The Boom of Electricity Demand in the Residential Sector in the Developing World and the Potential for Energy Efficiency

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ABSTRACT

With the emergence of China as the world's largest energy consumer, the awareness of developing country energy consumption has risen. According to common economic scenarios, the rest of the developing world will probably see an economic expansion as well. With this growth will surely come continued rapid growth in energy demand. This paper explores the dynamics of that demand growth for electricity in the residential sector and the realistic potential for coping with it through efficiency.

In 2000, only 66% of developing world households had access to electricity. Appliance ownership rates remain low, but with better access to electricity and a higher income one can expect that households will see their electricity consumption rise significantly. This paper forecasts developing country appliance growth using econometric modeling. Products considered explicitly - refrigerators, air conditioners, lighting, washing machines, fans, televisions, stand-by power, water heating and space heating– represent the bulk of household electricity consumption in developing countries.

The resulting diffusion model determines the trend and dynamics of demand growth at a level of detail not accessible by models of a more aggregate nature. In addition, the paper presents scenarios for reducing residential consumption through cost-effective and/or 'best practice' efficiency measures defined at the product level. The research takes advantage of an analytical framework developed by LBNL (BUENAS) which integrates end use technology parameters into demand forecasting and stock accounting to produce detailed efficiency scenarios, which allows for a realistic assessment of efficiency opportunities at the national or regional level.

Introduction

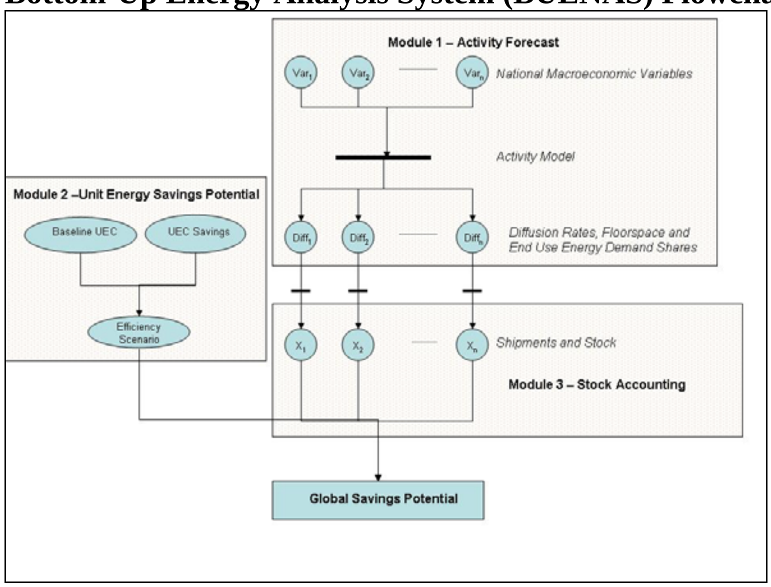
The past decades have seen some of the developing world moving towards a standard of living previously reserved for industrialized countries. Rapid economic development, combined with large populations has led to first China and now India to emerging as 'energy giants', a phenomenon that is expected to continue, accelerate and spread to other countries. This paper explores the potential for slowing energy consumption and greenhouse gas emissions in the residential sector in developing countries and evaluates the potential of energy savings and emissions mitigation through market transformation programs such as, but not limited to Energy Efficiency Standards and Labeling (EES&L)[1]. The bottom-up methodology used allows one to identify which end uses and regions have the greatest potential for savings.

[1] See S. Wiel and J.E. McMahon (2005). Energy-Efficiency Labels and Standards: A Guidebook for Appliances, Equipment, and Lighting, 2nd Edition. Washington, Collaborative Labeling and Standards Program. for a comprehensive discussion of this type of program.

Modeling Framework

This study is preceded by several case studies applying the bottom-up methodology to specific countries or end uses (McNeil, Letschert et al. 2006), (McNeil and Letschert 2007) and (Letschert and McNeil 2007). The framework developed for these studies, called the Bottom Up Energy Analysis System (BUENAS) has now been expanded to the global level, and covers both the residential and commercial sectors. This paper, describes a subset of the full model, focusing on residential electricity in developing country regions. The strategy is to construct the analysis in a modular way. The first module models demand for energy at the end use level, while a second builds a high-efficiency scenario based on meeting equipment efficiency targets by a specified year. A third module tracks market penetration and stock turnover for efficient products. Finally, these three components are brought together, and savings are calculated as the difference in consumption and emissions in the efficiency scenario versus the base case. The analysis framework is shown in Figure 1.

Figure 1. Bottom-Up Energy Analysis System (BUENAS) Flowchart



Scope of Study: Regional Breakdown and Covered End Uses

This study considers the developing world and divides it into 5 regions following the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (SRES) decomposition[2]: Latin America (LAM), Sub-Saharan Africa (SSA), North Africa and Middle East (MEA), Centrally Planned Asia (CPA) and South Asia and Other Pacific Asia (SAS-PAS).

[2] The SAS and PAS regions have been gathered in one region, and South Korea is excluded of the analysis because it belongs to the OECD region. Assumptions can be found at http://www.grida.no/climate/ipcc/emission/

The analysis focuses on electricity use and covers end uses that represent most of the residential consumption and/or present great potential for efficiency programs. These are: lighting, refrigerators, air conditioners, washing machines, fans, televisions, stand-by power, water heating and space heating.

Module 1: Forecasting Appliances Diffusion

Appliance ownership is projected according to a diffusion[3] model using readily-available national-level variables as inputs. A logistic function[4] describes the penetration of appliances in the households. Over 300 data points were gathered for the following equipment: light points, refrigerators, washing machines, fans, televisions, stand-by products[5], and water heaters. Appliance diffusion is modeled with the same functional form, given by:

$$Diff_c = \frac{\alpha}{1+\gamma \exp\left(\beta_{inc} I_c + \beta_{elec} E_c + \beta_{Spe} SPE_c\right)}$$

Where:

$Diff_c$ is the diffusion of the appliance for the country c

α is the maximum diffusion, which may be greater than 1

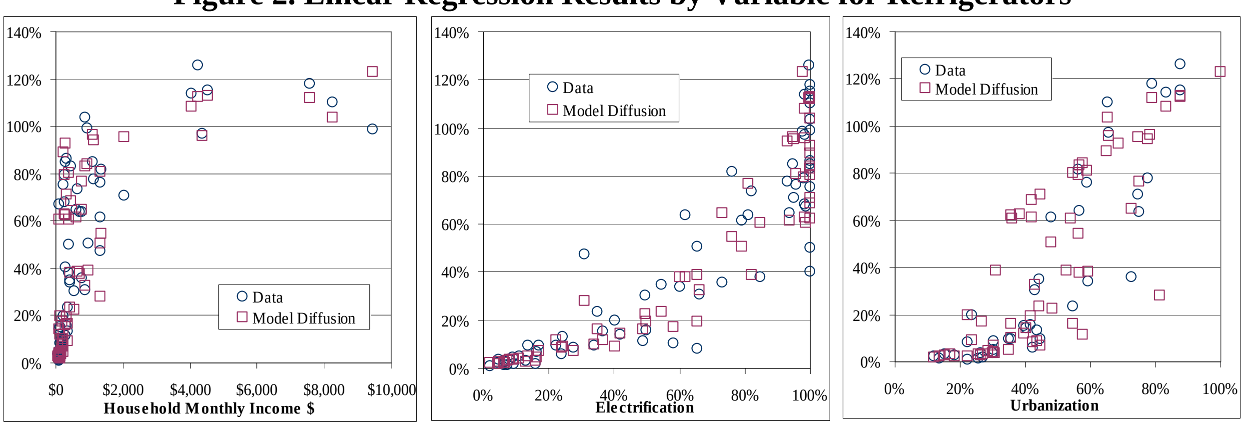
I_c is the monthly household income, given by GDP divided by the number of households in the country

E_c is the national electrification rate

SPE_c is an appliance-specific variable (urbanization for refrigerators, cooling degree days for fans, and heating degree days for space heating)

The collected data points, allow determination of the model parameters (β values) for each appliance using regression (after linearization). Figure 2 shows the relation between the model and the data for the three (3) variables for refrigerators. Each variable has a significant influence on the large variation of diffusion around the world.

Figure 2. Linear Regression Results by Variable for Refrigerators



[3] The term "diffusion" refers to the number of products per household, which can be greater than one.

[4] Because of its S-shape, the logistic function is often used in consumer choice models

[5] The number of products using stand-by consumption is based on total standby wattage divided by 5W which is assumed to be the average device stand-by power

Air Conditioning Saturation

Air conditioning is modeled distinctly from other end uses due to its status as a luxury item in the developing world and its strong dependence on climate. Also, ownership of air conditioners is formulated in terms of whether air conditioning is used or not[6]; the use of multiple units is taken into account in the unit energy consumption (*UEC*) model. U.S. ownership rates are taken as the maximum possible for a given number of cooling degree days (*Climate Based Maximum Saturation- CBMS*). Household income then determines the fraction of the maximum saturation actually achieved (*Availability*). The equations are:

$$Saturation = CBMS \text{ x } Avail$$

Where $CBMS = 1 - 0.949 \times \exp(-0.00187 \times CDD)$ and $Avail = 1/\left(1 + \gamma \exp(\beta_{Inc} \times \text{Inc})\right)$

Table 2 summarizes diffusion model parameters for all end uses:

Table 2. Diffusion Parameters for all End Uses

	α	$\ln\gamma$	β_{Inc}	β_{Elec}	β_{Urb}	β_{CDD}	β_{HDD}	Obs.	R^2
Lighting Bulbs	40.0	1.852	-4.7E-04					39	0.74
Refrigerators	1.4	4.750	-6.0E-05	-3.55	-2.69			64	0.92
Air Conditioning	1.0	1.269	-8.3E-04					24	0.70
Washing Machine	1.0	7.982	-3.2E-04	-8.74				27	0.64
Fan	3.0	1.018		-1.41		3.3E-04		11	0.92
Television	3.0	3.502	-9.5E-05	-3.11				139	0.75
Stand By Power	12.0	2.100	-4.8E-04					30	0.57
Water Heating	1.0	5.528	-6.1E-04	-4.53			-1.4E-03	15	0.77

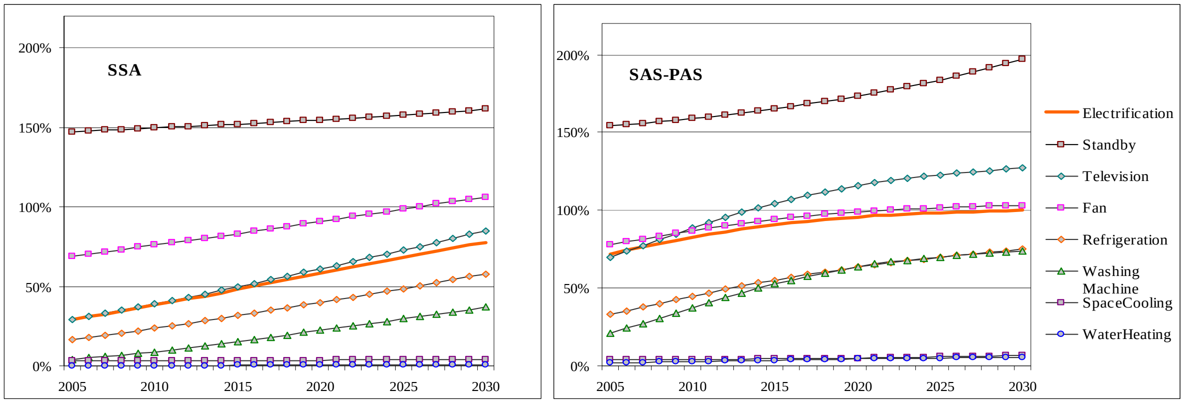
The diffusion forecast relies on projections of the independent variables. Household size and urbanization projections are available from the United Nations[7]. Income per capita is projected according per capita GDP growth rates from the Department of Energy's International Energy Outlook (IEO) (USEIA 2007). Electrification is projected assuming that the relation between economic growth and electrification rate reflects the fact that electrification is higher priority countries with the lowest electrification rates. Using data from consecutive surveys from Development Health Surveys[8] (DHS) in the same country, the following relationship between GDP growth and electrification growth is determined:

$$\frac{\Delta Electrification}{Electrification} = (-3.73 \times Electrification + 3.85) \times \frac{\Delta GDP}{GDP}$$

The resulting diffusion forecast is shown in Figure 3 for Sub-Saharan Africa, and the SAS-PAS region.

[6] Which is referred as “saturation” instead of “diffusion”
[7] from UNhabitat: http://ww2.unhabitat.org/habrdd/CONTENTS.html
[8] DHS data compiler: http://www.statcompiler.com/

Figure 3. Appliances Diffusion Projections in SSA and SAS-PAS Regions



Lighting Type

Lighting efficiency potential is considered separately for fluorescent and incandescent lamps. Estimates of the fraction of each type of lighting by region are given in Table 3.

Table 3. Incandescent, Fluorescent and CFL Lamp Shares by Region

Region	%IL	%FL	%CFL	Reference/Assumption[9]
LAM	68%	12%	20%	(Figueroa and Sathaye 1993), (McNeil 2003), (Lutz, McNeil et al. 2008), (IEA 2006), (Friedmann, DeBuen et al. 1995)
SSA	53%	32%	15%	(Constantine and Denver 1999)
MEA	100%	0%	0%	(IEA/OECD 2001)
CPA	57%	20%	23%	(IEA 2006)
SAS-PAS	59%	37%	4%	(CLASP 1997),(Kulkarni and Sant 1994),(Kumar, Jain et al. 2003)

Space Heating in Centrally Planned Asia

China is the only country for which it is assumed that space heating consumption is significant. Electric space heating in China is mostly of the resistance type, but a growth in heat pump use from 1% in 2005 to 9% in 2030 is assumed, following (Zhou, McNeil et al. 2007).

Module 2: Unit Energy Consumption and Efficiency Potential

The following section describes the methods and assumptions for determining the average unit energy consumption (*UEC*) for each end use, as well as the efficiency in the base case and efficiency scenarios. These assumptions are summarized below in Table 6.

Lighting

Estimates of lighting energy consumption required gathering estimates of hours of use per day for each fixture, which were found to be 2.3 hours per day on average for the regions considered. This usage was used to calculate lighting consumption according to the lamp type

[9] Regional averages from multiple data sources weighted by electrified households.

described in the previous section, and lamp wattage. The most common wattage found in the surveys is 60W for incandescent bulb, 15W for CFLs and 36W for fluorescent tubes.

Although the penetration of CFLs varies from country to country, there is significant savings to be gained from a labeling program promoting CFLs. The impact of CFL endorsement labeling programs was modeled by simply assuming that between 2010 and 2030, households will gradually replace half of their incandescent bulbs (60W) with CFLs (15W).

The energy consumption of fluorescent tube lamps is a function of lamp efficacy[10] and of losses in the lamp ballast. Ballast losses can be reduced by switching to low-loss electromagnetic ballasts or electronic ballasts which reduce total consumption respectively by 12% and 25%.

Refrigerators

Because of their high share of household electricity consumption, and because they are a priority for many efficiency programs around the world, refrigerators were the first focus of a prior analysis such as the present one by the authors (McNeil, Letschert et al. 2006). Much of the data and assumptions supporting savings estimates are provided in that report and are not repeated here. Instead, the scenarios for each region are summarized in Table 6. In general, quite aggressive targets are assumed to be feasible for refrigerators, especially in 2020, when all regions will reach the current 'A+' level defined by the European Commission.

Air Conditioners

Climate plays the dominant role in determining air conditioning energy consumption. Not only will households in warm climates potentially own more and/or larger units, they will likely use each unit more often. As in the case of saturation, UEC is modeled according to cooling degree days (*CDD*) and income[11]. Thirty-seven data points were gathered and a linear regression was performed:

$$UEC\ (kWh) = 0.345*Income + 1.44 * CDD - 967$$

Two modifications were made to the model. First, we assume a maximum cooling load of 3500 kWh, which is about the modeled value for the United States. Second, our model overestimates heat pump use in China; therefore, we added a correction factor for space cooling in the CPA region[12], which is found to be 0.41 (Zhou, McNeil et al. 2007).

Air conditioning scenarios are based on the assumption that since the market is internationalized, standards have a good chance for alignment with the best practice. China is leading the way with its "reach standards" that, when coming into effect in 2009, will be among the most stringent in the world. Currently, the EU 'A' level is set at 3.2 EER (W/W), but units at 4 or 5 EER are reportedly already on the market there (Bertoldi and Atanasiu 2006). Therefore, the 2020 efficiency target assumes that an EER of 4.0 is achievable.

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[10] The term 'efficacy' is commonly used in place of 'efficiency' in describing the amount of light output per unit input energy of a lamp or lamp-fixture system.

[11] A result of the income dependence is that baseline UEC is increasing with time (with income).

[12] It's the only region where heat pumps are significantly present. Bouma, J. (2001). International Heat Pump Status and Policy Review, published in Energy Efficiency in Household Appliances and Lighting, Springer Verlag.

Washing Machines

Washing machine energy varies by product class, and by the number of loads used. The three types of washer can be characterized as: horizontal axis, vertical axis and impeller type. Washing machine energy consumption can be reduced both through the efficiency of the motor system, and the reduction of hot water use.

Fans

Fan energy consumption is clearly a function of CDD, which determine the length of the cooling season, and the number of hours per day they are necessary. Data on fan energy is very sparse, however. Therefore, fan energy was estimated at the region level only, and extended some estimates to regions with similar climates. Potential fan efficiency improvement is based on studies in the U.S. targeting ceiling fans (USDOE 2005).

Televisions

Only color televisions are considered, since efficiency programs will only cover products sold after 2010. This is a rapidly evolving product, but one which is relatively uniform across regions, as it is manufactured mostly by large multinational companies for global markets. The consumption of a TV is mainly dependent on the size and the image technology. The model considers three types of TVs: CRT, LCD and Plasma TVs. Display Bank provides data and projections on market shift from CRTs to LCD and plasma TVs between 2003 and 2010 (Jones, Harrison et al. 2006). CRTs are assumed decrease at a constant rate and that their lost market share splits between plasma and LCDs. The resulting market share and UEC for televisions are shown in Table 4.

Table 4. Baseline UEC and Market Shares of CRT, LCD and Plasma TVs

			Market Share			
Technology:	**Power (W)**	**UEC (4 hrs/day)**	**2000**	**2010**	**2020**	**2030**
CRT	70	102	100%	43%	18%	8%
LCD	130	190	0%	43%	55%	61%
Plasma	300	438	0%	14%	26%	32%
		Ave. UEC kWh	**102.2**	**186.9**	**238.8**	**261.1**

Four hours per day per TV was derived from Gfk data (Bertoldi and Atanasiu 2006)

A recent study (Armishaw and Harrison 2006) considering the environmental impacts of TVs identified design options through which LCD consumption can be reduced by 43% and plasma TVs' consumption by 36% .

Stand-by Power

Since this end use is active 24h hours a day, the base case UEC is a straightforward calculation.. For a maximum 60W stand-by power (which represents 12 devices consuming a stand by power of 5W), the annual consumption is 512 kWh, given by

$$UEC(kWh) = 60W \times 24h \times 365 \times 10^{-3} = 512kWh$$

Efficiency scenarios are given simply as 3W and 1W stand-by, values that appear commonly as proposed standards or endorsement levels.

Water Heaters

The share of electric water heaters in the modeled penetration will be assumed to be the same as electric cooking for all regions (DHS 2008) except CPA, for which we follow (Zhou, McNeil et al. 2007). Ideally, the estimation of water heater energy consumption should account for climate, household size and on cultural practices and preferences. Due to the lack of data these effects were impossible to model. Therefore, water heater unit energy consumption is estimated for each region, based on available data.

The efficiency of electric water heaters for all regions is based on a study for the European Commission (Sakulin and Hoelblinger 2000) which proposes a rating system for residential water heaters.

Table 5 . Overall Electric Water Heating Ownership and Unit Energy Consumption

	Electric Water Heating	UEC (kWh)[13]	Reference
LAM	9.3%	955	(Jannuzzi G. 2005) (McNeil 2003)
SSA	1.3%	414	Assumed to be equal to MEA UEC
MEA	1.8%	414	(Anwar 2005),(Davoudpoura and Ahadib 2006)
CPA	32.0%	1062	(Zhou, McNeil et al. 2007)
SAS-PAS	0.3%	225	(Letschert and McNeil 2007)

Space Heating

Space heating is modeled only for China, since the other regions have low average heating loads. Resistance electric heating is assumed to have an efficiency of nearly 100% (assuming all Joule heat enters the space to be conditioned) whereas heat pumps are assumed to follow the same efficiency as air conditioners. The useful energy is estimated to be 596 kWh from (Zhou, McNeil et al. 2007).

Module 3: Stock Accounting

In order to account for equipment turnover, the stock of each end use in each year is calculated, and the portion impacted by programs in place starting in 2010 and 2020 is made. This portion will be determined by the number of appliances that have retired since the year of the first standard and that have been replaced by efficient products compared to the national stock in each year given by:

$$S_i(y) = Diffusion_i(y) \times HH(y)$$

The time it takes to retire all of the pre-program stock depends on the average life of the product. The stock is assumed to decrease linearly and reaches zero after 1.5 times the average lifetime. Estimates of average equipment lifetimes are given in Table 7.

[13] Weighted by country GDP when more than one point available

Table 7. Equipment Lifetime

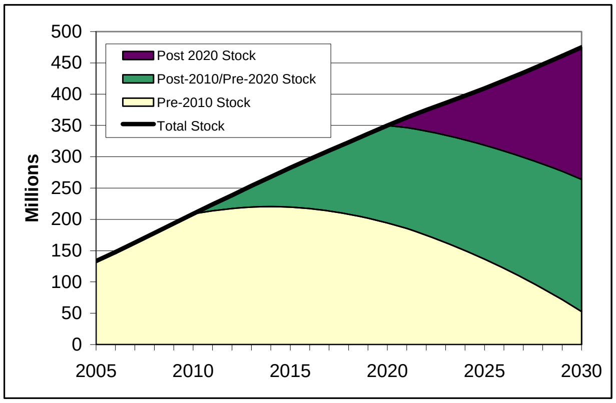
End use	Lifetime (years)	Reference
Washing Machine	15	(Novem and Ademe 2001)
Water Heating	15	(Novem 2001)
Space Heating	15	(European Comission 2002)
Refrigeration	15	(European Comission 2000)
Fluorescent Lamp Ballast	14	(Rosenquist, McNeil et al. 2006)
Air Conditioner	12	(Rosenquist, McNeil et al. 2006)
Fan, Television	10	LBNL Estimate
Stand-by Power Device	7	LBNL Estimate

An equivalent calculation of remaining stock can be made for 2020, when a new set of generally more stringent EES&L programs comes on line. With this, the stock in each year can be divided into three categories as shown in Figure 4, for refrigerators.

Table 6. Regional Scenarios of Base Case Consumption and Energy Efficiency Potential

End use	Region	Average Efficiency Base Case	2010	2020	Reference	Assumption
Fluorescent Lamp (W)	SAS+PAS	40	36	36	Voice Mag. (oct 2005)	Low-Loss electromagnetic ballasts mandatory in 2010, electronic ballast in 2020
	Other	46	40	36	(IEA 2006)	
Refrigerator (kWh/year)	LAM	440	261	216		Based on current EES&L program in Mexico and Brazil. Assume 39% improvement in Brazil by 2010. Mexican standards harmonized with U.S. by 2010. Efficiency reaches EU A+ level by 2020.
	SSA+MEA	445	364	271		Currently at pre-standard European levels. Achieves current EU levels by 2010. Efficiency reaches EU A+ level by 2020.
	CPA	489	353	302		2010 Baseline according to 2007 MEPS. Average meets current A level by 2010. Efficiency reaches EU A+ level by 2020.
	SAS-PAS	548	301	223	(McNeil, Letschert et al. 2006)	Based on current Indian standards and assumes an aggressive update in 2010. Efficiency reaches EU A+ level by 2020.
Air Conditioners (EER)	LAM	2.64	2.96	4	(McNeil and Letschert 2007)	Same as WEU, except baseline at 'E' level
	CPA	2.6	3.2	4	(Lin J. 2006)	Baseline Corresponds to 2005 Standard (Split Systems). Reach Standard in 2009 is 3.2. Assume new standards at 4 by 2020
	SAS-PAS	2.55	3.2	4	(McNeil and Iyer 2007)	Weighted average based on Baseline efficiency in India, Malaysia and Thailand. Assumes Harmonization with Chinese standards by 2010
	SSA+MEA	2.4	2.6	3.2		Estimate based on current lack of efficiency programs. Will reach China 2009 standard by 2020.
Washing Machines (kWh/year)	LAM	191	149	108	(Lutz, McNeil et al. 2008)	For horizontal axis machines, European Level C in 2010, Level A in 2020 (same usage as baseline, and baseline is level E), 2004 US standard adopted in 2010, 2007 US standard in 2020 for vertical axis machines
	SSA	181	97	68	(Pretoria 2003)	
	MEA	183	141	99	(Davoudpoura and Ahadib 2006)	
	CPA	12	6	6	(Lin and Iyer 2007)	32Wh/kg/c. for the baseline, 17Wh/kg/cycle for the efficiency scenario (current endorsement label) -2.5 kg/c. and 250 c./yr
	SAS-PAS	190	102	102	(Letschert and McNeil 2007)	Based on India Market consideration (semi automatic machines versus horizontal axis)
Fans (kWh/year)	Others	88	72	54		
	CPA	10	8	6		
	SAS-PAS	150	123	92	(USDOE 2005)	Energy Star Level by 2010, best technology available by 2020
Water Heater (EF)	LAM	0.79	0.88	0.91	(Sakulin and Hoelblinger 2000)	Level F to Level C in 2010, and Level A in 2020
	Others	0.76	0.83	0.88		Level G to Level E in 2010, and Level C in 2020

Figure 4. Stock of Refrigerators in SAS-PAS



Once the amount of stock in each category is estimated, calculation of delivered (site) energy and savings is straightforward. Electricity demand per end use and region is given by:

$$E_{i,j}(y) = S_{\Pr e-2020}(y) \times UEC_{i,j}^{Base}(y) + S_{2010-2020}(y) \times UEC_{i,j}^{Eff\,1}(y) + S_{Psst-2020}(y) \times UEC_{i,j}^{Eff\,2}(y)$$

Where *S* is the stock of products in each category in year *y*, and *UEC(y)* is the annual unit energy consumption (kWh) of product type *i* in region *j* in year *y*. The superscript on the variable UEC determines the overall energy demand, and savings. *UEC* values in the *Base, Eff1* (2010) and *Eff2* (2020) case are the parameters of Module 2. In the Base Case, all products operate at the base case efficiency:

$$E_{i,j}^{BaseCase}(y) = S_{Total}(y) \times UEC_{i,j}^{Base}(y)$$

Savings is given by the difference of the two:

$$E_{i,j}^{BaseCase}(y) - E_{i,j}(y)$$

Saving Potential Results and Conclusions

The analysis reports two main metrics for evaluating the potential of efficiency programs. These are (1) delivered (site) electricity savings and (2) emissions reductions. Delivered electricity is an important metric because it is the energy which is actually reduced by equipment efficiency, and therefore what is usually targeted in efficiency specifications. The following figure shows the potential of electricity savings as well as the resulting consumption. By 2030 these programs could save an amount of energy equivalent to 90% of the amount of electricity consumed in 2005 by the developing world, and reduce the annual growth rate (AAGR) of electricity consumption between 2005-2030 to 2.8% (compared to 4.3% in the base case, close to the economic AAGR of 4.6%). Figure 5 shows forecasted electricity demand in the base case, along with the efficiency case for each end use in the economic scenario defined by IEO.

Finally, energy demand savings is converted to CO_2 mitigation using electricity generation carbon factors (from IEA data). Carbon factors, which take into account the electricity generation mix and transmission and distribution losses, are assumed to decrease by 1% per year in all regions[14]. The carbon factors are shown in Table 8.

[14] Due to efficiency improvement in the generation, transmission and distribution of electricity

Figure 5. Electricity Demand Forecast in the Base Case and the Efficiency Case

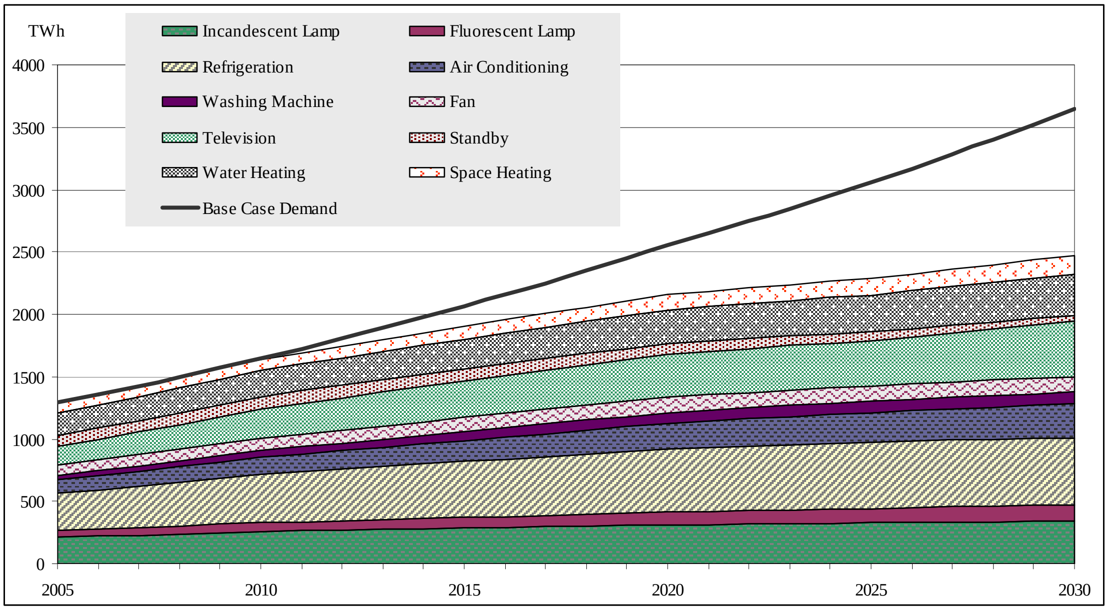


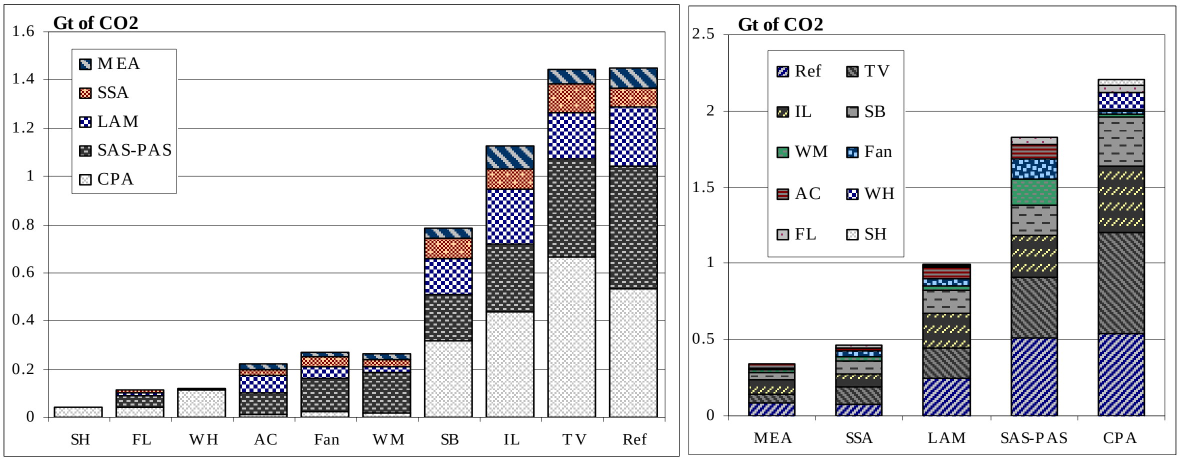
Table 8. Electricity Carbon Factors (kg of CO_2 per kWh)

	LAM	SSA	MEA	CPA	SAS-PAS
2000	1061	1101	413	1181	956
2020	744	643	405	792	628
2030	504	434	304	574	466

Figure 6 shows the resulting emissions reduction potentials that may be possible from efficiency programs targeting electricity consumption in developing countries, by end use and by region. Refrigerators have the largest potential overall, and in most regions. This is perhaps not surprising because this is the first major appliance purchased by most households, and there is ample room for efficiency improvement for this equipment. Less obviously, mitigation from televisions are as large, because this is the most common user of electricity after light bulbs, but technology shifts are leading towards a higher television consumption per unit, if the efficiency is not improved from today's levels. Savings from incandescent lighting is high, but these savings are highly dependent on the number of light bulbs that are actually be switched to CFLs.

Regionally, the Asian regions show the most potential. The analysis finds that there is more savings potential in the CPA region, which contains China, than any other region, and that this is generally true across end uses. The region representing the rest of Asia, including India, provides nearly as much potential, as China. Due to their smaller population, the other three regions have less potential overall, and for most end uses. A notable exception is the case of air conditioners in Latin America, where higher average household incomes will permit a significant level of ownership for this highly intensive appliance. In total, the model estimates that 5.8 Gt of CO_2 emissions could be mitigated through 2030, saving 870 Mt each year in 2030.

Figure 6. Cumulative Emissions Mitigation Potential 2010-2030



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