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Material World: Forecasting Household Appliance Ownership in a Growing Global Economy

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Abstract

Over the past years the Lawrence Berkeley National Laboratory (LBNL) has developed an econometric model that predicts appliance ownership at the household level based on macroeconomic variables such as household income (corrected for purchase power parity), electrification, urbanization and climate variables. Hundreds of data points from around the world were collected in order to understand trends in acquisition of new appliances by households, especially in developing countries. The appliances covered by this model are refrigerators, lighting fixtures, air conditioners, washing machines and televisions.

The approach followed allows the modeler to construct a bottom-up analysis based at the end use and the household level. It captures the appliance uptake and the saturation effect which will affect the energy demand growth in the residential sector. With this approach, the modeler can also account for stock changes in technology and efficiency as a function of time. This serves two important functions with regard to evaluation of the impact of energy efficiency policies. First, it provides insight into which end uses will be responsible for the largest share of demand growth, and therefore should be policy priorities. Second, it provides a characterization of the rate at which policies affecting new equipment penetrate the appliance stock. Over the past 3 years, this method has been used to support the development of energy demand forecasts at the country, region or global level.

Introduction

This paper presents a methodology for modeling residential appliance uptake as a function of macroeconomic variables, and presents forecasts of appliance diffusion through 2030 for several scenarios of economic (GDP) growth. Contrary to previous studies where the authors presented their work on specific products (McNeil, 2007) or regions (McNeil, 2005; Letschert,2007), this paper broadens the scope of study with the global modeling of five appliances based on international studies. The development of an appliance diffusion model serves two purposes. First, it allows for interpolation of diffusion rates for countries where data is unavailable. Second, it provides a basis for which projections can be made into a future where the main drivers – wealth, urbanization and electrification are all likely to be increasing. The appliances modelled here are the first appliances that a household will acquire once connected to the grid. The appliances ladder is a concept similar to the fuel ladder well described in energy literature. Thus, in order to understand the bulk of household energy consumption, the appliances modelled are lighting fixtures, televisions, refrigerators, air conditioners and washing machines.

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Modeling Diffusion

The strategy is to collect international data on appliance ownership in order to develop a relationship between them and widely available macroeconomic data. This involved a wide search for publicly available survey results and research publications. The result of this effort is a library of 200 appliance diffusion[1] data points between 1991 and 2007 (METI, 2008). We found that income, electrification, urbanization and climate were the most significant determinant of appliance ownership.

Household Income

The most obvious determining variable for national average appliance ownership is average household income, which is approximated by Gross Domestic Product (GDP) per capita, multiplied by household size. Household size is estimated by the United Nations Human Settlement Programme (UN Habitat). In order to more accurately relate income to ability to purchase appliances, household GDP is corrected for Purchase Power Parity (PPP). The PPP factor adjusts currency market exchange rates (MER) by taking into account the difference in prices for a given basket of goods.

Electrification and Urbanization Rates

Electrification rates were found primarily in the IEA's World Energy Outlook (WEO) 2002 (2000 data), and World Energy Outlook 2006 (2005 data). In addition, data for some countries not covered by WEO were taken from demographic health surveys (Measure DHS, 2008). Historical urbanization rates and projections were available from the United Nations Department of Economic and Social Affairs (UNDESA).

Climate variable (for air conditioners)

Modeling of air conditioner diffusion is similar to that of the other products, but with the main difference that air conditioner ownership is climate-dependent. This means that in some very wealthy regions, such as Northern Europe, air conditioner ownership remains low, even though air conditioners are generally affordable. On the other hand, in tropical developing countries, air conditioners might be considered among the most desirable appliances, but their high cost continues to categorize them as a luxury item. A climate maximum saturation (CMS) variable was developed in McNeil (2007) in order to take in account the climate effect, using U.S. ownership data as a maximum for a given climate zone, characterized by Cooling Degree Days (CDD), through the relation:

Eq. 1: $$CMS = 1.0 - 0.949 \times \exp(-0.00187 \times CDD)$$

Functional Form

The general form of the diffusion relationship follows an S-shaped function. There are various options for modeling this type of relationship. We used a linear combination of the independent variables that we transform into a logistic function, which is appropriate for econometric modeling of a simple binary choice (market share) (Train 2003). Defined in this way, the equation for the studied appliances is given by:

Eq. 2 $$Diff_{c,y} = \frac{\alpha}{1 + \gamma \exp\left(\beta_{inc} I_{c,y} + \beta_{elec} E_{c,y} + \beta_{urb} U_{c,y}\right)}$$

Where: $Diff_{c,y}$ is the diffusion of the appliance for the country *c*, in the year *y*

α is the saturation level, which may be greater than 1

$I_{c,y}$ is the average household income in the country *c*, in the year *y*

$U_{c,y}$ is urban population as a percent of total population of the country *c*, in the year *y*

$E_{c,y}$ is the national electrification rate, in the year *y*

The logistic function ranges from 0 to α, which sets the maximum diffusion reachable, and is typically set equal to the diffusion in the United States. The model parameters β are scale parameters that determine the dependence of diffusion on each variable.

Table 1: Saturation Parameter for all appliances

Appliance	Refrigerator	Air Conditioner	Washing Machine	Television	Lighting
Saturation Parameter	1.4	CMS	1	3	40

The logistic diffusion function can be converted to a linear function, allowing linear regression analysis. Rearranging and taking the logarithm of both sides gives:

$$\ln\left(\frac{\alpha}{Diff_c}\right) = \ln\gamma + \beta_{inc} I_c + \beta_{elec} E_c + \beta_{urb} U_c$$

[1] Defined as the average number of appliances per household

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Regression Results

Refrigerators

The data for refrigerators ranges from 1992 to 2007, and consist of 64 data points. With an R^2 of 0.918, refrigerator ownership is very well described by a logistic functional form with income, electrification rate and urbanization as independent variables. Each of these variables is statistically significant. Each parameter also has the expected sign, that is, ownership increases with increasing household income, electrification, or urbanization, as shown in Table 2.

Table 2- Linear Regression Results for Refrigerators

Observations	64			
R^2	0.918			
	Coefficients	*Standard Error*	*t Stat*	*P-value*
ln γ	4.84	0.197	24.508	5.98E-33
β_{Inc}	-1.34E-05	4.82E-06	-2.774	7.37E-03
β_{Elec}	-3.594	0.268	-13.424	9.97E-20
β_{Urb}	-2.24	0.593	-3.779	3.65E-04

The graphical representation used here will be the same throughout the paper. Each point corresponds to a single country, and shows either data (red square) or model result (blue circles). The y-axis gives number of appliances per household, and the x-axis is one of the variables of the fit.

As Figure 1 shows, refrigerators are still rare in households in many countries, usually below 20% for countries with average PPP adjusted incomes below \$10,000 per year. The cluster of data points with relatively low incomes, but high diffusion rates are largely from countries of the former Soviet Union and Eastern Europe, where electrification is universal, and incomes may not reflect purchase ability in the same way as countries in the developing world. Electrification and urbanization rates add additional explanation to diffusion rates. In particular, the close relationship with electrification suggests that most households with access to electricity will purchase a refrigerator if they can afford it.

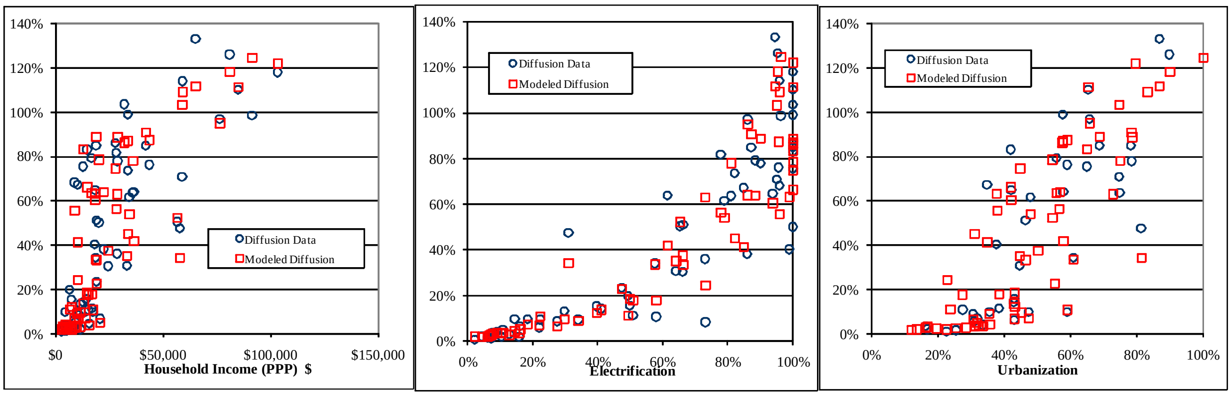

Figure 1 – Linear Regression Results by Variable for Refrigerators

Washing Machines

The data for washing machines ranges from 1991 to 2006, and consists of 27 datapoints. Income and electrification are found to be statistically significant determinant of washing machine ownership. Urbanization, however, was not found to be a significant variable for this appliance; therefore, we eliminated this variable in the linear regression. The resulting fit has an R^2 of 0.661 as shown in Table 3.

Table 3 – Linear Regression Results for Washing Machines

Observations	27			
R^2	0.661			
	Coefficients	*Standard Error*	*t Stat*	*P-value*
ln γ	8.914	1.564	5.701	7.14E-06
β_{Inc}	-3.48E-05	1.43E-05	-2.439	2.25E-02

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β_{Elec}	-8.984	2.062	-4.356	2.14E-04

Figure 2 shows the relationship between washing machine diffusion and the two remaining variables. There were fewer data points for the washing machine regression than for refrigerators, especially at very low income and electrification levels (no data point for countries with less than 40% electrification). The income plot suggests that washing machine ownership has a higher income threshold for uptake, but then grows very rapidly, reaching near saturation and then levelling off rapidly at high incomes.

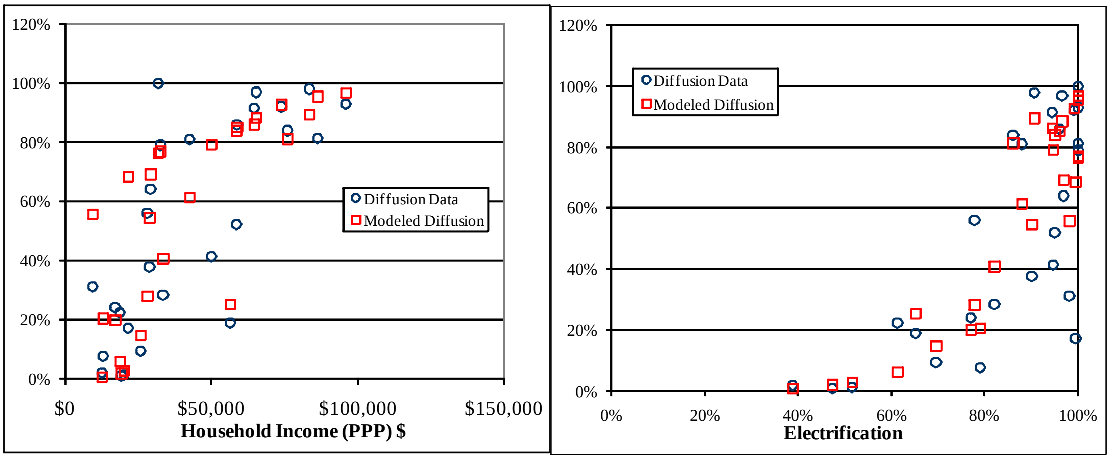

Figure 2 – Linear Regression Results by Variable for Washing Machines

Televisions

The data for televisions ranges from 2002 to 2007, and consists of 46 data points. As Table 4 shows, the parameters describing income and electrification are highly significant. As in the case of washing machines, urbanization was not found to be a significant variable for television ownership, and was not included in the regression.

Table 4 – Linear Regression Results for Televisions

Observations	46			
R^2	0.847			
	Coefficients	*Standard Error*	*t Stat*	*P-value*
ln γ	3.701	0.134	27.584	5.65E-29
β_{Inc}	-2.52E-05	4.96E-06	-5.071	8.01E-06
β_{Elec}	-2.387	0.312	-7.661	1.44E-09

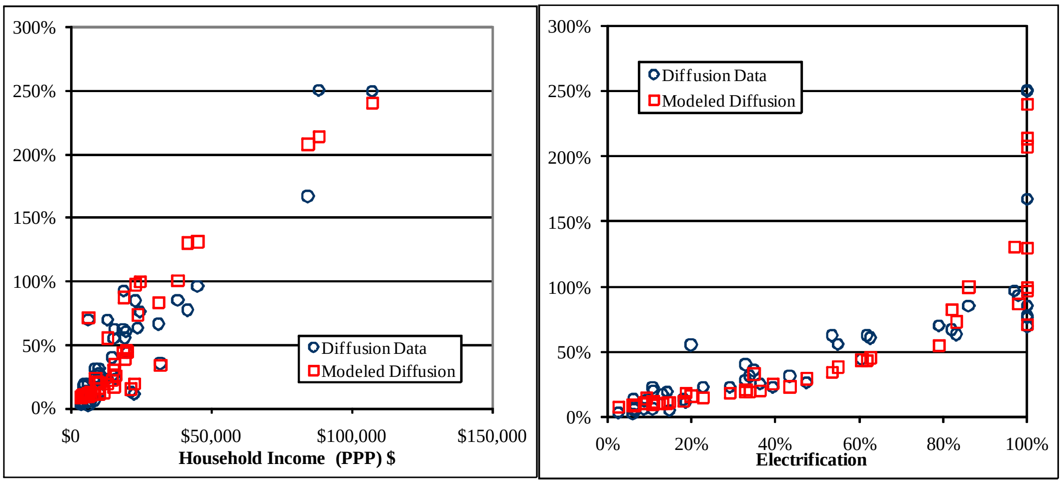

Figure 3 – Linear Regression Results by Variable for Televisions

As expected, television diffusion follows closely to electrification rates, indicating that nearly every electrified household has at least one television (Figure 3). At high incomes, diffusion exceeds 100%, and continues growing.

Air Conditioners

As explained in McNeil (2007), air conditioner diffusion is corrected for climate by the CMS. This corrected variable is called *Availability*. We define it as:

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Diffusion=Availability x CMS

The regression for air conditioners is then performed on availability versus income. The dataset consists of 24 points ranging from 1992 to 2007. Table 5 shows the regression results where income is a highly significant variable. The R^2 of the fit is 0.693.

Table 5 – Linear Regression Results for Air Conditioner Diffusion

Observations	24			
R^2	0.693			
	Coefficients	*Standard Error*	*t Stat*	*P-value*
ln γ	4.843	0.503	9.635	2.36E-09
β_{Inc}	-6.91E-05	9.82E-06	-7.041	4.59E-07

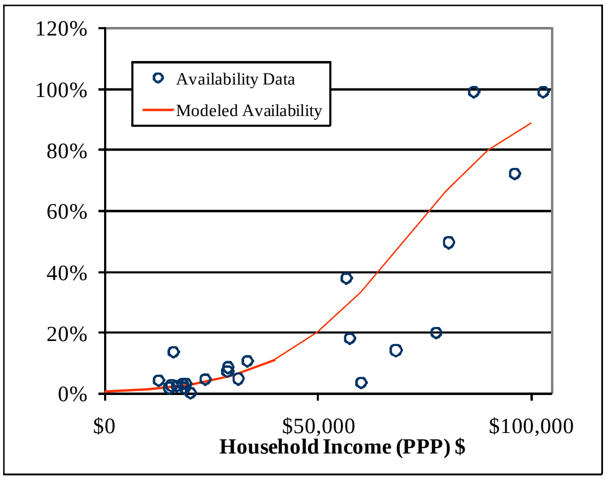

Figure 4 – Air Conditioner Availability vs. Income (Source: (McNeil, 2007))

Figure 4 shows graphically the relationship between income and air conditioner diffusion. The shape of the income curve is distinct from the other appliances due to the high price of this appliance. Below about $25,000, diffusion remains quite low, but then rises rapidly after this point.

Lighting Fixtures

The regression that describes the number of bulbs per household is based on 42 data points, from 1989 to 2006. Income was found to be the only relevant variable with a correlation of 0.714 as shown in table 2.

Table 6- Linear Regression Results for Lighting Fixtures

Observations	42			
R^2	0.714			
	Coefficients	*Standard Error*	*t Stat*	*P-value*
ln γ	2.20	0.177	12.446	2.46E-15
β_{Inc}	-2.98E-05	2.98E-06	-10.002	1.92E-12

Figure 5 illustrates the model along with the diffusion data point.

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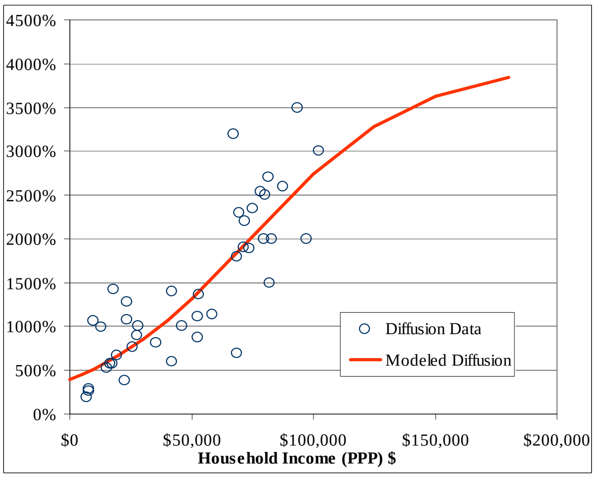


Figure 5 – Linear Regression Results for Lighting Fixtures

The lighting fixtures model has been used in combination with bulb type information relative to every country/region in order to describe lighting consumption (McNeil, 2008).

Forecasting Diffusion

Forecasting Variables

Household Income:

GDP_{MER} was projected using growth rates developed in the IPCC SRES scenarios (Morita, 2000). SRES developed a wide range of economic scenarios, from which we derived 3 regional scenarios according to the average and standard deviation of the regional growth rates provided by SRES (REF, LOW and HIGH).

In order to project GDP_{PPP} as a function of GDP_{MER}, we determined a relation between the two using data from the World Bank from 2007, with very good agreement (R^2=0.92). This relation is given by:

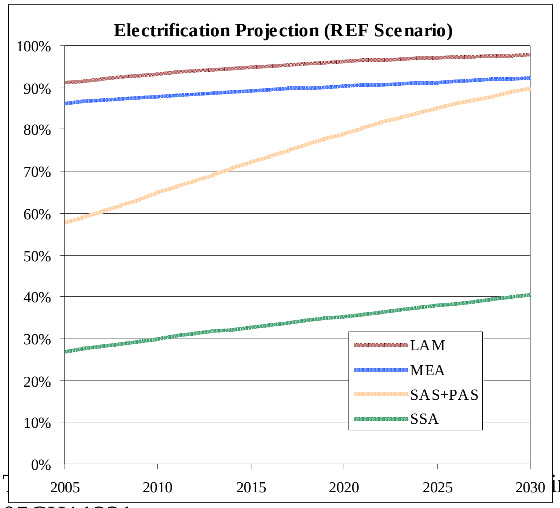
Eq. 3: $$GDP_{PPP}/Household = 54.311 \times GDP_{MER}/Household^{\,0.6554}$$

Electrification:

In order to project electrification rate, a regression was performed on the 59 data points provided by IEA in 2005 (IEA, 2006), assuming that electrification growth is related to economic growth rate and current electrification rate by a logistic function:

Eq. 4: $$Elec(y) = \frac{100\%}{1 + \exp\left(\beta \times I_c(y)\right)}$$

In this formula, $I_c(y)$ is the household income in year y. We find a value of 1.42 x 10^{-4} for β, and an R^2 value of 0.77. The resulting projections are shown in the following figure for the 4 regions defined in Morita (2000) not yet universally electrified: Latin America (LAM), Sub-Saharan Africa (SSA), Middle East and North Africa (MEA) and South Asia- Pacific Asia (SAS+PAS):



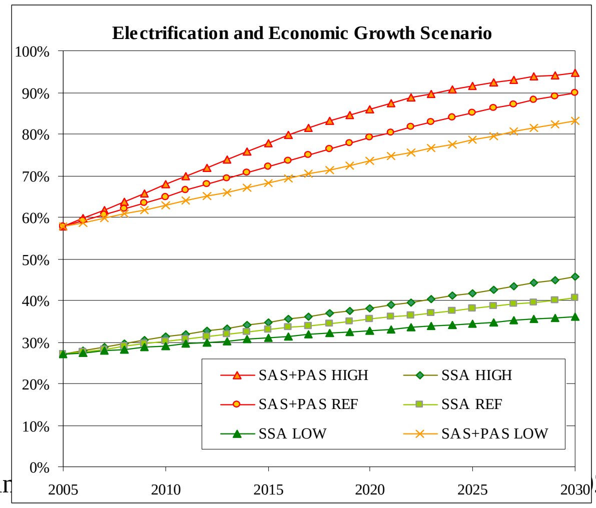


Figure 6- – Linear Regression Results for Household Electrification Rate

Results

Once the trends for each driver variable are established for each economic scenario, the forecast of diffusion for each country follows in a straightforward way from Eq.2. In each year, for a given level of household income (projected using Eq.3), urbanization and electrification rates (projected using Eq.4), and given the time-independent climate variable for each country (from Eq.1), ownership level of each major appliance is calculated for 160 countries and for each year of the forecast, using a spreadsheet model. Results are then aggregated to the regional level, as defined in Morita (2000), in order to show the results.

Table 7- Results for all modelled appliances under the 3 economic scenarios

		Oceania Pacific OECD	North America	Western Europe	Central and Eastern Europe	Former Soviet Union	Latin America	Sub-Saharan Africa	North Africa and Middle East	Centrally Planned Asia	South Asia+Pacific Asia
REF	2000	107%	129%	115%	88%	87%	84%	12%	65%	66%	22%
	2030 REF	121%	129%	118%	100%	95%	103%	25%	78%	92%	77%
	2030 LOW	120%	128%	117%	96%	93%	101%	24%	76%	89%	74%
	2030 HIGH	123%	130%	119%	103%	98%	105%	25%	80%	96%	80%
WM	2000	81%	79%	91%	76%	71%	58%	3%	53%	66%	8%
	2030 REF	96%	98%	93%	83%	78%	78%	11%	61%	81%	72%
	2030 LOW	95%	98%	92%	79%	74%	75%	10%	60%	77%	69%
	2030 HIGH	96%	99%	93%	86%	81%	81%	11%	63%	84%	75%
TV	2000	167%	244%	148%	117%	100%	99%	24%	99%	93%	43%
	2030 REF	231%	263%	204%	151%	122%	145%	37%	128%	135%	121%
	2030 LOW	223%	257%	197%	134%	110%	131%	35%	119%	122%	110%
	2030 HIGH	237%	268%	211%	171%	136%	160%	40%	138%	151%	135%
AC	2000	27%	85%	2%	3%	2%	10%	4%	16%	3%	4%
	2030 REF	69%	76%	27%	9%	5%	28%	6%	28%	14%	13%
	2030 LOW	66%	75%	25%	6%	3%	21%	5%	23%	9%	9%
	2030 HIGH	71%	76%	29%	14%	8%	37%	6%	34%	21%	19%
LIGHT	2000	2119%	2783%	1819%	852%	644%	922%	561%	953%	611%	622%
	2030 REF	2421%	3080%	2066%	1306%	1017%	1336%	666%	1411%	1021%	1012%
	2030 LOW	2289%	2946%	1952%	1085%	872%	1147%	619%	1265%	889%	882%
	2030 HIGH	2556%	3208%	2185%	1590%	1209%	1559%	718%	1571%	1191%	1177%

Conclusion

The development of the LBNL model is a significant step towards the larger goal of forecasting global energy consumption. What the current method brings to the energy demand modelling field is a highly disaggregated basis for bottom-up energy forecasting, and perhaps most importantly, efficiency scenario building. Further research may include the effects of income distribution and the effect of decreasing prices of appliances, if price data becomes available.

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