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Price and income elasticities of residential energy demand in Germany

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ABSTRACT

We apply a quadratic expenditure system to estimate price and expenditure elasticities of residential energy demand (electricity and heating) in Germany. Using official expenditure data from 1993 to 2008, we estimate an expenditure elasticity for electricity of 0.3988 and of 0.4055 for space heating. The own price elasticity for electricity is −0.4310 and −0.5008 in the case of space heating. Disaggregation of households by expenditure and socio-economic composition reveals that the behavioural response to energy price changes is weaker (stronger) for low-income (top-income) households. There are considerable economies of scale in residential energy use but scale effects are not well approximated by the new OECD equivalence scale. Real increases in energy prices show a regressive pattern of incidence, implying that the welfare consequences of direct energy taxation are larger for low income households. The application of zero-elasticities in assessments of welfare consequences of energy taxation strongly underestimates potential welfare effects. The increase in inequality is 22% smaller when compared to the application of disaggregated price and income elasticities as estimated in this paper.

1. Introduction

The response of consumers to changes in prices of goods is instrumental for any ex ante assessment of the welfare consequences of taxation. In particular in the case of taxes (or subsidies) on energy or taxes on the carbon content of fossil fuels, such assessments are of importance for at least two reasons: First, they allow for an appraisal of the expected quantitative response of demand. Second, they allow for an estimation of the incidence of carbon or energy taxation. Both aspects are relevant for the design of energy and climate policy.

This paper contributes to the literature by providing detailed empirical information on energy demand of households in Germany. We use official German income and expenditure microdata at the household-level (Einkommens- und Verbrauchsstichprobe, EVS) to estimate a quadratic expenditure system (QES) and derive expenditure elasticities and price elasticities for a number of goods, including electricity, space heating, transportation, food, clothing, housing, health, mobility and education. The results are disaggregated in order to provide evidence on the demand of different household types (singles, couples, with and without children). This demographic translation is used to assess demand at the household level and it allows a cross-evaluation of the 'new OECD equivalence scale', which is used to compare income or expenditure across households of different sizes. In addition, the elasticities are estimated at different loci of the expenditure distribution (i.e. the quartile means of the total expenditure distribution) in order to provide richer information of the impact of total expenditure on energy consumption and substitution patterns. These results are eventually used to assess the incidence and welfare consequences of energy taxation in a counterfactual scenario.

Our work is related to different strands of literature and it augments a number of studies on energy consumption. In this canon of articles, evidence on energy consumption for many countries can be found. The literature - which we cannot review in full length here - ranges from macroeconomic aspects of energy consumption[1] and energy price shocks (Kilian, 2008) to the estimation of price and income elasticities of final consumption based on microdata. This article in particular is related to the estimation of price and income elasticities based on household micro-data.

Espey and Espey (2004) provide a meta-analysis of long-run and short-run price and income elasticities of residential electricity demand. One important finding of the meta-analysis, in which results from different methodological approaches are compared, is a statistically significant difference in price elasticities derived from dynamic vs. non-dynamic models. Dynamic models tend to produce smaller elasticities (p. 71).

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[1] See for example with regard to the 'energy-growth nexus': Ajmi et al. (2013), Narayan et al. (2008), Narayan and Prasad (2008), Narayan and Smyth (2009).

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Fouquet (2014) examines the demand for energy in the United Kingdom over the past two hundred years and notes that both - the income and price elasticity of energy demand - decreased over time (p. 13). This pattern is consistent with the theory of declining marginal utility in consumption and related saturation effects (p. 18). However, other aspects, such as technological development and the emergence of energy markets also play an important role in explaining the observed trends. Another important aspect is that the demand for energy services is (among other things) contingent on national income or economic development. Thus, strong differences in price and income elasticities are to be expected for industrialised countries when compared to less advanced economies.

Narayan et al. (2007) examine the household electricity demand in the G7 countries over several decades. In a panel cointegration framework, Narayan et al. (2007) use per capita annual electricity consumption as dependent variable and per capita income as well as energy prices as explanatory variable. The authors find strong evidence for panel cointegration, which implies that there are deterministic or stochastic trends in the time-series data, for example economic trends as described by Fouquet (2014). Narayan et al. (2007) find that long-run residential demand for electricity in the G7 countries is income inelastic and price elastic. Similar approaches are used to forecast energy consumption (Pourazarm and Cooray, 2013; El-Shazly, 2013) or to assess potential energy savings (Salari and Javid, 2016).

Krishnamurthy and Kriström (2015) provide an empirical analysis of electricity demand, i.e. by estimating price elasticities for selected OECD countries based on household survey data from 2011. The sample does not include Germany, the country considered in this study, and there is no differentiation by income or size of households. However, Krishnamurthy and Kriström (2015) find rather strong differences in the price sensitivity of consumers across the considered countries. Price elasticities range from about −0.3 (South Korea, the Netherlands) up to −1.5 (Australia).

Brounen et al. (2012) examine the driving forces of residential energy use in the Netherlands with a strong focus on demographic characteristics. Their main findings are that space heating is largely determined by the characteristics of the occupied dwelling (space, age, building type) while electricity consumption is strongly driven by household composition. These results imply that equivalence scales for electricity consumption and space heating may differ because of the different driving forces of consumption. With respect to space heating Rehdanz (2007) and Meier and Rehdanz (2010) also find a strong influence of non-pecuniary variables (i.e. property ownership). Furthermore, Rehdanz (2007) shows that the actual type of heating system - in particular the type of used fuels - can have a strong influence on the price sensitivity of households.

Meier et al. (2013) investigate the relationship between household income and expenditure on energy services in the United Kingdom. As a key-result, Meier et al. (2013) find that the income elasticity of electricity and gas demand is contingent on household income. Households with low income exhibit a rather low income elasticity of energy demand (about 0.2). Households at the top end of the income distribution exhibit an income elasticity of up to about 0.6.

Over the last decades, attempts have been made to place empirical examinations of household consumption in a comprehensive theoretical framework (Deaton, 2016). These demand systems allow the estimation of income, price, and cross-price elasticities per commodity and are based on an indirect utility function. We describe the demand system applied in this article in detail in the following section. However, there are a number of relevant contributions which we want to highlight here. Baker et al. (1989) apply a two-stage model of energy demand to British expenditure data. In a first step, durable good equipment is modelled which, in a second step, determines the energy demand of households. Baker et al. (1989) emphasise that the welfare cost of subsidising or taxing fuel prices will differ substantially across households with differing income and other characteristics. This perspective on energy prices is of particular importance in relation to climate policy which may lead to increasing energy prices. Demand systems are used to assess the welfare consequences of climate policy related changes in energy prices: for instance by Labandeira et al. (2009) for the case of Spain and Pashardes et al. (2014) for the case of Cyprus. Rising energy prices lead to a regressive pattern of incidence and have a non-uniform impact on different household types (e.g. differentiated by location or demographic composition).

Kohn and Missong (2003) estimate a quadratic demand system based on German household expenditure data but do not consider energy consumption as a separate good. Instead energy consumption is comprised in the commodity group ‘housing’. Nikodinoska and Schröder (2016) estimate a demand system based on German household expenditure data to examine the consequences of car fuel surcharges and find a moderately regressive impact. Nikodinoska and Schröder (2016) also derive price and income elasticities for several types of goods but do not further investigate differences in consumption contingent on household type and composition.

Our results show that there are considerable differences in price and income elasticities of energy consumption - i.e. with regard to electricity consumption and space heating - across income levels and household types. Energy services clearly have the notion of a necessary good. Energy demand of low-income households shows a weak reaction to changes in energy prices. Energy demand of households belonging to the upper 25% of incomes is about factor three times more price-elastic when compared to households belonging to the lowest 25% of incomes.

The observed consumption and substitution patterns have several important implications. First, an increase in energy prices will cause a moderate reduction in consumption of low-income households, while households belonging to the upper brackets of the income distribution show a more pronounced change in demand. Second, a given change in energy prices, has a significantly different impact on households' welfare as a result of the price change. Welfare losses (expressed as compensating variation) tend to be large for low-income households and/or ‘small’ households (e.g. single households). Thus, a given change in energy prices will impose unequal burdens on the considered types of households, which is at odds with many principles of just taxation (Musgrave, 2002). Finally, the observed consumption patterns will have a bearing on the affordability of energy services, as low-income households face larger burdens compared to wealthier households. This, prima facie, justifies a ‘priority view’ on low-income households in the design of energy and climate policies (Parfit, 1997).

These results have some direct policy implications related to energy and climate policy in Germany. In recent years, German electricity prices have increased strongly, inter alia because of a surcharge for renewable energy promotion levied on top of the electricity price. Thus, an important part of the German ‘energy transition’ towards renewable energy is financed via the surcharge on electricity prices. While this scheme is very effective in promoting renewable energy carriers it also causes rather unequal relative burdens for different household types, which are discussed in detail in this article. One of the most salient features of this policy is, that it tends to increase economic inequality among households. Therefore policy-makers face a trade-off between effective renewable energy promotion (or other policies which might increase energy prices) and aspects of vertical equity in taxation. The results presented in this paper can be used to further investigate such trade-offs based on the price and expenditure elasticities which are reported in detail. Such ex ante assessments of the expected changes in energy demand and relative burdens can be highly useful in order to design climate and energy policies in an efficient, effective, and non-regressive manner.

The remainder of this paper is organised as follows. Section 2 presents a description of the quadratic expenditure system. Section 3 provides a detailed data description and a description of the estimation procedure. Section 4 comprises the discussion of the empirical results. Section 5 concludes.

2. Methodology

2.1. Demand Systems

The use of demand systems has a long history. The development has moved from rather inflexible systems like the *Linear Expenditure System* (*LES*), first estimated by Stone (1954), to more flexible systems. The *Almost Ideal Demand System* (*AIDS*), proposed by Deaton and Muellbauer (1980), has achieved a high degree of popularity due to the flexibility of its underlying cost function. The *Quadratic Expenditure System* (*QES*) (Pollak and Wales, 1978) and the *Quadratic Almost Ideal Demand System (QUAIDS)* (Banks et al., 1997) are examples of demand systems that exhibit a high degree of flexibility in the total expenditure dimension. The most modern system that has emerged from this long-lasting development is the *Exact Affine Stone Index Implicit Marshallian Demand System* (*EASI*), proposed by Lewbel and Pendakur (2009). It combines a high degree of flexibility in both aforementioned categories.

The use of demand systems plays an important role in the estimation of consumer demands. Their wide acceptance stems from the possibility to impose desirable properties on the system of fitted demand equations and to create a theoretically plausible model. A theoretically plausible model satisfies four conditions, known as *Integrability conditions* (Barnett and Serletis, 2009). Its demand curves exhibit:

- *Positivity* - Demands are nonnegative
- *Summability* - The product of prices and demanded quantities sums up to the total expenditure: $\boldsymbol{P}^T \cdot \boldsymbol{q}(\boldsymbol{P}, \mu) = \mu$. $\boldsymbol{P}^T = (p_1, \ldots, p_n)$ is the vector of prices for n commodity groups, $\boldsymbol{q}^T = (q_1, \ldots, q_n)$ are quantities, and μ denotes total expenditure. The realisation of the variable vector $(\boldsymbol{P}, \mu)$ can differ for each entity which is described by the demand system.
- *Homogeneity of degree zero* in $(\boldsymbol{P}, \mu)$ - If prices and total expenditure are multiplied by a common factor, demand is not affected: $\boldsymbol{q}(\boldsymbol{P}, \mu) = \boldsymbol{q}(t\boldsymbol{P}, t\mu)$
- The *Slutsky substitution matrix* is symmetric and negative semidefiniteHurwicz and Uzawa (1971) show that a demand system can be generated by utility maximization if, and only if, these properties hold.

2.2. The quadratic expenditure system

While all typical demand systems impose at least some of the above mentioned properties, different demand systems differ in the exact forms of their demand and utility functions. These differences lead to different properties of the systems. The most suitable demand system has to be chosen on the basis of the given problem and data set. In our study, we chose to work with the *QES*. The system exploits the full potential of Engel curve flexibility and can be estimated with a relatively small number of free parameters. We thus find that – in the context of the data set at hand – the *QES* is the best compromise between flexibility, especially in the total expenditure dimension, and feasibility in the face of few cross sections and a wide range of commodity groups.

A mathematically rigorous description of the *QES* is provided by Howe et al. (1979). A description of the major features of the system applied in this paper is comprised in A.1.

2.3. Demographic translating, Strone-Lewbel cross section prices, and elasticities

Demographic variables are incorporated via the method of *demographic translating*, described by Pollak and Wales (1978).

Demographic translating is based on the assumption that demographics influence the indirect utility function mostly via some total expenditure offset:

$$\overline{\Psi}(\boldsymbol{P}, \mu) = \Psi(\boldsymbol{P}, \mu - \sum_{i=1}^{n} p_i \cdot d_i(\boldsymbol{\delta})), \tag{1}$$

where $\overline{\Psi}$ denotes the indirect utility function of the translated system and $d_i(\boldsymbol{\delta}) = \sum_j \beta_{ij} \cdot \delta_j$ sums up the direct influence of the N demographic variables δ_j for $j \in \{1, \ldots, N\}$ on the ith equation.

This results in the modified Marshallian demand equation:

$$\overline{q}_i = d_i + q_i(\boldsymbol{P}, \mu - \sum_{k=1}^{n} p_k \cdot d_k). \tag{2}$$

Since the d_i act in the same way on the demand equations as the $\widetilde{b}_i$ parameters, we present them in the following as the combined sum $b_i = \widetilde{b}_i + d_i$.

As we will see in Section 4.2 b_i can be interpreted as subsistence parameter. Through demographic translation the subsistence parameters become dependent on demographic variables. The underlying idea of this method is that demographics primarily influence the basic needs of households rather than the changes in their tastes with increasing financial resources. It is appropriate for our work in two respects: First, the consumption of energy goods, i.e. necessity goods, is primary need-driven. Second, as we will later focus especially on the burdens of price increases for poorer households, we need a high resolution of demographic impacts in the range of subsistence expenditure levels. A famous alternative for incorporating demographic variables into demand systems is *demographic scaling* (Pollak and Wales, 1981). We refrain from implementing it into our demand system for three reasons: First, the above-mentioned focus on the subsistence expenditure range is not given. Second, it adds an additional nonlinear demographic element to the system and thus can make it computational unfeasable (as for example in the case of Kohn and Missong, 2003). Third, Kohn and Missong (2003) use the method of demographic translation. Doing so as well facilitates comparison of the results.

We further introduce household specific *Stone-Lewbel cross section prices* as proposed by Lewbel (1989). These reflect the fact that the composition of consumed commodity groups differs between households and therefore the perceived prices for these commodity groups differ between households as well. The increased price variation can additionally improve the fitting routine thanks to the higher variation in the price variables. Further details regarding the applied method are comprised in A.2.

Finally, price and expenditure elasticities can be derived from the expenditure system as documented in A.3.

3. Data and estimation method

3.1. Expenditure data

Income and expenditure data in the following analysis is drawn from the German Income and Expenditure Survey (IES). This survey is published every five years by the German Federal Office of Statistics. It comprises detailed expenditure data based on a survey of about 60,000 German households, which are selected by quota sampling. Participation in the survey is voluntary (Statistisches Bundesamt, 2012). We use data from the IES of the years 1993, 1998, 2003 and 2008. To adjust data sets to each other, we convert all expenditures into quarterly values (relevant for IES1993) and euros (relevant for IES1993, IES1998) using the constant conversion rate of 1 euro=1.95583 DM. Our estimation is based on a pooled cross section data set comprising 108686 households. For a more detailed description of the data preparation process, see Appendix C.

Table 1
Definition of commodity groups.

No.	Code	Comprised goods
1	ELECTRICITY	electricity
2	HEATING	gas, oil, solid fuels, district heating
3	TRANSPORT	car fuel, public transport
4	FOOD	food, food away from home, (alcoholic) beverages, tobacco
5	CLOTHES	clothes, shoes, shoe repair
6	HOUSING	rent, rent equivalent for homeowners, maintenance and repair
7	HEALTH	health care, personal hygiene, care of the elderly/disabled
8	MOBILITY	private transport (except for car fuel), communication
9	EDUCATION	education, entertainment, child daycare
10	OTHERS	furniture, household appliances, jewellery, vacation trips, financial services, other services

3.2. Commodity groups

We start the analysis with a demand system comprising ten commodity groups. Seven commodity groups are chosen as in Kohn and Missong (2003) and the energy dimension is added via three additional energy categories. The final aggregation allows for comparability with the results by Kohn and Missong (2003) and gives the opportunity to identify the interactions between energy consumption and other consumption on a differentiated level. Table 1 gives an overview of the commodity groups.

Durable goods represent a large part of the commodity groups 'mobility', 'education' and 'others.' The choice on the inclusion of durable goods in demand systems is based on a trade-off. On the one hand, durable goods are long-time investments due to their high transaction costs. Hence, their actual consumption does not necessarily reflect an optimal consumption choice.[2] Additionally, the resulting infrequent purchases in this category are hardly accurately captured by a time-limited survey. On the other hand, neglecting categories of durable goods leads to the exclusion of a potentially important portion of consumption. This holds also true in the context of energy demand analysis, since households' energy consumption is closely related to the possession of electrical appliances and motorised vehicles.

Thus, we feel that the information gain of including durable goods surmounts its drawbacks. Like Kohn and Missong (2003), we therefore include durable goods in the analysis. We distinguish durable goods by the three categories 'mobility', 'education' and 'others.' In doing so, we get a mixture of durables in each of these categories, so that reported expenditure is more likely to reflect average expenditure on durables.

3.3. Demographic groups

The demand system can be refined by introducing demographic variables, which allow to differentiate the behaviour of different groups in society. We therefore introduce demographic variables which describe the household composition. We follow the differentiation of household types found in Kohn and Missong (2003) and group households according to the number of children and adults living in the household. The resulting household types are single adults without children (S0) or with one child (S1) and couple households without children (C0), with one child (C1) or with two (C2) or three children (C3). Other household types were excluded from the analysis due to their infrequent appearance in the data set. In the definition of household types, children are up to 17 years old.

Table 2 shows the 6 household types used in the analysis and their shares in the data set. The share of couple households without children is largest, followed by singles without children, couples with two children, couples with one child, couples with three children and singles with one child.

[2] See Deaton (1981) for an introductory discussion.

Table 2
Definition of household types and composition of data set.

Code	S0	S1	C0	C1	C2	C3
Type	*Single without children*	*Single with one child*	*Couple without children*	*Couple with one child*	*Couple with two children*	*Couple with three children*
Share	25.8%	2.8%	39.3%	11.6%	15.8%	4.7%

Age of children: from 0 up to and including 17 years.

3.4. Price data

Besides expenditure data, price indices are needed for the estimation of expenditure curves. We use differentiated price data from the German consumer price index (CPI) of the years 1993, 1998, 2003 and 2008. For the years 1998, 2003 and 2008 we make use of the monthly CPI. We average the monthly CPI over three-month periods to obtain quarterly price data. For 1993 the IES provides expenditure data on a yearly basis. Correspondingly, we use the twelve-month averaged CPI. The CPI is based on price data collected by the German Federal Office of Statistics and provides price indices which correspond to the sub-commodity groups of the IES.

3.5. Estimation method

3.5.1. Stochastic specification

A typical form of heteroscedasticity arising in the context of demand system estimation is a positive correlation of the demand curve error variances and total expenditure. If households have a higher total expenditure, their attainable spendings in each category cover a larger range. Thus, the observed variation of spending in each category is likely to increase with total expenditure. A common approach to correct for this form of heteroscedasticity is to estimate expenditure systems with share equations, hence with expenditure equations divided by total expenditure. However, as Park (1966) already points out, dividing by total expenditure is a rather restrictive approach since it assumes that the error variance increases proportionately to the squared expenditure. Park therefore proposes a more general approach by assuming that the error variance $\sigma_{u_i}^2$ increases proportionately to the power of γ_i of total expenditure:

$$\sigma_{u_i}^2 \propto \mu^{\gamma_i} \cdot \exp(\nu_i) \tag{3}$$

with ν_i being a '*well-behaved error term*' (Park, 1966). It is possible to estimate γ_i in a two-step procedure. First, an estimate of the standard error σ_{u_i} is obtained. For this purpose expenditure in each category is regressed on total expenditure, total expenditure squared, and the regression residuals are calculated:

$$\hat{\sigma}_{u_i} = y_i - \widehat{\Theta}_{0i} - \widehat{\Theta}_{1i}\mu - \widehat{\Theta}_{2i}\mu^2. \tag{4}$$

$\widehat{\Theta}_{0i}$, $\widehat{\Theta}_{1i}$, $\widehat{\Theta}_{2i}$ denote the estimation coefficients. The squared residual $\hat{\sigma}_{u_i}^2$ can then be inserted into the logarithmic version of Eq. (3), so that one obtains the linear regression equation:

$$ln(\hat{\sigma}_{u_i}^2) = const + \gamma_i \cdot ln(\mu) + e_i \tag{5}$$

with e_i being again a well-behaved additive error term.

With Eq. (5) a linear regression can be run and the obtained coefficients $\hat{\gamma}_i$ can be used to divide the expenditure equations by generalised total expenditure $\mu^{\frac{\hat{\gamma}_i}{2}}$ to obtain generalised expenditure shares with homoscedastic error terms.

Adopting this approach, we obtain the final regression equations based on Eqs. (17) and (2), extended by an additive error term ε_i and divided by generalised total expenditure:

$$w_i = \frac{q_i p_i}{\mu^{\frac{\hat{\gamma}_i}{2}}} = \{\theta_{1i} + \theta_{2i}\mu + \theta_{3i}\mu^2 + \varepsilon_i\}/\mu^{\frac{\hat{\gamma}_i}{2}}. \tag{6}$$

Thereby the θ_{mi} for $m \in \{1, 2, 3\}$ are provided by Kohn and Missong (2003) as follows:

$$\theta_{1i} = p_i b_i - a_i \sum_k p_k b_k + \theta_{3i}(\sum_k p_k b_k)^2, \tag{7}$$

$$\theta_{2i} = a_i - 2\theta_{3i} \sum_k p_k b_k, \tag{8}$$

$$\theta_{3i} = (p_i c_i - a_i \sum_k p_k c_k) \prod_k p_k^{-2a_k}. \tag{9}$$

3.5.2. Estimation procedure

The summability constraint $\sum_i q_i p_i = \mu$ imposed by the *QES* results in a zero sum of regression residuals $\sum_i \hat{\varepsilon}_i = 0$ for each household. This however means that each household's residual variance covariance matrix $\hat{\tilde{\boldsymbol{\varepsilon}}}\hat{\tilde{\boldsymbol{\varepsilon}}}^T$ with $\hat{\tilde{\boldsymbol{\varepsilon}}}^T = (\hat{\varepsilon}_1/\mu^{\frac{\hat{\gamma}_1}{2}}, \ldots, \hat{\varepsilon}_n/\mu^{\frac{\hat{\gamma}_n}{2}})$ becomes singular. Inversion of the matrix needed for parameter estimation is no longer possible. To make the estimation feasible, we drop the "others" category and reconstruct its parameters from the estimated system.[3]

We thus specify the system as a nonlinear seemingly unrelated regression model and we use an iterated feasible generalised least squares estimator. Accordingly the errors $\tilde{\varepsilon}_i = \varepsilon_i/\mu^{\frac{\hat{\gamma}_i}{2}}$ for $i \in \{1, \ldots, n\}$ are assumed to be correlated for different expenditure curves of the same household, but not for different households (Zivot and Wang, 2007, section 10.4).

To find starting values for the iterative estimation process, we follow a step-wise procedure. In a first attempt, we estimate a *LES*, with parameter starting values set to zero. We then estimate an aggregated *QES*, using the coefficient estimates from the *LES*, where available. All other parameter estimates are again set to zero. We continue in the same manner with the demographically translated system.

The final estimates of the demographically translated *QES* are tested for heteroscedasticity in the total expenditure dimension by regressing the estimation residuals on total expenditure and total expenditure squared. For residuals of all equations, coefficients on total expenditure are significant at the 1% level. We therefore report heteroscedasticity robust standard errors.

4. Results

Table 10 presents the estimated basis coefficients of the demographically translated demand system. All c_i coefficients are significant at the 1% percent level and so is the Wald test of their joint significance. We therefore conclude that the quadratic model is superior to an *LES* for the demand system at hand. The Akaike information criterion and Bayesian information criterion yield superior values for the demographically translated model (AIC: −2642460, BIC: −2641702) as compared to an aggregated model (AIC: −2602648, BIC: −2602370). Hence, the differentiation by household types adds valuable information to the demand system.

Furthermore, the estimated demand system is theoretically plausible at the means of the household type specific 2008 total expenditure quartiles for which we present elasticities in Section 4.1 below. That is, demands are positive and the Slutsky matrix is negative semidefinite. The negative semidefiniteness of the Slutsky matrix is tested by calculating its eigenvalues. Table 11 shows the eigenvalues of the system Slutsky matrix at the means of the household type specific total expenditure quartiles. One of the eigenvalues is by construction zero within the range of computer precision. This is due to the singularity of the Slutsky matrix which follows from the imposed summability constraint of the demand equations (Mas-Colell et al., 1995, p. 35). All other eigenvalues are negative, confirming the negative semidefiniteness of the Slutsky matrix at the analysed points.

4.1. Elasticities

4.1.1. Expenditure and income elasticities

Table 3 shows the weighted means of household type specific predicted elasticities, evaluated at the means of the total expenditure and price distributions of the year 2008. Predicted elasticities characterise electricity, heating, transport, food and housing as necessity goods with expenditure elasticities $\mu < 1$. The corresponding price elasticities p_i are inelastic. The remaining commodity groups are characterised as luxury goods.[4]

We take a closer look at the price and expenditure elasticities for electricity, heating, transport, and food in Tables 4, 5 by using the demographic translation and by differentiating the quartiles of the expenditure distribution (see Tables 12, 13 for the remaining goods). The disaggregated figures show that expenditure elasticities increase monotonically with increasing total expenditure, implying a decreasing necessity character of the respective goods for households with higher total expenditure. The only exemptions are the heating expenditures of families with two or more children (C2, C3) which decrease slightly for the top expenditure profiles (μ_{50-100}). Energy goods might also have a luxury component with regard to high income households. With increasing expenditure more (luxury) goods which rely on energy inputs become attainable. The cross-price elasticities in Table 3 provide evidence in support of this hypothesis: Heating is a complementary good to housing, which exhibits expenditure elasticities that increase with total expenditure, and transport is a complementary good to the luxury good education.

Park et al. (1996) note that the use of real income elasticities instead of expenditure elasticities can result in a different trend over the total expenditure range. This is due to the fact that most demand systems do not capture all expenditures, so that the variation of the neglected expenditure can affect income elasticity trends. We therefore apply the method used by Park et al. (1996) as a robustness check and derive estimates of real income elasticities for comparison. Total expenditure is regressed on disposable income, disposable income squared and indicator variables for each household type. An estimated analytical relationship between disposable income (ι) and total expenditure (μ) is obtained which allows for the calculation of income elasticities of total expenditure η_ι^μ. Real income elasticities for the different commodity groups are then obtained by multiplying their expenditure elasticities with the income elasticity of total expenditure: $\eta_\iota^i = \eta_\mu^i \cdot \eta_\iota^\mu$. Table 14 shows the income elasticities for energy commod-

[3] In a preliminary analysis possible instrumentations of the system were tested. We failed to identify valid instruments, despite the testing of a variety of instruments and different forms of introducing them to the system. The Sargan-Hansen test rejected the independence of error terms from the instruments at the 1% level. We then compared demand elasticities of an aggregated total expenditure system estimated with (1) a generalised methods of moments regression using disposable income as an instrument and (2) a non-instrumented nonlinear seemingly unrelated regression. The situations described by the different results resemble each other. The invariance to the instrumentation with a typical income variable convinced us to continue the estimation procedure without instrumentation.

[4] A detailed account of elasticities by expenditure profile and household type is comprised in Tables 12, 13. Interestingly, education is characterised as a necessity for family households with two or three children, i.e. in the lower half of the expenditure distribution. Mobility also shows an expenditure elasticity below unity for family households with three or more children in the upper quarter of the expenditure distribution. All remaining consumption categories show an expenditure elasticity above unity.

Table 3
Mean expenditure, own-price and cross-price elasticities for all commodity groups**:** Weighted average of household type specific predicted elasticities at the means of the 2008 total expenditure and prices distributions. Standard errors in parentheses are derived with the delta method.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
μ	**0.398 8** (0.003 6)	**0.405 5** 0.006 4)	**0.636 9** (0.004 9)	**0.658 3** (0.002 7)	**1.196 2** (0.004 1)	**0.696 2** (0.003 3)	**1.367 8** (0.006 0)	**1.412 0** (0.006 3)	**1.204 7** (0.003 8)	**1.748 3** (0.005 0)
p_1	**−0.431 0** (0.005 9)	−0.004 8 (0.000 2)	−0.009 5 (0.000 1)	−0.008 7 (0.000 1)	−0.016 6 (0.000 2)	−0.011 2 (0.000 1)	−0.017 6 (0.000 3)	−0.017 4 (0.000 3)	−0.017 7 (0.000 2)	−0.026 0 (0.000 3)
p_2	−0.008 0 (0.000 2)	**−0.500 8** (0.005 4)	−0.015 4 (0.000 3)	−0.013 5 (0.000 2)	−0.025 6 (0.000 4)	−0.018 5 (0.000 2)	−0.024 9 (0.000 5)	−0.024 5 (0.000 6)	−0.028 1 (0.000 3)	−0.039 7 (0.000 5)
p_3	−0.008 6 (0.000 2)	−0.007 3 (0.000 4)	**−0.572 6** (0.005 9)	−0.014 6 (0.000 3)	−0.028 0 (0.000 5)	−0.020 7 (0.000 2)	−0.027 6 (0.000 7)	−0.026 6 (0.000 7)	−0.030 9 (0.000 4)	−0.044 7 (0.000 7)
p_4	−0.021 4 (0.000 9)	−0.014 8 (0.001 7)	−0.050 2 (0.001 2)	**−0.725 9** (0.004 9)	−0.075 0 (0.001 6)	−0.065 1 (0.000 8)	−0.063 4 (0.002 3)	−0.057 0 (0.002 3)	−0.089 1 (0.001 4)	−0.127 1 (0.002 3)
p_5	0.007 0 (0.000 4)	0.011 7 (0.000 7)	0.002 2 (0.000 5)	0.010 6 (0.000 5)	**−1.209 9** (0.005 1)	−0.002 9 (0.000 4)	0.037 2 (0.001 0)	0.042 7 (0.000 9)	0.010 1 (0.000 6)	0.020 2 (0.000 8)
p_6	−0.038 8 (0.000 8)	−0.033 4 (0.001 7)	−0.074 7 (0.001 3)	−0.065 5 (0.000 9)	−0.122 4 (0.001 7)	**−0.625 7** (0.004 7)	−0.119 4 (0.002 5)	−0.116 6 (0.002 7)	−0.134 3 (0.001 5)	−0.190 4 (0.002 3)
p_7	0.015 5 (0.000 5)	0.022 1 (0.000 8)	0.013 0 (0.000 6)	0.024 3 (0.000 6)	0.043 5 (0.000 8)	0.007 7 (0.000 5)	**−1.549 3** (0.007 8)	0.081 6 (0.001 3)	0.033 2 (0.000 8)	0.059 8 (0.001 2)
p_8	0.028 8 (0.000 9)	0.039 8 (0.001 4)	0.026 3 (0.001 1)	0.045 4 (0.001 0)	0.081 2 (0.001 3)	0.017 6 (0.000 8)	0.133 3 (0.002 1)	**−1.587 5** (0.005 5)	0.064 1 (0.001 2)	0.109 9 (0.001 8)
p_9	0.007 1 (0.000 6)	0.013 9 (0.001 1)	−0.001 7 (0.000 8)	0.010 3 (0.000 7)	0.017 0 (0.001 0)	−0.009 4 (0.000 6)	0.043 0 (0.001 5)	0.051 0 (0.001 5)	**−1.122 9** (0.005 4)	0.015 5 (0.001 4)
p_{10}	0.048 5 (0.001 4)	0.066 6 (0.002 2)	0.045 4 (0.001 7)	0.076 6 (0.001 6)	0.137 7 (0.001 9)	0.031 8 (0.001 3)	0.226 4 (0.003 3)	0.245 2 (0.002 8)	0.109 6 (0.001 9)	**−1.520 9** (0.005 1)

1: ELECTRICITY, 2: HEATING, 3: TRANSPORT, 4: FOOD, 5: CLOTHES, 6: HOUSING, 7: HEALTH, 8: MOBILITY, 9: EDUCATION, 10: OTHERS.

ities and food. Income elasticities do not differ substantially from expenditure elasticities. Income elasticities are slightly lower, since total expenditure on consumption goods does not increase proportionately with disposable income. We see a trend inversion for income elasticities of food for the highest expenditure quartile of couple households (C0-C3). Similar to expenditure elasticities of heating, income elasticities of heating exhibit a trend inversion for the highest expenditure quartiles of couple households.

The variation of expenditure elasticities between different household types is especially interesting for the lowest expenditure quartile since these households are the most vulnerable ones. Electricity and heating have a stronger necessity character for single households (S0) and lone parents (S1) when compared to couples. This finding is in line with the concept of economies of scale in energy use, which is well documented in the literature (Brounen et al., 2012).

4.1.2. Price elasticities

The modulus of price elasticities (in the following simply termed price elasticities) for energy goods and food, shown in Table 5, increases monotonically with increasing total expenditure. While all energy commodity groups remain in the inelastic range over the whole total expenditure distribution (with the exception of food for couples without children), price elasticities are relatively low in the lower quartile of the expenditure distribution and particularly low for single households (S0) and lone parents (S1) with respect to electricity.

Concerning the differences between household types, there seems to be a significant increase in price elasticities from single to couple households. The number of children, on the other hand, plays a minor role in determining elasticities. Looking at single households, the price elasticities for all households, except those belonging to the lowest expenditure quartile, is higher for singles without children (S0) than for lone parents (S1). The differences are, however, small and sometimes not significant at the 5% level.

Our results yield the same classification of necessities and luxury goods as found in Kohn and Missong (2003), but price elasticities show a different pattern. Unlike Kohn and Missong (2003), we observe price elasticities below and above unity. This can be explained by different time horizons underlying the studies. While Kohn and Missong (2003) use data from 1988 to 1993, we use data from 1993 to 2008, and thus cover a longer period in time and take a long-run perspective. The price elasticities obtained in the present study do not reflect instant demand changes due to increased prices under constraint budget. They also entail demand changes which are due to long-term effects, such as changes in lifestyle or the social environment and acquisitions or replacement of durable goods over time as alternative reaction to changes in prices. The latter aspect could include the increase in energy efficiency over time.

Nikodinoska and Schröder (2016) classify electricity, car fuels and other fuels as necessity goods, their estimates – especially for expenditure on energy – are somewhat higher than the ones obtained in this study. The predominant form of elasticity curves derived by Nikodinoska and Schröder (2016) over total expenditure is inverted U-shape, whereas we observe a monotonic increase of elasticities. It is, however, not clear to which extent both demand systems comprise the same goods and there are methodological differences. Therefore, the comparability of the results is limited. Our results are in line with those by Beznoska (2014), i.e. with respect to a higher price responsiveness in the case of heating fuels when compared to electricity. Rehdanz (2007) estimates price elasticities for different fuels used for residential space heating in Germany (p. 179). Her study implies a rather elastic demand for light heating oil (−2.03 to −1.68) and a less elastic demand for gas (−0.63 to −0.44). Other types of heating systems such as district heating are not considered. This shows that price elasticities are contingent on the type of heating system used, so that the figures

Table 4
Expenditure elasticities for energy goods and food for different household types at different total expenditure levels: Predicted values at the means of the 2008 household type specific total expenditure quartiles and at respective price means. Standard errors in parentheses are derived with the delta method.

Good		S0	S1	C0	C1	C2	C3
1	μ_{0-25}	0.260	0.253	0.281	0.291	0.298	0.281
		(0.004)	(0.004)	(0.003)	(0.003)	(0.004)	(0.004)
	μ_{25-50}	0.333	0.302	0.353	0.355	0.356	0.342
		(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
	μ_{50-75}	0.391	0.348	0.407	0.405	0.403	0.389
		(0.004)	(0.005)	(0.004)	(0.004)	(0.004)	(0.005)
	μ_{75-100}	0.485	0.437	0.495	0.477	0.471	0.462
		(0.004)	(0.005)	(0.007)	(0.006)	(0.007)	(0.008)
2	μ_{0-25}	0.279	0.293	0.311	0.353	0.362	0.367
		(0.003)	(0.004)	(0.003)	(0.005)	(0.005)	(0.006)
	μ_{25-50}	0.343	0.338	0.364	0.401	0.408	0.405
		(0.003)	(0.005)	(0.005)	(0.006)	(0.007)	(0.009)
	μ_{50-75}	0.387	0.378	0.398	0.431	0.436	0.432
		(0.004)	(0.005)	(0.008)	(0.009)	(0.010)	(0.012)
	μ_{75-100}	0.452	0.445	0.419	0.447	0.434	0.407
		(0.007)	(0.008)	(0.017)	(0.017)	(0.019)	(0.024)
3	μ_{0-25}	0.447	0.485	0.482	0.425	0.484	0.515
		(0.005)	(0.009)	(0.005)	(0.005)	(0.005)	(0.008)
	μ_{25-50}	0.533	0.556	0.584	0.522	0.588	0.613
		(0.005)	(0.009)	(0.005)	(0.005)	(0.006)	(0.008)
	μ_{50-75}	0.601	0.618	0.668	0.592	0.652	0.687
		(0.005)	(0.009)	(0.006)	(0.006)	(0.007)	(0.009)
	μ_{75-100}	0.723	0.736	0.807	0.721	0.773	0.830
		(0.005)	(0.009)	(0.009)	(0.008)	(0.010)	(0.012)
4	μ_{0-25}	0.610	0.570	0.540	0.546	0.576	0.581
		(0.005)	(0.006)	(0.004)	(0.004)	(0.004)	(0.005)
	μ_{25-50}	0.667	0.625	0.595	0.605	0.634	0.649
		(0.004)	(0.006)	(0.003)	(0.003)	(0.003)	(0.004)
	μ_{50-75}	0.705	0.660	0.625	0.642	0.662	0.688
		(0.003)	(0.005)	(0.003)	(0.003)	(0.003)	(0.004)
	μ_{75-100}	0.749	0.736	0.656	0.677	0.693	0.720
		(0.003)	(0.004)	(0.006)	(0.005)	(0.005)	(0.005)

1: ELECTRICITY, 2: HEATING, 3: TRANSPORT, 4: FOOD.

presented in this paper (−0.5 average own-price elasticity for heating, see Table 3) can only be understood as an average across the prevailing heating systems in Germany (Table 6).

4.2. Subsistence expenditure

The *QES* includes b_i parameters, which can be interpreted as absolute subsistence quantities with corresponding expenditure b_ip_i (compare Kohn and Missong, 2003 or Lewbel, 1997, p.188). The interpretation as subsistence parameters is illustrated by the expenditure functions (Eq. (17)), which describe expenditure as the fixed term b_ip_i and additional terms depending on the supernumerary expenditure $\mu - \sum_i p_i b_i$.

There are however differing views on the interpretation of the b_i parameters as subsistence expenditure. Pollak and Wales (1978) argue that the b_i parameters are generally allowed to be negative, which contradicts the interpretation as subsistence quantities. In the demand system at hand, there are in fact negative b_i parameters for the commodity groups health, mobility and other goods. All of these goods are luxury goods, especially for households of the lowest expenditure quartiles. It is therefore possible, that any purchasing decision for these goods happens within the range of apportionment of supernumerary expenditure, implying that actual subsistence levels for these goods are zero. Given the methodological issues attached to negative b_i parameters, we refrain from evaluating overall subsistence expenditure, and focus on subsistence expenditure on heating and electricity. Table 7 shows the respective monthly subsistence expenditures in euros at the price level of 2014.

Table 5
Price elasticities for different household types: Predicted values at the means of the household type specific total expenditure quartiles and respective prices. Standard errors in parentheses are derived with the delta method.

Good		S0	S1	C0	C1	C2	C3
1	μ_{0-25}	−0.179	−0.174	−0.234	−0.227	−0.238	−0.215
		(0.004)	(0.007)	(0.004)	(0.005)	(0.005)	(0.006)
	μ_{25-50}	−0.282	−0.244	−0.353	−0.341	−0.351	−0.324
		(0.005)	(0.007)	(0.006)	(0.006)	(0.006)	(0.007)
	μ_{50-75}	−0.376	−0.319	−0.467	−0.440	−0.449	−0.430
		(0.006)	(0.008)	(0.007)	(0.007)	(0.007)	(0.008)
	μ_{75-100}	−0.566	−0.501	−0.724	−0.657	−0.665	−0.676
		(0.008)	(0.010)	(0.011)	(0.010)	(0.010)	(0.012)
2	μ_{0-25}	−0.205	−0.215	−0.281	−0.302	−0.320	−0.311
		(0.003)	(0.008)	(0.004)	(0.006)	(0.006)	(0.009)
	μ_{25-50}	−0.313	−0.294	−0.413	−0.439	−0.463	−0.451
		(0.004)	(0.009)	(0.005)	(0.007)	(0.007)	(0.010)
	μ_{50-75}	−0.411	−0.378	−0.542	−0.559	−0.587	−0.592
		(0.005)	(0.009)	(0.006)	(0.009)	(0.008)	(0.012)
	μ_{75-100}	−0.616	−0.584	−0.845	−0.829	−0.861	−0.921
		(0.008)	(0.012)	(0.013)	(0.014)	(0.014)	(0.020)
3	μ_{0-25}	−0.295	−0.316	−0.367	−0.308	−0.350	−0.352
		(0.005)	(0.012)	(0.006)	(0.006)	(0.006)	(0.010)
	μ_{25-50}	−0.416	−0.412	−0.506	−0.433	−0.485	−0.488
		(0.006)	(0.012)	(0.006)	(0.007)	(0.007)	(0.010)
	μ_{50-75}	−0.515	−0.502	−0.628	−0.533	−0.585	−0.605
		(0.006)	(0.012)	(0.007)	(0.007)	(0.008)	(0.011)
	μ_{75-100}	−0.700	−0.693	−0.862	−0.731	−0.786	−0.842
		(0.007)	(0.013)	(0.010)	(0.009)	(0.010)	(0.013)
4	μ_{0-25}	−0.471	−0.446	−0.495	−0.476	−0.497	−0.480
		(0.006)	(0.012)	(0.005)	(0.006)	(0.005)	(0.008)
	μ_{25-50}	−0.602	−0.543	−0.628	−0.609	−0.629	−0.615
		(0.006)	(0.011)	(0.005)	(0.006)	(0.006)	(0.008)
	μ_{50-75}	−0.707	−0.630	−0.746	−0.715	−0.731	−0.731
		(0.006)	(0.011)	(0.006)	(0.007)	(0.006)	(0.008)
	μ_{75-100}	−0.902	−0.831	−1.010	−0.934	−0.946	−0.975
		(0.007)	(0.011)	(0.009)	(0.009)	(0.009)	(0.011)

1: ELECTRICITY, 2: HEATING, 3: TRANSPORT, 4: FOOD.

Table 6
Comparison of predicted expenditure elasticities: Comparison between own estimations (QES) and estimations by Nikodinoska and Schröder (2016) (QUAIDS). Mean of predicted expenditure elasticities from 1993 to 2008. 95% confidence intervals are shown in parentheses.

Good	eta_μ^i (QES)	eta_μ^i (QUAIDS)
Electricity	0.456 [0.455; 0.457]	0.507 [0.505; 0.509]
Heating/ *other fuels*	0.624 [0.623; 0.626]	0.724 [0.723; 0.725]
TRANSPORT/ *car fuels*	0.740 [0.738; 0.741]	0.832 [0.831; 0.833]
Food	0.636 [0.635; 0.637]	0.415 [0.376; 0.445]

Italic good description denotes deviating definitions by Nikodinoska and Schröder (2016).

The table also shows actual electricity expenditure of low income households in Germany which receive basic social security allowances (SGB II). These figures are drawn from Aigeltinger et al. (2015).[5] The last column shows 'modified' electricity expenditure. It denotes electricity expenditure as predicted by the QES at total expenditure levels

[5] There are no corresponding figures for heating expenditures available since heating expenses are directly reimbursed by the welfare agency as part of housing costs.

Table 7
Comparison of monthly subsistence expenditures for different household types: Own estimations are evaluated at 2014 CPI prices. Age of children in QES up to 17 years, German unemployment benefit (ALGII) scales vary with age of children: lower limit: all children are up to 5 years old, upper limit: all children are between 14 and 17 years old. Modified electricity expenditure describes estimated electricity expenditure for households whose overall expenditure corresponds to the ALGII. Standard errors in parentheses are derived with the delta method.

HH-Type	Heating subsistence (QES)	Electricity subsistence (QES)	Electricity needs[a]	Electricity (QES, modified)
S0	69.16 (0.51)	35.35 (0.24)	35.9	38.43 (0.19)
S1	84.87 (1.57)	47.32 (0.68)	42.7–52.8	51.98 (0.58)
C0	98.78 (0.78)	55.42 (0.38)	52.8	60.87 (0.29)
C1	97.26 (1.27)	62.97 (0.57)	49.6–69.7	69.50 (0.47)
C2	108.44 (1.26)	72.54 (0.57)	56.4–86.6	80.89 (0.45)
C3	117.07 (2.31)	84.70 (0.93)	63.2–103.5	94.57 (0.79)

[a] According to estimates by Aigeltinger et al. (2015).

corresponding to the German social security allowances.[6] The amount of German social security allowances roughly corresponds to the 'risk of income poverty line' in Germany (60% of median equivalised income, see also BMAS (2013)). Thus, the allowances define an overall expenditure level at which expenditures in the energy categories correspond to a more generous definition of subsistence levels.

Table 7 shows that subsistence expenditure is contingent on household type (i.e. the number of persons in the household), and that heating subsistence expenditures are in general higher when compared to electricity, as expected. The ratio between necessary heating and electricity expenditures decreases with an increasing number of household members. This implies that scale effects in energy use are stronger with regard to space heating when compared to electricity consumption. When we compare the subsistence expenditure on electricity with actual electricity expenditure of low-income households receiving basic social security payments, we find that actual expenditure is very close to the subsistence level. We find that modified electricity expenditure, as predicted by the *QES*, is slightly higher than what households receiving basic social security payments actually spend.

Overall, the concept of subsistence expenditure, and the corresponding figures as shown in Table 7 are relevant with respect to the discussion on fuel or energy poverty. The prevailing methodological approach is to evaluate the risk of fuel poverty based on energy expenditures and income of households (Hills, 2012; Moore, 2012). Such approaches appear arbitrary since they lack theoretical foundation and partly violate widely accepted demands of poverty measurement (Healy, 2004; Heindl and Schuessler, 2015; Heindl, 2015). Subsistence expenditure can be interpreted as an 'absolute fuel poverty line', i.e. an amount of money spent on energy, which must at least be available to households in order to afford a minimum standard of energy services. Arguably, there are conceptual difficulties attached to this concept, but subsistence expenditure might at least provide a rough indication of necessary minimum energy expenditure that – on average – corresponds to a level of energy consumption free from severe restrictions.

[6] To overcome conceptual difference of subsistence expenditure estimates and basic social security allowances, we estimate electricity expenditures at total expenditure levels corresponding to the German overall benefit payments. The necessary analytical relationship between total expenditure and expenditure comprising only the goods which are covered by benefit payments is derived through an auxiliary linear regression. Resulting electricity expenditures are shown in the last column of Table 7. Where the benefit payments cover a range, we provide estimated electricity expenditures at the mean of the upper and lower bounds of total benefit payments.

4.3. Equivalence scales

It is interesting per se how 'shareable' energy goods are, in particular because economies of scale in residential energy use might exist, implying that larger households can use energy goods more effectively compared to smaller ones. But economies of scale in energy use also play an important role in the discussion on fuel poverty. In the presence of economies of scale, smaller households might face a higher risk of being deprived compared to larger households, other things equal. To account for scale effects in residential energy use, Hills (2012) suggests using equivalised figures of household energy expenditure and income in assessments of affordability of energy services and fuel poverty. By doing so, Hills refers to the new OECD equivalence scale. This scale assigns a weight of 0.5 to any additional adult person in the household and a weight of 0.3 to any child ($\leq$ 15 years) in the household (Anyaegbu, 2010). In the QES, Kohn and Missong (2003) present a way to determine equivalence scales. Again using the b_i parameters, equivalence scales are estimated by dividing subsistence levels $\sum_i p_i b_i$ for each household type by the subsistence level of the reference household type S0 (single household).

The results, comprised in Table 8, show that the OECD scale matches the estimated empirical equivalence scale for electricity very well. However, heating expenditures show very strong scale effects, implying that the OECD scale overestimates actual expenditure of larger households in this case. With respect to expenditure on energy services in total (electricity and heating), the OECD scale approximates expenditure of lone parent households (S1) and couple households (C0) well, but overestimates expenditure of couple households with children (C1-C3). This implies that the OECD scale should not be applied to generate figures of energy expenditure 'per head' as suggested by Hills (2012) because such an approach would yield inaccurate figures.

4.4. Effects of price changes

The *QES* allows for a counterfactual assessment of the incidence of changing energy prices at the household level. The standard tool for such an assessment is the 'compensating variation'. For given house-

Table 8
Comparison of equivalence scales for different household types: *QES*-estimations are evaluated at 2014 prices. Age of children in *QES* up to 17 years, in OECD up to 15 years (Anyaegbu, 2010). Standard errors in parentheses are derived with the delta method.

HH	Energy ES (QES)	Electricity ES (QES)	Heating ES (QES)	OECD-modified scale
S0	1	1	1	1
S1	1.26 (0.02)	1.34 (0.02)	1.23 (0.02)	1.3
C0	1.48 (0.01)	1.57 (0.02)	1.43 (0.02)	1.5
C1	1.53 (0.02)	1.78 (0.02)	1.41 (0.02)	1.8
C2	1.73 (0.02)	2.05 (0.02)	1.57 (0.02)	2.1
C3	1.93 (0.03)	2.40 (0.03)	1.69 (0.04)	2.4

hold preferences - as derived from the estimated demand system - we exogenously change the prices of energy goods and obtain a new consumption schedule for each household. The compensating variation is the amount of money that would be required to obtain the original utility level given the new price vector.[7] This amount of money is eventually divided by the expenditure budget of the respective household, so that it represents a *relative* burden.

To assess the effects of price increases on welfare between 2000 and 2015, we create a base scenario for the year 2000 and analyse behavioural responses to changes in the prices of the base scenario. In the base scenario, we use the total expenditure and household type distribution of 2008. The prices for all commodity groups apart from electricity and heating are also taken from 2008. We use mean prices of the individualised prices described in Section A.2. For the energy commodities electricity and heating fuels, real prices for 2000 in terms of the 2008 price level are used.[8] This scenario is contrasted by the 2015 scenario. In the 2015 scenario, the total expenditure and household type distribution as well as prices for non-energy goods are kept constant (viz. at the level of the base scenario). The prices for electricity and heating are set at their real 2015 price level in terms of the 2008 price level. The resulting price increases amount to 61.5% of 2000 prices for electricity and to 35.5% of 2000 prices for heating fuels.

By comparing the two described settings, we can assess the consequences of energy price increases for a society composed as in 2008 and with a wealth level as in 2008. While the analysis is based on the status of society in 2008, its main findings have a more universal character, since the composition of the German society in terms of wealth distribution has not changed crucially since 2008. Deflated overall consumption expenditure of private households increased by about 4% between 2008 and 2014 according to a report by the German Federal Statistical Office (Statistisches Bundesamt, 2016, p.9). Inequality has remained on a constant level since 2005 according to Goebel et al. (2015).

Fig. 1 shows the predicted compensating variation of energy price increases between 2000 and 2015 divided by total expenditure for each household type. For energy price increases between 2000 and 2015, relative compensating variation covers a range of about 1.75% for the richest couple households to 3.75% for the poorest singles without children. It has a mean value of 2.5%. The result clearly shows that there are significant differences of relative burdens born across the quartiles of the expenditure distribution. Thus, energy price increases (electricity and heating fuels) tend to be regressive. The variation of relative burdens across household types is less pronounced. While burdens are somewhat smaller for families with children when compared to single households or single parents, the expenditure budget appears to be the most important determinant.

Previous research has shown, that the expenditure share for necessities, and in particular for energy services, differs strongly across the income distribution, whereby low-income households spend larger portions of income on energy services when compared to wealthier households (Meier et al., 2013; Heindl, 2015). This pattern contributes to regressive effects of energy price increases, but the impact of differentiated price elasticities has not been discussed so far. The assumption of zero price elasticities made in previous studies (Grösche and Schröder, 2014; Neuhoff et al., 2013) distorts actual income distributions after imposition of the burdens of price increases in two respects: If the modulus of energy price elasticities is larger than zero, households will reduce their energy consumption in response to price increases. Thus, the burden of price increases decreases. If price elasticties are the same for all households, the inequality in remaining income/total expenditure after subtraction of the burden is smaller than in case of zero expenditure elasticities. On the other hand, energy price elasticities in the system estimated in this article are not constant over households. Richer households reduce their consumption relatively more than poorer households and thus evade the burdens of price increases more effectively. This effect increases inequality compared to the case of constant elasticities.

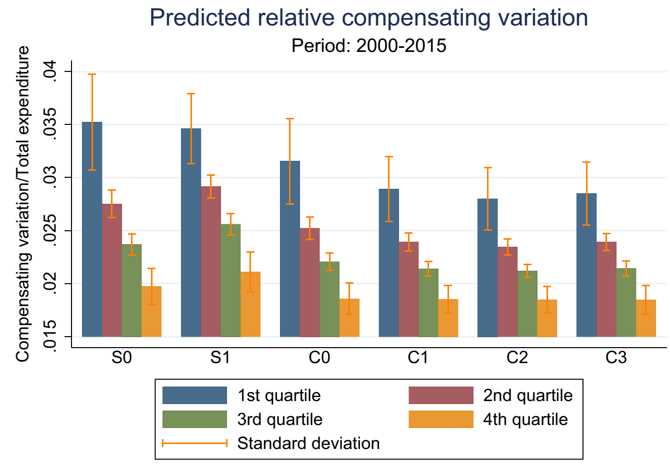

Fig. 1. Predicted compensating variation divided by total expenditure due to real price increases for electricity and heating fuels between 2000 and 2015. The x-axis depicts the household types 'single' (S) and 'couple' (C) followed by the number of children in the household, e.g. C1 represents a couple with one child.

To investigate the effect of behavioural responses to price increases, we estimate the change in the Gini coefficient[9] of the equivalent total expenditure distribution due to residential energy price increases as between 2000 and 2015. The change in the expenditure distribution is induced by the subtraction of the burden $\sum_{i=1}^{2}(p_{i,2015} - p_{i,2000})\cdot q_{i,2015}$ which arises from price increases of electricity (p_1) and heating fuels (p_2).

After subtraction of the burden arising from residential energy price, the Gini coefficient of equivalent total expenditure increases between 2000 and 2015 amounts to 2.143 (+1.3%). Thus, uncompensated energy price increases lead to increasing inequality in the *QES*. This is in line with the findings by Grösche and Schröder (2014) which are based on a different methodology. However, the increase is 22% higher than the change in the Gini coefficient resulting from a scenario with zero price elasticities. The assumption of zero elasticities therefore clearly understates the true effects of residential energy price increases as between 2000 and 2015.

4.5. Robustness of results

To assess the robustness of the estimated system, we compare the obtained elasticities with results from other meaningful system specifications. We test for robustness in face of variations in two dimensions: the number of commodity groups and the time-dependence of preferences. As a first alternative system specification we estimate a demand system comprising five commodity groups: electricity, heating, transport, food and other goods. The other goods category comprises

[7] Please note, that this is not an inter-personal (or inter-household) comparison of utility, because utility levels before and after a change in prices are compared within and not across households.

[8] Price developments are calculated using the German CPI for electricity and heating fuels deflated by the overall German CPI. The price for heating fuels is a combined price of gas, oil, coal and district heating prices. The combination follows the weighting schemes of the German Federal Statistical Office used for the calculation of the CPI in the respective year. For 2000 prices the weighting scheme of 2000 is used, for 2008 prices the 2005 weighting scheme is used and for 2015 prices the 2010 weighting scheme is applied.

[9] The Gini coefficient is an inequality measure based on the difference between the actual Lorenz curve and the Lorenz curve of perfect equality. The Lorenz curve depicts normalised cumulated income/wealth/etc. as a function of the share of population, ordered from 'poor' to 'rich'. For a detailed description of the Gini coefficient and other inequality measures see Grösche and Schröder (2014).

Table 9
Elasticity robustness check: Comparison of weighted averages of household type specific predicted elasticities; upper part shows elasticities evaluated at the 2008 price and expenditure means, lower part shows elasticities evaluated at the means of the 2008 total expenditure quartiles and respective price means. Predictions are obtained from the ten goods demographically translated QES with household types as demographic variables (10goods), a ten goods demographically translated QES with household types and years as demographic variables (Years) and a five goods demographically translated QES with household types as demographic variables (5goods). Standard errors in parentheses are derived with the delta method.

		η_μ^i			$\eta_{p_i}^i$		
Good		10*goods*	*Years*	5*goods*	10*goods*	*Years*	5*goods*
1		0.399	0.411	0.470	−0.431	−0.438	−0.467
		(0.004)	(0.004)	(0.004)	(0.006)	(0.006)	(0.005)
2		0.406	0.393	0.584	−0.501	−0.457	−0.579
		(0.006)	(0.006)	(0.004)	(0.005)	(0.006)	(0.004)
3		0.637	0.613	0.738	−0.573	−0.563	−0.709
		(0.005)	(0.005)	(0.004)	(0.006)	(0.005)	(0.005)
4		0.658	0.656	0.654	−0.726	−0.661	−0.685
		(0.003)	(0.003)	(0.002)	(0.005)	(0.005)	(0.003)
5		1.196	1.361		−1.210	−1.218	
		(0.004)	(0.005)		(0.005)	(0.008)	
6		0.696	0.664		−0.626	−0.573	
		(0.003)	(0.003)		(0.005)	(0.005)	
7		1.368	1.312		−1.550	−1.315	
		(0.006)	(0.006)		(0.008)	(0.010)	
8		1.412	1.523		−1.588	−1.472	
		(0.006)	(0.008)		(0.005)	(0.011)	
9		1.205	1.171		−1.123	−1.010	
		(0.004)	(0.004)		(0.005)	(0.007)	
10		1.748	1.816	1.173	−1.521	−1.416	−1.016
		(0.005)	(0.006)	(0.001)	(0.005)	(0.008)	(0.001)
1	μ_{0-25}	0.301	0.332	0.410	−0.235	−0.217	−0.350
		(0.004)	(0.004)	(0.005)	(0.004)	(0.004)	(0.005)
	μ_{25-50}	0.354	0.377	0.445	−0.337	−0.334	−0.419
		(0.004)	(0.004)	(0.004)	(0.005)	(0.005)	(0.005)
	μ_{50-75}	0.389	0.401	0.456	−0.423	−0.432	−0.456
		(0.004)	(0.004)	(0.004)	(0.006)	(0.006)	(0.005)
	μ_{75-100}	0.465	0.441	0.469	−0.647	−0.683	−0.522
		(0.006)	(0.006)	(0.004)	(0.009)	(0.010)	(0.005)
2	μ_{0-25}	0.316	0.319	0.504	−0.264	−0.220	−0.444
		(0.003)	(0.003)	(0.005)	(0.004)	(0.004)	(0.005)
	μ_{25-50}	0.370	0.365	0.557	−0.389	−0.346	−0.525
		(0.004)	(0.004)	(0.005)	(0.004)	(0.005)	(0.004)
	μ_{50-75}	0.402	0.387	0.580	−0.504	−0.460	−0.579
		(0.007)	(0.006)	(0.005)	(0.006)	(0.006)	(0.004)
	μ_{75-100}	0.435	0.395	0.585	−0.790	−0.683	−0.647
		(0.015)	(0.016)	(0.006)	(0.011)	(0.010)	(0.005)

1: ELECTRICITY, 2: HEATING, 3: TRANSPORT, 4: FOOD, 5: CLOTHES, 6: HOUSING, 7: HEALTH, 8: MOBILITY, 9: EDUCATION, 10: OTHERS.

commodity groups 5–10 of the ten-good-system presented above (reference system). In the second alternative specification we extend the translation of the b_i parameters by adding year indicator variables for the years 1993–2003. We, therewith, overcome the assumption of constant preferences implicit in the reference system.

Table 9 gives an overview of predicted elasticities for 2008. In the upper part it shows household means of elasticities evaluated at the mean total expenditure and price level in 2008 for all commodity groups. In the lower part it shows household means of elasticities evaluated at the means of the 2008 total expenditure quartiles and respective price means for electricity and heating fuels. The upper part shows that the classification into necessity and luxury goods as well as into price elastic and inelastic goods is robust over all demand system specifications. Mean elasticities for comparable commodity groups, however, differ significantly in most cases. The mean absolute relative difference of the comparable expenditure elasticities $1/n\sum_i|(\eta_\mu^i - \eta_\mu^{i'})/\eta_\mu^{i'}|$ between the five goods and the reference system amounts to 0.2 whereas it amounts only to 0.05 in the comparison of the ten-good-system with year indicator variables to the reference system. For price elasticities, the respective differences are 0.13 and 0.07. It thus seems that estimated elasticities are rather robust in face of the time dependence of the subsistence parameters. They are, however, less robust against the number of commodity groups described by the demand system. The lower part of the table focuses on residential energy goods. It provides a similar picture as the upper part. The estimated trends of elasticities over the total expenditure distribution are robust. In all three systems expenditure elasticities and absolute price elasticities increase with increasing total expenditure for both commodity groups. However, the range of elasticities covered differs between systems.

5. Conclusion and policy implications

We investigate price and expenditure elasticities of residential energy demand (electricity and space heating) in Germany by applying a quadratic expenditure system (QES) and using official expenditure data from 1993 to 2008. Households are disaggregated along two dimensions: (i) total expenditure and (ii) household size. This approach allows a detailed description of consumption behaviour, which is instrumental for understanding the consequences of changes in energy prices for welfare, e.g. as a result of direct energy taxation.

The results suggest that the reaction to changes in prices for energy goods is strongly dependent on total household expenditure. Households in the top expenditure quartile are much more price sensitive - both with respect to electricity and heating - compared to households in the lowest expenditure quartile. This view is supported by the analysis of an isolated increase in energy prices, where expenditure and prices for other goods are kept constant. The relative compensating variation clearly shows a regressive pattern of price increases for energy services. Thus, relative burdens at the household level are strongly dependent on total expenditure.

The disaggregated view on household size and composition further shows that there are considerable economies of scale in residential energy use. Larger households tend to use energy services more effectively compared to smaller ones. A household consisting of two adults, for instance, faces costs for energy services of about 1.48-times the amount a single household spends on energy services. A household consisting of one adult person and one child spends about 1.26-times the amount a single person spends on energy services. The empirical estimation indicates, that the ‘new OECD equivalence scale’ can be used to approximate scale effects in residential electricity use but not scale effects with respect to space heating.

The results have important implications for energy and climate policy. A real increase in energy prices has regressive effects at the household level. This implies that direct energy taxation or carbon finance mechanisms based on a surcharge per unit of energy consumption will tend to increase economic inequality. Larger relative burdens which fall on households with low income or low expenditure budget will further increase the likelihood of energy related deprivation or deprivation which occurs in other domains of consumption as a consequence of increased energy prices.

The inter-relationship between household characteristics, prices, and incomes, demonstrated in this study, provides important information for ex ante assessments of the welfare consequences of energy subsidies or taxes. The results allow an assessment of the trade-off between efficiency and equity resulting from changes in energy prices. Such assessments may, for example, take place in a behavioural microsimulation framework, which takes changes in expenditure of various household types into account by using the respective price and expenditure elasticities estimated in this paper.

Of course price increases also contribute to a reduction of energy consumption and therefore to energy conservation. However, these effects are contingent on the position of households in the expenditure distribution. The estimated price elasticities imply that low income households will tend to decrease energy consumption to a lower extent compared to households with a higher income. Our empirical results also offer an avenue to estimate expected changes in energy consumption of different household types, which is useful for the design of policies which aim at energy conservation by pecuniary incentives.

The results clearly show that assessments of the welfare consequences of real energy price changes and the accompanying shifts in demand hinge on the modelling assumptions. Most importantly, adequate modelling of the behavioural response of households is instrumental. The increase in inequality as a consequence of an increase in real energy prices as between 2000 and 2015 is about 22% larger if detailed price and expenditure elasticities are used when compared to a situation in which elasticities are set to zero. The application of differentiated price and income elasticities of energy demand across the dimensions of expenditure, income, and household size will further help to improve the accuracy of behavioural models of energy demand. This is because the average behavioural response, viz. using uniform price and expenditure elasticities for all households, overestimates behavioural responses at the lower end of the expenditure distribution and underestimates the response at the upper end.

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Appendix A. Mathematical Appendix

A.1. The quadratic expenditure system

Each theoretically plausible quadratic expenditure system is generated by the following indirect utility function:

$$\Psi(\boldsymbol{P}, \mu) = -\frac{g(\boldsymbol{P})}{\mu - f(\boldsymbol{P})} - \frac{\alpha(\boldsymbol{P})}{g(\boldsymbol{P})}, \tag{10}$$

where $\boldsymbol{P}^T = (p_1, \ldots, p_n)$ is the vector of prices for n commodity groups and μ denotes total expenditure. The realisation of the variable vector $(\boldsymbol{P}, \mu)$ can differ for each entity which is described by the demand system. For Ψ to be homogeneous of degree zero in $(\boldsymbol{P}, \mu)$, the functions $f(\boldsymbol{P})$, $g(\boldsymbol{P})$ and $\alpha(\boldsymbol{P})$ must be homogeneous of degree one in $\boldsymbol{P}$. Applying Roy's identity yields the following Marshallian demand equation for the demand q_i of the ith good:

$$q_i(\boldsymbol{P}, \mu) = \frac{1}{g^2}\left(\alpha_{p_i} - \frac{g_{p_i}}{g}\alpha\right)(\mu - f)^2 + \frac{g_{p_i}}{g}(\mu - f) + f_{p_i}. \tag{11}$$

The subscript p_i denotes partial derivatives with respect to p_i. As specification of the functions f, g and α, we use a system also presented by Howe et al. (1979):

$$g(\boldsymbol{P}) = \prod_i p_i^{a_i}, \tag{12}$$

$$f(\boldsymbol{P}) = \sum_i p_i \tilde{b}_i, \tag{13}$$

$$\alpha(\boldsymbol{P}) = \sum_i p_i c_i, \tag{14}$$

$$\sum_i a_i = 1. \tag{15}$$

This system includes the final model parameters a_i, $\tilde{b}_i$, c_i for $i \in \{1, \ldots, n\}$. Restriction (15) ensures summability of the resulting demand system. The resulting system is characterised by the indirect utility function (16) and expenditure functions (17) (adopted from Kohn and Missong (2003)):

$$\Psi(\boldsymbol{P}, \mu) = -\frac{\prod_i p_i^{a_i}}{\mu - \sum_i p_i \tilde{b}_i} - \frac{\sum_i p_i c_i}{\prod_i p_i^{a_i}}, \tag{16}$$

$$p_i q_i(\boldsymbol{P}, \mu) = p_i \tilde{b}_i + a_i(\mu - \sum_k p_k \tilde{b}_k) + \left(c_i p_i - \sum_k p_k c_k\right) \prod_k p_k^{-2a_k} \left(\mu - \sum_k p_k \tilde{b}_k\right)^2, \quad \sum_k a_k = 1. \tag{17}$$

Note here, that the i index in sums and products (12)–(15) is changed to k for notational clarity. This specification reduces to a linear demand system in case of $c_i = 0\ \forall\ i$. The system of Marshallian demands $\boldsymbol{q}^T = (q_1, \ldots, q_n)$ satisfies by construction the summability constraint, is homogeneous of degree zero in $(\boldsymbol{P}, \mu)$ and has a symmetric Slutsky matrix. Testing for theoretical plausibility of the estimated demand system therefore consists in testing for positivity and negative semidefiniteness of the Slutsky matrix. The specification shown here is to be preferred over others due to its low number of free parameters. It has $3n - 1$ free parameters, i.e. for each of the n equations exists a parameter set $\{a_i, \tilde{b}_i, c_i\}$. However, due to the summability constraint realised by $\sum_i a_i = 1$ one a_i is determined by the others.

A.2. Stone-lewbel cross section prices

Lewbel presents a theory of household specific price indices under the assumption of *weakly separable* demands.[10] We adopt Lewbel's approach, who constructs price indices for the case of Cobb-Douglas within group utility functions:

$$u_i(\boldsymbol{q_i}, \boldsymbol{s}) = g_i \cdot \prod_h q_{ih}^{w_{ih}(\boldsymbol{s})}, \quad \sum_h w_{ih}(\boldsymbol{s}) = 1. \tag{18}$$

Thereby s denotes a vector of demographic characteristics, g_i is a scaling factor, and q_{ih} and w_{ih} denote consumed quantity and group budget share of good h in commodity group i. In the case of within group utility functions as in Eq. (18) one obtains the household specific price index $p_i(\boldsymbol{s})$:

$$p_i(\boldsymbol{s}) = \frac{1}{g_i} \cdot \prod_h \left(\frac{\widehat{p}_{ih}}{w_{ih}}\right)^{w_{ih}}, \tag{19}$$

whereby $\widehat{p}_{ih}$ denotes prices for good h of commodity group i and the scaling factor g_i represents the reference household with its group budget shares $\overline{w_{ih}}$:

$$g_i = \prod_h (\overline{w_{ih}})^{-\overline{w_{ih}}}. \tag{20}$$

We adopt the approach by Hoderlein and Mihaleva (2008) and use as reference household a fictive household with average within group budget shares in each good category of each commodity group.

A.3. Elasticities

Price and expenditure elasticities can be derived from the well-defined expenditure system. In the *QES* expenditure elasticities $\frac{\delta q_i(\boldsymbol{P}, \mu)}{\delta \mu} \frac{\mu}{q_i(\boldsymbol{P}, \mu)}$ are given by:

$$\eta_\mu^i = \frac{\mu}{q_i}\left\{\frac{a_i}{p_i} + 2\left(c_i - \frac{a_i}{p_i}\sum_{k=1}^n p_k c_k\right)\prod_{k=1}^n p_k^{-2a_k}\left(\mu - \sum_{k=1}^n p_k b_k\right)\right\} \tag{21}$$

and own-price elasticities $\frac{\delta q_i(\boldsymbol{P}, \mu)}{\delta p_i} \frac{p_i}{q_i(\boldsymbol{P}, \mu)}$ are given by:

$$\eta_{p_i}^i = -\frac{1}{p_i q_i}\left\{a_i\left(\mu - \sum_{k=1}^n p_k b_k\right) + p_i a_i b_i - \left(a_i \sum_{k=1}^n p_k c_k - p_i a_i c_i\right)\prod_{k=1}^n p_k^{-2a_k}\left(\mu - \sum_{k=1}^n p_k b_k\right)^2 - 2\left(a_i \sum_{k=1}^n p_k c_k - p_i c_i\right)\prod_{k=1}^n p_k^{-2a_k}\left(\mu - \sum_{k=1}^n p_k b_k\right)\left(a_i\left(\mu - \sum_{k=1}^n p_k b_k\right) + p_i b_i\right)\right\}$$

$$. \tag{22}$$

Finally, cross-price elasticities $\frac{\delta q_i(\boldsymbol{P}, \mu)}{\delta p_j} \frac{p_j}{q_i(\boldsymbol{P}, \mu)}$ are given by:

$$\eta_{p_j}^i = -\frac{p_j}{q_i}\left\{\frac{a_i b_j}{p_i} + \left(\mu - \sum_{k=1}^n p_k b_k\right)^2 \prod_{k=1}^n p_k^{-2a_k}\left\{\frac{a_i c_j}{p_i} + 2\left(c_i - \frac{a_i}{p_i}\sum_{k=1}^n p_k c_k\right)\left(\frac{a_j}{p_j} + \frac{b_j}{\mu - \sum_{k=1}^n p_k b_k}\right)\right\}\right\}. \tag{23}$$

Appendix B. Tables

Tables 10–14

Table 10
Nonlinear seemingly unrelated regression coefficients: Estimation is based on a *QES* with demographic translation; dependent variables: expenditure on different commodity groups divided by generalised total expenditure; translation coefficients are not shown.

	Coefficient	(Robust Std. Err.)
b1	0.843	(0.006)
b2	1.796	(0.013)
b3	1.720	(0.019)
b4	3.858	(0.040)
b5	0.045	(0.017)

(continued on next page)

[10] The assumption of weak separability requires that goods are partitioned into subsets in "such a way that every marginal rate of substitution involving two goods from the same subset depends only on the goods in that subset." (Pollak and Wales, 1992, p. 44). This assumption is widely applied in demand system analysis, and yet, it is never trivial. However, our model exhibits a rather high level of commodity disaggregation, since only fairly similar goods are allocated to the same commodity group. Hence the condition of weak separability is likely to be met at least approximately. It is probably well met in the case of energy goods where the categories consist of very few and similar sub-categories. The disaggregation into three different energy categories is shared by many other authors (e.g. Beznoska, 2014; Nikodinoska and Schröder, 2016; Böhringer et al., 2016) Other categories have a broader definition, but still, differentiating into six more non-energy categories instead of only one "other goods" category optimizes the system in that respect. So does the decision to disaggregate durable goods into three categories rather than one despite the need to average consumption over durable goods (compare Section 3.2).

Table 10 *(continued)*

	Coefficient	(Robust Std. Err.)
b6	7.179	(0.051)
b7	−0.278	(0.021)
b8	−0.890	(0.029)
b9	0.464	(0.028)
b10	−3.421	(0.070)
a1	0.0953	(0.0001)
a2	0.0202	(0.0002)
a3	0.0280	(0.0003)
a4	0.1259	(0.0011)
a5	0.0743	(0.0004)
a6	0.1180	(0.0012)
a7	0.0914	(0.0006)
a8	0.1528	(0.0012)
a9	0.1118	(0.0007)
c1	−4.95e-05	(0.17e-05)
c2	−13.92e-05	(0.54e-05)
c3	−11.39e-05	(0.50e-05)
c4	−63.79e-05	(1.98e-05)
c5	−35.70e-05	(0.73e-05)
c6	−26.18e-05	(1.37e-05)
c7	−54.81e-05	(1.10e-05)
c8	−95.43e-05	(1.84e-05)
c9	−42.73e-05	(1.01e-05)
c10	−151.85e-05	(3.98e-05)
n	108686	
AIC	−2642460	
BIC	−2641702	

Wald test $c_i = 0\ \forall\ i$: $\chi^2(10) = 3814.62$, Prob $> \chi^2 = 0.00$.

Table 11
Slutsky matrix: Eigenvalues (eg) evaluated at the means of the 2008 total expenditure quartiles of the household type specific distributions and at respective price means.

Good		eg1	eg2	eg3	eg4	eg5	eg6	eg7	eg8	eg9	eg10
S0	μ_{0-25}	−0.000	−0.002	−0.005	−0.009	−0.014	−0.017	−0.021	−0.025	−0.029	−0.058
	μ_{25-50}	0.000	−0.004	−0.009	−0.015	−0.025	−0.031	−0.037	−0.042	−0.050	−0.104
	μ_{50-75}	0.000	−0.005	−0.014	−0.021	−0.038	−0.045	−0.053	−0.059	−0.069	−0.153
	μ_{75-100}	0.000	−0.010	−0.024	−0.036	−0.068	−0.084	−0.094	−0.099	−0.122	−0.286
S1	μ_{0-25}	0.000	−0.003	−0.007	−0.011	−0.017	−0.022	−0.026	−0.033	−0.039	−0.073
	μ_{25-50}	0.000	−0.004	−0.011	−0.016	−0.026	−0.030	−0.037	−0.048	−0.057	−0.111
	μ_{50-75}	−0.000	−0.006	−0.015	−0.022	−0.036	−0.043	−0.052	−0.066	−0.079	−0.161
	μ_{75-100}	−0.000	−0.011	−0.028	−0.039	−0.069	−0.083	−0.097	−0.118	−0.135	−0.305
C0	μ_{0-25}	0.000	−0.004	−0.012	−0.017	−0.030	−0.036	−0.044	−0.053	−0.061	−0.126
	μ_{25-50}	0.000	−0.008	−0.019	−0.028	−0.052	−0.061	−0.074	−0.084	−0.096	−0.213
	μ_{50-75}	0.000	−0.011	−0.028	−0.040	−0.077	−0.090	−0.106	−0.116	−0.135	−0.315
	μ_{75-100}	0.000	−0.020	−0.051	−0.073	−0.147	−0.177	−0.190	−0.204	−0.257	−0.605
C1	μ_{0-25}	0.000	−0.005	−0.012	−0.019	−0.031	−0.037	−0.045	−0.058	−0.068	−0.136
	μ_{25-50}	−0.000	−0.008	−0.020	−0.031	−0.053	−0.062	−0.073	−0.093	−0.109	−0.222
	μ_{50-75}	0.000	−0.011	−0.028	−0.042	−0.076	−0.088	−0.102	−0.125	−0.145	−0.308
	μ_{75-100}	−0.000	−0.020	−0.049	−0.073	−0.133	−0.155	−0.178	−0.209	−0.258	−0.569
C2	μ_{0-25}	0.000	−0.006	−0.015	−0.022	−0.035	−0.042	−0.053	−0.070	−0.087	−0.162
	μ_{25-50}	0.000	−0.010	−0.024	−0.036	−0.058	−0.068	−0.084	−0.110	−0.134	−0.268
	μ_{50-75}	−0.000	−0.013	−0.034	−0.048	−0.081	−0.096	−0.116	−0.149	−0.176	−0.372
	μ_{75-100}	0.000	−0.023	−0.056	−0.081	−0.145	−0.171	−0.202	−0.246	−0.294	−0.666
C3	μ_{0-25}	0.000	−0.006	−0.015	−0.023	−0.035	−0.043	−0.056	−0.074	−0.095	−0.169
	μ_{25-50}	−0.000	−0.010	−0.025	−0.037	−0.060	−0.070	−0.088	−0.113	−0.147	−0.278
	μ_{50-75}	0.000	−0.014	−0.036	−0.052	−0.087	−0.104	−0.130	−0.164	−0.203	−0.384
	μ_{75-100}	−0.000	−0.026	−0.063	−0.096	−0.167	−0.202	−0.241	−0.295	−0.345	−0.743

List of goods: 1: ELECTRICITY, 2: HEATING, 3: TRANSPORT, 4: FOOD, 5: CLOTHES, 6: HOUSING, 7: HEALTH, 8: MOBILITY, 9: EDUCATION, 10: OTHERS.

Table 12
Expenditure elasticities for different household types: Table 4 continued.

Good		S0	S1	C0	C1	C2	C3
5	μ_{0-25}	1.610	1.188	1.442	1.196	1.121	1.121
		(0.015)	(0.018)	(0.010)	(0.010)	(0.008)	(0.012)
	μ_{25-50}	1.377	1.156	1.298	1.144	1.089	1.096
		(0.007)	(0.013)	(0.006)	(0.007)	(0.006)	(0.009)
	μ_{50-75}	1.276	1.116	1.229	1.122	1.068	1.075
		(0.005)	(0.010)	(0.005)	(0.006)	(0.005)	(0.007)
	μ_{75-100}	1.173	1.076	1.150	1.084	1.046	1.036
		(0.003)	(0.006)	(0.005)	(0.005)	(0.006)	(0.007)
6	μ_{0-25}	0.380	0.437	0.529	0.559	0.579	0.556
		(0.004)	(0.005)	(0.004)	(0.005)	(0.005)	(0.006)
	μ_{25-50}	0.489	0.516	0.653	0.677	0.694	0.670
		(0.003)	(0.005)	(0.004)	(0.005)	(0.004)	(0.006)
	μ_{50-75}	0.581	0.594	0.755	0.765	0.783	0.776
		(0.003)	(0.005)	(0.004)	(0.005)	(0.005)	(0.006)
	μ_{75-100}	0.730	0.756	0.923	0.920	0.934	0.952
		(0.003)	(0.005)	(0.005)	(0.005)	(0.006)	(0.007)
7	μ_{0-25}	2.039	2.593	1.635	2.242	2.230	2.367
		(0.024)	(0.065)	(0.014)	(0.028)	(0.023)	(0.043)
	μ_{25-50}	1.534	1.920	1.327	1.633	1.642	1.714
		(0.010)	(0.029)	(0.007)	(0.012)	(0.011)	(0.019)
	μ_{25-50}	1.335	1.599	1.183	1.406	1.412	1.439
		(0.006)	(0.017)	(0.006)	(0.008)	(0.008)	(0.013)
	μ_{75-100}	1.144	1.266	1.016	1.156	1.164	1.154
		(0.004)	(0.008)	(0.008)	(0.008)	(0.009)	(0.011)
8	μ_{0-25}	2.551	2.419	2.164	1.989	1.978	1.988
		(0.030)	(0.068)	(0.020)	(0.026)	(0.022)	(0.036)
	μ_{25-50}	1.731	1.831	1.567	1.516	1.513	1.506
		(0.010)	(0.032)	(0.009)	(0.013)	(0.011)	(0.019)
	μ_{50-75}	1.449	1.549	1.311	1.303	1.303	1.273
		(0.006)	(0.019)	(0.007)	(0.009)	(0.009)	(0.014)
	μ_{75-100}	1.171	1.196	1.017	1.066	1.039	0.959
		(0.004)	(0.010)	(0.009)	(0.009)	(0.010)	(0.013)
9	μ_{0-25}	1.348	1.074	1.457	1.137	0.977	0.959
		(0.011)	(0.015)	(0.010)	(0.009)	(0.007)	(0.010)
	μ_{25-50}	1.255	1.044	1.342	1.123	0.992	0.977
		(0.006)	(0.011)	(0.006)	(0.006)	(0.005)	(0.008)
	μ_{50-75}	1.210	1.052	1.290	1.118	1.013	0.987
		(0.004)	(0.009)	(0.004)	(0.005)	(0.005)	(0.007)
	μ_{75-100}	1.175	1.049	1.243	1.099	1.028	1.036
		(0.003)	(0.006)	(0.004)	(0.005)	(0.006)	(0.007)
10	μ_{0-25}	5.019	5.166	2.607	2.916	2.820	3.055
		(0.076)	(0.178)	(0.018)	(0.031)	(0.025)	(0.046)
	μ_{25-50}	2.328	2.754	1.823	1.979	1.972	2.076
		(0.011)	(0.040)	(0.006)	(0.011)	(0.009)	(0.017)
	μ_{50-75}	1.804	2.068	1.563	1.684	1.701	1.738
		(0.005)	(0.018)	(0.005)	(0.007)	(0.007)	(0.011)
	μ_{75-100}	1.440	1.542	1.340	1.423	1.452	1.444
		(0.003)	(0.007)	(0.005)	(0.006)	(0.006)	(0.008)

5: CLOTHES, 6: HOUSING, 7: HEALTH, 8: MOBILITY, 9: EDUCATION, 10: OTHERS.

Table 13
Own-price elasticities for different household types: Table 5 continued.

Good		S0	S1	C0	C1	C2	C3
5	μ_{0-25}	−1.045	−0.799	−1.132	−0.909	−0.881	−0.850
		(0.014)	(0.025)	(0.012)	(0.013)	(0.011)	(0.017)
	μ_{0-25}	−1.113	−0.912	−1.228	−1.063	−1.050	−1.028
		(0.009)	(0.020)	(0.008)	(0.010)	(0.009)	(0.014)
	μ_{0-25}	−1.170	−1.006	−1.315	−1.173	−1.174	−1.173
		(0.007)	(0.018)	(0.007)	(0.009)	(0.008)	(0.013)
	μ_{0-25}	−1.294	−1.194	−1.521	−1.396	−1.418	−1.475
		(0.007)	(0.014)	(0.008)	(0.010)	(0.009)	(0.014)
6	μ_{0-25}	−0.327	−0.355	−0.449	−0.446	−0.460	−0.431

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Table 13 *(continued)*

Good		S0	S1	C0	C1	C2	C3
		(0.004)	(0.009)	(0.005)	(0.007)	(0.006)	(0.008)
	μ_{25-50}	−0.439	−0.439	−0.580	−0.574	−0.585	−0.555
		(0.005)	(0.009)	(0.005)	(0.007)	(0.006)	(0.008)
	μ_{50-75}	−0.532	−0.519	−0.688	−0.671	−0.680	−0.665
		(0.005)	(0.009)	(0.005)	(0.007)	(0.006)	(0.008)
	μ_{75-100}	−0.691	−0.692	−0.878	−0.843	−0.851	−0.860
		(0.005)	(0.008)	(0.007)	(0.007)	(0.007)	(0.008)
7	μ_{0-25}	−1.355	−1.706	−1.404	−1.761	−1.817	−1.826
		(0.021)	(0.059)	(0.017)	(0.029)	(0.024)	(0.041)
	μ_{25-50}	−1.320	−1.561	−1.463	−1.693	−1.763	−1.788
		(0.012)	(0.039)	(0.011)	(0.018)	(0.016)	(0.028)
	μ_{50-75}	−1.349	−1.530	−1.551	−1.708	−1.807	−1.825
		(0.009)	(0.029)	(0.010)	(0.015)	(0.014)	(0.023)
	μ_{75-100}	−1.461	−1.575	−1.799	−1.888	−1.989	−2.068
		(0.009)	(0.020)	(0.013)	(0.016)	(0.016)	(0.022)
8	μ_{0-25}	−1.617	−1.558	−1.752	−1.534	−1.588	−1.528
		(0.018)	(0.032)	(0.016)	(0.017)	(0.013)	(0.020)
	μ_{25-50}	−1.435	−1.451	−1.658	−1.535	−1.615	−1.609
		(0.009)	(0.022)	(0.010)	(0.012)	(0.009)	(0.016)
	μ_{50-75}	−1.430	−1.432	−1.712	−1.619	−1.702	−1.707
		(0.007)	(0.017)	(0.008)	(0.011)	(0.009)	(0.015)
	μ_{75-100}	−1.523	−1.568	−1.942	−1.821	−1.950	−2.060
		(0.007)	(0.016)	(0.011)	(0.012)	(0.013)	(0.018)
9	μ_{0-25}	−0.869	−0.719	−1.079	−0.848	−0.774	−0.733
		(0.012)	(0.021)	(0.012)	(0.013)	(0.010)	(0.016)
	μ_{25-50}	−0.977	−0.817	−1.161	−0.997	−0.940	−0.906
		(0.008)	(0.019)	(0.008)	(0.010)	(0.009)	(0.014)
	μ_{50-75}	−1.049	−0.913	−1.233	−1.100	−1.062	−1.048
		(0.007)	(0.016)	(0.007)	(0.009)	(0.008)	(0.013)
	μ_{75-100}	−1.172	−1.096	−1.390	−1.304	−1.290	−1.320
		(0.006)	(0.013)	(0.008)	(0.010)	(0.009)	(0.013)
10	μ_{0-25}	−2.651	−2.726	−1.768	−1.847	−1.832	−1.879
		(0.045)	(0.116)	(0.018)	(0.028)	(0.023)	(0.042)
	μ_{25-50}	−1.647	−1.825	−1.536	−1.597	−1.609	−1.637
		(0.012)	(0.042)	(0.008)	(0.014)	(0.012)	(0.022)
	μ_{50-75}	−1.483	−1.591	−1.500	−1.555	−1.579	−1.625
		(0.008)	(0.025)	(0.007)	(0.011)	(0.009)	(0.018)
	μ_{75-100}	−1.424	−1.485	−1.562	−1.585	−1.624	−1.689
		(0.006)	(0.015)	(0.009)	(0.010)	(0.010)	(0.015)

5: CLOTHES, 6: HOUSING, 7: HEALTH, 8: MOBILITY, 9: EDUCATION, 10: OTHERS.

Table 14
Disposable income elasticities for energy goods and food: Predicted values at the means of the 2008 household type specific total expenditure quartiles and at respective price means. Standard errors in parentheses are derived with the delta method.

Good		S0	S1	C0	C1	C2	C3
1	μ_{0-25}	0.253	0.244	0.268	0.274	0.277	0.259
		(0.004)	(0.004)	(0.003)	(0.004)	(0.003)	(0.004)
	μ_{25-50}	0.320	0.289	0.327	0.326	0.324	0.305
		(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
	μ_{50-75}	0.371	0.328	0.368	0.362	0.353	0.334
		(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)
	μ_{75-100}	0.446	0.398	0.415	0.398	0.379	0.353
		(0.004)	(0.005)	(0.007)	(0.006)	(0.007)	(0.009)
2	μ_{0-25}	0.272	0.282	0.296	0.333	0.336	0.339
		(0.003)	(0.004)	(0.003)	(0.005)	(0.005)	(0.006)
	μ_{25-50}	0.329	0.322	0.337	0.368	0.367	0.361
		(0.003)	(0.005)	(0.005)	(0.006)	(0.007)	(0.008)
	μ_{50-75}	0.367	0.357	0.359	0.386	0.381	0.371
		(0.004)	(0.005)	(0.007)	(0.008)	(0.009)	(0.011)
	μ_{75-100}	0.415	0.405	0.351	0.372	0.349	0.311
		(0.007)	(0.008)	(0.015)	(0.015)	(0.016)	(0.019)
3	μ_{0-25}	0.435	0.468	0.458	0.400	0.450	0.475
		(0.006)	(0.009)	(0.005)	(0.005)	(0.005)	(0.007)

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Table 14 *(continued)*

Good		S0	S1	C0	C1	C2	C3
	μ_{25-50}	0.513	0.530	0.542	0.479	0.530	0.547
		(0.005)	(0.009)	(0.005)	(0.005)	(0.006)	(0.008)
	μ_{50-75}	0.570	0.583	0.604	0.529	0.570	0.590
		(0.005)	(0.009)	(0.006)	(0.006)	(0.007)	(0.009)
	μ_{75-100}	0.665	0.669	0.677	0.601	0.621	0.634
		(0.005)	(0.008)	(0.010)	(0.009)	(0.011)	(0.014)
4	μ_{0-25}	0.594	0.550	0.513	0.514	0.535	0.536
		(0.006)	(0.007)	(0.004)	(0.004)	(0.004)	(0.005)
	μ_{25-50}	0.641	0.597	0.552	0.555	0.571	0.579
		(0.005)	(0.006)	(0.003)	(0.004)	(0.004)	(0.004)
	μ_{50-75}	0.669	0.622	0.565	0.574	0.578	0.591
		(0.004)	(0.005)	(0.003)	(0.004)	(0.004)	(0.005)
	μ_{75-100}	0.688	0.669	0.550	0.564	0.557	0.550
		(0.004)	(0.004)	(0.007)	(0.007)	(0.008)	(0.011)

1: ELECTRICITY, 2: HEATING, 3: TRANSPORT, 4: FOOD.

Appendix C. Data preparation

Table 15 shows the allocation of expenditure variables to the different commodity groups for each cross-section.

After the allocation of expenditures to the commodity groups, the data is corrected for outliers and misreporting. We first deal with zero expenditure data in any category. Zero expenditure data amounts to about 21% of all data points. However, 80% of it is due to zero expenditure in the heating category alone, where infrequency of purchase prevents an accurate consumption recording. To correct for this inaccuracy without having to drop data, we impute heating expenditure values for zero heating expenditure households. We, therefore, use a linear regression based on data from households reporting a positive expenditure on heating fuels. As independent variables we use among others heating fuel prices, total expenditure and powers of disposable income, household type and year bivariate variables and expenditure in related categories.

The second category with a notable amount of reported zero expenditures is the transport category. We again impute expenditure values for these households in a similar procedure as for heating expenditure.[11] The occurrences of the remaining reported zero expenditures show a random pattern. We drop them under the assumption of misreporting given the broad definition of the expenditure categories. About 5% of the data is dropped due to zero expenditures.

We also drop outliers characterised by an extreme ratio between expenditure and disposable income or by an extreme expenditure share in at least one commodity group. That is, observations are dropped if they either fall in any commodity group in the highest or lowest percent of the distribution of the expenditure to disposable income ratio (adopted from Nikodinoska and Schröder, 2016) or if they deviate by more than three standard deviations from the year-specific mean expenditure share in any commodity group.[12] In total about 15% of the zero expenditure adjusted data is dropped during the process.

Further descriptive statistics for the IES are published by the German Federal Office of Statistics. An overview of incomes and expenditures in the 2008 cross section is presented by the German Federal Office of Statistics (Statistisches Bundesamt, 2010).

Table 15
Allocation of variable identifiers: 1993 data was transformed from monthly/yearly basis to a quarterly basis and 1993/1998 data was transformed from DM to euro basis.

	1993	**1998**	**2003**	**2008**
ELECTRICTY	ef705	ef770-ef772	ef258	ef251
HEATING	ef707, ef709, ef711, ef713, ef715, ef717-ef719	ef773-ef784	ef259-ef262	ef252-ef255
TRANSPORT	ef761-ef762, ef771-ef773	ef 810, ef814-ef818	ef299, ef305-ef308	ef300, ef306, ef308
FOOD	ef642-ef645	ef737-ef740, ef847-ef850	ef225-ef228, ef343, ef344	ef217-ef220, ef350, ef351
CLOTHES	ef664-ef699	ef741-ef750	ef230-ef242	ef222-ef234
HOUSING	ef702, ef704, ef738, ef739	ef751, ef763, ef766-ef769	ef245, ef247-ef249, ef252-ef255	ef237, ef239–242, ef245-ef248
HEALTH	ef740-ef754	ef798-ef804, ef853, ef854, ef857	ef280-ef291, ef346-ef350, ef354	ef279-ef286, ef288-ef292, ef353-ef358, ef364, ef365
MOBILITY	ef755-ef760, ef764, ef765, ef767, ef774, ef775	ef805-ef809, ef811, ef813, ef819-ef821	ef292-ef295, ef297, ef298, ef300, ef304, ef309-ef313	ef293-ef296, ef298, ef299, ef301, ef305, ef310-ef315
EDUCATION	ef777-ef808, ef811-ef814, ef824-ef827, ef 852, ef855	ef134, ef822-ef841, ef858	ef63, ef314-ef336, ef368	ef73, ef316-ef342, ef362, ef363, ef381
OTHERS	ef816-ef829, ef721-ef737, ef843-ef848	ef129, ef842, ef843, ef851, ef852, ef855, ef856, , ef859, ef860, ef866-ef870	ef58, ef337, ef338, ef345, ef351-ef353, ef355, ef357, ef363-ef367	ef68, ef343, ef344, ef352, ef359-ef361, ef366, ef369, ef375-ef380

[11] The analysis of the consumption behaviour and the wealth status of these households suggests that the large majority is not in possession of a motorised vehicle. Thus the regression used for imputation is based exclusively on households which report positive expenditure on public transport but not on car fuels.

[12] In the case of the mobility category we drop data points only if the expenditure shares deviate by more than 5 standard deviations from the mean expenditure share. This is to account for the fact that in this category expenditure on expensive durable goods and expenditure on consumption goods are superimposed. This yields a strongly positively skewed expenditure share distribution.

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