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ENERGY-SAVING TECHNOLOGICAL CHANGE AND HOUSEHOLD ENERGY DEMAND IN THE U.S.

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Abstract:

This paper deals with energy saving technical change in U.S. households' energy demand. The framework applied represents a model of demand for non-durables taking into account the durable stock and 'services' (heating/lighting and transport) that result from energy use. Embodied technical change is implemented by the average energy efficiency of the stock of energy using durables, which has been taken from a new data set compiled for this study. The efficiency has a double link with prices. On the one hand higher energy prices result in higher efficiency of installed equipment (price induced technical change). On the other hand increases in efficiency lower the corresponding service price and lead to the well known 'rebound effect'. The model makes these complex links explicit and comprises all energy relevant household consumption (transport, heating and electricity). Simulation exercises show the role of energy prices and investment in efficient appliances for policies aiming at energy saving in U.S. households.

JEL Code: D12, Q55, Q41

Key words: household energy demand, embodied and induced technical change, rebound effect

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1. Introduction

Emissions of greenhouse gases from transport and private households are growing rapidly and are the objective of EU as well as U.S. climate policy. Whereas large stationary sources in industry and power generation can be covered by emission trading systems (ETS), like the EU-ETS, the many diverse and partly mobile emission sources in households call for different policy instruments. The U.S. climate policy initiatives mainly comprise cap-and-trade bills for certain sectors with overall emission targets. These cap-and-trade propsals are often combined with regulatory climate policies like mandatory energy efficiency standards and vehicle emission standards, like the Sanders-Boxer and the Kerry-Snowe bill (Moslener and Sturm, 2008). For the EU climate policy the adequate policy mix for the non-ETS sector of the economy is also a still intensively debated issue. An economic evaluation of the adequate policy-mix for the non-ETS sector (mainly transport and households) therefore requires a model explicitly covering the influence and effectiveness of price changes, mandatory energy efficiency standards and fostering of technical change towards higher energy efficiency.

The existing research on households' energy demand is mainly focused on partial demand analysis for electricity (e.g.: Larsen, Nesbakken (2004), Holtedahl, Joutz (2004), Hondroyiannis (2004)) and passenger cars (Meyer, et al. (2007)). Some recent studies cover the whole residential energy demand (Labandeira, Labeaga, Rodriguez (2006)) and only a few the whole energy relevant consumers demand, including residential and passenger transport (e.g.: Brännlund, et al. (2007)). However, the role of capital or appliances is not incorporated in most of these kinds of models. In the past several attempts have been made 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, Schröder (1991)). This is often labelled as a synthesis between economic and engineering models (Larsen, Nesbakken (2004)) or as a combination of bottom-up and top-down modelling (Rivers, Jaccard (2005)). A further step in modelling technological change is given by the concept of 'induced technological change' (Sue Wing (2006)). The concept of inducement of technological change comprises different forms like 'price-induced' and induced in the form of embodiment in the stock of knowledge represented by the cumulated R&D expenditures. The impact of regulation inducing energy saving technical change for selected household appliances has first been analysed in Newell, Jaffe and Stavins (1999).

In models of private consumption where technological change is embodied in the physical capital stock (e.g. Conrad, Schröder (1991)), the input of capital leads to decreases in energy expenditures. That allows deriving an estimation of the 'shadow price' of capital. This in turn determines the optimal stock and consequently investment demand depends on prices. As technological change is linked to investment it therefore becomes price induced. A purely theoretical application of this approach can be found in Willet, Naghshpour (1987), who apply a household production function. Another extension to deal with the impact of capital stocks on energy demand is the introduction of the concept of 'services' into the consumers' model. In such a model technology (i.e. technical efficiency of capital stocks) transforms energy into these 'services'. This efficiency which changes by new investments (Khazzoom (1980), (1989)) can be used as an explicit variable. An important aspect in these approaches is a feedback-loop from technological change (= changes in the efficiency of the stock) to the price of 'services' and the resulting 'rebound effect' in service demand. Many empirical studies have focussed on this rebound effect, especially for private car transport (e.g.: Greene, et.al., (1999)).

The present study attempts a synthesis and extension of these different approaches in one comprehensive econometric model of U.S. household demand including non-energy commodities. An important aspect is the integration of all categories of household energy demand (heating, electricity, transport) into one model which allows for a broader range of substitution possibilities. In addition, the approach also integrates energy saving technological change by using a new data set for the energy efficiency of the capital stock (e.g.: average fleet consumption of private cars, average consumption of electrical appliances). Therefore, energy saving technological change is not treated as exogenous or captured with any proxy variable (like the capital stock), but is explicitly dealt with as a variable. It depends on the pace of capital accumulation and on energy prices. The model is then used to quantify the impact of embodied and price induced technical change compared to the short term influence of energy prices on the energy use of households.

2. Consumers' demand with embodied and induced technical change

The structure of the model distinguishes between aggregate household consumption, capital expenditure of households, and expenditure for heating and transport energy as well as for other goods and services. In principle the consumers' decisions can be described by utility maximization under constraints or by cost/expenditure minimization for a given level of utility (the dual model). 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.

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 (3) and the envelope condition for the capital stock (4):

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

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

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 in this simple case just states that the shadow price of fixed assets must equal the user costs of capital, i.e. the marginal benefit of an 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. In the present model investment is not included in the expenditure function and no dynamic optimization model is set up to derive the explicit form of the investment function. Instead we use the shadow price – relationship for modelling the link between energy efficiency and the capital stock.

Energy commodities are used by consumers for the 'production' of services (heating, lighting, communication, transport). 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 level of service:

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

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 that allows to derive a service price p_S (marginal cost of service), which is influenced by the energy price and the conversion efficiency:

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

This is similar to Khazzooms (1980, 1989) approach of dealing with services and shows the same 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': $\frac{p_E E}{C} \equiv \frac{p_S S}{C}$.

The shadow price-relationship in (4) describes the impact of the capital stock on expenditure. We decompose that in order to arrive at the effect of efficiency on expenditure by 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 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 becomes embodied in appliances (i.e. the surface of efficiency of appliances as defined in Newell, Jaffe and Stavins, 1999) 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. This would be in line with approaches that link embodied efficiency with energy prices (Newell, Jaffe and Stavins, 1999) and describe price induced technological change. This approach starts from the observation of a distribution of energy efficiency across the 'capital goods menu' and assumes that the consumer chooses more efficient appliances at higher levels of energy prices (besides other factors of influence, like regulation). One general approach of modelling this link for the term ($\frac{\partial \log \eta_{ES}}{\partial \log K}$) starting from a time series point of view is an autoregressive distributed lag (ADL) model. This model allows us calculating long run elasticities of efficiency (η_{ES}) with respect to the main influencing variables. We model both aspects captured in $\frac{\partial \log \eta_{ES}}{\partial \log K}$ in a function with the capital stock and the energy prices as explanatory variables. The capital stock describes the autonomous technical progress embodied in appliances and the energy prices the consumers' choice among the menu of capital goods. The ADL model therefore has the following structure:

$$\log \eta_{ES} = \kappa_0 + \sum_{\tau=1}^{l} \psi_\tau \log \eta_{ES,t-\tau} + \sum_{\tau=0}^{n} \theta_\tau \log K_{E,t-\tau} + \sum_{\tau=1}^{m} \varphi_\tau \log p_{E,t-\tau} \qquad (9)$$

The long run elasticities of efficiency (η_{ES}) with respect to the capital stock (K) and the energy prices (p_E) are given by:

$$\frac{\sum \theta_\tau}{1-\sum \psi_\tau} \text{ and } \frac{\sum \varphi_\tau}{1-\sum \psi_\tau} \qquad (10)$$

2.1 Consumers' demand for non-durables

To model non-durables we use the quadratic AIDS model (QUAIDS) as proposed by Banks, Blundell and Lewbel (1991). There are several advantages of the QUAIDS approach over the AIDS model. The Engel curves implied by AIDS are monotonic in total expenditure, which is often empirically violated, because AIDS is a demand sytem of rank 2.[1] Empirical studies with U.S. data strongly indicate that an adequate demand sytem should imply rank 3 (Lewbel, 1991). The QUAIDS model represents a parsimonious demand system of rank 3 (Banks, Blundell and Lewbel, 1997). It includes quadratic terms for expenditure where the coefficient for this term varies with prices and therefore is not constant, which directly follows from utility maximization. The quadratic term for expenditure allows that goods can be luxuries or necessities at different expenditure levels. In empirical studies using cross sectional data for countries with large differences in income levels (Cranfield, et. al., 2003) it could be shown that QUAIDS is best suited.

One way to arrive at the budget shares is applying Roy's identity to the indirect utility function (see Banks, Blundell and Lewbel, 1997 for details). Our starting point is the cost function. The QUAIDS indirect utility function can be stated as:

$$\log U = \left[\frac{\log X}{b(p) + \lambda(p) \log X} \right] \tag{11}$$

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[1] According to Lewbel (1990,1991) the rank of a demand system is the dimension of the space defined by it's Engel curves and has a maximum of 3 for an exactly aggregable demand system. He has further pointed out, that the rank of a demand system has implications for separability, for functional form and for aggregation across goods and agents.

with $\log X = \log C(u,p) - \log a(p)$, the translog price index for *a*(*p*): $\log a(p) = \alpha_0 + \sum_k \alpha_k \log p_k + 0.5 \sum_k \sum_j \gamma_{ij} \log p_k \log p_j$, the Cobb-Douglas price index for *b*(*p*): $b(p) = \prod_k p_k^{\beta k}$ and expenditure *C*(*u*,**p**) depending on the level of utility, *u* and the price vector, **p**. The additional term λ(**p**) is given by: $\lambda(p) = \sum_{i=1}^{n} \lambda_i \log p_i$.

Resolving for log *X*, ($\log X = \frac{b(p)\log U}{1-\lambda(p)\log U}$) we can derive the cost function of the QUAIDS model:

$$\log C = \log a(p) + \log X \tag{12}$$

Applying Shephard's Lemma to that ($w_i = \frac{\partial \log C}{\partial \log p_i} = \frac{\partial \log a(p)}{\partial \log p_i} + \frac{\partial \log X}{\partial \log p_i}$) yields the budget shares:

$$w_i = \alpha_i + \sum_j \gamma_{ij} \log p_j + \beta_i \log\left(\frac{C}{a(p)}\right) + \frac{\lambda_i}{b(p)}\left[\log\left(\frac{C}{a(p)}\right)\right]^2 \tag{13}$$

Our result using the cost function and Shephard's Lemma is identical to the result of Banks, Blundell and Lewbel (1991) using the indirect utility function and Roy's identity. The budget share equations satisfy the standard properties of demand functions given by three sets of restrictions, namely adding-up, homogeneity in prices and total expenditure and symmetry of the Slutsky equation. $\sum_{i=1}^{n} \alpha_i = 1$; $\sum_{i=1}^{n} \gamma_{ij} = 0$; $\sum_{i=1}^{n} \beta_i = 0$; $\sum_{j=1}^{n} \gamma_{ij} = 0$; $\gamma_{ij} = \gamma_{ji}$ and $\sum_i \lambda_i = 0$. For non-energy commodities the budget share w_i is given as in the traditional model, for energy commodities by the term $\frac{p_S S}{C}$.

In order to derive income and price elasticities in a first step the budget share equations can be differentiated with respect to log(C) and log(p_i):

$$\mu_i = \frac{\partial w_i}{\partial \log C} = \beta_i + \frac{2\lambda_i}{b(p)}\left[\log\left(\frac{C}{a(p)}\right)\right] \tag{14}$$

$$\mu_{ij} = \frac{\partial w_i}{\partial \log p_j} = \gamma_{ij} - \mu_i\left(\alpha_j + \sum_k \gamma_{jk} \log p_k\right) - \frac{\lambda_i \beta_j}{b(p)}\left[\log\left(\frac{C}{a(p)}\right)\right]^2 \tag{15}$$

The elasticities are then in a second step derived from these expressions. First taking into account that $\log w_i = \log x_i + \log p_i - \log C$ and differentiating that with respect to log C and log p_j and applying the chain rule gives the following expressions for income (ε_i) and uncompensated price elasticities (ε_{ij}^U):

$$\varepsilon_i = \frac{\mu_i}{w_i} + 1 \tag{16}$$

$$\varepsilon_{ij}^U = \frac{\mu_{ij}}{w_i} - \delta_{ij} \tag{17}$$

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 QUAIDS yields for the compensated elasticity:

$$\varepsilon_{ij}^{C} = \frac{\mu_{ij}}{w_i} - \delta_{ij} + \varepsilon_i w_j \tag{18}$$

In (17) and (18) δ_{ij} is the Kronecker delta with $\delta_{ij} = 0$ for $i \neq j$ and $\delta_{ij} = 1$ for $i = j$.

2.2 Energy efficiency, energy demand and rebound effects

The demand for energy-commodity E_i is determined by the level of service demand S_i and energy efficiency for the appliance using this 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 the cross price effect, 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.

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

$$\frac{dE_i}{dt} = \frac{\partial E_i}{\partial \eta_j}\frac{d\eta_j}{dt} + \frac{\partial E_i}{\partial S}\frac{dS}{dt} \tag{19}$$

In (19) the total change in E_i is described as the sum of direct effects of efficiency changes and of indirect effects via service demand. The direct effects of an efficiency increase on energy demand (the first term in (19)) is equal to -1. But an increase in efficiency also leads to a decrease in the service price and thereby to an increase in service demand. Dividing both sides of (19) by E_i rearranging and taking into account the compensated or uncompensated price elasticity of demand for energy services (ε_{ij}) gives:

$$\frac{d \log E_i}{d \log \eta_j} = -\left(1 + \varepsilon_{ij}\right) \tag{20}$$

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 own price elasticity ε_{ii} of energy demand or, more precisely, the (service) price elasticity of service demand. Actually in our model energy commodities enter as services (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 appliance on all the 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: $\varepsilon_{ii}^{U} - \varepsilon_{ii}^{C} = -w_i \varepsilon$.

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 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 sources for the consumers' demand data are time series of expenditure for durables (vehicles, kitchen and other appliances, video and audio goods/computer goods), for non-durable energy (gasoline, fuel oil and coal, electricity, gas), and for non-durable, non-energy (food, clothing, housing, other), all from U.S. National Accounts as published by the Bureau of Economic Analysis (BEA).

Data on the efficiency of stocks have been obtained from many different sources. For vehicles a large number of empirical studies is available for the U.S. (s.: Greene, 1999) where databases are included or cited, which have been used in an updated version. These data have been published by the U.S. Department of Transportation, Federal Highway Administration and contain time series of vehicle stock, vehicle miles traveled and fuel consumed by passenger cars and motorcycles. These variables have been used to calculate the average fuel consumption of the vehicle fleet by applying the identity: fuel consumed = average fleet consumption * vehicle miles traveled. There is a small consistency problem between the consumption data for gasoline/diesel from BEA in millions of $ and the fuel consumption of vehicles in gallons yielding an implicit price per gallon that shows a slightly different evolution than the price index for gasoline/diesel from BEA accounts. Anyway the difference was considered to be small enough to make no adjustment process in the data necessary.

Therefore the calculated average fleet consumption of vehicles from transport statistics could be directly combined with the consumption data from BEA accounts.

For household appliances we have mainly drawn on studies and databases from Lawrence Berkely National Laboratory, specifically the datasets on energy efficiency in the Environmental Energy Technology Division (EETD). These data partly stem from the 2005 factbook of the Association of Household Appliance Manufacturers (AHAM). Those datasets contain numbers of shipment of different appliances covering electricity use, heating, and water heating as well as the 'shipment weighted efficiency factor' for new appliances. This efficiency factor measures the specific consumption of an appliance per unit of service (e.g.: per course of washing, per square meter of cooling/heating, etc.). Combining different publications from Lawrence Berkely National Laboratory and AHAM it was possible to achieve data back to 1972 with some minor gaps which have been filled applying interpolation techniques. In a second step the efficiency factors for new equipment had to be converted into efficiency factors for the existing stock. This is only possible by calculating some starting value of efficiency of the stock and using the capital accumuluation equation:

$K_t = (1 - \delta)K_{t-1} + I_t$ with K as capital stock, I as (gross) investment and δ as the depreciation rate. Data for these variables have been taken from BEA-National Accounts. The gross investment is given by expenditure for durables and the capital stock from capital accounts for households. Setting up the capital accumuluation equation as described above allows us to derive the depreciation rate as the residual. This procedure yields all neceassry building blocks for calculating the time path of efficiency of the existing stock once a starting value for 1972 is given. The starting value has been arrived at by extrapolating the change in efficiency of new equipmemt before 1972 until the year of investment in household appliances that has been fully depreciated in 1972. This was done at the level of appliance using the different implicit depreciation rates from BEA capital accounts for different appliances. The starting value for the efficiency of the existing stock in year t=0 following from this procedure enables us to set up the full data set of efficiency of the existing stock for the sample 1972 – 2005.

This procedure has been applied to all energy using household appliances using solid fuels, oil products, gas and electricity. The electricity using appliances comprise air conditioning, electric water heating, refrigerators, freezers, cloth washers and dish washers. Data on unit consumption have also been collected for cooking and lighting appliances and for audio/video and TV sets, but no efficiency factors have been found for these equipments. The gas using appliances include gas heating and gas water heating, the oil (and solid fuels) using appliances are represented by oil heating. Table 1 shows the result of data compilation in terms of efficiency indices by (selected) household appliances. Efficiency has increased much more slowly for heating equipment than for electricity using appliances and also slightly more slowly for air conditioning equipment.

>>> *Table 1: Energy efficiency of the stock of selected household appliances, quantity index (2000 = 100)*

The last step of the data compilation process consists of transforming the data of efficiency by appliance (stock) into data of efficiency by fuel. This is carried out by applying the data on unit (actual) consumption of appliances, which shows the distribution of the consumption of an energy commodity across appliances. These data are available from Lawrence Berkely National Laboratory for some base years. The final result of this data compilation process is shown in Figure 1. As for some electrical appliances (cooking and lighting, audio/video, TV sets) no efficiency factors could be found, these appliances do not enter the unit consumption-weighted average efficiency of electricity. That leads to the result that only 65% of electricity consumption is affected by efficiency improvements and the progress in efficiency for the aggregate 'electricity' is considerably smaller than for the electricity using appliances shown in Table 1. Energy efficiency is growing most rapidly for gasoline due to the improvements in the average fleet consumption. As can be expected from the data in Table 1, the efficiency is increasing more for electricity than for gas and for oil (products), which show the slowest progress in efficiency. In general an enhancement of the efficiency improvement trend can be oberved during the 1980es and a leveling off thereafter. This stylized fact is in line with our specification of ADL equations for efficiency (9) driven by embodied and price induced technical change.

>>>>>*Figure 1: Efficiency index (2000 = 100) for fuels*

For our model the main consequence of this energy saving technological progress lies in the impact on service prices as shown in Figure 2 to 5. Considerable progress in energy efficiency for all fuels between 1972 and 2005 has led to a much slower growth in service prices than in energy prices. The difference between service price and energy price development by fuel just resembles the different efficiency improvement by fuels, being highest for gasoline and lowest for fuel oil (and coal). The impact that efficiency improvement lowers the effective price level for energy from the energy market price to the service price induces rebound effects of enery efficiency improvement, depending on the price elasticity of (service) demand.

>>>> *Figure 2: Energy and service prices for gasoline, 1972 – 2005*
>>>>> *Figure 3: Energy and service prices for fuel oil, 1972 – 2005*
>>>>> *Figure 4: Energy and service prices for gas, 1972 – 2005*
>>>>> *Figure 5: Energy and service prices for electricity, 1972 – 2005*

The non-durable goods (services in the case of energy) included in our model comprise: food/beverages/tobacco, clothing/shoes, gasoline, fuel oil/coal, electricity, gas and other goods. The durable goods in our model comprise: motor vehicles, household appliances, video/audio goods and other durables.

4. Estimation results

A system of budget share equations of the QUAIDS approach as laid down in (13) has been estimated for the non-durable goods. We use the SUR estimator and include also a linear and a quadratic trend in the budget shares. The usual restriction of symmetry and homogeneity are imposed. Following the results of Banks, Blundell and Lewbel, 1997 we restricted the parameter λ in the QUAIDS Model with $\lambda = 0$ for food and automotive fuels.

>>>> Table 2: Parameter estimation results, QUAIDS-Model for non-durables, 1972 – 2005

>>>>> Table 3: Uncompensated and compensated price elasticities, QUAIDS-Model for non-durables

The estimation procedure yields the parameter estimates shown in Table 2. 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 (17) and (18). 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.

According to expression (20) 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 13%, for heating fuels of 19% and for electricity of about 18%. 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 within the range found in the literature. 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.

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 only the case for electricity, but not for gasoline/diesel and heating. The cross price elasticities show a positive sign - indicating a substitutive relationship – between heating and the other two energy commodities (gasoline/diesel and electricity). This 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 'reinforcement effect' working through cross price effects. For gasoline/diesel and electricity the cross price elasticities are negative indicating a complementary relationship. This complementary relationship leads to a cross price-rebound effect, so that an increase in the efficiency of electrical appliances would not only lead to a rebound of electricity demand, but additionally also of gasoline/diesel demand and *vice versa*.

The pure income rebound effects are determined by the difference between the uncompensated and the compensated elasticity, which is positive for gasoline/diesel and heating (0.024 for heating and 0.026 for gasoline/diesel) and significantly negative (- 0.094) for electricity. That means that due to negative income elasticities for gasoline/diesel and heating no (price induced) income rebound effect can be observed. This income rebound effect is on the other hand rather large for electricity.

Using equation (10) we derive the long run elasticities of efficiency (η_{ES}) with respect to the capital stock (K) and the energy prices (p_E). These are shown in Table 4 and turn out to be rather small with respect to energy prices (about 0.046 to 0.069). These elasticities of efficiency with respect to the capital stock are considerably larger ranging from 0.081 to 0.427. This is due to the fact that the capital stock-elasticities capture embodied technical change and the energy price-elasticities only measure the consumers' choice among the menu of capital goods for a given capital stock. Therefore equation (9) is no full account of the impact of energy price changes on efficiency, as energy price changes would also lead to an adjustment in the capital stock. This would in turn have an additional feedback effect on embodied efficiency.

>>>>>*Table 4: Long run elasticities of efficiency, 1972 – 2005*

5. The role of efficiency for energy demand

In order to measure the impact of energy saving technological change we carry out two simulation exercises. The first exercise assumes a long run price increase of 10% and the second one a 10% increase in the (real) value of the appliance stock.

Technical efficiency is a function of the appliance stock and of energy prices and therefore endogenous. The dependence on energy prices represents 'price-induced' technical change (Sue Wing, 2006). The dependence on the appliance stock measures the positive relationship between the efficiency (higher quality) and the (real) costs of capital, which is well documented for selected household appliances in Newell, Jaffe, Stavins (1999). For both simulations we use the model consisting of the ADL equations (9) for efficiency and the QUAIDS demand model (13).

The first exercise consists of a 10% percent increase in the prices of the three energy commodities (gasoline/diesel, heating and electricity) compared to the actual development during the period 1975 to 2005.[2] In this setting the *ceteris paribus* assumption used for elasticities does not hold anymore and we take into account all indirect effects induced by price changes. These include cross price effects, income effects and the feedback mechanism via changes in efficiency of the appliance stock. All these effects in turn contribute to all different kinds of rebound effects described above. The simulation results can be used to derive 'implicit elasticities' of energy demand to price changes by simply calculating the relationship between both. As Table 5 shows, these long run 'implicit' price elasticities derived from the results are significantly larger (in absolute terms) than the partial short term elasticities. For gasoline/diesel the short run price elasticity of – 0.13 rises to a long run implicit price elasticity of – 0.56, for heating the respective values of elasticities are -0.19 and -0.47 and for electricity -0.08 and – 0.15 respectively. These findings are consistent with the well established empirical result that long-run reactions in energy demand to energy prices exceed the short- run reactions by far (Hogan, 1989). Instead of simply assuming this property of energy demand via the dynamic specification of a model, we explicitly model price induced embodied efficiency and its role for long-run reactions in energy demand.

>>>>>*Table 5: Calculated and 'implicit' (short and long run) elasticities*

These results confirm the importance of energy saving technological change induced by energy price increases. It must be noted again that this model only takes into account the

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[2] Due to the lag structure applied in the ADL equations we could not cover the whole sample of our data (1972 – 2005)

aspect of the consumers' choice among the menu of capital goods and does not capture the adjustment process in capital goods induced by energy price increases. Therefore the full impact of energy saving technological change induced by energy price increases could be expected to be even larger.

The second exercise consists of a 10% percent increase in the (real) value of the appliance stock compared to the actual development during the period 1975 to 2005. This increase could represent a shift in the capital goods menu towards higher quality (energy efficiency) and therefore higher costs per unit of capital or a more rapid diffusion of embodied technical change due to higher capital accumulation. In both cases this shift increases efficiency and thereby decreases service prices. Therefore we expect all different forms of rebound effects to counteract (or reinforce) the initial impact depending on price and income effects. Again we use the simulation results to derive 'implicit elasticities', in that case of energy demand to appliance stock changes by simply calculating the relationship between both. As Table 5 shows, these 'implicit' long run elasticities are not very different from the *ceteris paribus* elasticities derived from the ADL equation for efficiency. In general the *ceteris paribus* long run elasticities of efficiency with respect to the capital (appliance) stock are higher. We find that a significant rebound effect is only at work for heating, where the elasticity drops from – 0.43 to – 0.18. For electricity we find even a small re-inforcement effect that might be explained by real income effects. In general the potential impact of technical improvements in the appliance stock is reduced by rebound effects.

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for the simulation.

5. Conclusions

This study combines bottom-up and top-down elements of households' energy demand in one comprehensive econometric model of U.S. households' demand. Energy saving technical change is modelled by technical efficiency embodied in capital stocks (appliances), integrating heating, electricity and transport into one model. Technical efficiency is not treated as exogenous or captured with any proxy variable (like the capital stock), but is explicitly dealt with as a variable and depends on investment in appliances (embodied technical change) as well as energy prices (price induced technical change). This relationship only takes into account the aspect of the consumers' choice among the menu of capital goods and does not capture the adjustment process in capital goods itself. Future research in this direction should integrate the adjustment of capital stocks and take into account also other factors (like time) that contribute to household utility in the concept of household production as in Gronau, Hemermesh (2008):

The estimation results can be used to quantify different forms of 'rebound effects' of higher energy efficiency. The magnitude of these 'rebound effects' calculatd here is within the range found in the literature. Our specification allows dividing between price and income induced 'rebound effects' and takes into account a broad range of substitution effects via cross price elasticities.

The model is used to quantify the role of embodied and price induced technical change (compared to other factors of influence) in two simulation exercises. It can be shown that for a long run 10% percent increase in the prices of the three energy commodities (gasoline/diesel, heating and electricity) , the demand effects are significantly larger than the partial elasticities would suggest. The short run price elasticities rise to long run 'implicit' price elasticities which are twice or four times larger. These findings are a result of explicitly modelling price induced technical change and not of the dynamic specification structure of energy demand like in other studies. In the case of a long run 10% percent increase in the (real) value of appliances representing a shift in the captial goods menu towards higher quality or higher diffusion of embodied technical change the impact on energy consumption is smaller than implied by the elasticity in the efficiency-equation. This result clearly reveals the role of 'rebound effects' which counteract technical improvements in the appliance stock.

The two simulation exercises show that in the case of a permanent energy price increase the short term energy demand reaction is significantly reinforced by price induced technical change in the appliance stock. This effect is increasing over time and proves the result of much higher long run- than short run- energy demand elasticities. We assume that this long run impact of prices is still underestimated in our model, as the adjustment process in capital accumulation is not taken into account. On the other hand improvements in energy efficiency brought about by changes in the capital stock without energy price changes lead to effective decreases in the service price of energy and therefore to rebound effects. These rebound effects dampen the direct energy saving-impact of embodied technical change, especially in the case of heating.

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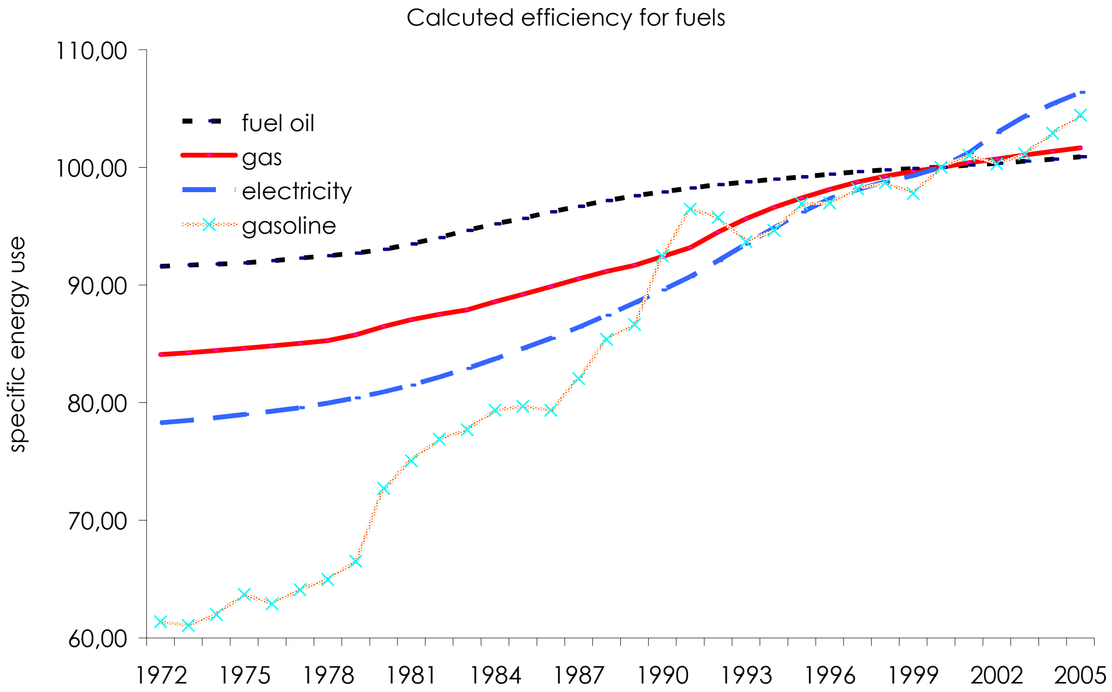
Table 1: Energy efficiency of the stock of selected household appliances, quantity index (2000 = 100)

	oil heating	gas heating	central air conditioning	refrigerators	freezers	cloth washer	dish washer
1972	90.7	79.6	61.1	55.1	64.0	63.2	62.9
1973	90.8	79.8	61.7	55.4	64.4	63.6	63.2
1974	90.9	80.0	62.3	55.6	64.9	64.1	63.5
1975	91.0	80.3	63.1	55.9	65.4	64.7	64.2
1976	91.2	80.5	63.8	56.2	65.9	65.4	64.8
1977	91.5	80.8	64.5	56.6	66.6	66.2	65.3
1978	91.7	81.1	65.5	57.1	67.2	67.1	66.2
1979	91.9	81.8	66.5	57.7	68.1	68.2	66.9
1980	92.3	82.7	67.5	58.4	69.0	69.4	68.0
1981	92.8	83.5	68.7	59.2	70.1	70.6	69.3
1982	93.4	84.0	70.4	60.1	71.2	71.8	70.7
1983	94.1	84.5	72.1	61.1	72.3	72.9	72.3
1984	94.7	85.4	73.8	62.4	73.5	73.9	73.6
1985	95.2	86.2	75.6	63.7	74.7	74.4	74.7
1986	95.8	87.0	77.1	65.3	76.0	74.8	76.0
1987	96.3	87.9	78.6	67.0	77.3	75.0	77.0
1988	96.9	88.7	80.0	69.0	78.7	75.1	77.5
1989	97.3	89.3	81.5	71.2	80.2	75.5	78.0
1990	97.7	90.2	82.8	73.5	81.8	76.0	78.3
1991	98.0	91.2	84.3	76.1	83.6	76.7	78.7
1992	98.4	92.9	86.9	79.0	85.4	77.4	79.3
1993	98.6	94.4	89.4	82.4	87.6	77.7	80.1
1994	98.9	95.6	91.5	86.2	90.1	80.7	83.7
1995	99.1	96.7	93.3	90.3	92.9	83.5	87.0
1996	99.3	97.6	94.9	93.7	95.3	86.2	89.7
1997	99.6	98.4	96.2	95.6	97.1	89.4	92.7
1998	99.8	99.0	97.7	97.0	98.4	93.0	95.6
1999	99.9	99.6	99.0	98.0	99.4	96.8	98.0
2000	100	100	100	100	100	100	100
2001	100.2	100.5	101.1	104.0	102.0	103.7	102.4
2002	100.4	100.9	101.9	111.4	104.2	107.9	105.1
2003	100.6	101.3	102.9	117.8	105.2	113.8	107.3
2004	100.8	101.6	103.6	122.8	106.3	112.5	110.9
2005	101.0	102.0	104.6	126.2	106.8	111.8	113.9

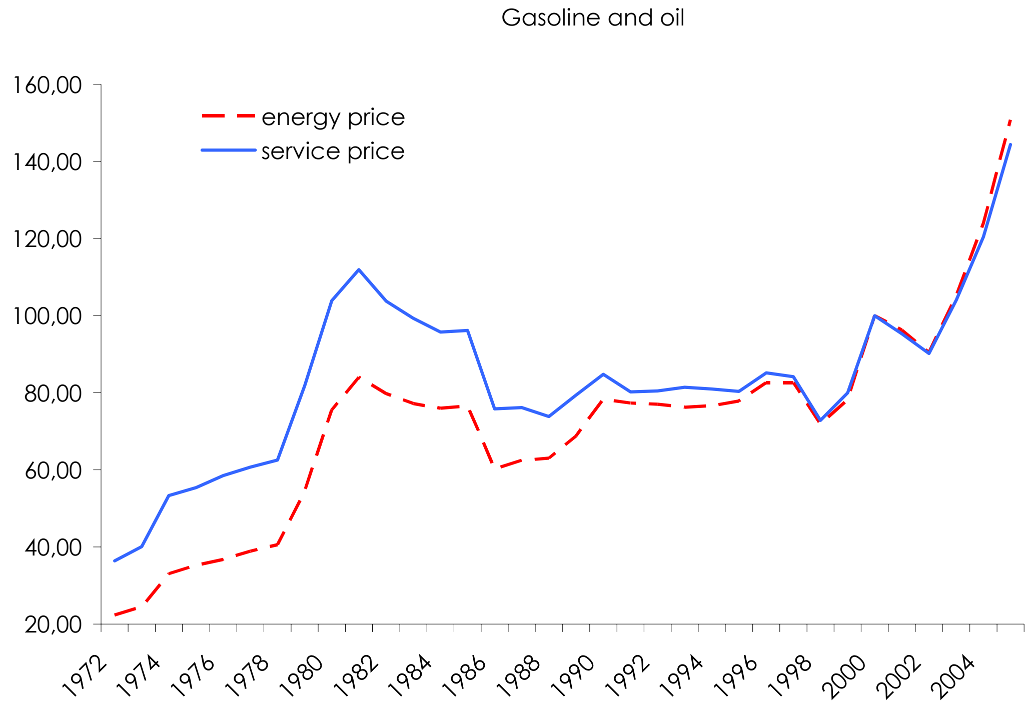
Source: Own calculations, based on the Lawrence Berkely National Laboratory EETD/EAD

Figure 1: Efficiency index (2000 = 100) for fuels



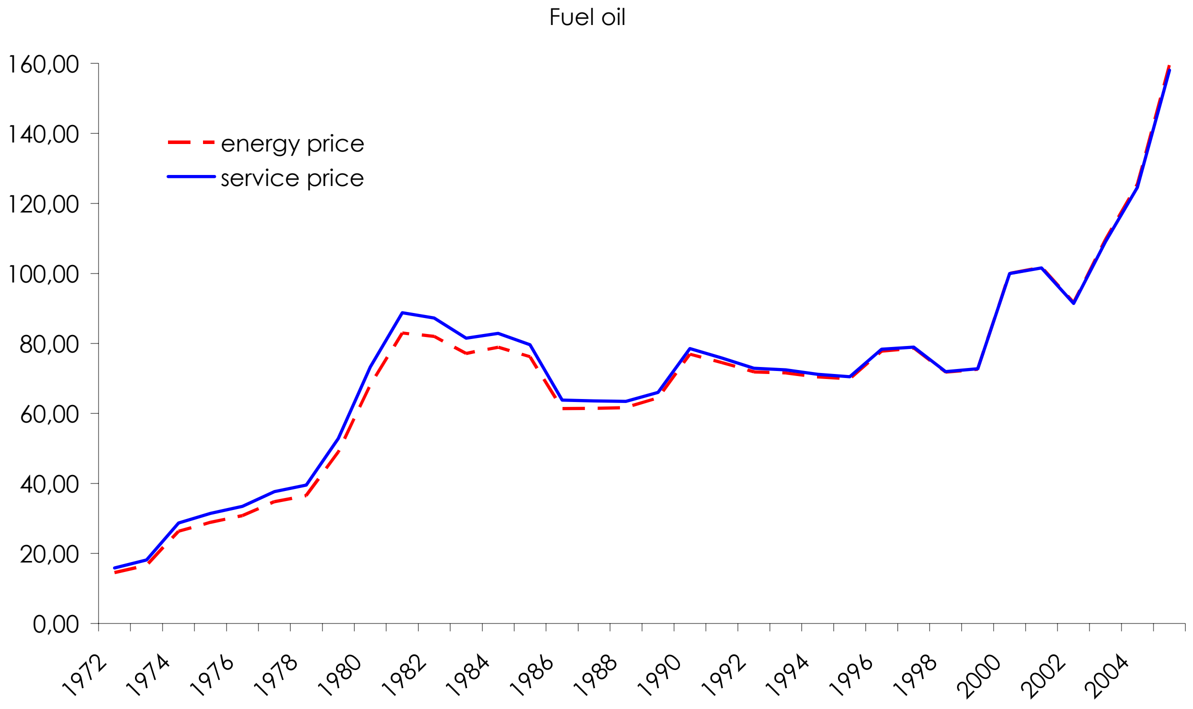
Source: Own calculations, based on the Lawrence Berkely National Laboratory EETD/EAD

Figure 2: Energy and service prices for gasoline, 1972 – 2005



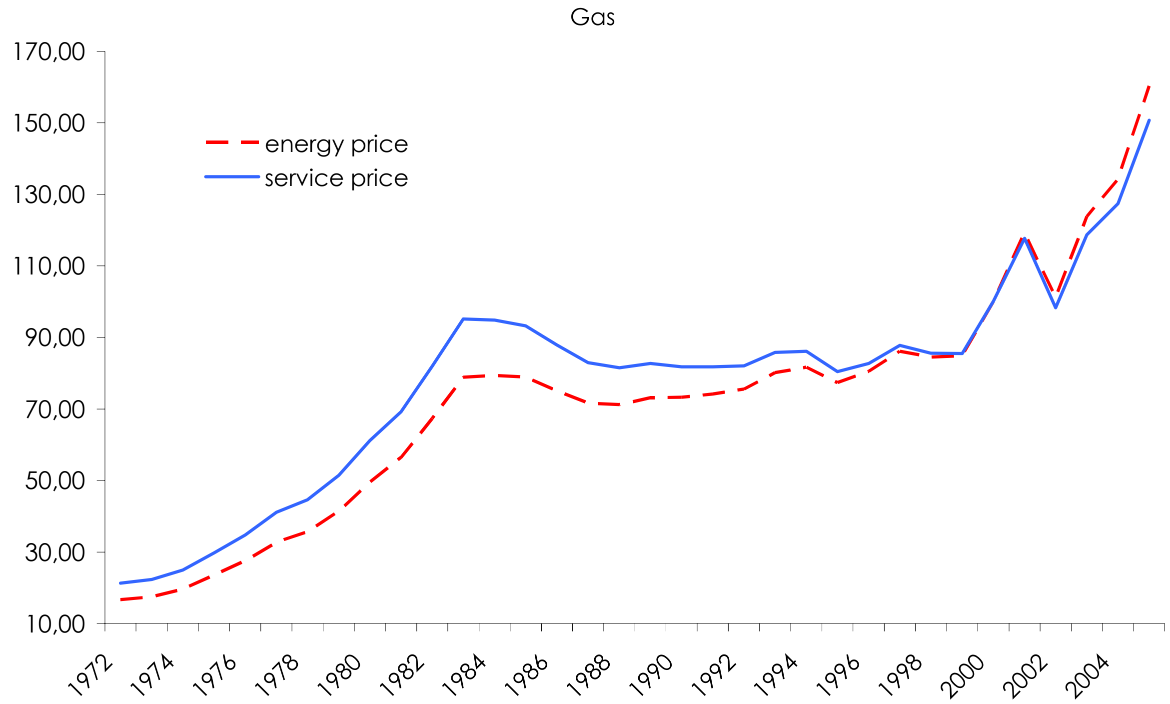
Source: Own calculations, based on the Lawrence Berkely National Laboratory EETD/EAD

Figure 3: Energy and service prices for fuel oil, 1972 – 2005



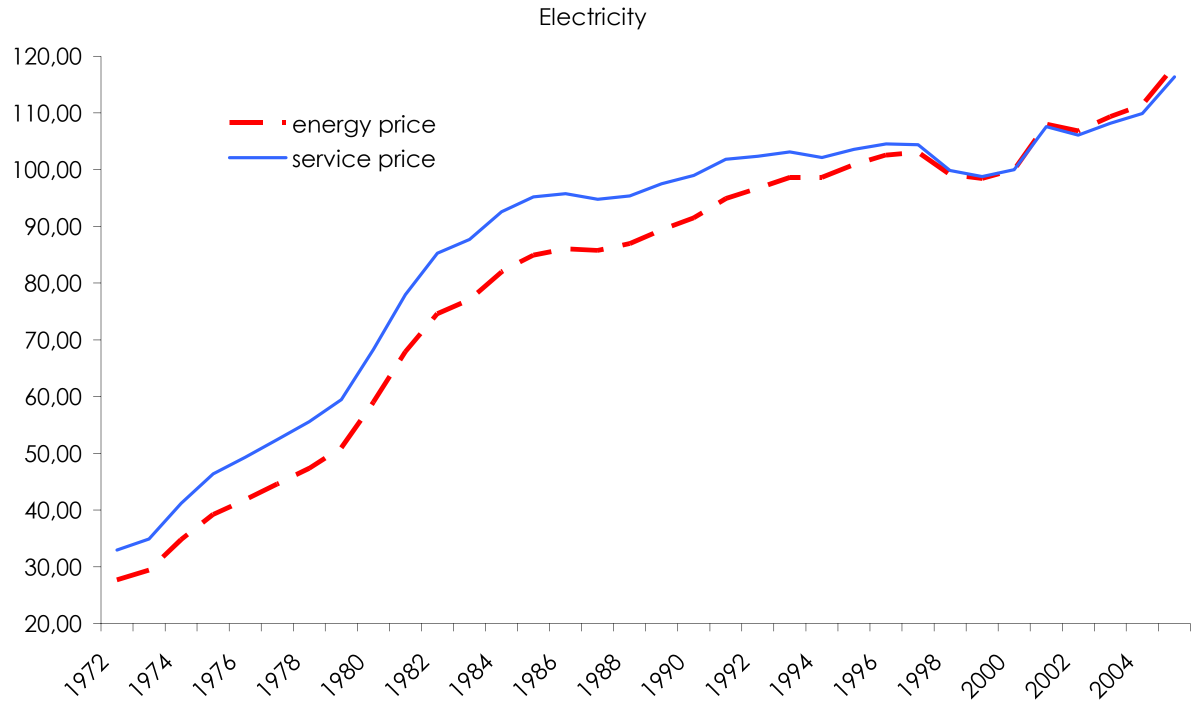
Source: Own calculations, based on the Lawrence Berkely National Laboratory EETD/EAD

Figure 4: Energy and service prices for gas, 1972 – 2005



Source: Own calculations, based on the Lawrence Berkely National Laboratory EETD/EAD

Figure 5: Energy and service prices for electricity, 1972 – 2005



Source: Own calculations, based on the Lawrence Berkely National Laboratory EETD/EAD

Table 2: Parameter estimation results, QUAIDS-Model for non-durables, 1972 – 2005

	Parameters	standard errors	
γ_{FOFO}	0.088	0.021	***
γ_{FOCL}	0.007	0.008	
γ_{FOF}	0.015	0.006	***
γ_{FOH}	-0.008	0.005	
$\gamma_{FOH\ E}$	-0.020	0.007	***
β_{FO}	-0.062	0.030	**
γ_{CLCL}	0.017	0.007	***
γ_{CLF}	-0.006	0.005	
γ_{CLH}	-0.002	0.003	
$\gamma_{CLH\ E}$	-0.004	0.011	
β_{CL}	0.043	0.036	
γ_{FF}	0.027	0.003	***
γ_{FH}	0.004	0.002	*
$\gamma_{FH\ E}$	-0.017	0.004	***
β_{F}	-0.060	0.013	***
γ_{HH}	0.011	0.003	***
$\gamma_{HH\ E}$	-0.001	0.006	
β_{H}	-0.010	0.018	
$\gamma_{H\ EH\ E}$	-0.025	0.027	
$\beta_{H\ E}$	-0.169	0.041	***
R^2			
FO	0.994		
CL	0.996		
F	0.991		
H	0.974		
H_E	0.888		

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

Table 3: Uncompensated and compensated price elasticities, QUAIDS-Model for non-durables

Uncompensated price elasticities					
	Food	Clothing	Gasoline	Heating	Electricity
Food	**-0.4766**	0.0986	0.1135	-0.0291	-0.0820
Clothing	0.3437	**-0.8239**	-0.0296	-0.0143	0.0591
Gasoline	0.7265	-0.1153	**-0.1347**	0.1370	-0.4701
Heating	-0.5894	0.0105	0.3224	**-0.1916**	-0.4589
Electricity	0.0222	-0.6243	-0.0241	0.1031	**-0.1786**
Compensated price elasticities					
	Food	Clothing	Gasoline	Heating	Electricity
Food	**-0.3430**	0.0563	0.0893	-0.0391	-0.0965
Clothing	-0.0938	**-0.6865**	-0.1100	-0.0474	0.0108
Gasoline	0.8760	-0.0674	**-0.1587**	0.1483	-0.4536
Heating	-0.1799	0.1418	0.3977	**-0.2175**	-0.4137
Electricity	-0.8527	-0.9048	-0.1849	0.0369	**-0.0842**

Table 4: Long run elasticities of efficiency, 1972 – 2005

	Gasoline	Heating	Electricity
long run elasticity			
energy price	0.069	0.064	0.046
capital stock	0.171	0.427	0.081

Table 5: Calculated and 'implicit' (short and long run) elasticities

price elasticity	short run	imlicit (long run)
Gasoline	-0.1587	-0.563
Heating	-0.2175	-0.467
Electricity	-0.0842	-0.153
capital stock elasticity	long run	imlicit (long run)
Gasoline	-0.171	-0.167
Heating	-0.427	-0.175
Electricity	-0.081	-0.091

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