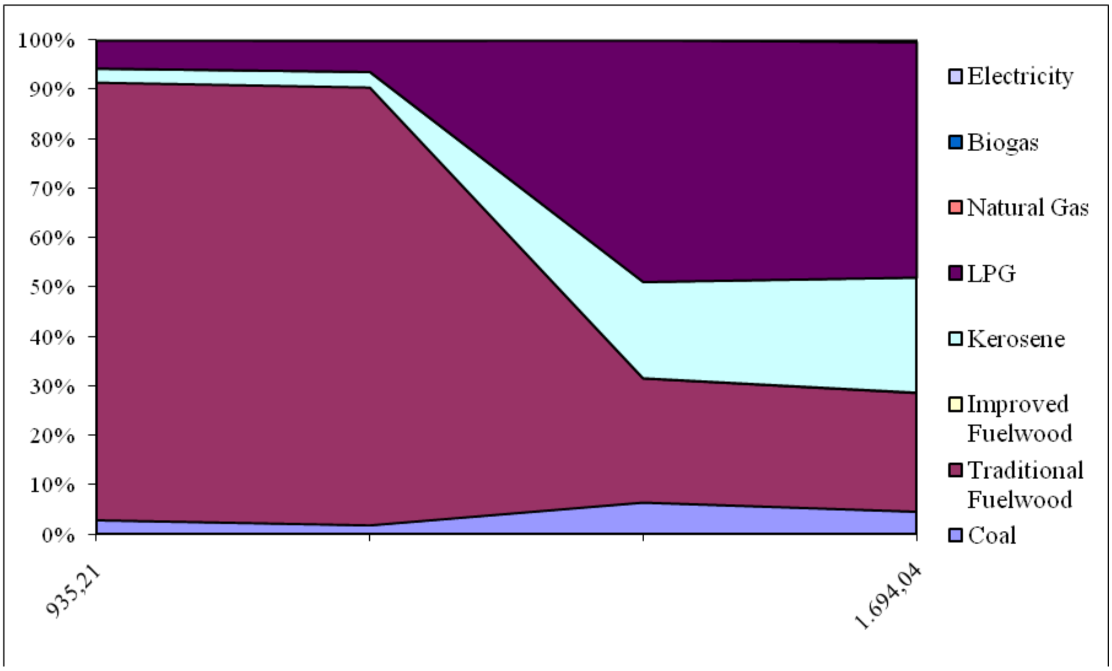

Figure 84Fuel Shares vs. Expenditures (South Asia)

Concerning Western Europe, it can be seen in Figure 85 that even within the same region there are variations. In Germany the vastly more popular fuel is electricity while in the United Kingdom electricity and Natural gas each hold a ~50% share.

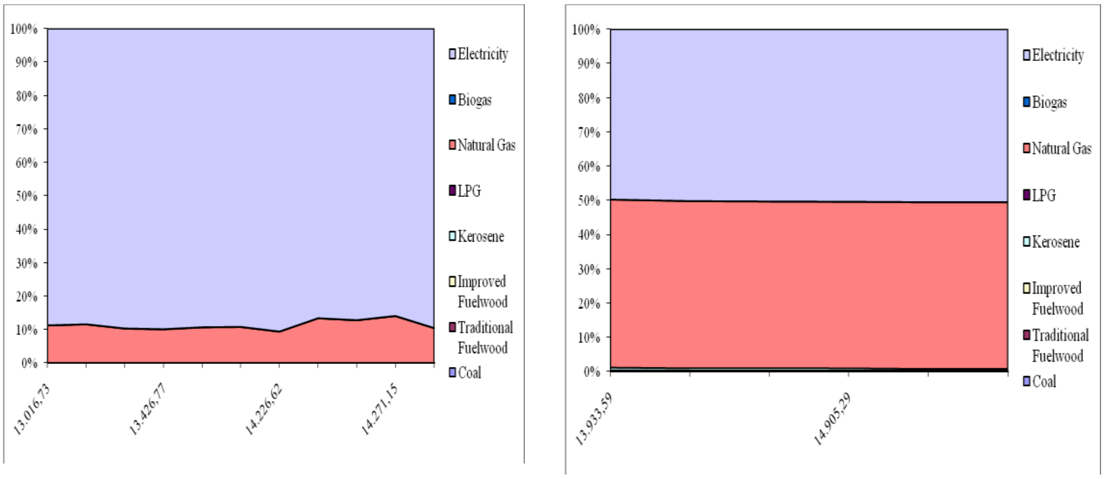

Figure 85. Fuel Shares vs. Expenditures for Germany and the United Kingdom

Within the 'Rest of South Asia', data for Bhutan and Sri Lanka show that with respect to expenditures, Sri Lanka makes the transition from fuel wood to kerosene later than Bhutan.

5.3.3 Urban/Rural difference

The difference between urban and rural households is twofold. Firstly they use *better* fuels, and also there is a much higher diversity. Data for urban/rural cooking options exists for Mexico, Rest of South America, Eastern Africa, South Asia, East Asia, Southeast Asia, Rest of South Asia and Rest of Southern Africa.

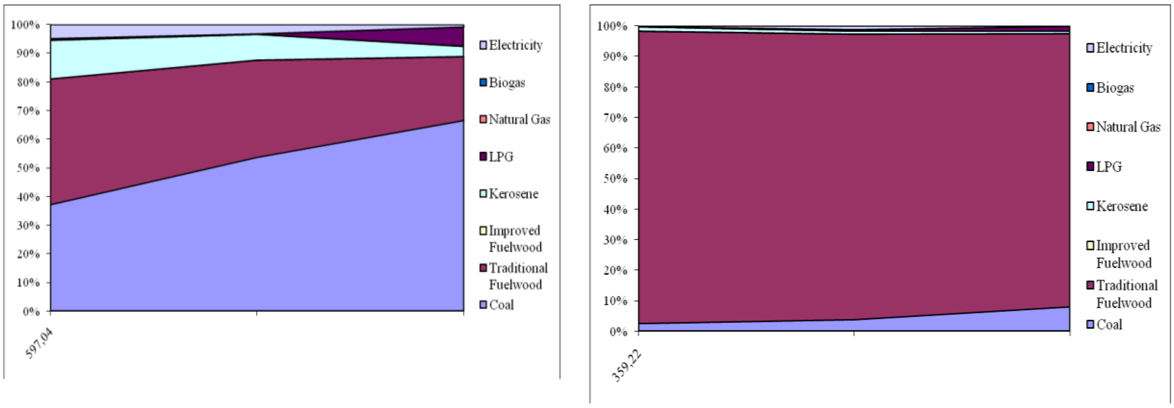

Figure 86. Fuel Shares vs. Expenditures, Urban and Rural Households (Eastern Africa)

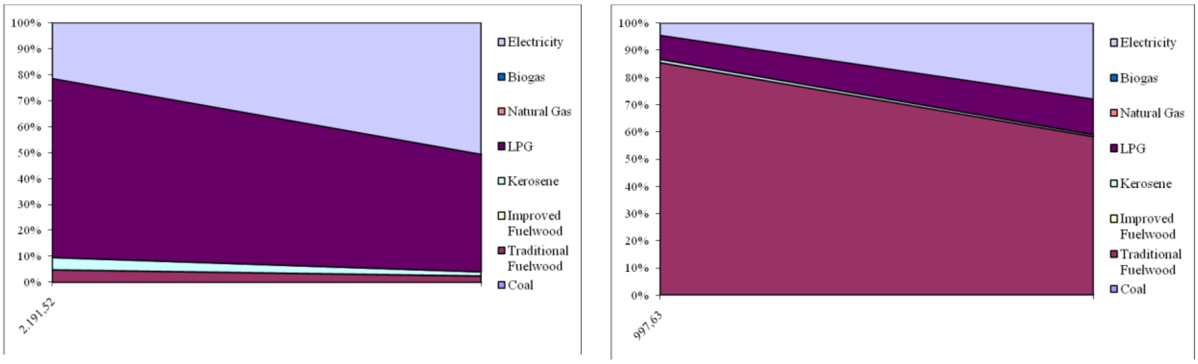

Figure 87. Fuel Shares vs. Expenditures, Urban and Rural Households (Rest of Southern Africa)

5.3.4 Analysis

The shares of useful fuel for cooking are dependant on a multinomial logit allocation here the cheapest option is given the highest market share. Within REMI, the economic lifetime of a cooking technology is calculated via the technical lifetime and the household expenditures. Subsequently an annuity factor (annualized costs) is determined with an interest rate. The annual capital costs are the technologies capital costs multiplied by the annuity factor minus any subsidies. The annual capital costs, together with the fuel costs and an extra premium factor (increased utility of cleaner options) are what are used in the abovementioned multinomial logit function. In REMG the calculation method has slightly changed (see section 9.1).

5.3.4.1 Capital Costs

In REMI, the capital costs are an exogenous data input determined from specific studies in India relating to the diffusion of cooking stoves to households, and thus primarily relate to the cheapest options (Gupta *et al.*, 1997; D'Sa *et al.*, 2004; Reddy *et al.*, 2006).

Concerning Biogas (option 7), a natural gas stove is needed, as well as special biogas production equipment. The stove price for biogas is set in the CookCapCost.dat file, while when the Annual Capital Costs are computed, the special biogas equipment is added on (only dimension 7 has non-0 value). Thus the cooking capital cost development of biogas is going to be linked to Gas/LPG capital costs, and the cost of the equipment is going to remain constant.

Concerning the capital cost for a domestic biogas plant, data exists from development agencies such as the *Netherlands Development Organization SNV* (SNV, 2008). Capital costs for stoves are deducted from the capital cost data, and labor is included. The following capital costs are available.

Table 26. Capital costs for domestic biogas plant

Country	***Capital Cost 2005MER$***
Rwanda	1021.08
India	409.17
Nepal	417.46
Bangladesh	336.27
China	385.81
Cambodia	396.27

African countries have the highest capital costs (other sources confirm this), while South and East Asian countries all have similar capital costs.

6 Water Heating

Energy for water heating is very significant and accounts for 10-30% of total energy consumption and is increasing (Tyler *et al.*, 1990; Scheinbaum *et al.*, 1996; Schipper *et al.*, 1996; Perez-Lombard *et al.*, 2008; Rosas-Flores *et al.*, 2010). Also it shows massive variance across regions due primarily to behavioral and climate aspects. Concerning the development of water heating energy with increasing household expenditures, one can assume that as lifestyles evolve, demand for hot water increases. At some point however this demand for hot water may (or may not) saturate, and then energy efficiency gains act as a force in the opposite direction reducing the energy demand.

Major data sources are scientific papers or government releases as well as the *IEA 30 years of Energy Use in IEA countries* (IEA, 2004). Unfortunately the IEA data rarely agreed with the other sources and almost always gave significantly higher values. All data has been corrected for efficiency. This includes the IEA data (assume 70% efficiency), which is contrary to how the IEA data was treated for cooking energy in Section 5.

6.1 *Remarks*

Australia and Turkey: A value for solar water heating is also provided. These were not accounted since they do not demand energy. For turkey the value for LPG is suspiciously high.

Bhutan: The 2003 and 2007 Living Standard Surveys list water boiler ownership rates. Even though they are reported together with other electrical appliances, it is unclear if *only* electrical water boilers were considered (NSB-Bhutan, 2003; NSB-Bhutan, 2007).

Canada: Heating oil is classed under kerosene, Wood under Improved Fuel wood. According to the source, “Other” includes propane and coal. The *Natural Resources Canada*, *Comprehensive Energy Use Database* gives the “Secondary Energy use” for water heating on a national scale. This was not treated as useful energy and thus was multiplied by an efficiency factor.

China: Only data for rural households is available.

Norway/Sweden/Denmark (1986) USA (1999): These values are for houses which only heat their water via electricity.

USA: Average energy use per house which uses specific fuel is used is reported. The variation between Electricity and Natural gas cannot be explained by regional or income variations.

6.2 *Useful Energy for Water Heating*

6.2.1 Inferences

Limited amounts of data are available and many time different sources have conflicting results. Some form of data exists for Canada, USA, Mexico, Western Europe, Turkey, South Asia, East Asia, Japan and Oceania as shown in Figure 88. As can be seen there is quite some variance, but this variance can be explained. Canada has very high water heating energy demands and this can be explained by its cold climate. Canada's values are also comparable to the higher values for Western Europe, which happen to be the Scandinavian countries. The low value for USA was determined from a study performed in Florida (which has a significantly warmer climate than average), while the other two values are national figures.

Also it can be seen that low income regions (East Asia), rural households have lower water heating energy demands. By looking at the Canada points it seems like there is a peak in heating energy demand at around expenditures of $13,000/cap after which the demand falls. Yet for Japan and Oceania this peak is not seen (but there are also fewer data points).

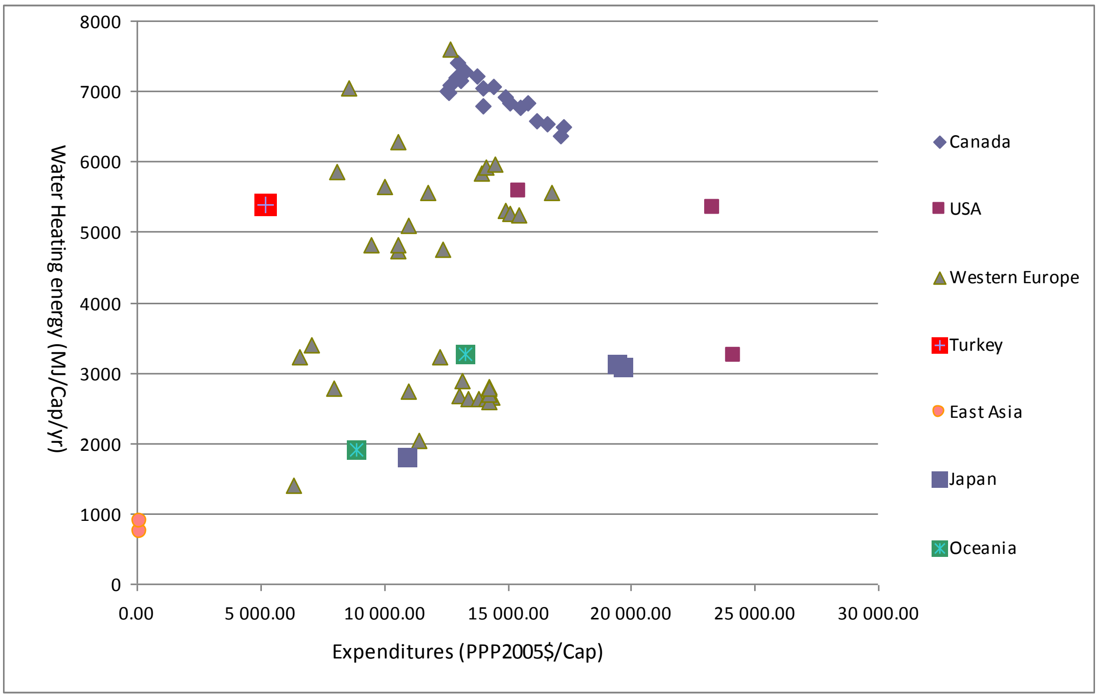

Figure 88. Water Heating Energy vs. Expenditures

Concerning urban/rural differences, unfortunately data was only available for the USA. Still, rural households had a lower demand for hot water.

6.2.2 Analysis

As pointed out in section 6.2, the useful energy for water heating may be dependent on climatic conditions or behavioral/cultural aspects. In order to get insight in how much climate affects water heating energy use, it is interesting to plot the useful energy requirement for water heating against the heating degree days of the particular region. Data for heating degree days is available in the form of an output file from IMAGE where HDD is reported for 27 regions, for 12 months and total (per region).

In doing this analysis it is important to keep in mind that besides climate, welfare levels play an important role when it comes to this energy requirement. This is evident since low income regions have low energy requirement, simply because they cannot afford water heaters or do not live a lifestyle which requires hot water demand. For richer regions it is witnessed that demand for hot water useful energy flattens out, thus only these "saturated" regions were compared with their respective HDD.

Figure 89 shows the useful energy requirement for water heating versus the HDD for Canada, USA, Western Europe, Japan and Australia. The cluster of points at HDD ≈ 3000 is Western Europe, and the higher MJ_{UE} correspond to Scandinavian countries (HDD used was constant across the region). An interesting point is that the cluster around HDD ≈ 2400 consists of the USA and Japan, which have very similar HDD, and are both amongst the richest countries, but yet the USA's requirement is substantially higher. This is probably related to behavioral aspects of the USA. The cluster with the highest HDD and highest requirement is Canada. Thus it can be concluded that water heating requirement can be related to climate aspects.

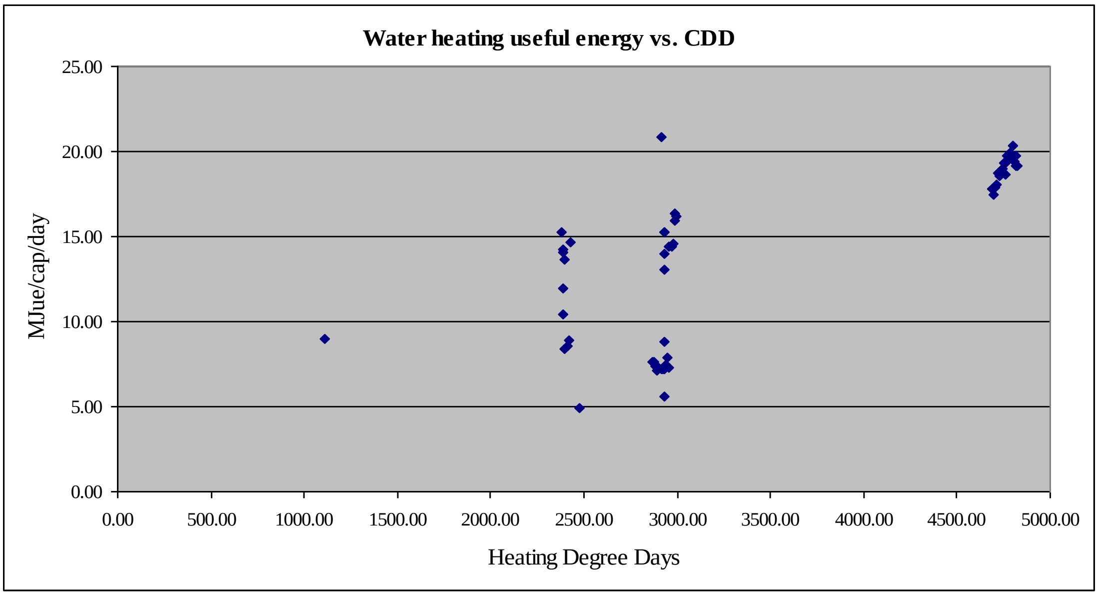

Figure 89. Useful energy for water heating vs. Heating Degree Days

In REMI, the useful energy for water heating is modeled as a stylized curve with the form:

$$UE_{HotWater} = 8.5 \cdot (1 - EXP \cdot (-(0.1/1000) \cdot HHExp)) \quad (MJ_{UE}/cap/day)$$

This equation determines the energy requirement per urban/rural and income level households (via HHExp).

First and foremost, the *maximum useful energy requirement* (i.e. the 8.5 in the above equation) has to vary amongst regions based on climate. This was determined by associating the useful energy requirement with heating degree days (HDD) for regions where this demand has been saturated, or in other words there has not been a marked increase in this demand for many years. The data shows a linear relationship. Furthermore, it was decided that a gompertz function is more appropriate since data from China, India and Mexico indicate a very low demand at their low incomes despite a much higher maximum useful energy demand (Xiaohua *et al.*, 2002; Tonooka *et al.*, 2006; van Ruijven, 2008; Rosas-Flores *et al.*, 2010). The new equation describing useful energy demand is:

$$UE_{HotWater} = (m \times HDD + c) \times \ EXP(\varphi_2 \times EXP\ (-(\varphi_2/1000) \cdot HHExp)) \quad (MJ_{UE}/cap/day)$$

A regression with the data gives the following coefficients. The available data together with the equivalent modeled points are shown in Figure 90.

$m = 0.003$, $c = 2.756$, $\varphi_2 = 3.356$, $\varphi_3 = 0.237$,$R^2 = 0.60148$

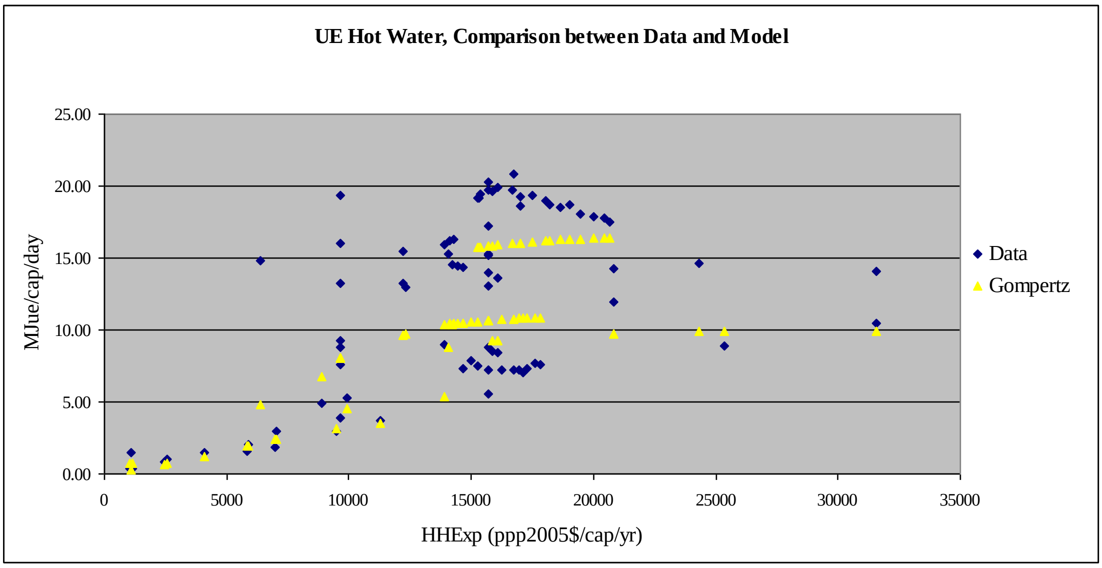

Figure 90. Comparison between data and model for useful energy demand for hot water.

6.3 *Shares of Hot Water fuels*

6.3.1 Inferences

Very little data is available for what portion of the load each fuel covers. At least one data point was available for Canada, Western Europe, Turkey and Oceania, yet only for Canada, Western Europe and Oceania were time series available. Yet even with these few data points it is evident that with increasing affluence households tend to go towards electricity or natural gas for their hot water needs.

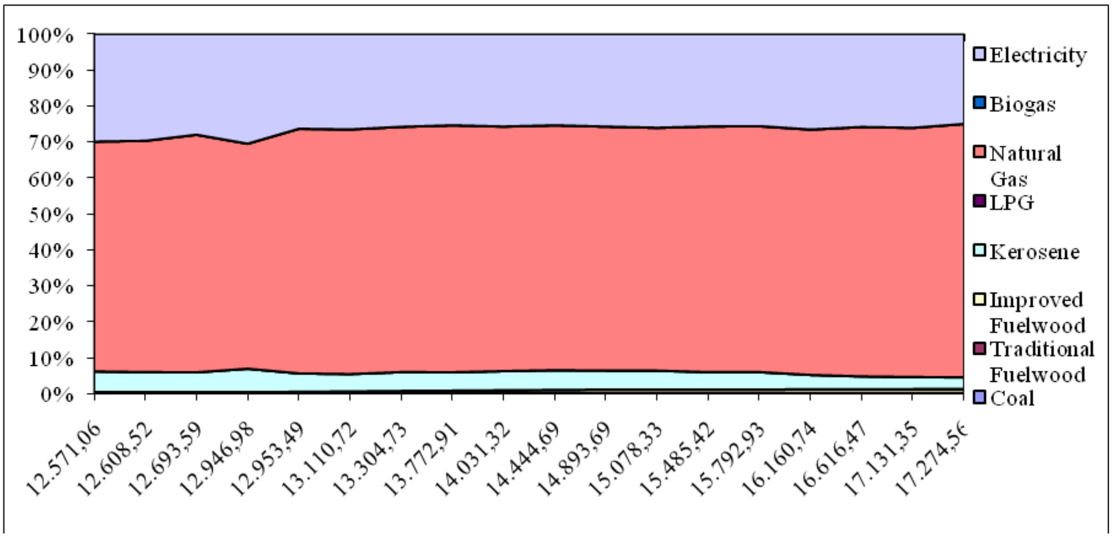

Figure 91. Fuel Shares vs. Expenditures for Canada.

Figure 91 indicates that affluent houses share their load between Natural gas and Electricity, with a small increase in natural gas with time (~8% in 16 years). This is confirmed for Western Europe (though amongst different countries within the region the portion of each fuel changes) and Oceania.

Data for less affluent countries exists only for Turkey and rural households of East Asia. They show that fuel wood and coal are primarily used and then there is a switch to LPG and electricity. Not enough data is available to make urban/rural distinctions.

6.3.2 Analysis

In REMI, ownership of electric water heaters is modeled with appliances (gompertz function related to household expenditure). Then, households who own electric water heaters use electricity; otherwise they use their cooking fuel which is determined according to section 5.3.4. Even though this represents India (and other developing regions such as South Africa and to a lesser extent Botswana) well, it cannot remain in the global model since water heating fuel is related much more to space heating fuel, especially in developed countries. Data from Australia, Canada, Germany, Portugal, the United Kingdom and the USA verify this (NRCan, ; ABS, 1992; De Almeida *et al.*, 2004; EIA, 2005; DoECC, 2009; FSO, 2010). Unfortunately, data on fuel use for water heating is extremely sparse for developing regions and thus the hypothesis that water heating fuel and space heating fuel are the same for developing regions as well as developed regions cannot be verified. Furthermore, ownership rates of electric water heaters are barely reported. Thus it is proposed that the shares of water heating fuels are directly coupled to the shares of space heating fuels (see section 7.3). Thus, water heating useful energy requirement and space heating useful energy requirement are lumped together (see also section 7.3).

Low Income Allocation:

In REMI space heating fuel shares are determined from cooking fuel shares (including an ownership of electric water heaters which have now been removed). This represents developing countries very well as cooking fuels tend to be used for water and space heating and also the energy ladder dynamic is well represented here.

In REMG, the shares of cooking capital will be used to determine the shares of heating energy use. This is used (instead shares of cooking energy) due to the difference in cooking and heating efficiencies.

High Income Allocation:
As households get richer, the energy ladder is not the main dynamic (as argued earlier), instead regional accessibility to high quality fuels determines market shares. Thus the market allocation mechanism has to follow another path as households get richer. It is proposed that as households get richer (or as consumer discount rates get lower, section 9.1) the market allocation of water/space heating becomes independent of cooking. Instead it will follow a multinomial logit allocation as with lighting and cooking end uses (but with its own pricing mechanism).

The transition between the low income and high income allocations will follow a linear transition from one to the other. The transition will start at $1000\$_{2005}$/cap household expenditures and end at $5000\$_{cap}$. The 1000$ starting point has been chosen since at around that point the consumer discount rate has reached its minimum of 10% (see section 9.1) and thus investments in other technologies are more attractive. Also data from Botswana and Bhutan show this behavior[12] (CSO-Botswana, 2004; Lhendup *et al.*, 2010).

An allocation factor ($0 \leq AllocationFac \leq 1$) will be multiplied with the *High Income* and *Low Income* (1-*AllocationFac*) market shares in order to determine the *Real Heat Shares*. This is performed as follows:
$\text{AllocationFac}_{R,URQ} = 0.00025 \times \text{HHExp}_{R,URQ} - 0.25$

Then:

```
IF $\text{AllocationFac}_{R,URQ} < 0$
    THEN $\text{RealHeatShares}_{R,URQ} = \text{LowIncShares}_{R,URQ}$
    ELSE
    IF $0 < \text{AllocationFac}_{R,URQ} < 1$
        THEN $\text{RealHeatShares}_{R,URQ} = (\text{AllocationFac}_{R,URQ} \cdot \text{HighIncShares}_{R,URQ}) + [(1- \text{AllocationFac}_{R,URQ}) \cdot \text{LowIncShares}_{R,URQ}]$
        ELSE $\text{RealHeatShares}_{R,URQ} = \text{HighIncShares}_{R,URQ}$
```

---

[12] It should be noted that at even higher expenditures ($\approx 7000\$_{2005}$/cap) South Africa still shows a strong relationship between cooking and heating fuels. Perhaps this transition can be made region specific in further revisions.

7 Space Heating

The absolute energy for space heating is not required as it is modeled separately, but the shares of heating fuels is required to break down this load. Data is available for Canada, USA, South Africa, Western Europe, Japan, Oceania and Rest of Southern Africa. Time series (at least 2 points) are available for all except Rest of Southern Africa, while urban/rural is only available for this region.

7.1 *Remarks*

Ireland: The *Energy in the Residential Sector* report (EPSSU, 2008) lists the fuel used for *central heating* from 1987 to 2005. The proportion of houses using central heating has increased from 52% to 91% in this time period. The values used have been corrected for central heating levels. Solid Fuel treated as Improved Fuel Wood. “Dual System” treated as “Other”.

Botswana: A value for solar water heating is also provided. This is placed under other. In the household income survey (CSO-Botswana, 2004) the heading is “Heating”. It is not clear if this is water heating or space heating. Curiously, urban households heat their houses less than rural households are indicated by the field “None”.

Canada: Three sources are available, the *30 years of energy use in IEA countries* (IEA, 2004), the Comprehensive Energy use Database of the Energy resources Canada (NRCan), and the *Selected dwelling Characteristics* of the Statistical Agency of Canada (Statistics-Canada). Though these three sources agree on which fuels are used, they show a variation of ±10% on the actual shares.

Western Europe: Within this region, across different countries there is a huge variation. If an average is to be computed, it has to be done carefully since the United Kingdom and Germany provide most of the data points and so would get a disproportionate weight.

7.2 *Inferences*

The data shows that in poorer regions (such as Rest of Southern Africa) traditional fuel wood is used while as households increase their expenditures they move towards kerosene, natural gas and electricity. However, the relative shares of these fuels are very region specific.

Figure 92 shows that in Canada, natural gas gets the lions’ share while electricity comes in second with kerosene used by very few households. Yet for the neighboring USA, kerosene and natural gas are the main fuels used with electricity getting a minimal share. Figure 94 and Figure 95 show that within Western Europe there is quite some variance (more examples of this exist). In Germany kerosene and Natural gas get the most of the load while electricity and remote heating also cover small portion. Ireland shows a transition phase where over 18 years there was a move from fuel wood to kerosene and natural gas with electricity playing a minimal role.

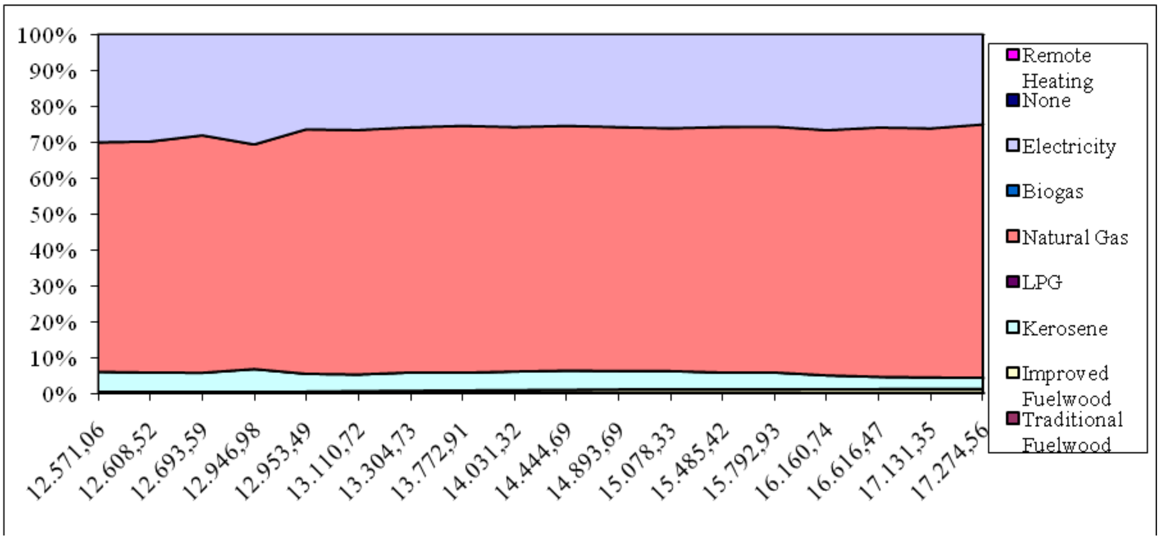

Figure 92. Space Heating Fuel Shares vs. Expenditures (Canada)

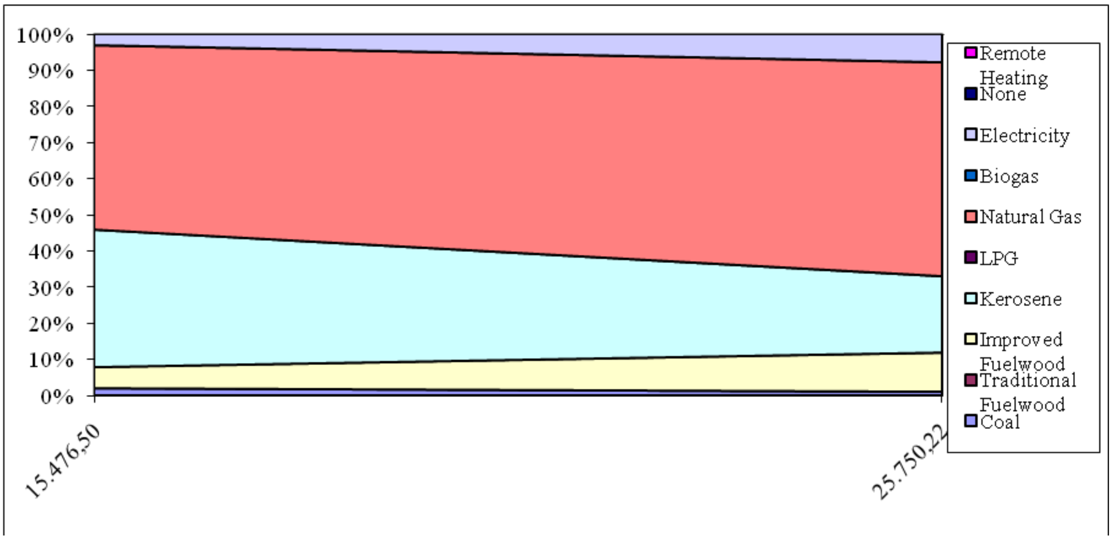

Figure 93. Space Heating Fuel Shares vs. Expenditures (USA)

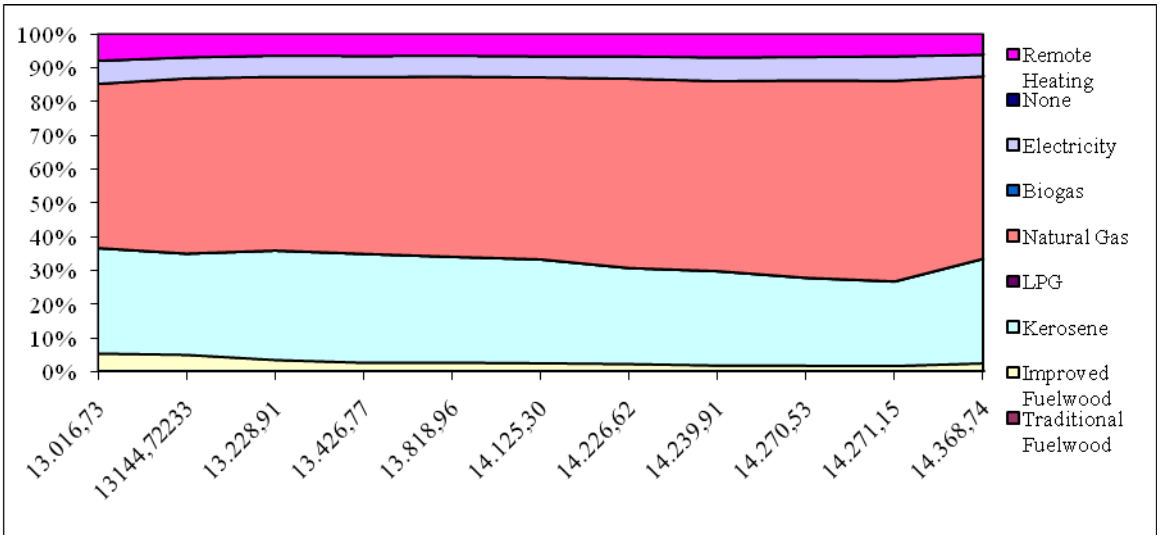

Figure 94. Space Heating Fuel Shares vs. Expenditures (Western Europe, Germany)

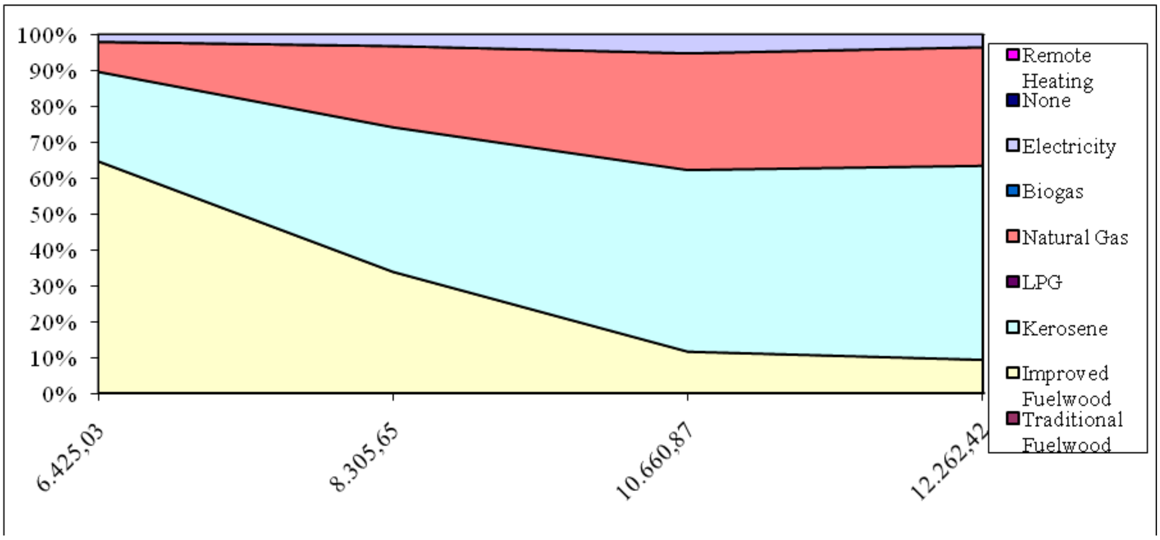

Figure 95. Space Heating Fuel Shares vs. Expenditures (Western Europe, Ireland)

7.3 *Analysis*

The REMI model was made specifically for India. In that case the space heating share is minimal and thus the market shares of space heating fuels were calculated as a residual of what was left after determining cooking and lighting (which in the case of India are the largest residential energy users). For the Indian case this works well, but it cannot be kept for the global model since residual residential energy use may also consist of other end uses which are not specifically modeled here. An additional difficulty is that ownership of heating appliances cannot be modeled as use of heating fuel is primarily a cultural feature (see commentary in section 7.2).

The useful energy demand for heating is derived from Isaac and van Vuuren (2009) and is described as useful energy demand for residential space heating per capita as a function of floor space, heating degree days and heating intensity:

$$UEheating_{TURQ,R} = FS_{TURQ,R} \cdot HDD_{R} \cdot Intensity_{R}$$

In the global model the useful energy demand calculation will remain the same\. It is important to note that this useful energy demand is not in fact met in very poor households, since they cannot afford to heat themselves to comfortable levels. Data does not exist on how this demand is met as households get richer. In order to account for this dynamic in REMI, as households get richer they gradually meet this demand finally reaching it at a given expenditure level called the *Heat saturation Price*, a number which is arbitrarily set. The way this is computed is as follows:

$$\begin{aligned}&HeatSaturation_{TURQ,R} = IF\ HHExp_{TURQ,R} < 10\ 000\\&\text{THEN } (1/HeatSatPrice) \times HHExp_{TURQ,R}\\&\text{ELSE } 1\end{aligned}$$

$$RealUEheating_{TURQ,R} = HeatSaturation_{TURQ,R} \times UEheating_{TURQ,R}$$

In REMG, the useful energy for space heating and the useful energy for water heating are combined in order to determine a general *Useful Energy for Heating*. Fuel shares are then allocated according to the process explained in section 6.3.2.

8 Lighting

Lighting, especially in low income regions where household appliances have not yet become the major consumer of electricity, accounts for a significant share of total electricity use. For OECD countries it accounts for roughly 18% of the electricity demand and about 5% of the total energy demand of the residential sector (IEA, 2008; Weiss *et al.*, 2008).

In the REMI model, once a household is electrified it is assumed that electricity will be the prime source of lighting. If not electrified, it is assumed that kerosene lamps are used. Once a household is electrified, it is assumed that only electric lighting is used. Data concerning lighting energy per unit floorspace as well as differentiation of lighting shares between different lighting options was looked into.

8.1 *Pre Electrification*

Even though in the REMI model non-electrified households are assumed to get their lighting from kerosene lamps, in reality lighting is provided by a multitude of fuels including candles, wood or kerosene/gas lamps. Thus data concerning lighting shares amongst developing countries was sought. This was done in order to determine if it is feasible to retain the kerosene lamp assumption, and also to see how fuel choices may change.

8.1.1 Remarks

When the reported lighting method was “Kerosene/Gas Lamps”, the fuel share has been assigned to “Kerosene”. Publicly, and privately generated electricity have been placed under “Electricity”. Solar power was not accounted for since it is not an energy demand.

Botswana: “Candles” and “Paraffin/Candle” have been lumped together (there is also a separate “Paraffin” category, placed under “Kerosene”).

*Cambodia: “*Battery” has been placed under electricity.

Malawi: “Grass” has been placed under “Traditional Fuel Wood”

South Africa: Poorer household use a significant amount (greater than 20%) of “Other” fuel (i.e. besides kerosene, natural gas and electricity). It is not know what this “Other” fuel is but comparisons with surrounding countries would lead to believe that candles and fuelwood may be important.

*Tanzania: “*Firewood & Other” placed under “Traditional Fuel Wood”, “Gas” has been placed under “LPG”.

Uganda: According to the text of the *Uganda National Household Survey 2005/2006* (BoS-Uganda, 2006), “Other” includes “Firewood, Biogas”. Thus it was placed under “Firewood”.

8.1.2 Inferences

The hypothesis that kerosene is the key fuel for lighting pre-electrification is verified to an extent. Data South Africa, South-East Asia and Rest of South Asia show negligible use of candles for lighting with electricity and kerosene sharing the load.

Yet, data for Eastern Africa (Just Uganda, not Tanzania) as well as Rest of South Africa (all countries) show that amongst the poorest of household's candles and, to a lesser extent, traditional firewood are still used.

Still the general trend is that initially, the poorest of households, houses use candles and firewood, which is replaced by kerosene lamps, and eventually by electricity. So an energy ladder is visible in the data. The dynamic is visible in Figure 96 and Figure 97 which show all the available data for urban and rural households respectively.

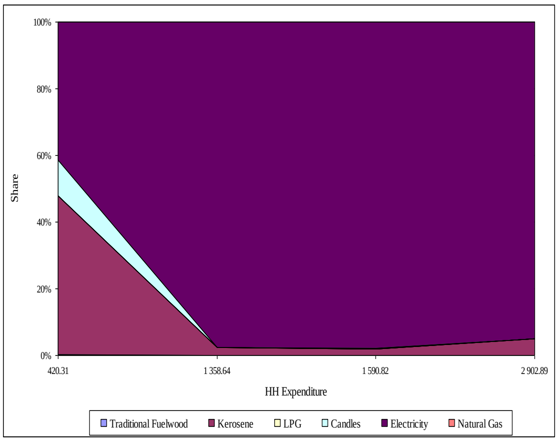

Figure 96. Lighting Shares for Urban Households

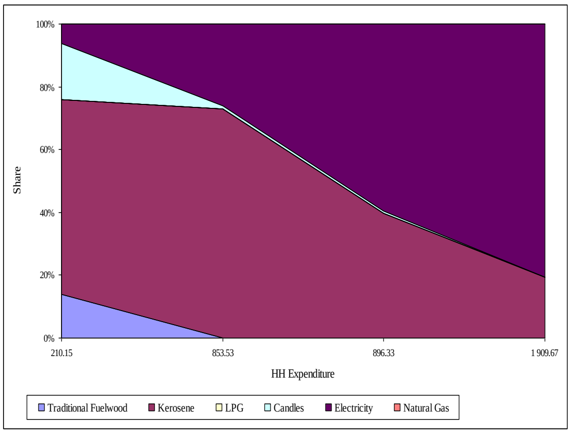

Figure 97. Lighting Shares for rural Households

8.1.3 Analysis

The inclusion of candles is not required since, strictly speaking, it is not an energy demand. Also the use of firewood for lighting is minimal since the highest value in the data is just 14%, with most data points at less than 5%. Thus it is deemed that in order to retain simplicity the assumption that lighting is provided either by kerosene or electricity will remain.

In REMI the monthly kerosene use (liters/month) for lighting was taken as 4l/month from a specific study focusing on India (ESMAP, 2003). Another paper lists the usage for 22 countries (ranging over 10 regions, all developing), in Liters of kerosene for lighting per month (Mills, 2005). Surprisingly, this variation does not show any significant relationship with household expenditures or the price of liquid fuels. Presumably there are other factors determining this difference between regions. Thus kerosene usage is not modeled in REMG but rather each region is given a value based on the Mills paper.

8.2 *Post Electrification*

As mentioned, once a household is electrified, electric lighting is going to be used. To retain simplicity this assumption is going to be retained in the global model. Yet it is important to determine what the dynamics are for efficient and non efficient lighting. Thus additional to lighting energy per m^2, the share of efficient and non-efficient lighting was looked into. This is important in order to get a relationship for energy requirement for lighting assuming a “frozen” efficiency for lighting.

Data is available for the USA, Western Europe and South Asia.

8.2.1 Remarks

Specific data on shares between efficient/standard lighting options and lighting energy demand per household floorspace is very limited, and data exists primarily only for developed countries.

When dealing with electricity consumption for lighting, it is important to keep in mind that the ratio of standard to efficient lighting is hidden within. In order to make a meaningful analysis it is important to determine the consumption assuming either standard or efficient lighting *only*. Thus useful data could only be gathered when this ratio was available, which significantly limited the data sources. In all cases it was assumed that efficient lighting has wattage of 20W, while standard (incandescent) lights are at 70W.

United Kingdom: The DoECC gives total annual energy use for lighting divided into *Standard light bulb, Halogen, Fluorescent Strip lighting, Energy saving light bulb* and *LED*. The first three were allocated under *Standard*, and the last two under *Efficient*.

Sweden: Data comes from a micro level study (Bladh *et al.*, 2008) where details from seven households concerning floorspace, household size, number of lights, annual electricity use and the potential for the reduction of this electricity use if all incandescent lights are replaced. Using this data and with assumption on efficient/incandescent light bulb wattage it was possible to derive the ‘frozen’ electricity rate. However since it’s a micro level study there are some outliers.

IEA: Data concerning Italy, Sweden and the US was available in an IEA report (IEA, 1989), which gave share of incandescent, fluorescent and high intensity lighting. *Incandescent* and *high intensity* were placed under ‘Standard’, while *fluorescent* was placed under ‘efficient’.

Prices of CFL: The price development for *Compact Fluorescent Lamps* was determined by various reports and academic papers (Moriera, 1996; Urge-Vorsatz *et al.*, 2001; Reddy *et al.*, 2006; Oosterhuis, 2007; Weiss *et al.*, 2008). The prices were all converted to PPP2000$, yet it is unclear if taxes are included.

8.2.2 Inferences

When electricity demand is frozen for standard lighting, there is a clear linear relationship between electricity demand and floorspace. This is shown in Figure 98. Yet since the efficiency is not frozen in reality and, especially lately, the share of efficient lighting has been increasing, the rate of electricity consumption is de-coupled from electricity demand (frozen efficiency). Consequently, as can be seen in Figure 99, in the UK lighting energy consumption has been reducing the past few years.

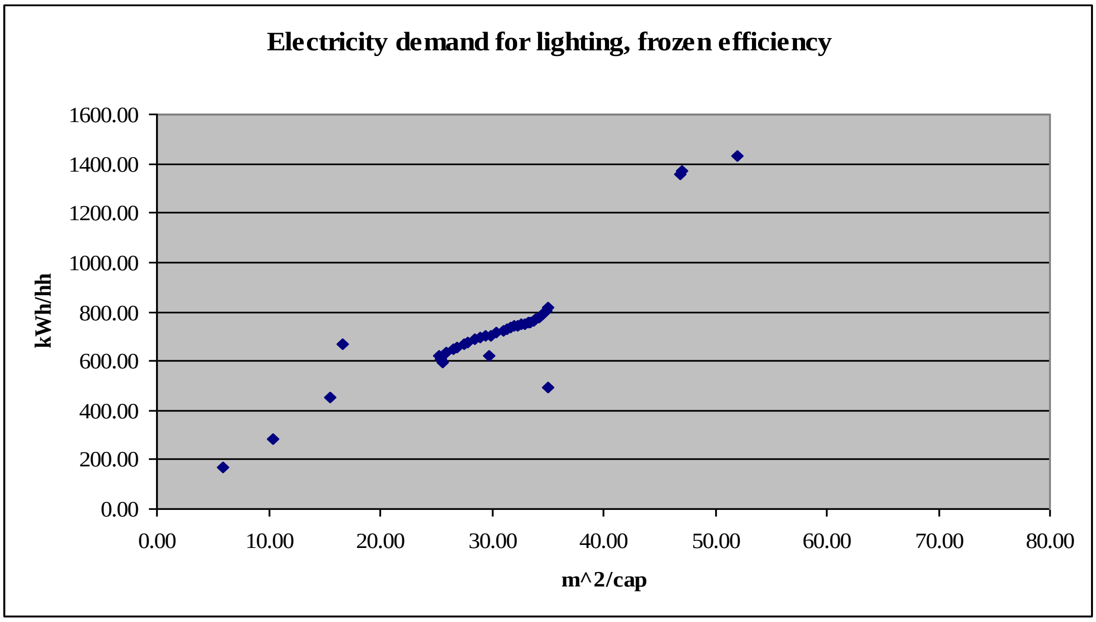

Figure 98. Electricity Demand (frozen efficiency) vs. Floorspace

Unfortunately, besides India, data is not available in order to determine the difference between urban and rural households.

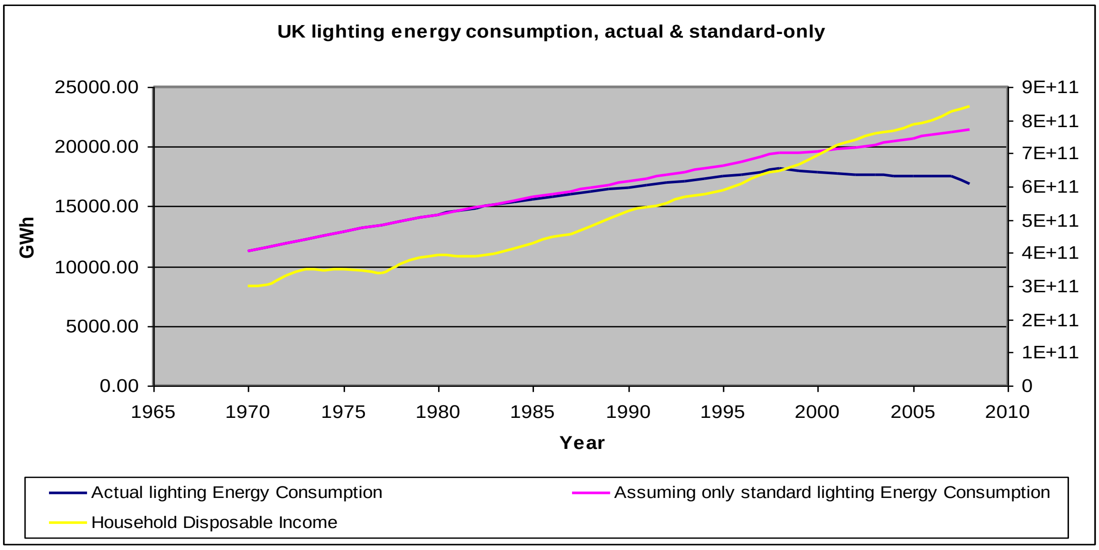

Figure 99. UK lighting Energy consumption, actual and standard lighting only.

An extremely important dynamics is how and why households switch between standard an efficient lighting. Figure 100 shows how the energy share of efficient lighting has increased with income. A similar curve can be drawn with time. Clearly though the uptake of efficient lighting is related to the relative price as well as possible regulation.

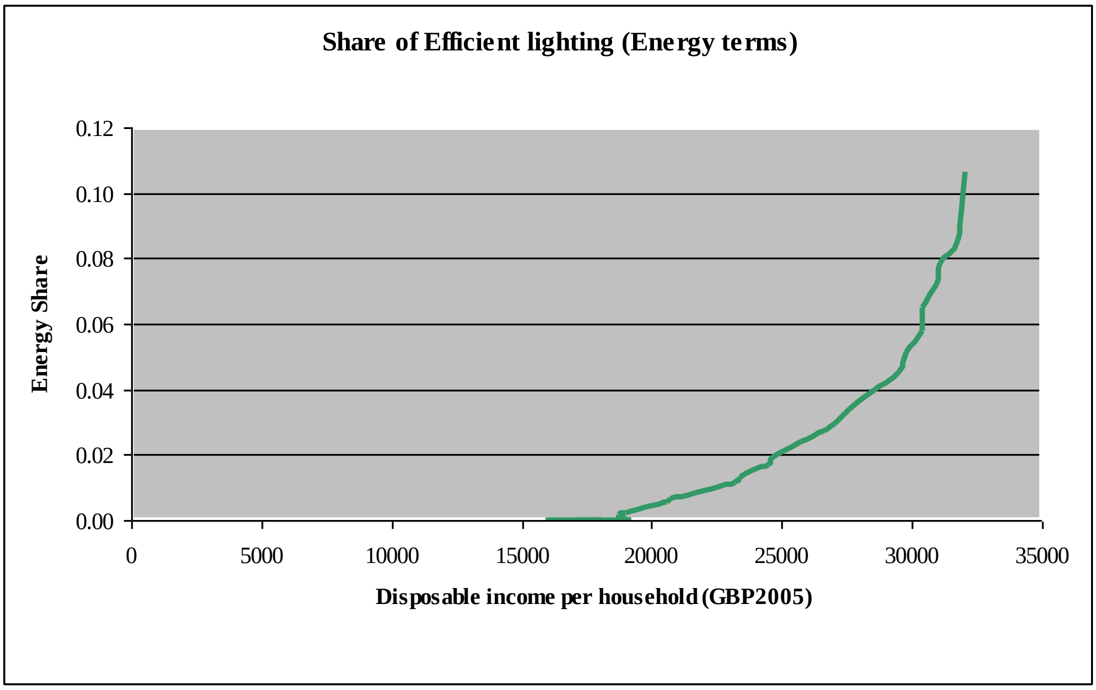

Figure 100. Energy share held by efficient lighting vs. income

In order to see the effect of CFL prices, historic data concerning the price development (in MER$2005) was sought. Data for the USA, Western Europe and to a lesser degree Brazil, Eastern Europe and South Asia is available and shown in Figure 101. It is obvious that CFL prices are almost identical between these three regions so it may be safe to assume a global price for CFL, since further data is lacking.

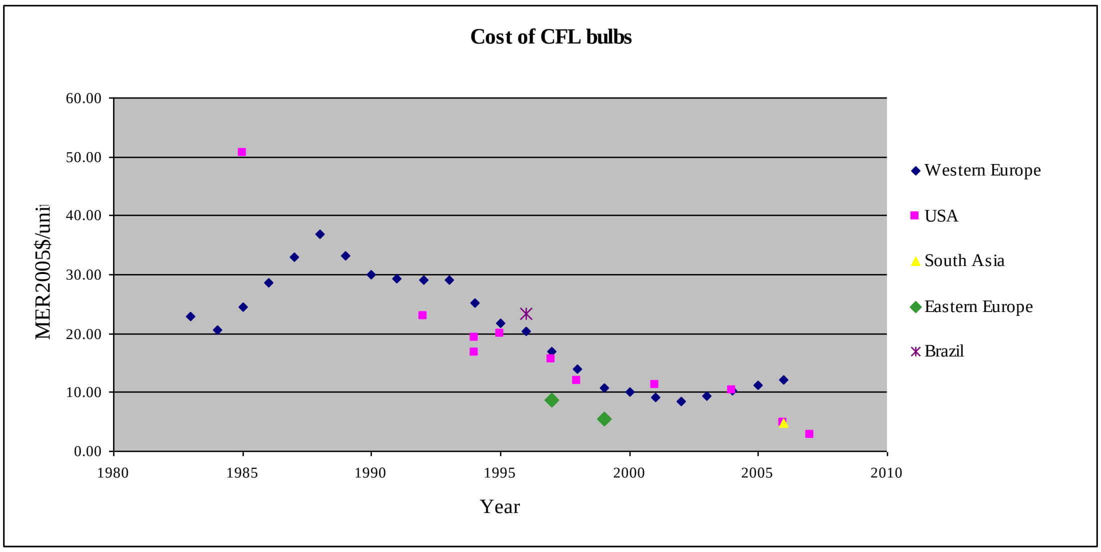

Figure 101. Price development (MER) of Compact Fluorescent Lamps

8.2.3 Analysis

In the REMI model two different energy packages are specified, namely: Standard and Efficient. These energy packages are based on an analysis by Reddy (Reddy *et al.*, 2006) which set up these energy packages for households at different income levels, indicating capital costs and energy consumption. These energy packages are strictly defined with varying mixtures of incandescent, fluorescent tubes and CFLs.

Following, linear relationships between capital costs and floorspace and electricity consumption and floorspace are determined. These are used to determine total costs which finally dictate the market share of each package via a multinomial logit function.

For the Global model, it has been proposed to add two extra elements in the lighting sub-model. These are, 1. Account for difference in daylight hours between regions, and, 2. Account for the change in CFL prices with time, thus have a dynamics market allocation. A further correction that ought to be made is that the energy packages should be strictly divided, with efficient containing only efficient lighting and standard, only standard lighting. As already stated, in REMI non-electrified households automatically use kerosene, while electrified households use electric lighting, with an allocation to efficient and standard lighting. This methodology will remain.

With the new method first a factor is set up relating Floorspace per capita to required light fittings. Based on available data, this variable seems to be constant with time and across regions. The underlying assumption is that the *lighting needs per floorspace are the same globally*. This is justified since Figure 98, though multiregional, is roughly a straight line. Figure 102 shows that the available data clusters around a mean of 0.68 fittings/m^2/cap with one outlier (which is a specific case in Sweden). It has been impossible to determine if this differs between urban and rural households however by using the Reddy data the way it was used in REMI in order to get such results (i.e. by superimposing it with externally derived and allocated floor spaces), similar results between urban/rural households are given. This simply assumes that lighting needs of urban and rural households (per floorspace) are similar.

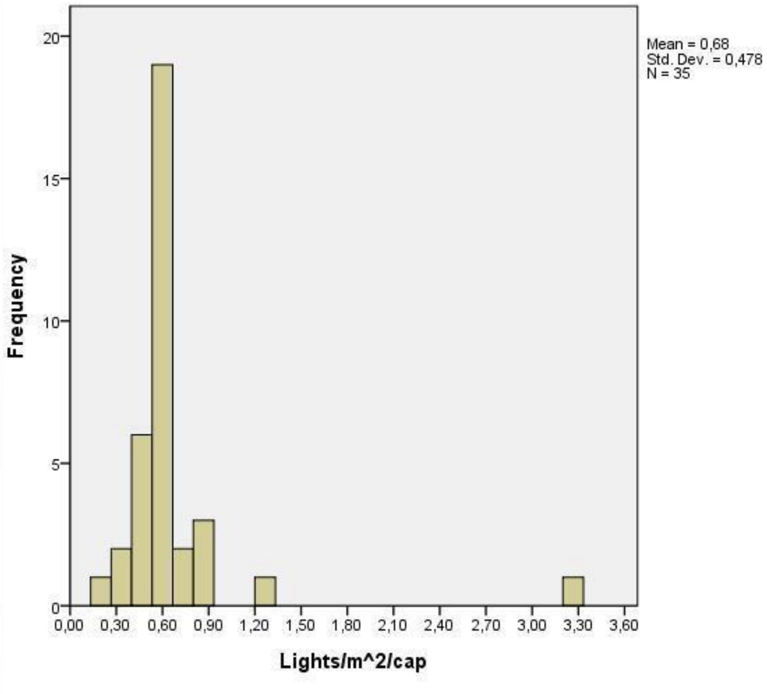

Figure 102. Lights per m^2/cap histogram

By multiplying this factor (0.68) by the floorspace (which is derived via household expenditures and population density, section 3.2.3), we can get for urban and rural quintiles the required installed capacity (in Watts) of standard or efficient lights, and thus capital costs. Note that through this methodology it is implicit that one efficient light replaces one standard light. By multiplying the installed capacity by lighting hours (per year), the electricity consumed and thus the fuel costs for lighting per year, demographic, quintile and energy package can be determined. This is summarized mathematically below:

$\text{Fixtures\_PHH}_{URQ,\,R} = 0.68 \cdot \text{Floorspace\_PC}_{URQ,R}$
$\text{LightCapacity\_PHH}_{URQ,EP,R} = \text{Fixtures\_PHH}_{URQ,R} \cdot \text{UnitCapacity}_{EP}\text{(W)}$
$\text{AnnEnergyUse\_PHH}_{URQ,EP,R} = \text{LightCapacity\_PHH}_{URQ,EP,R} \cdot \text{LightingHoursFactor (Wh/day)}$

$\text{CapitalCost\_PHH}_{URQ,EP,R} = \text{LightCapacity\_PHH}_{URQ,EP,R} \cdot \text{UnitCost}_{EP}$
$\text{FuelCost\_PHH}_{URQ,EP,R} = \text{AnnEnergyUse\_PHH}_{URQ,EP,R} \cdot \text{FuelCost}_{electricity}$

URQ = Urban and Rural Quintiles
R = Region
EP = Energy Package

Following this, the Annual costs, Multinomial Logit Function, Capital Stock Vintage Model and Total Energy Use modules existing in REMI can be used. As can be seen, the only external data required is the Unit Capacity (Standard = 70W, Efficient = 20W), unit cost, and Lighting Hours.

The "lighting hours" factor is the equivalent time all lights spend on, per day. It is not related to the day-light hours each region gets due to geographical position since over the course of a year all regions enjoy approximately the same total daylight time. The *LightingHoursFactor* is determined by comparing results from the above equations to available data points for annual energy use at frozen efficiency, and is set as **1.38**(h). The accuracy of this is limited since the data upon which it is based is limited and skewed due to the multitude of UK data. Alternatively, this factor can be calibrated to IEA data for a regional factor.

As already mentioned, a goal of the global model is to also capture changes in prices of the lighting technologies. As can be seen in Figure 101, the prices of CFL have been falling and seem to be the same globally. Weiss and Oosterhuis attribute the fall in CFL prices to a number of factors including learning and outsourcing labor to cheaper areas. They are also cautious about future reductions due to possible resource scarcity. Still however in scenarios where policy promotes uptake of CFLs via subsidy or regulation, this can be reflected in the apparent price.

The according the Weiss study, the prices of incandescent bulbs have fallen from 1.23$(2005) in 1983 to 0.77$(2005) in 2006. For sake of simplicity, it will be assumed that the price of incandescent lights remain constant at 1$(2005) and CFL price follows an exponential decay. The absolute minimum price for CFL bulbs is set as equal to the price of incandescent bulbs. Equation 25describes the price development of CFL bulbs.

Equation 25. Price development of CFL bulbs

$$CFL_{2005\$} = 1 + 242.264 \cdot EXP(-0.104 \cdot (t-1970))$$

A weak point of this analysis is that it is based on a number of assumptions from limited data. But sadly, the required analysis requires lots of data which simply does not exist.

9 Other

A number of amendments and additions were made to REMI concerning certain dynamics which are common to some or all sub modules. These are described in this section.

9.1 *Depreciation*

In order to run the multinomial logic function to allocate market shares of various fuels, the costs of each option are required. These costs come in the form of investment costs and fuel costs. Since investments costs 'mature' during the operating period of, applying an interest rate, or a *Consumer Discount Rate* is necessary.

In REMI the technical lifetime and the expenditures determine the economic lifetime, which together with a CDR determine the annuity factor. Thus the CDR is set constant (10%) and the household expenditure, via the economic lifetime determined the annuity factor. In the global version it is desired to get rid of the economic lifetime and instead just have a CDR decreasing with income. This is justified by the fact that low-income households have higher CDRs than high income households since they cannot afford to purchase high-efficiency devices (even though their life cycle costs are lower) because of their prohibitive investment costs. A further explanation is that lower income households have less access to education and thus are less aware of cost savings that energy investment can induce (Goett, 1978; Hausman, 1979; Train, 1985; Reddy, 1996; Winer, 1997). These studies also indicate that CDRs vary from appliances to appliances with refrigerators having higher discount rates and other appliances and air conditioners having the lowest.

Even though these studies show that discount rates are always highest for lower income classes, for the purposes of the model it is more useful to have discount rate as a function of absolute welfare (household expenditures in REMI/REMG) rather than income class. This is because even though for luxury appliances lower income classes in rich regions may have a high discount rate, when it comes to basic appliances (such as an efficient stove), it is absolute poverty which is of importance. Since in the model, and its purpose, the acquisition of basic appliances is important rather than luxury appliances, and also when it comes to the switching of fuels it is poor regions which are of interest, relating CDR with household expenditures is more appropriate in this case.

Thus, the Reddy analysis is used which describes discount rate as a function of income. Based on the discount rates which richer households tend to settle upon even with luxury good, an absolute minimum CDR is set as 10%. Thus:

$$CDR_{R,UR,Q} = 10 + EXP(6.902 - 0.008 \cdot HHExp_{R,UR,Q})$$

As can be seen in Figure 103, the minimum 10% discount rates is approached at expenditures of around 700$/cap. The same description for CDR's will be kept for urban and rural households. Since at any given moment in the model rural households are poorer than urban households, their CDR is going to be higher, thus no correction has to be made. As already mentioned, studies show that discount rates for household appliances, and especially refrigerators, tend to be higher. This is relevant in REMG concerning consumer willingness to switch to more energy efficient appliances (and in particular refrigerators), and so for appliances minimum CDR is set as 40%.

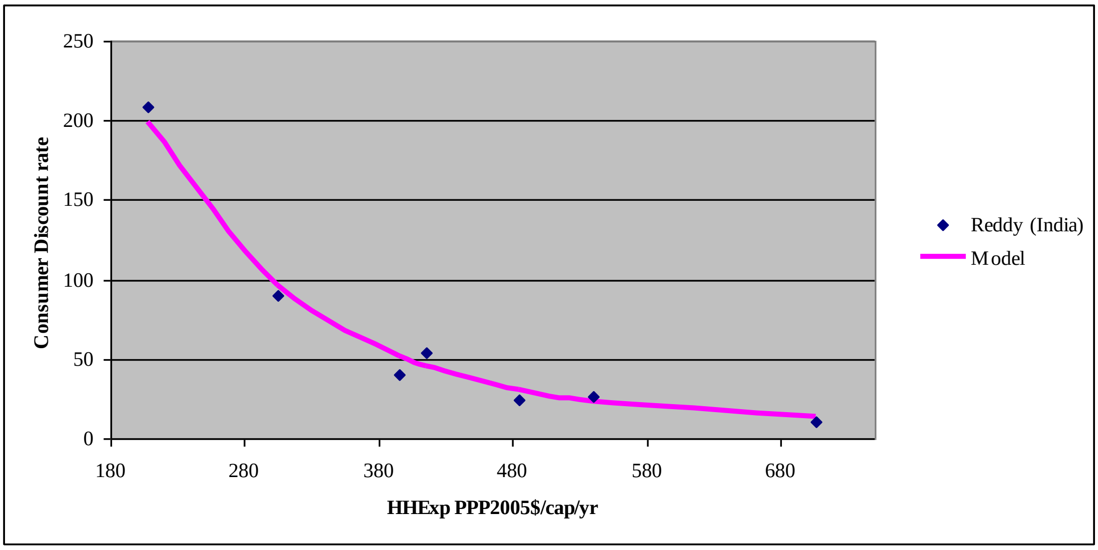

Figure 103. Consumer Discount Rates as a function of HHExp

So in the new formulation the annuity factor is determined by:

$\alpha = CDR_{Q,UR,R}/(1-(1+CDR_{Q,UR,R})\wedge\text{-}L_{OPT})$

Where
α = Annuity Factor
$CDR_{Q,UR,R}$ = Consumer discount rate determined for all income classes and regions
L_{OPT} = Lifetime of the technology in question (constant across regions)

Following, the calculation of annual capital costs (Annuity Factor × [Capital Costs – Capital Subsidy]) and total perceived costs (Capital Costs + Fuel costs + Premium Factor) and the subsequent multinomial logit market allocation can remain unchanged.

9.2 *Cooking/Water Heating Efficiency*

As stated in section 6.3.2, water heating and cooking fuel will follow a very similar methodology in the global version. The useful energy demands of the two end-uses are summed up, and subsequently primary energy demand, costs and market allocations are computed. It is also implied that the conversion efficiencies for cooking and water heating are the same (as was in REMI). In order to confirm that the efficiencies of the two are equal, it is important to make sure that the method of determining efficiency is consistent in both cases, thus only studies which list both of the efficiencies can be used. Few studies do this, and they show that generally water heating is more efficient than cooking, but only slightly. In determining the efficiency of cooking, it is important keep in mind the difference between *combustion efficiency* of cookers, and *cooking efficiency*. The former can reach very high levels (the order of

95%) while the latter is limited and depends on the materials and shape of cooking utensils, which themselves are limited (Lucky *et al.*, 2001).

Some data has been found concerning cooking water heating efficiency and these are summarized in Table 27. As can be seen, data is limited to very few regions and there are differences between and amongst the available regions. Thus for the time being the efficiencies will remain the same as in REMI. Unfortunately no such data could be found for the developed world, which may have higher efficiencies.

Table 27. Data on Cooking and Water Heating efficiencies

Region	**Coal**	**Trad. Biomass**	**Imp. Biomass**	**Kerosene**	**LPG**	**Nat. Gas**	**Biogas**	**Electricity**	**Sources /Notes**
South Asia	*0.15*	*0.14*	*0.334*	*0.503*	*0.604*	*0.604*	*0.451*	*0.713*	*REMI*
East Asia	**0.28**	0.18			0.6		0.36		(Xiaohua *et al.*, 2002), Rural
South Asia		0.13	**0.35**	0.3					(Reddy *et al.*, 2006)
South Asia				0.45					(Reddy *et al.*, 2006)
S.E. Asia					**0.65**				(Saidur *et al.*, 2007)
S.E. Asia	0.2	0.15	0.275	0.4	0.55			0.7	(Lefevre *et al.*, 1997)
W. Africa			0.25	0.46		**0.73**		**0.7833**	(Anozie *et al.*, 2007)
Turkey		0.22			0.5	0.5		0.8	(Utlu *et al.*, 2005)
South Asia[13]		**0.286**		**0.534**		0.622			(Lucky *et al.*, 2001)
W. Africa (Senegal)	0.21	0.2		0.399	0.433				(Visser, 2005)
W.Africa (Mauritania)		0.252		0.487	0.554				(Visser, 2005)

9.3 *Active Fuel*

For cooking, water heating, and lighting, active fuels are defined. These are the fuels that are available in order to fulfill the energy function, and vary across urban/rural and across time. Determining active fuel is important in the calibration process in order to simulate past data. The IEA gives total residential energy usage per fuel, which shows what fuels are used, but does not show in which energy function they are used. Wherever more specific data is not available, the active fuel is set for both cooking and heating.

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[13] The values come from a study which tested a number of different pots and pans. The numbers presented here are the highest efficiencies found.

A more tricky aspect is determining what fuels will become active in the future. In regions where clean fuels are already widely used (developed countries), it is safe to say that the active fuels will change, since they are already at the top of the energy ladder. But when will sub-Saharan countries start using electricity for cooking and heating? In order to accommodate this a switch is added so that when electrification surpasses 80% and the outage factor is equal to 1 (see section 9.6.1), electricity automatically becomes an active fuel. Due to the way electrification is modeled, electricity as an active fuel is now also a function of income class.

9.4 *Premium Factors*

As already explained, the choice of fuel for cooking and heating is based on monetized costs (annual capital and fuel costs) and non-monetized costs (accessibility, public perception/attitude, cleanliness, ease of use, etc.). The non-monetized costs are captured vie the so called *Premium Factors*. These premium factors are based on the push/pull forces of fuel choice under which REMI was designed (van Ruijven, 2008).

There are three types of premium factors:

1. An expenditure based increase which applies to coal, and fuelwood. Thus as households get richer the perceived cost of these fuels increases thus the household moves to cleaner fuels.
2. An arbitrary premium factor which is used for calibration purposes. This changes according to income in the future as explained below.
3. A fuel trade based premium factor which sets the perceived cost of a fuel dependent on the fraction of the fuel imported by the country, only used in future projections.

The *expenditure* based factor which represents a push force away from cheap but inconvenient fuels. is based on the hypothesis that richer households have more options to use more expensive fuels, more education concerning fuel use and perceive the disadvantages of cheaper fuels as more important than poor households. This factor simulates the fuel ladder dynamic.

There is also the *arbitrary* premium factor which is solely dependant on region and is related to accessibility and breakthrough of fuels. It primarily acts as a calibration factor since if only fuel and capital costs are taken into account past data is not reproduced. This premium factor becomes problematic in future projections. In the calibration process it may be set very high because for various reasons (lack of accessibility, education, understanding of energy systems, extreme poverty) they are not used. If this very high premium factor is maintained in future projections (for clean fuels), then even if the perceived cost of dirty fuels increase (according to the expenditure based push force) cleaner fuels will never become dominant The central hypothesis of the fuel ladder is that as households get richer their understanding, and thus desire, of cleaner fuels increases. Thus after t-scenario the arbitrary premium factor is set to decline logistically towards zero with household expenditures. The rate at which it declines is arbitrary but set so that the transition time is approximately 20 years.

The *trade* based premium factor is employed only in future projections. It purpose is to differentiate between which clean fuels a developing region will chose in the future. Data shows that gas producing countries such as the Netherlands and the United Kingdom tend to use natural gas for cooking and heating, while Germany uses Electricity. Thus the hypothesis is that if there is local production of natural gas/kerosene/LPG, that fuel will be used, otherwise the more generic electricity will be used. The fraction of imported fuel (coal, oil, natural gas) has been computed in TIMER runs till 2100, and this is used to determine a premium factor for those fuels.

The multinomial logit function is used the same way as it is in the TIMER model.

9.5 *The Energy Ladder*

Both REMI and REMG are based on the concept of the energy ladder. As households get more affluent and gain socioeconomic status, they move from traditional fuels which are inefficient, polluting and less costly to modern. These modern fuels are usually more costly but require less labor input (from the households perspective) and are less polluting (Masera *et al.*, 2000). The data collected for the development of REMG also confirms this (see sections (5.3.1 and 7.2). In REMI/REMG the energy ladder is simulated by creating perceived costs (see section 9.4). These perceived costs are made up of the annual fuel and capital costs (monetized costs), and other non-monetized costs made up from the premium factors. The non-monetized costs include fuel preference, accessibility, fraction of income spent on fuel, practicality, education, intra-household dynamics, societal barriers, cooking properties of various stoves and life style (Clancy, 2006). The allocation of fuels is determined by a multinomial logit allocation method, as is done in TIMER.

However, this method gives rise to very rapid fuel switches when relative perceived costs change. This simply does not represent the world well since households tend to stick to a certain fuel even if in the short term it stops being the most rational option. Thus the market shares of fuels are averaged out over 10 years in order to depress the rate of fuel switching in cases of sudden changes in perceived cost.

A further issue which has to be addressed rises from the question: *Is it possible to go down the energy ladder?* If affluence falls, or more relevant for REMI/REMG, if the relative (perceived) price of a traditional fuel falls with respect to cleaner fuels, will a household which used to use the cleaner fuels switch back to traditional? A study conducted in the peri-urban households of Kano in Nigeria between 2002 and 2006 (a time where the real cost of kerosene increased) confirms that households did descend the energy ladder (Maconachie *et al.*, 2009). The study is based on questionnaires given to households where amongst other things they are asked the reasons for their fuel choice and whether or not price fluctuation affected choice. The responses indicate that price fluctuation were the most important factor, and this is evident from the fact that the portion of households using fuelwood increased in the given time period. However, concerning households using kerosene interesting observations can be made. The proportion of household which used kerosene for non-economic reasons (but instead because it was smokeless and safer) increased in the given time period. This shows that it is not a purely economic choice which makes households descend the energy ladder. Furthermore, in the given time period, the proportion of houses which used both fuels increased, again indicating towards the fact that clean fuels are not completely abandoned if they get more expensive once they have been used.

Thus it is possible to conclude that even though households do go down the energy ladder; there is greater inertia to when descending it. In order to incorporate this in REMG a function is set up which determines if in any particular year households are going up or going down the ladder (by comparing the relative costs of biomass to advanced fuels). If households are going down the energy ladder, then the new market share of fuels has a biased weighting (2:1) towards the market shares during the last time period when they were going up the ladder. Then these shares are averaged out over the last 10 years as discussed earlier.

9.6 *Electrification*

Regional electrification levels (on a global scale) have been modeled previously for the TIMER framework (Schers, 2009). The level of aggregation is however only set towards *Total, Urban* and *Rural.* In order to be useful in REM-G, this has to be further disaggregated amongst urban and rural *Quintiles*. The chosen methodology is the same as that used for household size (section 3.1.3.2), where in this case the assumption is that as *Urban/Rural* electrification → 1, Quintile variance → 0. This quintile variance is described by a ‘gradient’ across the quintiles. Using quintile electrification levels available for India for 1993 and 2003 for both urban and rural households (NSSO, 1997; NSSO, 2004), it was possible to derive the following:

$$\text{Gradient} = -0.4606 \cdot \text{Electrification}_{U,R} + 0.4606$$

Then, to get the factor for each quintile by which the average electrification has to be multiplied[14]:

$$\text{ElectrificationQFac}_{Q} = 1 + (-\text{Gradient} \cdot (3 - \text{Quintile}))$$

And thus quintile electrification rate:

$$\text{Electrification}_{UR,Q} = \text{ElectrificationQFac}_{Q} \cdot \text{Electrification}_{UR}$$

9.6.1 Outage Factor

Electricity demand has been modeled as demand for appliances (section 4), demand for lighting (section 8) and the use of electricity for space/water heating. Especially for appliances and lighting, a diffusion level of the electricity end use is modeled, and this is multiplied by a specific electricity consumption in order to get final load. This ignores the quality of the electricity (dictated by power cuts). Thus the model over-estimates the electricity demand since it assumes that once a household is electrified, this electricity comes constantly, which is not true for all except the richest regions.

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[14] Note the ‘-‘ sign in front of the Gradient which is not present in the household size version of the function (section 3.1.3.2). This is because unlike household size, here the quintile factors increase with quintile.

In order to correct for this, a certain *fudge factor* is necessary. In REMG (and REMI) this was called the *OutageFactor* and it ranges between 0 and 1. An OutageFactor of 1 implies that high quality electricity is constantly available, while 0 means that even though the household is electrified, at no times does it actually get electricity (0 is an extreme and is not used for electrified households).

Another source of error is that in many poor regions, households generate their own electricity via fuel oil generators rather than being connected to an electricity grid. In official statistics, this energy consumption may be listed under fuel oil rather than electricity, thus leading to discrepancies between the electricity consumption of poor households determined by the bottom up model and top down data.

10 Outstanding Issues

Due to the massive data requirement and the limited time involved, certain aspects of REMG require further work. These are outlined here.

10.1 *Specific Regions*

As already mentioned (section 2.1), REMG operates under generic global equations (a single equation roughly describing behavior across time/regions), and when more detailed data was available, the coefficients of these equations were changed so that the specific region could be represented better. This essentially means that many of the dynamics of the model have to be calibrated to specific regions. Appendix II lists how each region was calibrated. For many regions part or all of the required data is missing and so either they have been calibrated according to similar regions, or they keep the default dynamics. It is unlikely that the results they yield are very good (but better than nothing). With the availability of better/more data, calibration should be re-done especially in regions where calibration is weak.

10.2 *Poverty*

As stated in section 3.3.3, though the model requires time series of total, urban and rural GINIs, these have only been available and so far implemented for Total **only.** The available urban and rural GINIs (derived from the GIDD database of 2005) have to be adapted so that they can also vary over time, since now they are kept constant at the 2005 value.

10.3 *Space Cooling*

Due to time restrains, the space cooling sector of appliances (fans, air coolers and air conditioners) has not been changed much from REMI. Thus it is unclear if the results for space cooling energy demand are correct.

Space cooling electricity demand is calculated via a number of steps. First a climate based saturation level of cooling appliances is set (*ClimateMaxSaturation*). For poor regions, an income based growth (of the saturation level) towards the maximum saturation point (*SatPrice*) ranging from 0 to 1 is set so that poor households tend towards ClimateMaxSaturation as they get richer. Note that the actual diffusion (as opposed to saturation) follows a gompertz growth. Then, for fans this saturation level can be altered based on floorspace, while for air coolers and air conditioners the saturation level is divided unequally between them (see 10.3.3). Finally the Unit energy consumption is based on climatic properties from previous modeling work (Isaac *et al.*, 2009). Under this methodology, A number of these aspects have to be further looked into in order to improve the space cooling electricity demand.

10.3.1 Climate Based Saturation

This is based on equations from studies by Sailor and Pavlova, adapted to reach 100% by McNeil and Letschert (Sailor *et al.*, 2003; McNeil *et al.*, 2007). Note that concerning air coolers and air conditioners, multiple ownership of appliances is accounted for via the UEC which is income based, thus a 100% climate based saturation is appropriate. For fans, multiple ownership is accounted for by increasing the ClimateMaxSaturation based on a relationship with floorspace.

10.3.2 SatPrice

The Saturation Price (SatPrice) is the time based maximum diffusion rate allowed for one of the space cooling appliances. It is based on the fact that as appliances get cheaper there is a tendency to by more of them. Thus SatPrice acts as a control on this.

The current value for SatPrice is the same as the value set for REMI which was based on the development of maximum ownership and price of appliances for India. As shown in section 4.1.3.1, this dynamic is important mainly for poorer households, where sadly the detailed information required to make such a set up simply does not exist. However, using the REMI sat price is also not very good.

10.3.3 Air Conditioners/Air Coolers

Besides fans (which are important only for the poorest households), air conditioners and air coolers have been modeled for the air cooling end-use function. The reason for this distinction is because these represent two radically different (in energy consumption terms) appliances which perform the same end use function, air cooling. However, air coolers can only function under certain climatic conditions, mainly dictated from relative humidity and dew point temperature.

In REMI, once households get air cooling equipment (besides a fan), 32.3% of those households get air-coolers and 67.7% get air conditioning. This ratio has been set based on climate conditions and population distribution of India, thus is inappropriate for the Global Model. This is a rather serious problem, since air cooling (by air-conditioning) is one of the main end uses of residential energy for rich households, and especially in warm climates. Thus this ratio of households eligible for air cooling as opposed to air-conditioning greatly affects the final results.

The proposed methodology to counter this issue is to use relative humidity maps superimposed with population maps, and from there to determine what fraction of conditioned households can employ air-coolers.

10.4 *Space Heating*

The method by which space heating is calculated has not changed between REMI and REMG. It is based on a previous analysis by Isaac and van Vuuren (Isaac *et al.*, 2009) where space heating space heating is a function of floorspace and heating degree days. Thus each region has a specific heating intensity in kJ/m^2/HDD. This method provides fairly large space heating loads, especially for poor regions. This probably happens because this function calculates the space heating demand, but for poor households, it is very likely that this demand is not met. Thus to compensate for this, an income based function has been added so that this demand is gradually met as households get richer, finally meeting the entire demand when the expenditures meet a certain *Heat Saturation Price.* This factor has been set arbitrarily for regions as a calibration factor (see Appendix II).

This problem is evident in Mexico where according to IEA fuel use data and studies performed in Mexico, cooking and water heating account for pretty much all non-electric residential energy use (Rosas-Flores *et al.*, 2010). It is suggested that further research is done on both the calculation of the useful energy demand, as well as how this demand is met as households get richer.

10.5 *Solar Water Heating/Cooking*

Solar water heating and solar cookers are technologies which can drastically decrease fuel use for hot water and cooking energy demand in climates rich in sunshine. Though the useful energy demand is unaffected, the fuel allocation can change severely. In the current set up fuels available for water and space heating are identical and so solar hot water is not accounted for.

10.6 *Marginal Unit Energy Consumption Stock Model*

The unit energy consumption of appliances has been modeled on a marginal basis as described in section 4.2.4. This was done in order to accommodate the possibility of energy policy with restrictions on maximum UEC. However there is the problem that when the policy is introduced, the policy dictated UEC is what remains. Further autonomous/price induced efficiency gains do not exist once the policy has been placed in effect and all new appliances (and after complete capital replacement, all appliances) will have the policy’s UEC. This has to be amended.

These errors have not been amended already because the *Marginal Unit Energy Consumption Stock Model* was introduced late in the development of the model.

10.7 *Public Distribution Systems*

In the development of the REMI model, in the allocation of cooking fuels, a certain percentage of households are forced to fulfill their cooking and lighting energy demands with kerosene (van Ruijven, 2008). This was because in India a significant fraction of the households have access to subsidized kerosene leading to a greater consumption of this fuel (Gangopadhay *et al.*, 2005; Rehman *et al.*, 2005). In REMI this is modeled by first assigning a fraction of houses to the *Public Distribution System* (on a *Total*, *Urban* and *Rural* basis) and the using a 1 – Gompertz function (i.e. asymmetric logistic decay) this fraction is shared amongst the quintiles (poorer households getting the main share of the subsidy, and this decreasing with income). Then also a certain subsidized quota is assigned which is used for free. Now, if the households are not electrified, a portion of this quota is assigned to lighting first (see section 8.1.3), and whatever remains from the quota is used for cooking.

It is generally desirable to maintain It has been chosen to keep this aspect of REMI in REMG since similar public distribution systems also exist in Brazil for LPG (Jannuzzi *et al.*, 2004; IEA, 2006).

At this point in REMG the only change that has been made is to accommodate the possibility of more subsidized fuels as opposed to just kerosene as in REMI, and the gompertz function sharing the fraction amongst quintiles has been re-calibrated for India in order to reflect data for subsidized kerosene. However the accessibility and distribution amongst quintiles only reflects policies pursued in India, and is not very relevant for other. In the current set up, two variables describe the public distribution system:

1. The fraction of houses with access to the subsidized fuel
    a. Dynamically driven with income across quintiles (see above)
2. The total amount of primary energy subsidized to the households with access (GJpe/hh/yr).

REMI dynamic with kerosene and lighting has remained, and the new code has been built around it. Also, subsidized fuel through the public distribution system can only be used for lighting (kerosene) and cooking, **not** for water and space heating.

Appendix I

The following table lists the TIMER/IMAGE regions as well as which countries are included in each region.

Region No.	Region Name	Countries
1	Canada	Canada
2	USA	Saint Pierre and Miquelon, United States, United States Minor Outlying Islands
3	Mexico	Mexico
4	Rest of Central America	Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, Cayman Islands, Costa Rica, Cuba, Dominica, Dominican republic, El Salvador, Grenada, Guadeloupe, Guatemala, Haiti, Honduras, Jamaica, Martinique, Montserrat, Netherlands Antilles, Nicaragua, Panama, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Trinidad and Tobago, Turks and Caicos Islands, British Virgin Islands, U.S. Virgin Islands
5	Brazil	Brazil
6	Rest of South America	Argentina, Bolivia, Bouvet Island, Chile, Colombia, Ecuador, Falkland Islands (Malvinas), French Guiana, Guyana, Paraguay, Peru, South Georgia and the South Sandwich Islands, Suriname, Uruguay, Venezuela
7	Northern Africa	Algeria, Egypt, Libyan Arab Jamahiriya, Morocco, Tunisia, Western Sahara
8	Western Africa	Benin, Burkina Faso, Cameroon, Cape Verde, Central African republic, Chad, Congo, the Democratic republic of the Congo, Cote D'Ivoire, Equatorial Guinea, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Saint Helena, Sao Tome and Principe, Senegal, Sierra Leone, Togo
9	Eastern Africa	Burundi, Comoros, Djibouti, Eritrea, Ethiopia, Kenya, Madagascar, Mauritius, Mayotte, Réunion, Rwanda, Seychelles, Somalia, Sudan, Uganda
10	South Africa	South Africa
11	Western Europe	Andorra, Austria, Belgium, Denmark, Faroe Islands, Finland, France, Germany, Gibraltar, Greece, Holy See (Vatican city state), Iceland, Ireland, Italy, Liechtenstein, Luxemburg, Malta, Monaco, Netherlands, Norway, Portugal, San Marino, Spain, Svalbard and Jan Mayen, Sweden, Switzerland, United Kingdom
12	Central Europe	Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, the Former Yugoslavian republic of Macedonia, Malta, Poland, Romania, Serbia, Slovakia, Slovenia
13	Turkey	Turkey
14	Ukraine +	Belarus, Republic of Moldova, Ukraine
15	Asia-Stan	Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan
16	Russia +	Armenia, Azerbaijan, Georgia, Russian Federation
17	Middle East	Bahrain, Islamic Republic of Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates, Yemen
18	India	India
19	Korea	Democratic Peoples Republic of Korea, Republic of Korea

20	China +	China, Hong Kong, Macau, Mongolia, Province of China - Taiwan
21	South Eastern Asia	Brunei Darussalam, Cambodia, People's Democratic republic of Lao, Malaysia, Myanmar, Philippines, Singapore, Thailand, Viet Nam
22	Indonesia +	East Timor, Indonesia, Papua New Guinnea
23	Japan	Japan
24	Oceania	American Samoa, Australia, Christmas Island, Cocos (Keeling) Islands, Cook Islands, Fiji, French Polynesia, French Southern territories, Guam, Heard Island and McDonald Islands, Kiribati, Marshall Islands, Federated States of Micronesia, Nauru, New Caledonia, New Zealand, Niue, Norfolk Island, Northern Mariana Islands, Palau, Pitcairn, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, Vanatu, Wallis and Fortuna
25	South Asia	Afghanistan, Bangladesh, Bhutan, British Indian Ocean Territory, Maldives, Nepal, Pakistan, Sri Lanka
26	Rest of South Africa	Angola, Botswana, Lesotho, Malawi, Mozambique, Namibia, Swaziland, United Republic of Tanzania, Zambia, Zimbabwe

Appendix II

This appendix describes the calibration of REMG. Ideally, any model reproduces past data faithfully, and this serves as a basis of accepting the model. In the calibration process, initially the parameters of certain key equations are adjusted in order to make the results fit gathered data. This is done on a regional basis. The final results of the model (total energy consumption, consumption per fuel) is made to reflect data available from the international energy agency, World Health Organization, United Nations or local data when available (IEA, 2007; UN, 2010; WHO, 2010).

First the factors which are used for the calibration of the model are outlined. Then the calibration progress is described. Since changing a single variable in the model affects a host of other variables, it is important to perform the calibration in a sequential manner. Finally, Table 28 shows which regions and model aspects have been calibrated, together with some notes which should be kept in mind concerning the calibration.

CALIBRATION FACTORS

1. HHSize
    a. HHsize_correction
2. Floorspace
    a. FScoeff
3. Electricity Use
    a. OutageFactor
4. Appliance Diffusion
    a. Beta, Gamma, phi1, phi2, phi3
5. Fuel use
    a. ActiveFuel
        i. Cooking (Fuels in OPT)
        ii. Space/Water Heating (Fuels in NECN)
    b. Fuel Shares
        i. Premium Factors
            1. CookPremFacIn
            2. CookPremFacArb
            3. HeatPremFac
    c. Fuel energy use
        i. Efficiency
            1. CookEff
            2. EffSecFuel(HeatEff)
        ii. Level of demand met
            1. HeatSatPrice
    d. Useful Energy
        i. UEIntHeat
        ii. CookingUEPCpd

Notes

1. All cooking variables are in OPT while all heating variables are in NECN
2. Heating and cooking share the same PremFacIn (income based premium factor, PUSH force)

CALIBRATION PROCESS

1. Fix Drivers
    a. HHSize: Correct TIMER inaccuracies via HHSize_correction
    b. Floorspace: Change FScoeff (Floorspace_Coefficients_for_individual_regions.xls)
2. Set Outage Factor to 1
3. Fix appliances
    a. For air coolers and air conditioners, compare data (which is always “Air Conditioners”) to CoolApplCapphh.
        i. Determine required diffusion based on ClimateMaxSaturation (Air_Conditioning_Required_diffusion.xls)
    b. For rest of appliances be careful with electrification rates. Compare DiffusionTOT variable with appliances_corrected_for_electrification.xls. These indicators show the appliance ownership within electrified households.
4. Set new outage factor by comparing electricity consumption for lighting and appliances with secfuelhist.
5. Find remainder of electricity use after appliances, lighting and outage factor have been accounted for
6. Determine Cooking active fuel
7. Check PDS
    a. FractionPDS
    b. PDSQuota
    c. PDSse
8. Determine Cooking Prem factors
    a. CookPremFac for energy ladder dynamic, on a quintile basis
    b. CookPremFacArb for arbitrary region specific choices
    c. Compare to IEA (secfuel hist) and WHO energy for cooking database. Also try to fit population cooking with solid fuels with UN MDG data.
9. Determine Cooking history
10. Determine Heating Active Fuel
11. Determine level of heating load compared to heating demand
12. Determine Heating Premium Factors
    a. HeatPremFac for arbitrary region specific choices (HeatPremFac2 = CookPremFac)
13. Determine Heating history
14. Fix arbitrary calibration factors
    a. UEIntHeat
        i. Determine RestNonElec = SFHist – Cooking – WaterHeat – Lighting (non-electric)
        ii. Determine SEIntHeat = RestNonElec/Floorspace*POP/HDD
        iii. Determine UERestNonElec = SEIntHeat * HeatEff
        iv. Determine UEIntHeat = UERestNonElec/Floorsapace*POP/HDD
    b. CookingUEPCpd

Repeat steps 8 to 12 till fuel shares (%) and fuel use (GJpe) correspond within 30% error of IEA data (secfuehist).

CALIBRATION PROGRESS *As of 10^{h} November 2010*

Table 28. Calibration Progress

Region	HHSize	Floorspace	Appliances[15]	Outage Factor	Cooking	Space Heating
1	X	X	X	X	X	X
2	X	X	X	X	X	X
3	X	O	X	X	X	X
4	X	X	X	X	X	X
5	X	X	X	X	X	X
6	X	X	X	X	X	X
7	X	X	X	X	X	X
8	X	X	X	X	X	X
9	X	X	X	X	X	X
10	X	X	X	X	X	X
11	X	X	X	X	X	X
12	X	X	X	X	X	X
13	X	O	X	X	X	X
14	X	X	X	X	X	X
15	X	X	X	X	X	X
16	O	O	O	X	X	X
17	X	X	X	X	X	X
18	X	X	X	X	X	X
19	X	O	X	X	X	X
20	X	X	X	X	X	X
21	X	X	X	X	X	X
22	X	O	X	X	X	X
23	X	X	X	X	X	X
24	X	X	X	X	X	X
25	X	X	X	X	X	X
26	X	O	X	X	X	X

X = Calibrated so that model output can reflect data to the closest possible extent.
O = Data does not exist to calibrate towards, kept default if not stated otherwise.

NOTES

United States (2): Final energy demand is very high in the available data. Concerning REMG, this has been attributed to wasteful use, or in other words reduced conversion efficiency.

Mexico(3): For the appliances data only exists for Refrigerators, washing machines and TV's, so calibration has been done against these appliances.

There is also a fairly large problem with the fact that REMG produces a significant energy demand for space heating, especially after the 1980's , while data does not

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[15] REMG models 11 appliances explicitly. For any given region there seldom is data for all 11 appliances. Calibration thus only focuses on appliances where data exists.

suggest this (Rosas-Flores *et al.*, 2010). IEA data suggests that liquid fuel use levels off after 1995. WHO data on the other hand suggests that use of LPG for cooking increases even after 2000. In order to better reflect WHO and UN data, the liquid fuel use in REMG does not level off after 1995.

Rest of South America (4): For floorspace only data for urban floorspace in 1998 is available (11 data points), and this is scattered from 4m/cap to 21m/cap). The saturation level of floorspace for this region has been limited in order to bring the urban average in 1998 to 14.8m/cap.

Brazil (5): According to IEA data, energy use in households decreased dramatically between 1971 and 1995. The data also shows that this decrease came from a massive cutting back of traditional fuelwood and a modest increase of liquid fuels and gas. However, fuel switching alone can not account for the total decrease in energy use. Thus in order to make REMG reflect this decrease, fuel switching as well as a gradual increase in fuelwood cooking/heating efficiencies was implemented, though there is no data to suggest this.

WHO data suggests a significant but not ultimate penetration rate of LPG, UN data suggests a very low fraction of population dependant on solid fuels (7%). Taking the WHO data into account as well as the biomass problem mentioned above, it is impossible to meet the 7% population dependant on solid fuels in 2007 of the WHO. The REMG number instead is 25%.

Rest of South America (6): This region consists of a number of countries, and unfortunately the given data varies amongst these countries significantly. Also, certain data may be available for only one country, but not for the rest. Thus calibration was based on average values or data was used simply as an indicator.

WHO data suggests that very little natural gas and electricity is used for cooking, except in Argentina (All other available countries show a clear preference towards LPG). IEA data shows a marked increase in both these fuels. Natural gas and electricity have been given preference for heating.

Western Africa (8): A number of countries are present in this region, and significant variation in household expenditures exist. The poorest countries and richest countries have been identified and it has been attempted to fit the REMG results in an intermediate level.

According to IEA data coal use is rather low, yet according to WHO main cooking fuel surveys there is a minority of coal users. A compromise has been made.

The future saturation of Refrigerators has been limited to the default 2000 value, 1.11 (for other regions it keeps increasing). There is no data for Clothes dryers, same relationship as with eastern Mexico is assumed, since Mexico has the lowest diffusion rate from all the countries where data is available.

Eastern Africa (9): The future saturation of Refrigerators has been limited to the default 2000 value, 1.11 (for other regions it keeps increasing). There is no data for

Clothes dryers, same relationship as with eastern Mexico is assumed, since Mexico has the lowest diffusion rate from all the countries where data is available.

IEA fuel use data suggests that very little coal and liquid fuel are used in this region. Yet country data as well as the WHO survey data show that households use liquid fuels and coal for cooking, albeit very little. A compromise has been made in the calibration.

South Africa (10): Top-down (IEA) data suggests that NO liquid fuel was consumed pre-1980, this is in direct contradiction with the use of kerosene for lighting. Furthermore, the same IEA data suggests that in 1979 liquid fuel use jumped from 0 to tens of PJ, indicating to possible reporting errors. Also, no gas consumption is reported after 2000, though survey data suggests that natural gas was used for cooking well after 2000 (SSA, 2002; SSA, 2007). The survey data and IEA data do not agree completely. According to the survey data a small but significant fraction of households use Natural gas, while the IEA data shows negligible use of natural gas. WHO data shows no use of natural gas for cooking. Furthermore the IEA data shows significant use of traditional biomass while the survey data shows that biomass use is limited, especially in richer households in both urban and rural settings, WHO data shows limited use of biomass in urban households but significant use in rural households.

In the calibration a compromise has been made natural gas to urban households for heating (as survey data says) and by lowering cooking efficiency of traditional biomass in order to increase its energy use. REMG overestimates use of gas compared to the IEA data.

A problem with South Africa is that there is little economic growth in the calibration years. Thus through there is a difference in expenditures amongst the quintiles, this difference in both absolute and relative term remains almost constant till 2005. Data across income levels is available for 2002 and 2007 to which the model is calibrated, but due to the lack of growth, the fuels shares of the 2000’s are the same as those of the 1970’s.

Central Europe (12): For floorspace, there is only data for urban households in 1998, and even there is huge variance amongst countries (8 – 26m^2/cap).

The driver for household expenditures experiences a sudden dip in the early 90’s. This leads to a significant decrease in space and water heating demand. Since these are the main end uses, the effect is very pronounced and influences the total residential energy demand quite significantly. The quality of the Data pre-1990 is also questionable due to the split up of the USSR. However, the REMG results are satisfactory for the post 1995 period where household expenditures settle again. The only major discrepancy is that the use of secondary heat is decreasing post 1990 according to the IEA while in REMG it is increasing.

Turkey (13): Data for this region is very limited. One data point exists for refrigerators and dish washers while there are two points for televisions and washing machines. Air cooling devices are completely missing but it is assumed that they have low penetration rates as of yet.

Ukraine Region (14): For household characteristics the only available data was for Moldova. No data exists concerning cooling devices, the same diffusion dynamics as with Central Europe are assumed.

According to the (exogenous) household expenditures, this region suffers a massive decline in energy demand in the early 1990's, with significant growth after 2000. According to the IEA data the decline in energy demand is much more gradual continuing up until 2007. Thus the REMG results to not reflect IEA data very well.

Kazakhstan Region (15): For the households characteristics of this region data is only available for Kazakhstan. No data exists concerning cooling devices, the same diffusion dynamics as with Central Europe are assumed. Data for appliances are only available for refrigerators and televisions, which show high diffusion rates considering the household expenditures. The rest of the appliances are scaled similarly.

The very high Natural Gas and secondary heat demand given from the IEA could only be met when setting HeatSatPrice to 2000 and adjusting efficiency levels for heating.

Russia (16): For household characteristics of this region there are only two data points for urban households in 1998, one for Armenia (Yerevan) and one for Azerbaijan (Baku). The data for Kazakhstan and Moldova was also used to represent this region. No data exists concerning cooling devices, the same diffusion dynamics as with Central Europe are assumed. For appliances only one data point for refrigerators in Armenia exists. Appliances have been made to have similar diffusion Kazakhstan and Central Europe

Middle East (17): Data concerning appliances is extremely limited, and these is no data concerning air condition ownership. WHO data suggests that electricity is not used for cooking. Appliances are calibrated based on whatever data exists and the remainder of electricity consumption is assigned to air conditioning and space heating.

IEA data suggests that post-1990 there is a sudden surge in the use of gas an electricity while liquid and biomass also maintain a steady growth. This dynamic cannot be simulated. .

Korea (19): No data exists concerning floorspace. A growth similar to Japan's is assumed. Concerning appliances, only ownership rates of televisions are available. For cooling appliances the same growth rates as China are assumed. It is assumed that all other appliance ownership rates follow trajectories similar to Japan, China and South East Asia.

Concerning fuel use, only the IEA data exists. Thus it is impossible to accurately allocate fuels for cooking and heating. Heating is the main end use function of this region. Since the remainder of electricity after appliances and lighting is low, it is assumed that electricity is only used for cooking. The IEA data suggests a high use of coal but according to WHO data the fraction of population cooking with solid fuels is low so coal is assigned to heating primarily. Gas is introduced after 1980 and is assigned to both cooking and heating. Liquid fuels are assigned to cooking and heating. Secondary heat is assigned to urban heating.

China (20): Data concerning Total residential energy use is available from IEA sources as well as the *Lawrence Berkeley National Laboratory China Energy Data book* (LBNL, 2008). These two sources generally except of the following points:

- LBNL provides higher electricity use (≈3 times more in 2006)
- LBNL data does not account fuelwood, which is significant according to the IEA
- LBNL breaks up liquid into LPG and Kerosene while the IEA lumps them. The summation of the LBNL *LPG* and *Kerosene* agrees with the IEA *Liquid*.
- LBNL data only available from 1980 onwards

The LBNL data book also gives urban and rural use of coal and electricity. Strangely the sum of the urban and rural fuel use does not equal the total use.

The difference in electricity has significant implications. If using the IEA data alone, REMG overestimates electricity significantly, to such an extend that the outage factor has to be close to 0 up until the year 2000. With the LBNL data, the outage factor does not go below 0.65 and surpasses 1 in 2000, leading to a much better agreement with REMG.

Data for the distribution of cooking fuels amongst quintiles only is only available from one source which is based on a survey in Rural Hubei in 2004 (Peng *et al.*, 2010). This reference indicated that between LPG and electricity, the households prefer electricity. Another study based on rural (Jiangsu) china indicates the opposite (Xiaohua *et al.*, 2002). By looking Thus it is assumed that these preferences are region specific. By looking at regional data spanning 2006 – 2006 (LBNL, 2008), it can be seen that LPG was not used in Hubei prior to 2003, and thus the low LPG values are attributed to that. This lack of LPG is limited to the Hubei, Sichuan and Chongqing provinces. This has been taken into account in the calibration of REMG, giving slight preference to LPG.

Southeast Asia (21)**:** Limited data from this region shows that rural households have a smaller floorspace than urban households. Something which is unique to this region. However, since this data is limited to Cambodia and Vietnam, it is not accounted for in REMG and the standard procedure for setting floorspace is followed.

Considering the households expenditures of this region, they still use a very large portion of traditional biomass. Thus the income based premium factor (which pushes away the use of coal and traditional biomass) is delayed by giving it a very low growth rate, and a low saturation value. In future projections the growth rate meets the levels of the other regions.

Indonesia (22): The only available data for this region is one data point for household size (2000) one for refrigerator ownership (1997) and one for air conditioner ownership (1997) Since IEA data suggest that electricity consumption of Indonesian households is low, the rest of the dynamics have been set as the most modest of the other regions.

IEA data suggests that energy use of all fuels increases with time, with no substitution taking place. More specifically, the IEA data shows a constant increase in fuelwood use, something which can only be driven by an increasing rural population. However in the exogenous population data, rural population stagnates in the early 90's and declines thereof, leading to a reduced use of fuelwood. Since the rise in traditional fuelwood in the IEA data is linear, there is reason to believe that it may not be completely accurate but rather extrapolations.

Another driver for this increase could be an increase in meeting heating demand. This is done by lowering the HeatSatPrice so that latent heating demand is met sooner. However, the space heating demand still is negligible since the *Heating Degree Days* (which are calculated in coolheat.m) for this regions is 0, and thus the increase cannot be met like this.

Thus in REMG fuel switching for the rural sector is very limited by setting a very low value for Alpha PF, thus there is limited growth in fuel wood usage but still more modest than the IEA data. This also means that the total energy demand in 2007 predicted from REMG is substantially lower than IEA data (≈1700PJ compared to 2300PJ), the majority of the difference due to the discrepancy in traditional biomass. The cooking efficiencies have also been lowered (as is also shown in the data for this region, see Table 27) for electricity, kerosene and LPG.

Rest South Asia (25): No data exists concerning air-conditioning. The same dynamics as with India are assumed.

Rest of South Africa (26): No data exists concerning floorspace. The floorspace coefficients were adjusted based on the averages of regions 8, 9 and 10. For appliances, there where data exists, it varies significantly between countries, some showing a very high ownership of an appliance and others barely any or not reported. A compromise has been made. Use of liquid fuels has been estimated slightly higher than values reported by the IEA in order to limit the percentage of population reliant on solid fuels.

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