International Conference on Policy Modelling (EcoMod 2008),
July 2-4, 2008

Modelling the energy demand of households in a combined top down/bottom up approach

Kurt Kratena, Ina Meyer, Michael Wüger *

Abstract:

This paper deals with integrating elements of a bottom-up model of energy demand into a top-down model of total private consumption. The bottom-up elements are represented by the energy efficiency embodied in household appliances. The top-down model describes demand for energy and non-energy commodities in an AIDS demand system. In this model households do not directly demand energy, but energy services (hours of washing, miles of driving). These services are measured via the service price defined as the relationship between the energy price and energy efficiency. Therefore an increase in energy efficiency leads to a decrease in the service price and, thereby, increases demand for services which compensates for parts of the energy savings due to efficiency improvements ('rebound effect'). The model presented can be used to derive different feedbacks (rebound effects) from efficiency changes on energy demand and to quantify the role of efficiency improvements in reducing energy demand and emissions from households.

JEL Code: D11, D13, Q53

* Austrian Institute of Economic Research (WIFO), P.O. Box 91, A-1103 Vienna (Austria), corresponding author: kurt.kratena@wifo.ac.at

1. Introduction

Energy-relevant consumption patterns are increasingly beeing recognized in the design of policies that foster a transition towards a low-carbon economy. Emissions from passenger transport, households' electricity and heat consumption are growing rapidly despite of technological progress. They, hence, need to become an integral part of efforts directed to mitigate global warming. Whereas large stationary sources, e.g. from industries and energy suppliers are regulated by the European Emissions Trading System (EU ETS) the many drivers and partly mobile emissions sources in households may call for different policy instruments such as emissions taxes or technological standards.

The existing research on private household energy demand is mainly focused on empirical investigations into partial demand analysis for electricity (e.g. Larsen and Nesbakken, 2004; Holtedahl and Joutz, 2004; Hondroyiannis, 2004) and passenger cars (Meyer et al., 2007). Some recent studies cover the whole residential energy demand (Labandeira et al., 2006) and only a few the whole energy relevant consumers' demand, including residential and passenger transport (e.g. Brännlund et al., 2007). Most of these studies do not explicitly take into account the role of capital or appliances. On the other side, we find several attempts in the analysis of consumers' energy demand to capture the role of prices as well as technology embodied in capital goods/appliances (e.g. Conrad and Schröder, 1991). This is often labelled as a synthesis between economic and engineering models (Larsen and Nesbakken, 2004) or as a combination of bottom-up and top-down modelling (Rivers and Jaccard, 2005).

Our study attempts this synthesis in one comprehensive econometric model of consumer demand with a focus on technical efficiency embodied in capital stocks (appliances). For this purpose the structure of bottom-up models concerning the technology detail is incorporated into the top-down model. The technologies are represented by efficiencies of the stock of appliances in use and are therefore classified by types of energy-using appliances. Bottom-up models usually apply a type of linear optimization (cost minimizing) to describe the choice of technology out of the menu of existing technologies. In this process energy prices play an important role, but all other socio-economic variables that influence the stock of appliances and the energy consumption (behaviour) are usually treated as exogenous.

It is the aim of this paper to incorporate the technology information of bottom-up models via energy efficiency embodied in appliances into a top-down model. The result is a model with a consistent link between bottom-up and top-down modelling, where demand is also derived from a cost minimization process, but other variables like income and linear trends are also incorporated. As the model describes total private consumption, all links and substitution relationships between energy and non-energy consumption are further considered. The role of efficiency in the top-down model is to lower the price of the service of energy (e.g. price per mile driven), so that rebound effects can be identified (Khazzoom, 1980 and 1989, Berkout, et.al., 2000). The model structure allows for the derivation of different types of such rebound effects. It can further be used to identify the role of efficiency improvements in counteracting the drivers of households' energy demand.

The paper is structured as follows: We present the methodological approach of modelling households' demand for heat, electricity and motorized mobility within a total model of private consumption in Section 2. This section is followed by a brief description of the input data used to model energy demand patterns (Section 3). Section 4 summarises the model results, i.e. price elasticites, cross prices elasticities and different reboud effect are calculated. We also show the importance of efficiency improvements compared to other components of energy consumption growth for the past. Conclusions will be presented in Section 5.

2. A consumers' demand model with embodied energy efficiency

The structure of the model distinguishes between aggregate household consumption, capital expenditure of households, and expenditure for heating/electrity and transport energy as well as for other goods and services. In the following a dual model of private consumption is applied starting from the expenditure function of a demand system. The level of utility u and the vector of commodity prices p_i are the arguments of an expenditure function for non-durables $C(u, p_i)$ which together with expenditure for durables (investment I in appliances with price index p_I) gives total expenditure G:

$$G = C(u, p_i) + p_I I \tag{1}$$

This inclusion of investment requires some dynamic cost minimization or utility maximization model. Willet, Nagshpour (1987) set up a model of dynamic utility maximization with budget constraints from which the optimality conditions for investment are derived. In the present approach the consumer chooses a time path of K to minimize discounted costs for a given level of utility over a time horizon τ for which values for the exogenous variables are given:

$$\min \int_{\tau}^{\infty} e^{-r(t-\tau)} \left[C_t(u, p_i) + p_I(\dot{K} + \delta K) \right] dt \tag{2}$$

where $\dot{K}$ stands for the change in K, r for the interest rate and δ is the depreciation rate.

In the case where the expenditure for non-durables also depends on the capital stock via embodied technical change, i.e. the expenditure function is $C(u, p_i, K)$, we can derive two main optimality conditions from this cost minimization problem, namely Shephard's Lemma and the envelope condition for the capital stock:

$$\frac{\partial C(u, p_i)}{\partial p_i} = x_i \tag{3}$$

$$-\frac{\partial C(u, p_i)}{\partial K} = (r + \delta)\, p_I \tag{4}$$

Shephard's Lemma determines the level of commodity demand x_i or in a logarithmic model the budget shares w_i according to: $\frac{\partial \log C(u, p_i)}{\partial \log p_i} = \frac{\partial C(u, p_i)}{\partial p_i} \frac{p_i}{C(u, p_i)} = \frac{x_i p_i}{C(u, p_i)} = w_i$. The envelope condition states that the shadow price of fixed assets must equal the user costs of capital, i.e. the marginal benefit of a unit of capital must equal its marginal cost. The shadow price of capital is given by the negative of the term that measures the impact of capital inputs on expenditure.

Energy commodities are used by consumers for the 'production' of services (heating, lighting, communication, transport etc.). These services are demanded by households and require inputs of energy flows, E and a certain capital stock, K. The main characteristic of this stock is the efficiency of converting an energy flow into a service level:

$$E = \frac{S}{\eta_{ES}} \tag{5}$$

In (5) E is the energy demand for a certain fuel and S is the demand for a service inversely linked by the efficiency parameter (η_{ES}) of converting the corresponding fuel into a certain service. For a given conversion efficiency, a service price p_S (marginal cost of service) can be derived, which is influenced by the energy price:

$$p_S = \frac{p_E}{\eta_{ES}} \tag{6}$$

This is similar to Khazzooms (1980, 1989) approach of dealing with services and shows the property of a service price decrease with an increase in efficiency. These prices of services (p_S) become arguments of the vector of commodity prices in the overall consumption model (p_i). The budget shares of energy demand can be defined as the traditional energy cost share or as the 'service share': $\frac{p_E E}{C} \equiv \frac{p_S S}{C}$.

We derive the impact of the capital stock on expenditure by the effect of the efficiency on expenditure applying the chain rule.

$$\frac{\partial \log C(u, p_i)}{\partial \log K} = \frac{\partial \log C(u, p_i)}{\partial \log \eta_{ES}} \frac{\partial \log \eta_{ES}}{\partial \log K} = -\frac{p_S S}{C} \frac{\partial \log \eta_{ES}}{\partial \log K} \tag{7}$$

Therefore the shadow price of capital z_K as defined in (4) can be written as:

$$-\frac{\partial C(u, p_i)}{\partial K} = \frac{p_S S}{K} \frac{\partial \log \eta_{ES}}{\partial \log K} = z_K \tag{8}$$

The shadow price is itself a function of the impact of the capital (appliance) stock on efficiency, measured by the term $\frac{\partial \log \eta_{ES}}{\partial \log K}$. This term describes the technical progress in efficiency that is then embodied in appliances (i.e. the most efficient appliance) as well as the consumers' choice among the menu of capital goods. It is, therefore, reasonable to assume that $\frac{\partial \log \eta_{ES}}{\partial \log K}$ is not a constant but itself a function of the energy price.

The model could, thus, be developed further by explicitly describing the link between efficiency and capital accumulation with respect to energy prices. An investment function for durables could also be added, where the relationship between the shadow price and ther user costs of capital would only represent one argument among others (e.g. income).

We proceed by applying the cost function of the AIDS model (Deaton, Muellbauer (1980)) for $C(u, p_i)$:

$$\log C(u, p_i) = (1-u)\log(a(p_i)) + u\log(b(p_i)) \tag{9}$$

with the translog price index for $a(p_i)$:

$\log a(p_i) = \alpha_0 + \sum_k \alpha_k \log p_k + 0.5\sum_k \sum_j \gamma_{kj}^* \log p_k \log p_j$, the Cobb-Douglas price index for $b(p_i)$: $\log b(p_i) = \log a(p_i) + \beta_0 \prod_k p_k^{\beta_k}$ and the level of utility, u. As the level of utility u is an argument of the expenditure function, an indirect utility function can be derived:

$$U = \left[\frac{\log C(u,p) - \log a(p_i)}{\beta_0 \prod_k p_k^{\beta_k}}\right] \tag{10}$$

Applying Shephard's Lemma to the cost function (9) and inserting the indirect utility function (10) gives the well known budget share equations for the i non-durable goods:

$$w_i = \alpha_i + \sum_j \gamma_{ij} \log p_j + \beta_i \log\left(\frac{C}{P}\right) \tag{11}$$

with price index P defined by $\log P = \alpha_0 + \sum_k \alpha_k \log p_k + 0.5\sum_k \sum_j \gamma_{kj}^* \log p_k \log p_j$, often approached by the Stone price index: $\log P^* = \sum_k w_k \log p_k$.

For non-energy commodities the budget share w_i is given as in the traditional model, for energy commodities by the term $\frac{p_S S}{C}$.

The following expressions for income and uncompensated price elasticities within AIDS can be derived (Green and Alston, 1992):

$$\varepsilon_i = \frac{\beta_i}{w_i} + 1 \tag{12}$$

$$\varepsilon_{ij}^U = \frac{\gamma_{ij} - \beta_i w_j}{w_i} - \delta_{ij} \tag{13}$$

Via the Slutsky equation the following general relationship holds between the compensated ε_{ij}^C and the uncompensated elasticity ε_{ij}^U : $\varepsilon_{ij}^C = \varepsilon_{ij}^U + \varepsilon_i w_j$. The compensated elasticity measures the pure price effect and assumes that the household is compensated for the income effect of a price change. Applying the Slutsky equation in the case of AIDS yields for the compensated elasticity:

$$\varepsilon_{ij}^C = \frac{\gamma_{ij} - \beta_i w_j}{w_i} - \delta_{ij} + \varepsilon_i w_j \tag{14}$$

In (13) and (14) δ_{ij} is the Kronecker delta with $\delta_{ij} = 0$ for i≠j and $\delta_{ij} = 1$ for i=j.

The demand for energy-commodity E_i is determined by the level of service demand S_i and energy efficiency for the appliance using the relevant energy carrier (η_i) as well as energy efficiency for the other appliances (η_j). Energy efficiency for a different appliance (η_j) has an impact on energy demand for good *i* due to cross price effects, which is a special feature of our model of total household consumption. We analyse the cross price effects on a pairwise base between the energy goods in our model.

By totally differentiating the quantity demanded E_i (S_i , η_j) with respect to t gives:

$$\frac{dE_i}{dt} = \frac{\partial E_i}{\partial \eta_j}\frac{d\eta_j}{dt} + \frac{\partial E_i}{\partial S_i}\frac{dS_i}{dt} \tag{15}$$

In (15) the total change in E_i is described as the sum of direct effects of efficiency changes and of indirect effects via service demand. This incorporates the rebound effect, as efficiency changes influence the service price and thereby service demand. Dividing both sides of (15) by E_i, rearranging and taking into account the price elasticity of demand for energy services (ε_{ij}) gives:

$$\frac{d \log E_i}{d \log \eta_j} = -(1 + \varepsilon_{ij}) \qquad (16)$$

This expression is identical with expressions of the total effect of efficiency on energy demand including the rebound effect derived by Berkhout, et.al. (2000) and Khazzoom (1980). The total impact is therefore also determined by the price elasticity ε_{ij} of energy demand or, more precisely, the (service) price elasticity of service demand. Actually in our model energy commodities enter as service (with corresponding service prices) and therefore we can directly derive service price elasticities.

It might be seen as an important advantage of a model for total household consumption that different feedbacks between different energy commodities can be analyzed. That gives a number of different rebound effects, i.e. effects of changes in the efficiency of a certain appliances on other energy demands. A change in the efficiency of an appliance implies an own price-rebound effect on *this* energy commodity, defined by the compensated own price elasticity ε_{ii}^{C}. Besides this pure price-induced effect there exists also an income-induced rebound effect, defined by the difference between the uncompensated and compensated price elasticity: $\varepsilon_{ii}^{U} - \varepsilon_{ii}^{C} = -w_i \varepsilon_i$.

The same holds true for the impact of the change in the efficiency of an appliance on the demand for another energy good. The pure price-induced effect is again given by the compensated cross price elasticity ε_{ij}^{C} and the income-induced effect by the difference of the elasticities $\varepsilon_{ij}^{U} - \varepsilon_{ij}^{C} = -w_j \varepsilon_i$.

3. Data sources

The commodity classification *i* in this model includes:

(i) services for private transport (via input of gasoline/diesel): *F*

(ii) services for heating (via input of solid fuels, oil, gas, district heating): *H*

(iii) services for electricity using appliances (via input of electricity): *H_E*

(iv)food and beverages, tobacco: *FO*

(v) clothing and footwear: *CL*

(vi) other (non-energy) commodities: *OTH*

The econometric model is applied to private consumption data of Austria (1990 – 2006). Data on private consumption in current prices and the corresponding price indices are directly taken from private household sector data in National Accounts of Austria (in COICOP classification).These data are then extended with information on conversion efficiency of household appliances. A special feature of this model is the derivation of a service price (marginal cost of service), which is defined by the relation of the energy price to conversion efficiency for a certain fuel. We treat this conversion efficiency as embodied in the stock of capital goods and appliances. This approach would, in a further step, allow us to directly link conversion efficiency to the path of capital accumulation resulting in a comprehensive description of embodied technological change, as mentioned above.

The data on conversion efficiency comprise efficiency indices of capital stocks for major energy-using appliances, differentiated by heating and electricity. For electrical appliances, i.e. only electricty using appliances, we use data for refrigerators, freezers, washing machines, dish washers, TVs and dryers. For heating, water heating and cooking we directly use aggregate efficiency indices for these purposes of energy use. The main data source on specific energy consumption of these capital stocks is the ODYSSEE database (http://www.odyssee-indicators.org) for the historical sample from 1990 to 2006. The ODYSSEE database is the result of a project on "energy efficiency indicators in Europe" comprising in total the EU 27 members plus Norway and Croatia. We use the variable ’specific consumption’ from the ODYSSEE database, which is defined as a hypothetical energy consumption given by the technological characteristics of the appliance and some base year unit consumption. In order to calculate an aggregate efficiency index for all electrical household appliances we derive a weighted average efficiency index according to the share of each appliance in total electricity consumption. In the area of energy for heating several primary energy carriers are affected – next to electricity this is mainly gas, oil, coal and district heating. In total, the efficiency index for household heating (the technical ODEX index) comprises elements of efficiency in the heating equipment as well as in the outer shell of the building, including data on specific energy consumption from single family houses and multi family flats. Here we use the stock of permanently occupied single family houses and multi family flats to calculate the heating efficiency index, by simply calculating the arithmetical average as these two types of dwellings are about identical in terms of their energy share in heating. Figure 1 shows the development of the specific consumption (the inverse of efficiency) of electrical appliances in Austria between 1990 and 2006. This development is rather heterogenous across appliances and the weighted average for electricity (aggregate) improves considerably. Figure 2 plots the specific consumption for heating, water heating and cooking, directly taken from the ODEX index data in ODYSSEE. Especially the indices for heating and cooking show a considerable improvement of efficiency of appliances between 1990 and 2006.

Data on efficiency of the private vehicle stock have been obtained from Statistics Austria.The database contains a differentiation of various engine power classes as to recognize different shares of power classes within the overall vehicle fleet as well as their differing levels in average fuel consumption. The link between the power class and the average fuel consumption of each power class are taken from a private car monitoring system, where drivers report their experience on fuel consumption (www.spritmonitor.de). This methodology is used for the period 1999 to 2006. For the period 1990 to 1998 the data on the private car stock disaggregated by engine power classes was not available from Statistics Austria. Here we had to use data on the private car stock disaggregated by the cubic capacity, which had to be linked to the power classes for the period 1999 to 2006. This link had then to be used to calculate a hypothetical disaggregation of the stock of private cars for 1990 to 1998. Again, applying the car monitoring system to this data set yielded the result for average fleet consumption from 1990 to 1998. Therefore, the data set on the efficiency of private cars is mainly based on calculations employing certain underlying assumptions and not primarily on observed data set. The most striking fact from these data is that the average car fleet fuel efficiency is not improving but is worsening over the period 1990 to 2006 due to the preference for cars with higher engine power and higher cubic capacity.

The direct consequence of these changes in efficiency for the top-down model is the difference in the development of energy and service prices as shown in Table 1. For heating and electricity the service price has increased much less than the energy price in the historical sample. For gasoline the increase is almost the same due to the lack of improvement in the car fleet fuel efficiency.

>>>Figure 1: Specific consumption of electrical appliances and electricity (weighted average)

>>> Figure 2: Specific consumption of heating, water heating and cooking

>>> Table 1: Energy and service prices for gasoline, heating and electricity, 1990 – 2006

4. Empirical results

The full model presented in the last section comprises the budget share equation system (11), where according to the homogeneity restriction in AIDS one equation can be dropped and the estimation results are robust with respect to the choice of equation that is dropped (in our case it was the aggregate of other non-energy commodities). We estimate the resulting AIDS system with Austrian data (1990 to 2006) applying the SUR (Seemingly Unrelated Regression) estimator and imposing the symmetry restrictions. Another general restriction in demand systems is that the underlying expenditure (cost function) must be concave and that own price elasticities must be negative for all values of budget shares in the sample. This turned out to be fulfilled for all parameter estimates except the one for food (γ_{FOFO}), where a small adjustment in the form of an additional restriction had to be introduced. We further introduced a linear time trend for those commodities (services) where this turned out significant.

The estimation results are shown in Table 2. Out of 20 parameters to be estimated, 15 parameters turned out to be significant. We find three insignificant cross price parameters (γ_{ij}) that concern food (*FO*) and clothing (*CL*) and two insignificant income parameters ($\beta_{i.}$). The explanatory power of the system is significantly lower for the energy commodities than for the non-energy commodities in private consumption. One major problem in the estimation of parameters is the huge difference in the value of the budget shares between different commodity groups. The budget shares of energy commodities are significantly smaller than those of non-energy commodities which may result in problems for the system estimation procedure. These problems could be avoided by using a nested model structure with higher aggregated commodity groups in the first step. However, this requires the application of separability assumptions between commodities groups, which are avoided here.

The estimated parameter values together with the data for the budget shares are, in a next step, used to calculate uncompensated as well as compensated price elasticities according to expression (13) and (14).

>>> Table 2: Parameter estimation results, 1990 – 2006

Table 3 shows the values for the calculated elasticities with the sample mean of the budget shares. All own price elasticities show the expected negative sign and are below unity except for clothing. According to expression (16) we can use the uncompensated price elasticity as a direct measure of the (price-induced) rebound effect of energy efficiency improvements. According to our result this would give a rebound effect for gasoline (automotive fuels) of 59%, for heating fuels of 31% and for electricity of about 20%. Comparing these results with other studies referred in the surveys of Greening, Greene (1997) and Greening, et.al. (2000) they can be characterized as lying at the upper bound of the range cited for rebound effects. For heating (including water heating) rebound effects found in the literature are between 10% and 30% (Greening, et.al., 2000). They are slightly higher for cooling and lower for private car transport. Therefore, the rebound effect for private car transport identified here for Austria (59%) is significantly above the results found in the literature.

As has been described in section 2 the uncompensated price elasticities also contain the income effect of price changes. The compensated price elasticities only comprise the substitution effect and are smaller (in absolute terms) than the uncompensated price elasticities, if the income elasticity of the respective commodity is positive. According to the elasticities presented in Table 3 this is the case for heating and electricity, but not for gasoline/diesel. The cross price elasticities between the energy commodities have a positive sign indicating a substitutive relationship with the exception of the cross price elasticities between gasoline and electricity. For cross price-rebound effects the substitutive relationship means that an increase in efficiency of one energy carrier leads to a decrease of the quantity demanded of the other energy carrier. This effect represents the contrary of the rebound effect and could be described as some 'inforcement effect' working through cross price effects. This effect is quantitatively important in the case of heating and electricity. In the case of gasoline and electricity we observe a cross price-rebound effect, so that an increase in the efficiency of either energy carrier would not only lead to a rebound of the quantity demanded of this energy carrier, but additionally also of the other.

The pure income rebound effects are determined by the difference between the uncompensated and the compensated elasticity, which is rather small (0.053 for heating and 0.02 for electricity) or even negative (- 0.016 for gasoline/diesel). These pure income effects are determined by the product of income elasticities and budget shares. The latter are very small for all three energy commodities so that the income rebound effects become quantitatively less important.

>>> *Table 3: Uncompensated and compensated price elasticities*

In section 3 we found that in the sample analysed here (1990 – 2006) considerable improvements in the efficiency of household appliances could be achieved with the exception of private car transport. As at the same time the energy demand of households has increased this has obviously been compensated by the increase of service demand. By reformulating the total differential in (15) we can describe the total change in energy demand (growth rate) as the difference between the growth rate of service demand and of efficiency:

$$\frac{dE_i}{E} = -\frac{d\eta_j}{\eta_i} + \frac{dS_i}{S_i} \tag{17}$$

Part of the growth rate in service demand (dS/S) is induced by price and income rebound effects which can be directly derived from the elasticities ($(dS/S)/(dp_S/p_S)$). Carrying out this decomposition analysis shows that service demand for heating and electricity grew about 40% in the period 1990 to 2006, which is an annual growth rate of more than 2 % per year. Service demand for car transport was increasing much more slowly by only 7.9% over the whole period. In the case of heating and electricity efficiency improvements have significantly reduced the actual energy demand of households compared to service demand, namely by 27% for heating and by more than 15% for electricity. In the case of private car transport no overall efficiency improvement could be realised, as the average fuel efficiency of the car fleet even slightly decreased.

The model set up in this paper can, in a further step, be used for quantifying the part of increase in service demand that is directly due to rebound effects that are induced by efficiency improvements.

These calculations show a significant amount of rebound effects partly explaining the growth in service demand in the case of heating: 8.5% of the total service demand growth of 39.4% can be explained by rebound effects. For electricity this part is much smaller and only amounts to 3% out of a total of 42.4%. In both cases a large part of growth in service demand between 1990 and 2006 is due to other influences than rebound effects, i.e. price and income effects in general. Due to the decrease in efficiency for private car transport the rebound effects are even negative for this energy carrier.

>>> Table 4: Decomposition of energy consumption growth, 1990 - 2006

5. Conclusions

In this paper a consistent link between bottom-up and top-down modelling of households' energy demand has been presented. The main element of bottom-up modelling is represented by the technical efficiency of household appliances. In the top down-model the main feedback of efficiency on energy demand is the rebound effect. An important feature of our model is the description of total private consumption via a demand system, so that important repercussions and feedbacks between different energy and non-energy commodities can be taken into account. That comprises different types of price and income-rebound effects directly derived from price and income elasticities.

An *ex post* decomposition analysis for Austria (1990 – 2006) shows that rebound effects induced by efficiency improvements only explain a small part of service demand growth. Apparently service demand has been mainly driven by the general development in prices and income and not by the service price-induced rebound effect. In general, the significant improvements in the efficiency of household appliances did not suffice to compensate for service demand growth. For private car transport we observe a contrary development, as the average fuel efficiency of the Austrian car fleet has been slightly rising and the service demand has been increasing much less than the service demand for heating and electricity.[1]

According to the results obtained, it is questionable, if policies aiming at the reduction of energy demand of households can only be based on efficiency improvements. In order to stabilize growth in energy demand the efficiency improvements should have been almost twice in the period 1990 to 2006. It must, however, be noted that 'business as usual' improvements in efficiency have already been significant in the time period considered. It is therefore not clear, whether a substantial additional enhancement of technological improvements via policy measures would have been feasible. Finally it must be taken into account that any efficiency improvement will be counteracted by rebound effects in the order of magnitute of 10 to 30%. But the crucial issue regarding the growth in energy consumption are the drivers of service demand, namely income growth and stable to lower energy prices. Therefore policy measures must address factors of consumer behaviour as well as prices of energy and carbon.

---

[1] This development can be partly attributed to the data base used here and the underlying assumptions.

References

Berkhout, P.H., Muskens, J.C. and Velthuisjen, J.W., 2000, Defining the rebound effect, *Energy Policy*, 28, 425 – 432.

Brännlund, R., Ghalwash, T., and Nordström, J., 2007, Increased Energy Intensity and the Rebound Effect: Effects on Consumption and Emissions, *Energy Economics*, 29(1), pp. 1-17.

Conrad, K., and Schröder, M., 1991, Demand for durable and nondurable goods, environmental policy and consumer welfare, *Journal of Applied Econometrics*, 6.

Deaton, A, and Muellbauer, J., 1980, An almost Ideal Demand System.

Green , R. D. and Alston, J. M., Elasticities in AIDS Models. *American Journal of Agricultural Economics*, 72, 1990, 442 – 445.

Greening, L.A., Greene, D.L., 1997. Energy use, technical efficiency, and the rebound effect: a review of the literature. Report to the Office if Policy Analysis and International Affairs, US Department of Energy, Washington, DC, December.

Greening, Lorna A., Greene, David L., Difiglio, Carmen, 2000. Energy efficiency and consumption – the rebound effect – a survey. Energy Policy 28, 389-401.

Holtedahl, P., and Joutz, F. L., 2004, Residential Electricity Demand in Taiwan, *Energy Economics*, 26(2), pp. 201-224.

Hondroyiannis, G., 2004, Estimating Residential Demand for Electricity in Greece, *Energy Economics*, 26(3), pp. 319-334.

Khazzoom, J. D., 1980, Economic Implications of Mandated Efficiency in Standards for Household Appliances, *The Energy Journal*, 1, pp. 21-40.

Khazzoom, J. D., 1989, Energy Savings from More Efficient Appliances: A Rejoinder, *The Energy Journal*, 10, pp. 157-166.

Labandeira, X., Labeaga, J. M., and Rodriguez, M., 2006, A Residential Energy Demand System for Spain, *The Energy Journal*, 27 (2), pp. 87-111.

Larsen, B. M., Nesbakken, R., Household Electricity End-Use Consumption: Results from Econometric and Engineering Models, *Energy Economics*, 2004, 26(2), pp. 179-200.

Meyer, I., Leimbach, M., and Jaeger, C. C., 2006, "International Passenger Transport and Climate Change: A Sector Analysis in Car Demand and Associated CO_2 Emissions from 2000 to 2050, *Energy Policy*, 35 (12), pp. 6332-6345.

Newell, R.G., Jaffe, a.B. and R.N. Stavins, 1999, The Induced Innovation Hypothesis and Energy-Saving Technological Change, Quarterly Journal of Economics, 941-975.

Rivers, N., and Jaccard, M., 2005, Combining Top-Down and Bottom-Up Approaches to Energy-Economy Modeling Using Discrete Choice Models, *The Energy Journal*, 26(1), pp. 83-106.

Sue Wing, I., 2006, Representing Induced Technological Change in Models for Climate Policy Analysis, *Energy Economics*, 28, pp. 539-562.

Willet, K. D, and Naghshpour, S., 1987, Residential demand for energy commodities: A Household Production Function Approach, *Energy Economics*, 9(4), pp. 251-56.

Figure 1: Specific consumption of electrical appliances and electricity (weighted average)

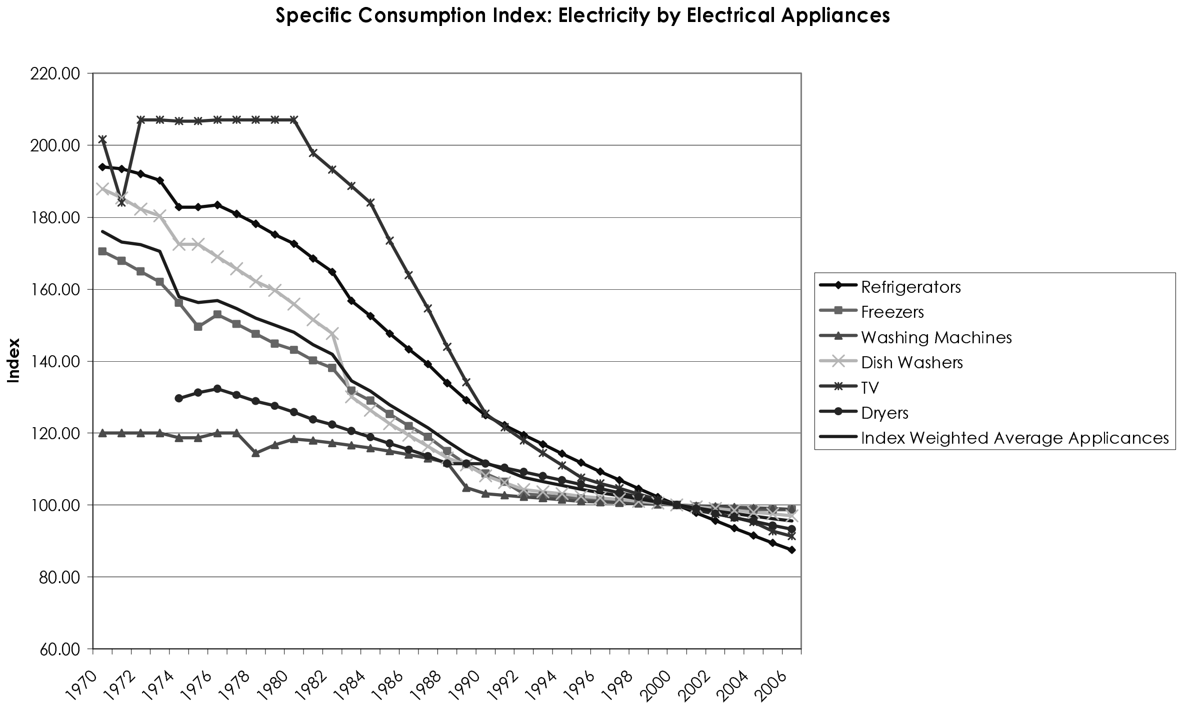

Figure 2: Specific consumption of heating, water heating and cooking

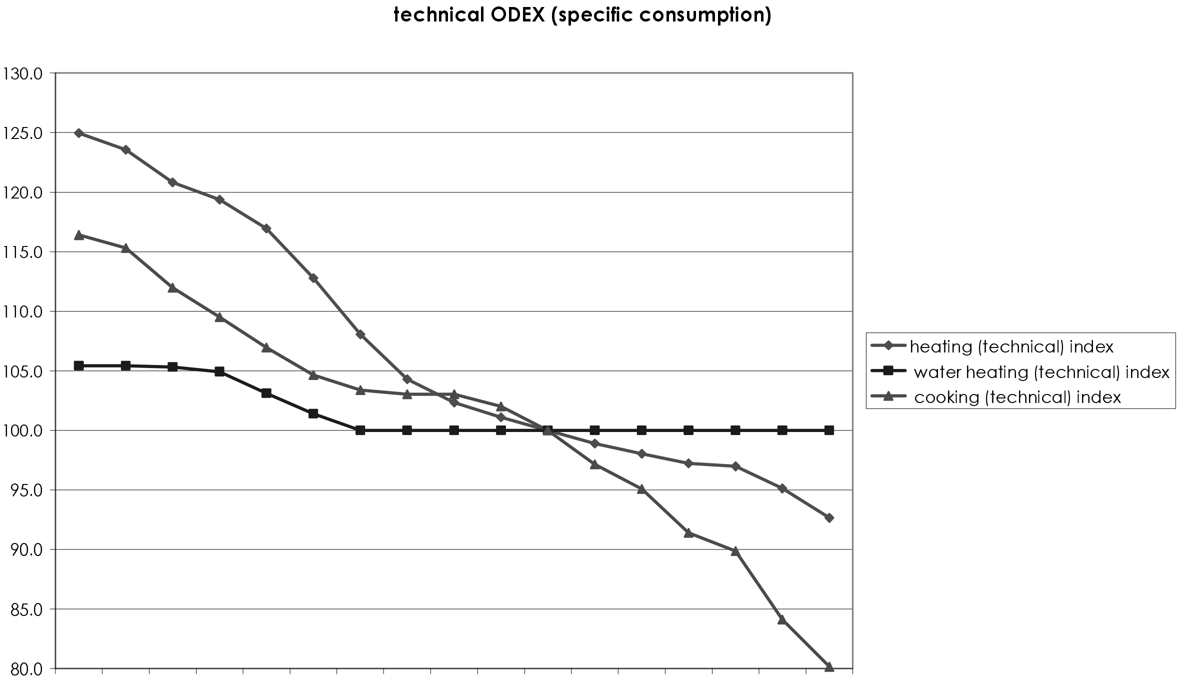

Table 1: Energy and service prices for gasoline, heating and electricity, 1990 – 2006

	Gasoline energy price	Gasoline service price	Heating energy price	Heating service price	Electricity energy price	Electricity service price
1990	70.84	68.99	82.51	101.17	84.58	94.49
1991	69.40	67.86	84.96	103.37	85.49	93.87
1992	73.96	72.59	84.59	100.67	87.04	93.70
1993	72.52	71.42	84.22	99.17	88.58	94.36
1994	74.84	73.96	84.23	97.08	89.58	94.45
1995	80.04	79.36	83.77	93.46	90.95	94.91
1996	86.29	85.83	88.22	94.62	95.95	99.27
1997	88.53	88.33	91.96	95.49	98.54	101.07
1998	83.84	83.87	88.43	90.27	98.54	100.20
1999	85.18	85.41	89.32	90.19	97.75	98.56
2000	100.00	100.00	100.00	100.00	100.00	100.00
2001	96.20	96.05	104.70	103.66	102.10	101.28
2002	93.60	93.21	103.15	101.35	99.04	97.40
2003	93.88	93.32	104.55	101.94	100.03	97.61
2004	101.96	101.19	111.66	108.63	102.73	99.52
2005	113.99	113.17	123.48	118.04	105.81	101.77
2006	122.36	121.68	132.03	123.34	109.46	104.60

Table 2: Parameter estimation results, 1990 – 2006

	Parameters	standard errors	
γ_{FOFO}	0.095	0.000	***
γ_{FOCL}	-0.008	0.017	
γ_{FOF}	0.012	0.010	
γ_{FOH}	0.012	0.006	**
γ_{FOH_E}	-0.045	0.012	***
γ_{CLCL}	-0.040	0.022	**
γ_{CLF}	-0.023	0.007	***
γ_{CLH}	0.019	0.005	***
γ_{CLH_E}	0.003	0.009	
γ_{FF}	0.009	0.005	*
γ_{FH}	0.007	0.003	**
γ_{FH_E}	-0.010	0.005	**
γ_{HH}	0.013	0.003	***
γ_{HH_E}	0.010	0.003	***
$\gamma_{H\_EH\_E}$	0.012	0.007	*
β_{FO}	-0.112	0.026	***
β_{CL}	-0.030	0.029	
β_{F}	-0.040	0.029	*
β_{H}	0.035	0.009	***
β_{H_E}	0.005	0.016	

equation	R^2
FO	0.954
CL	0.993
F	0.779
H	0.530
H_E	0.506

*, ** and *** indicate a significance level of 10%, 5% and 1% respectively. FO=food, CL= clothing, F=gasoline/diesel, H=heating (solid fuels, oil, gas, district heating), H_E=electricity.

Table 3: Uncompensated and compensated price elasticities

Uncompensated price elasticities					
	Food	Clothing	Gasoline	Heating	Electricity
Food	**-0.1054**	-0.0084	0.1239	0.1123	-0.3589
Clothing	-0.0701	**-1.6232**	-0.3656	0.3152	0.0608
Gasoline	0.7289	-0.8716	**-0.5880**	0.3266	-0.4019
Heating	0.4062	0.9174	0.3424	**-0.3133**	0.5524
Electricity	0.7586	0.2033	-0.7059	0.7166	**-0.1952**
Compensated price elasticities					
	Food	Clothing	Gasoline	Heating	Electricity
Food	**-0.0958**	-0.0038	0.1257	0.1137	-0.3578
Clothing	-0.0088	**-1.5916**	-0.3536	0.3243	0.0681
Gasoline	0.6465	-0.9134	**-0.6038**	0.3144	-0.4117
Heating	0.7679	1.1008	0.4127	**-0.2599**	0.5953
Electricity	0.9265	0.2884	-0.6732	0.7415	**-0.1753**

Table 4: Decomposition of energy consumption growth, 1990 - 2006

overall growth in %	Gasoline	Heating	Electricity
energy demand	9.97	12.16	26.81
efficiency	-2.09	27.19	15.62
service demand	7.88	39.36	42.43
of which			
price rebound	-1.26	7.07	2.74
income rebound	0.03	1.45	0.31
other effects	9.11	30.84	39.38