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THE FULL IMPACT OF ENERGY EFFICIENCY ON HOUSEHOLDS' ENERGY DEMAND

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Abstract:

This paper deals with technical progress in the energy efficiency of U.S. households' capital stock (appliances and passenger cars) and its potential for energy saving. An increase in the energy efficiency of households can only be achieved via a different capital stock. The link between the average energy efficiency and the stock of energy-using durables is econometrically estimated based on a new data set of household appliances and passenger cars. This relationship complements a Quadratic Almost Ideal Demand System (QUAIDS) for six consumption categories (non-durables), including heating, electricity and transport. Any increase in energy efficiency lowers the corresponding 'service' price and leads to a 'rebound effect'. A simulation exercise shows how the *ceteris paribus*-'rebound effect' is changed by taking into account the capital costs and other interdependencies and feedbacks that can only be captured by a full model of household demand.

JEL Code: D12, Q55, Q41

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

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1. Introduction

The U.S. climate policy initiatives mainly comprise cap-and-trade bills for certain sectors with overall emission targets. These cap-and-trade proposals are often combined with regulatory climate policies like mandatory energy efficiency standards and vehicle emission standards (Moslener and Sturm, 2008). An economic evaluation of the adequate policy-mix for the non-emission trading sector (mainly transport and households) therefore requires a model explicitly covering the influence and effectiveness of price changes, mandatory energy efficiency standards and other measures aimed at increasing energy efficiency.

The existing research on households' energy demand is mainly focused on partial demand analysis (for example: Larsen and Nesbakken, 2004; Holtedahl and Joutz, 2004; Hondroyiannis, 2004 and Meyer, et al., 2007). Some recent studies cover the whole residential energy demand (Labandeira, et. al., 2006) and only a few, like Brännlund, et al. (2007) and Mizobuchi (2008), deal with all energy relevant categories in a model of total consumers' demand. These studies include estimates of the 'rebound effect' from higher energy efficiency on energy demand via higher 'service' demand, based on the original idea of Khazzoom (1980, 1989). The modelling of the rebound effect is based on the link between the technical efficiency of capital stocks and the price of consumption of the 'services' of this stock (space heating, vehicle miles). An increase in the efficiency of the stock lowers the price of services, resulting in a 'rebound effect' on service demand. Many partial empirical studies have focussed on this rebound effect, especially for private car transport (Greene, et.al., 1999). The theoretical concept of Khazzoom (1980, 1989) has been extended by Henly et.al.

(1988) by including the neceassry capital costs for an efficiency increase into the formulation of the rebound effect. Although recent empirical work (Mizobuchi, 2008) accounts for this capital cost term, it is derived from technological data sets about costs and efficiency of appliances, and not explained within the model.

An empirical model of a consistent formulation of all feedback mechanisms from higher energy efficiency of the capital stock on households' energy demand is still missing. Filling this gap in the literature is the main objective of this paper. For this purpose it is crucial (i) to describe explicitly the link between the capital stock and efficiency, and (ii) to estimate the model based on services in order to derive the service demand elasticity. We will incorporate both extensions into our model of U.S. households' demand.

The first model feature is incorporated by a single equation describing this link, derived in a framework of dynamic cost minimization of consumers. This dynamic framework starts from a model, where technology is embodied in capital goods/appliances, like Conrad and Schröder (1991). The focus in this paper is on energy saving-technical change for selected household appliances and passenger cars in the long run. Our simple efficiency equation is based on the hypothesis that any technological change has to be brought about either by new vintages of capital goods (embodied technical change) or, as first described in Newell, et.al. (1999), by a different choice from the menu of existing capital goods. Therefore, the information about how much additional capital cost must be incurred for increasing energy efficiency in a certain amount, is taken from econometric estimation of this equation and not, as in other studies (Mizobuchi, 2008), assumed exogenously. A shortcoming of our model is, that this treatment only covers the path of embodied technical change and excludes the modelling of radical induced technical change (like 'efficiency-revolutions' or switching to backstop technologies). Econometric modelling of embodied technical change therefore only captures the influence of the capital accumulation path on the path of energy efficiency and no radical changes in the efficiency-structure of appliances.

The second model feature is captured by using a new data stock describing the efficiency of different energy-using household appliances as well as of passenger cars. Linking these data with consumption expenditure for energy results in the derivation of service prices for different energy uses of households. A QUAIDS model of household demand for non-durables, including all categories of household energy demand (heating, electricity, transport) into one model, is then estimated based on this data set. Relying on indices of service prices constructed from efficiency data allows for the direct estimation of a service price elasticity, which in most studies is approximated by the estimated energy price elasticity. From a theoretical and behavioural point of view, it might be reasonable to assume that consumers react to lower energy costs in the same fashion as they react to lower costs of services. In an econometric perspective, the parameter value based on the energy price is a biased estimate of the true service price elasticity, because the long-term time series of service prices differs considerably from the long-term time series of energy prices. The model is then used to quantify the full impact of an increase in energy efficiency brought about by investment in durables and takes into account all different types of rebound effects and other interactions. This can then be compared to the directly calculated influence of an increase in energy efficiency taking only into account a *ceteris paribus*-rebound effect. We show that these indirect effects are significant and that interaction effects between different categories of energy use are more important than *ceteris paribus*-rebound effects for results of total energy demand changes.

In section 2 the theoretical model of consumers' demand in a dynamic cost minimization framework is laid down. That includes the derivation of an equation describing the link between the capital cost of the stock of durables and the (average) energy efficiency of this stock. The new data set collected for this study is presented in section 3. The results of the econometric estimation of the demand system as well as of the energy efficiency surface of appliances are presented in section 4. These estimation results also allow for the derivation of different types of rebound effects. In section 5 the model simulations, using the full model of consumption, is presented in order to compare the impact of energy efficiency changes brought about by investment into appliances with the direct impact of energy efficiency changes, as calculated directly. Finally, section 6 draws some first and tentative conclusions.

2. Consumers' demand with embodied energy efficiency

The structure of the model distinguishes between capital expenditure of households, and expenditure for six non-durable goods (food/beverages, clothing, gasoline, heating, electricity, and other goods and services). The energy consumption (gasoline, heating, electricity) is modelled as a service demand by making use of a new data set of efficiency of household appliances and passenger cars. Total household consumption is not modelled and is assumed to be given. 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). The following section presents a dynamic dual model of private consumption without explicitly modelling the investment demand for durables.

2.1. Dynamic cost mimimization, durable goods and energy efficiency

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. The approach laid down in this paper starts with a consumer who 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. The utility that arises from the use of K is a service flow comprised in $C(u, p_i)$:

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

In equation (2) $\dot{K}$ stands for the change in K. The general solution of this model is defined by two main optimality conditions from this cost minimization problem, namely Shephard's Lemma (3) and the envelope condition (4), i.e. a relationship between capital expenditure and expenditure for non-durables:

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

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

Shephard's Lemma determines the level of commodity demand x_i or in a logarithmic model the budget shares w_i. Equation (4) shall be interpreted here as a separability assumption between durables and non-durables in consumption. Empirical work on consumption of durables, like Bernanke (1984) and Luengo-Prado (2006), has shown that the separability assumption between durables and non-durables is a valid approximation for the household's utility function. The separability condition (4) in our case could simply also be derived from the budget constraint in (1). The important consequence for the full impact of energy efficiency on household energy demand is that higher capital expenditure has an impact on total consumption of non-durables and therefore also on energy expenditure.This is especially relevant, if an increase in energy efficiency can only be brought about via an additional investment in more efficient capital goods used by households, as put foreward in Henly, et.al.(1988) and in Mizobuchi (2008).

Energy commodities E are used by consumers together with the capital stock, K for the 'production' of services (heating, lighting, communication, transport). The main characteristic of the capital 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 for deriving the 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 Khazzoom's (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 condition that an increase in energy efficiency requires additional investment in more efficient capital goods leads to the derivation of an effect 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 as well as the consumers' choice among the menu of capital goods. 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 efficiency as function of the capital stock and the energy prices. 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:

$$\log \eta_{ES,t} = \kappa_0 + \sum_{\tau=1}^{l} \psi_\tau \log \eta_{ES,t-\tau} + \sum_{\tau=0}^{n} \theta_\tau \log K_{E,t-\tau} + \sum_{\tau=1}^{m} \varphi_\tau \log p_{E,t-\tau} \tag{7}$$

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

$$\frac{\sum \theta_\tau}{1-\sum \psi_\tau} \text{ and } \frac{\sum \varphi_\tau}{1-\sum \psi_\tau} \tag{8}$$

2.2. Demand for non-durable goods

To model non-durables we use the quadratic AIDS model (QUAIDS) as proposed by Banks, et.al. (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, et.al., 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.

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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

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. Our starting point is the cost function. The QUAIDS indirect utility function can be stated as:

$$\log U = \left[\frac{\log X}{b(p) + \lambda(p) \log X} \right] \tag{9}$$

In (9), $\log X = \log C(u,p) - \log a(p)$, the translog price index for *a*(*p*) is $\log a(p) = \alpha_0 + \sum_k \alpha_k \log p_k + 0.5 \sum_k \sum_j \gamma_{ij} \log p_k \log p_j$, the Cobb-Douglas price index for *b*(*p*) is $b(p) = \prod_k p_k^{\beta k}$, and expenditure *C*(*u*,**p**) depends on the level of utility, *u* as well as 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*, ($\log X = \dfrac{b(p) \log U}{1 - \lambda(p) \log U}$) we can derive the cost function of the QUAIDS model:

$$\log C = \log a(p) + \log X \tag{10}$$

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pointed out, that the rank of a demand system has implications for separability, for functional form and for aggregation across goods and agents.

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:

$$w_i = \alpha_i + \sum_j \gamma_{ij} \log p_j + \beta_i \log\left(\frac{C}{a(p)}\right) + \frac{\lambda_i}{b(p)}\left[\log\left(\frac{C}{a(p)}\right)\right]^2 \tag{11}$$

Our result using the cost function and Shephard's Lemma is identical to the result of Banks, et.al. (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 expenditure ('income') and price elasticities in a first step the budget share equations can be differentiated with respect to log(C) and log(p_i):

$$\mu_i = \frac{\partial w_i}{\partial \log C} = \beta_i + \frac{2\lambda_i}{b(p)}\left[\log\left(\frac{C}{a(p)}\right)\right] \tag{12}$$

$$\mu_{ij} = \frac{\partial w_i}{\partial \log p_j} = \gamma_{ij} - \mu_i\left(\alpha_j + \sum_k \gamma_{jk} \log p_k\right) - \frac{\lambda_i \beta_j}{b(p)}\left[\log\left(\frac{C}{a(p)}\right)\right]^2 \tag{13}$$

The elasticities are then in a second step derived from these expressions:

$$\varepsilon_i = \frac{\mu_i}{w_i} + 1 \tag{14}$$

$$\varepsilon_{ij}^U = \frac{\mu_{ij}}{w_i} - \delta_{ij} \tag{15}$$

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:

$$\varepsilon_{ij}^C = \frac{\mu_{ij}}{w_i} - \delta_{ij} + \varepsilon_i w_j \tag{16}$$

In (15) and (16) δ_{ij} is the Kronecker delta with $\delta_{ij} = 0$ for $i \neq j$ and $\delta_{ij} = 1$ for $i = j$.

2.3. Energy efficiency 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. Differentiating the quantity of energy demanded E_i (S_i, η_i) with respect to η_i gives:

$$\frac{d\log E_i}{d\log\eta_i} = -(1+\varepsilon_{ii}) \tag{17}$$

In (17) the total change in E_i brought about by an efficiency change incorporates the direct (engineering) effect that equals -1 and the indirect effect via service demand. As an increase in efficiency also leads to a decrease in the service price and thereby to an increase in service demand, we get the reaction of service demand measured by the service price elasticity, ε_{ii}. Equation (17) is identical with formulas of the total effect of efficiency on energy demand including the rebound effect, as derived by Berkhout, et.al. (2000) and Khazzoom (1980).

Henly, et.al. (1988) have critizised this simple rebound formula, as it neglects the fact that energy efficiency is embodied in the stock of households' capital goods and therefore an energy efficiency improvement needs an investment in new and more efficient appliances. In their formulation, they take into account the necessary investment in order to increase efficiency by $\frac{\partial\log K}{\partial\log\eta_i}$ and the impact this additional investment has on service demand $\frac{\partial\log S_i}{\partial\log K}$, via income effects and expenditure elasticities within a given budget constraint. That yields the following expression for the rebound effect:

$$\frac{d\log E_i}{d\log\eta_i} = -\left(1+\varepsilon_{ii}+\frac{\partial\log K}{\partial\log\eta_i}\frac{\partial\log S_i}{\partial\log K}\right) \tag{18}$$

In our case the term $\frac{\partial \log K}{\partial \log \eta_i}$ is given by the inverse of the long run elasticity of efficiency to the capital stock as described in (8) and the term $\frac{\partial \log S_i}{\partial \log K}$ is made up as the product of different effects. One effect is that for a given total disposable income and hence given total consumption expenditure, any change in the capital stock leads to the corresponding change in non-durable expenditure. This in turn leads to a change in the expenditure for energy services, the magnitude of which mainly depends on the expenditure elasticity (equation (14)), describing the reaction of service demand to total non-durable expenditure.

An important advantage of the approach presented here compared to most of the existing literature is that in this 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 additional important advantage of a model for total household consumption that all 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 $\varepsilon_{ij}^{U} - \varepsilon_{ij}^{C} = -w_j \varepsilon_i$. In both cases, the simple direct rebound effects are complemented by income effects due to the – necessary – increase in consumers' spending for durables that decreases the disposable income for non-durables spending.

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, et.al. 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.

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) and 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 back to 1972. In a second step the efficiency factors for new equipment had to be converted into efficiency factors for the existing stock. This was possible by calculating some starting value of efficiency of the stock and using the capital accumuluation equation on data from BEA-National Accounts.

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 for some base years. The final result of this data compilation process is shown in Figure 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 until 1990 and a leveling off thereafter.

>>>>>*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 for gasoline. 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.

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

4. Estimation results

A system of budget share equations of the QUAIDS approach as laid down in (11) 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, et.al. (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 income elasticities, and uncompensated as well as compensated price elasticities according to expression (14), (15) and (16). 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 (17) we can use the uncompensated price elasticity as a measure of the (price-induced) direct rebound effect of energy efficiency improvements. The full rebound effect as described in equation (18) shall be derived from model simulations. Note that Henly et.al. (1988) as well as Mizobuchi (2008) argue that the inclusion of capital expenditure terms in the rebound effect formulation potentially reduces the direct rebound effect, because for a given total expenditure less can be spent on energy services. In the next section, model simulations are presented, where all interactions between the different energy services and all kinds of rebound effects are taken into account. That represents the specific *value added* of a model simulation compared to partial effects from (*ceteris paribus*) elasticities or from simulations, where only some feedbacks are taken into account. Though in this paper it is therefore emphasized that the full impact of energy efficiency on energy consumption only follows from model simulations, some indications can be derived from the expenditure elasticities in Table 3. The necessary capital expenditure has a *ceteris paribus* dampening impact on the direct rebound effect, if the expenditure elasticity is positive. If the expenditure elasticity is negative, the *ceteris paribus* impact of capital expenditure increases the direct rebound effect. As Table 3 shows, the expenditure elasticity is only positive for electricity (+ 4.47), whereas for gasoline as well as for heating the expenditure elasticities are negative. The large absolute numbers of the expenditure elasticities for electricity and heating must be seen in the context of the long-term time series in our analysis and also represent socio-demographic changes that have accompanied the process of income growth between 1972 and 2005. It must also be noted that - as we only model the non-durable part of consumption – the income elasticities are the product of these expenditure elasticities with the income elasticity of total non-durable consumption. Estimates of the latter show values of about 0.57, indicating that the real income elasticity of energy is 0.3 on average, with a value of -0.4 for gasoline, about -1 for heating and about 2.5 for electricity.

According to our calculations of elasticities, the direct rebound effect for gasoline (automotive fuels) amounts to 13%, and is about 19% for heating fuels, and about 18% for electricity. Comparing these results with other studies referred in the surveys of Greening and 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.

The compensated price elasticities only comprise the substitution effect and are smaller (in absolute terms) than the uncompensated price elasticities, if the expenditure 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 complementarity between gasoline/diesel and electricity directly follows from microeconomic theory behind the QUAIDS model, but is more difficult to interpret than the substitutive relationship (which is the 'normal' case within any pair of goods in household theory). In some cases complementarity just expresses some technological relationship. As our model does not include any additional household characteristics like socio-demographic variables which could measure life-styles, the complementarity between gasoline/diesel and electricity could also represent life-style combinations of housing and transport.

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 (0.026 for heating and 0.024 for gasoline/diesel) and significantly negative (- 0.094) for electricity. That means that due to negative expenditure 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.

For gasoline/diesel, heating and electricity we further estimated the efficiency equations as laid down in (7), but only included those variables of the full ADL specification, that turned out significant. In those equations, the efficiency of gasoline/diesel is related to the stock of vehicles, the efficiency of heating is related to the stock of household appliances and the efficiency of electricity is related to the stock of audio and video goods/computers. Only in the case of vehicles the energy price was included in order to measure the effect of choosing different types from the menu capital goods depending on the energy price (price induced technical change). All parameters turn out as highly significant and can be further used for calculating the the long run elasticities of efficiency (η_{ES}) with respect to the capital stock (K) as represented in equation (8). These elasticities are shown in Table 4 and range from 0.12 to 0.32. It must be noted here that these relatively low elasticity values represent the link between renovation of the households' capital stock and energy efficiency that can be found in the historical data.

>>>>>Table 4: Parameter estimation results and long run elasticities for efficiency, 1972 – 2005

5. Model simulations

In order to measure the impact of energy efficiency improvements, we carry out simulation exercises for each category of energy use in U.S. households. Technical efficiency is a function of the appliance stock and therefore endogenous. The dependence on energy prices in the case of vehicles 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 capital stock, which just represents the time path of embodied technical change. Taking Brännlund et.al. (2007) and Mizobuchi (2008) as starting points, we assume that the efficiency of gasoline/diesel would have increased more rapidly between 1990 and 2005, so that in 2005 it would have been by 10% higher than in the baseline (the historical data). The simulation for heating assumes an efficiency increase by 5% until 2005 and the simulation for electricity of 10% until 2005. For the model simulations the (exogenous) expenditure for durables between 1990 and 2005 is increased in a continous way, so that the new accumulation path of durables guarantees the corresponding efficiency difference until 2005. For the simulations we use the full model comprising the following equations:

$$\log\eta_{ES} = \kappa_0 + \sum_{\tau=1}^{l}\psi_\tau \log\eta_{ES,t-\tau} + \sum_{\tau=0}^{n}\theta_\tau \log K_{E,t-\tau} + \sum_{\tau=1}^{m}\varphi_\tau \log p_{E,t-\tau} \tag{7}$$

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

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

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

$$w_i = \alpha_i + \sum_j \gamma_{ij} \log p_j + \beta_i \log\left(\frac{C}{a(p)}\right) + \frac{\lambda_i}{b(p)}\left[\log\left(\frac{C}{a(p)}\right)\right]^2 \tag{11}$$

Equation (7) is used to calculate the necessary path of additional capital accumulation between 1990 and 2005 in order to achieve the corresponding increases in energy efficiency of appliances (η_{ES}) in the end year 2005. This capital expenditure on the one hand reduces the expenditure for non-durables (according to (4)) and on the other hand increases efficiency and reduces the service price (according to (6)). The increased energy efficiency still has the energy reducing impact as described in (5) and service demand S is calculated by dividing nominal service expenditure $p_S S$ derived from the budget shares (11) by the service price p_S. This model simulation therefore takes into account all interdependencies of increasing energy efficiency via investment in household appliances. It also considers the direct 'engineering' effect of energy efficiency and not only the rebound effect as other studies like Brännlund et.al. (2007). The interdependence between prices and budget shares and its impact on the aggregate consumer price (an issue discussed by Brännlund et.al., 2007 and Mizobuchi, 2008) is also taken fully into account in the model simulation.

In general, the simulation results in Table 5 show the difference in (real) consumption between the high efficiency-path and the historical data at the end of the period (2005). One important result is, by how much non-durable consumption would have been lower in 2005, due to the continous higher investment in appliances for increasing energy efficiency. In the case of gasoline and electricity that amounts to almost 10% of lower non-durable expenditure, in the case of heating the difference is almost negligible. Note that in the case of heating the efficiency increase is less. These different effects on non-durable consumption are due to the the different long run elasticities of efficiency to capital stock changes, as well as the different magnitude of investment compared to total non-durable consumption. In general, the simulation results show that important indirect effects are at work. These indirect effects strongly influence the energy demand of another category, if the efficiency for a certain category is increased. The total effect on energy demand in Table 5 is almost zero in the case of gasoline and heating, and amounts to + 3.5% in the case of electricity.[2]

The final result can deviate significantly from the *ceteris paribus* elasticity estimates. The case of a 5% efficiency increase for heating appliances represents the case where the difference between the simulation results and the *ceteris paribus* effect is less. Gasoline and heating are substitutes, but in the case of higher heating efficiency this cross price effect does not change gasoline demand. Heating and electricity are complementary, so that the cross price effect of a lower service price for heating has a *ceteris paribus* enhancing effect on electricity (service) demand. As electricity demand is also reduced as a result of the simulation, the expenditure effect obviously dominates the cross price effect. A similar expenditure effect also increases heating demand. It turns out that in total the indirect effects increase the rebound effect from the *ceteris paribus* estimate of 19% to an effective total rebound effect of 37%.

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[2] If one wants to translate that into emission effects, it has to be borne in mind that if (marginal) electricity is produced from thermal power plants, the electricity consumption reduction is twice as

A similar but much larger negative income effect is also present in the case of increasing the efficiency of vehicles by 10%. Gasoline demand only decreases by 1.4%, yielding an effective total rebound effect of 86% vs. the *ceteris paribus* estimate of 14%. In that case heating demand increases considerably which is also influenced by the negative expenditure elasticity and the 10% reduction of total non-durable consumption.

In the case of the increase in electricity using appliances by 10%, the *ceteris paribus* estimate of the rebound effect (18%) is even reversed: electricity demand decreases by 13.9%, though the efficiency only increases by 10%. One factor dominating this result is the large expenditure elasticity of electricity, combined with an almost 10% decrease of total non-durable consumption. This result might be seen as an extreme case of the theoretical argument put forward by Henly, et.al. (1988), that including capital expenditure feedbacks in the rebound formula decreases the rebound effect. This is not the case for gasoline and heating demand, where taking into account the feedbacks from capital expenditure has increased the rebound effect.

It is a general result of the simulations that indirect effects that can only be measured via full model simulations lead to results that are unpredictable from the estimates of elasticities. The most important result might be that an isolated increase in efficiency in one energy using category leads to considerable changes in the demand of other energy uses. Taking into account the necessary capital expenditure for efficiency improvements might decrease the rebound effect, as described by Henly, et.al. (1988) or increase it.

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large in terms of primary energy as the increase in gasoline and heating (oil, gas) demand.

6. Conclusions

This study combines bottom-up and top-down elements of households' energy demand in one comprehensive econometric model of U.S. households' demand. Technical efficiency is embodied in capital stocks (appliances), integrating heating, electricity and transport into one model. Efficiency is not treated as exogenous, but is explicitly dealt with as a variable and depends on investment in appliances (embodied technical change) and partly on energy prices. We use a new dataset of the energy efficiency of household appliances for this purpose and explicitly describe the impact of energy efficiency on 'service' prices. The rebound effect is therefore based on a non-biased estimate of 'service' price elasticities and not on energy price elasticities, as in other studies. The link between efficiency and capital expenditure is based on econometric estimates of the path of the 'efficiency surface' of appliances and not on exogenous engineering information as in Mizobuchi (2008). The full impact of a different energy efficiency-path on households energy demand can then be derived from model simulations, where all repercussions are taken into account.

Although the magnitude of rebound effects calculatd here is within the range found in the literature, the effective rebound effect calculated from model simulations differs considerably from that. The main *value added* of taking into account all the indirect effects is that income effects due to financing the capital stock for efficiency improvement and cross price effects can have significant effects on other categories of energy use, if the efficiency for one energy use increases. The simulation results indicate that especially the income effects due to reduced non-durable consumption are important, but cannot only reduce the rebound effect as argued by Henly et.al. (1988) but also increase it, if the expenditure elasticities have large negative values.

The main shortcomings of this approach, however, are that durables consumption is not fully integrated into the model and efficiency is only driven by embodied technical change. Changes in these two featurers might give completely different results in terms of how much investment must be finaced for a certain efficiency improvement and how much non-durables consumption has to be given up for that. These can be seen as core issues for future research. In the end this type of modelling should result in a more comprehensive model of the household, where the adjustment of capital stocks is integrated and other factors (like time) that contribute to household utility in the concept of household production as in Gronau, Hemermesh (2008), are taken into account.

References

Banks, J., Blundell, R., and A. Lewbel (1997). "Quadratic Engel Curves and Consumer Demand", Review of Economics and Statistics, LXXIX (4): 527-539.

Berkout, P.H.G., Muskens, J.C., and J.W. Velthuijsen 2000. "Defining the Rebound Effect", Energy Policy, 28: 425 – 432.

Bernanke, B. (1984). "Permanent Income, Liquidity and Expenditure on Automobiles: Evidence from Panel Data", Quarterly Journal of Economics, 99: 587 – 614.

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

Conrad, K., and M. Schröder (1991). "Demand for Durable and Nondurable Goods, Environmental Policy and Consumer Welfare", Journal of Applied Econometrics, 6: 271 – 286.

Cranfield, J.A.L., Eales, J.S. Hertel, T.W. and P.V. Preckel (2003). "Model Selection When Estimating and Predicting Consumer Demands Using International Cross Section Data", Empirical Economics, 28: 353 – 364.

Greene, D. L., Kahn, J. R. and R. C. Gibson (1999). "Fuel Economy Rebound Effect for U.S. Household Vehicles". The Energy Journal 20: 1–31.

Greening, L.A. and D.L. Greene (1997). "Energy Use, Technical Efficiency, and the Rebound Effect: a Review of the Literature". Report to the Office of Policy Analysis and International Affairs, US Department of Energy, Washington, DC, December.

Greening, L.A., Greene, D.L. and C. Difiglio (2000). "Energy Efficiency and Consumption – the Rebound Effect – a Survey". Energy Policy 28: 389-401.

Gronau, R. And D.S. Hamermesh (2008). "The Demand for Variety: A Household Production Perspective", Review of Economics and Statistics, 90 (3): 562 – 572.

Henly, J., Ruderman, H. and M.D. Levine (1988). "Energy Saving Resulting from the Adoption of More Efficient Appliances: A Follow-Up", The Energy Journal, 9 (2): 163 – 170.

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

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

Khazzoom, J. D. (1980). "Economic Implications of Mandated Efficiency in Standards for Household Appliances", The Energy Journal 1(1): 21-40.

Khazzoom, J. D. (1989). "Energy Savings from More Efficient Appliances: A Rejoinder", The Energy Journal, 10(2): 157-166.

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

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

Lewbel, A. (1990). "Full Rank Demand Systems", International Economic Review, 31: 289 – 300.

Lewbel, A. (1991). "The Rank of Demand Systems: Theory and Nonparametric Estimation", Econometrica, 59(3): 711 – 730.

Luengo-Prado, M.J. (2006), "Durables, Nondurables, Down Payments and Consumption Excesses", Journal of Monetary Economics, 53: 1509 – 1539.

Meyer, I., Leimbach, M., and C.C. Jaeger (2007). "International Passenger Transport and Climate Change: A Sector Analysis in Car Demand and Associated CO_2 Emissions from 2000 to 2050", Energy Policy, 35: 6332 – 6345.

Mizobuchi, K. (2008). "An Empirical Study on the Rebound Effect Considering Capital Costs", Energy Economics, 30: 2486 – 2516.

Moslener, U. and B. Sturm (2008). "A European Perspective on Recent Trends in U.S. Climate Policy", ZEW Discussion Paper No. 08-026.

Newell, R.G., Jaffe, a.B. and R.N. Stavins (1999). "The Induced Innovation Hypothesis and Energy-Saving Technological Change", Quarterly Journal of Economics, 114: 941-975.

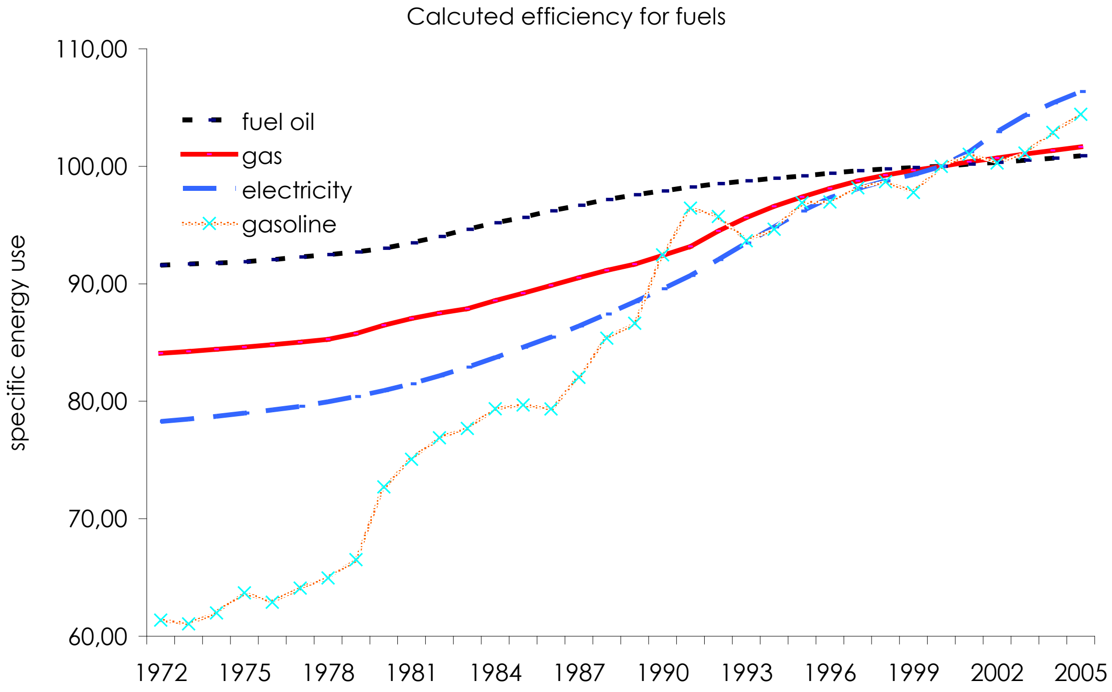
Sue Wing, I. (2006). "Representing Induced Technological Change in Models for Climate Policy Analysis", Energy Economics, 28: 539-562.

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

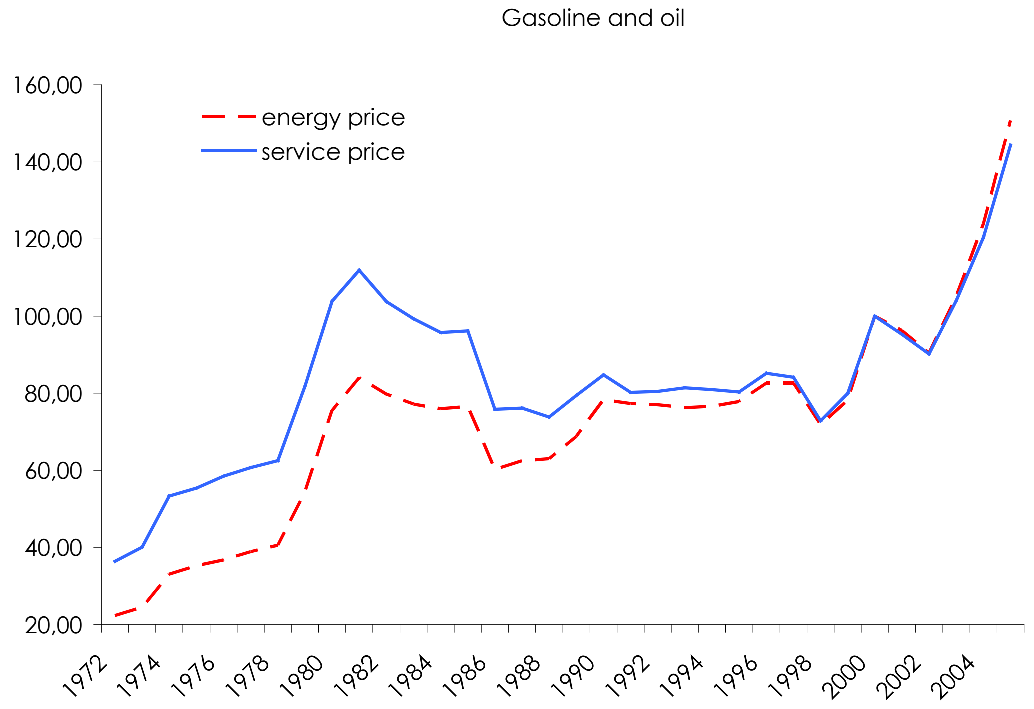
Source: Own calculations, based on the Lawrence Berkely National Laboratory EETD/EAD

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

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

		standard	
	Parameters	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	
γ_{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	
γ_{CLH_E}	-0.004	0.011	
β_{CL}	0.043	0.036	
γ_{FF}	0.027	0.003	***
γ_{FH}	0.004	0.002	*
γ_{FH_E}	-0.017	0.004	***
β_{F}	-0.060	0.013	***
γ_{HH}	0.011	0.003	***
γ_{HH_E}	-0.001	0.006	
β_{H}	-0.010	0.018	
$\gamma_{H\_EH\_E}$	-0.025	0.027	
β_{H_E}	-0.169	0.041	***
	R^2	S.E.	
FO	0.991	0.0031	
CL	0.994	0.0009	
F	0.988	0.0010	
H	0.958	0.0010	
H_E	0.815	0.0013	

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**
Expenditure elasticities					
	Food	Clothing	Gasoline	Heating	Electricity
	0.673	2.233	-0.763	-2.090	4.466

Table 4: Parameter estimation results and long run elasticities for efficiency, 1972 – 2005

	Gasoline	Heating	Electricity
ψ_1	0.5667	0.9258	0.9059
	(0.0889)***	(0.0220)***	(0.0149)***
φ_1	0.0324		
	(0.0137)**		
θ_0	-0.3146		
	(-0.0094)***		
θ_1	0.3865	0.0237	0.0113
	(0.0958)***	(0.0055)***	(0.0017)***
adjusted R^2	0.992	0.999	0.999
S.E.	0.0159	0.0024	0.0014
long run elasticity			
capital stock	0.17	0.32	0.12
energy price	0.07		

*, ** and *** represent 10%, 5% and 1% of significance respectively.

Table 5: Impacts of higher energy efficiency (in 2005)

Difference to "baseline" (in const. prices)	Gasoline + 10% efficiency	Heating + 5% efficiency	Electricity + 10% efficiency
Total non-durable consumption	-9.3	-0.3	-9.7
Consumption, Gasoline	-1.4	0.0	9.3
Consumption, Heating	12.3	-3.2	19.6
Consumption, Electricity	-1.9	-1.1	-13.9
Total energy consumption	0.5	-0.8	3.5
Direct rebound effect	0.135	0.192	0.179
Total rebound effect	0.857	0.365	-0.385

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