University of Neuchatel

Institute of Economic Research

IRENE Working paper 17-11

Interactions in Swiss Households' Energy Demand:

A Holistic Approach

Ivan Tilov

Benjamin Volland

Mehdi Farsi

UNIVERSITÉ DE NEUCHÂTEL

Institut de recherches économiques

Interactions in Swiss Households' Energy Demand: A Holistic Approach[1]

Ivan Tilov[2] Benjamin Volland[3] Mehdi Farsi[4]

Abstract

This article explores the interactions between direct and embodied energy requirements of households in Switzerland in order to assess the net impacts of standard energy policies focusing exclusively on direct energy use. For this purpose, we estimate direct and embodied energy demand of Swiss households by combining consumption data of a national expenditure survey with corresponding data on energy intensity mainly from life-cycle analysis. We find strong evidence of complementarity between direct and grey energy by first estimating model parameters in a system of equations setup. In particular, the analysis of various socio-economic and psychological determinants allows us to identify a non-linear relationship between energy demand and income, which suggests that energy possesses certain "luxury features" that go beyond staple resources. An additional indication that households in Switzerland use direct and indirect energy in a complementary manner is provided by the coefficient of cross-equation correlation of residuals in our system. Finally, we analyze the causal relationship between both energy domains by the method of instrumental variables and find indicative evidence of a positive causal effect of embodied on direct energy demand, but not the other way round. From a policy perspective, our findings are important as they suggest that the wide-spread policies targeting direct energy consumption are unlikely to cause a substantial shift in household energy demand from the direct to the indirect domain.

Keywords: Households Energy Requirements; Direct Energy; Embodied Energy; Interactions; Trade-offs; Complementarity.

JEL classification: Q400; Q410; D120.

---

[1] This research is part of the activities of SCCER CREST, which is financially supported by the Swiss Commission for Technology and Innovation (CTI).

[2] Corresponding author, University of Neuchâtel, Switzerland, Institute for Economic Research (IRENE), e-mail: ivan.tilov@unine.ch, address: A.-L. Breguet 2, CH-2000 Neuchâtel, Switzerland, tel. +41 32 718 19 54.

[3] University of Neuchâtel, Switzerland, Institute for Economic Research (IRENE).

[4] University of Neuchâtel, Switzerland, Institute for Economic Research (IRENE).

1. Introduction

In many developed economies household behavior accounts for a substantial share of total energy consumption and greenhouse gas emissions. In Switzerland, for instance, it has been estimated that the domestic sector is responsible for roughly one-third of direct energy use and thus has an environmental impact comparable to that of the transport sector, or of the industry and service sectors combined (SFOE, 2012). In the face of these findings, reducing energy consumption in the domestic sector has become one of the primary policy targets in the country's Energy Strategy 2050.

Yet, while this sectorial disaggregation provides a ready way to follow the material flows of energy in an economy, its focus on *direct* energy (i.e. the energy used by households for heating, electricity and private mobility) is likely to underestimate the true importance of household consumption for an economy's *total* energy demand. The reason is that many of the goods and services fashioned, produced in the different economic sectors eventually serve to cater for the needs of individuals and households. Thus, standard analysis of energy use by sectors often ignores the energy commonly known as *embodied*, *grey*, or *indirect*, which is contained in the value-chain of goods and services consumed by households.

In this contribution, we decompose household consumption into *direct* and *indirect* energy by combining data from the Swiss Household Budget Survey (SHBS) with information from Life-Cycle Analysis (LCA) and Environmentally-Extended Input-Output data (EEIO) in order to develop an understanding of the complementarities and trade-offs between the two energy domains. Given that households can theoretically treat indirect energy as a complement or as a substitute of direct energy, this understanding is vital for the design and implementation of policies reducing total energy consumption instead of simply inducing substitutions from direct energy to indirect energy demand (or vice versa). It is, for instance, perceivable that households react to energy-related policies such as changes in taxation on direct energy sources like fuel or electricity by outsourcing their energy demand and acquiring more indirect energy instead. For example, a raise in fuel prices can induce households to increase demand for online shopping and thus shift energy use from private transport to delivery services.[5] Hence, measures originally intended to induce energy saving may result in transferring (a part of) the energy burden to other sectors of the national economy or to other countries. The latter is particularly problematic as differences in energy-efficiency across countries may imply that efficiently produced domestic goods or services are replaced by less efficient foreign ones, eventually leading to an increase in total energy (Cole,

[5] For anecdotal evidence on the relationship between fuel prices and online purchasing behavior see (Jopson, 2011).

2004; Grether et al., 2012). Understanding the interaction between direct and embodied energy domains is thus especially important for the assessments of the net impacts of national energy policies and for avoiding global energy "leakages" due to energy-saving policy measures (Bruvoll & Fæhn, 2006; Kuik & Gerlagh, 2003).[6]

For this purpose, we proceed in the following way. Section 2, gives an overview over the current state of research in household energy demand. The ensuing section 3 introduces and discusses the methods and data sets used for deriving households' demand for direct and embodied energy. Descriptive statistics presented in this section, provide basic information on both energy domains. Results from regression-based estimation strategies, drawing on a broad literature from economics and psychology (Abrahamse & Steg, 2009; Lange et al., 2014; Sapci & Considine, 2014) are presented in section 4. Finally, implications and limitations are considered in the concluding section 5.

2. Previous research

Research into the relative importance of direct and indirect energy requirements in household demand initiated with the work of Herendeen and colleagues in the 1970s (Bullard & Herendeen, 1975; Herendeen, 1978; Herendeen et al., 1981). Combining expenditure data from budget surveys with input-output tables from the US and Norway this line of research demonstrated that the energy embodied in the goods and services households consume exceeds the energy directly consumed from electricity and other fuels by about 50%. Since then similar results have been found for a large number of developed (among others Bin & Dowlatabadi, 2005; Lenzen et al., 2006; Reinders et al., 2003; Vringer & Blok, 1995; Weber & Perrels, 2000; Wiedenhofer et al., 2013) and developing countries (e.g., Liu et al. 2009, Lenzen 2006, Cohen et al. 2005), including Switzerland (Dürrenberger et al., 2001; Girod & De Haan, 2010). Moreover, this literature has made an effort to uncover the determinants of total energy demand identifying income, household size, stage of the life-cycle and the household's position along the urban-rural continuum as the main socio-economic variables of influence (c.f. Lenzen et al., 2006; Wiedenhofer et al., 2013). One of the main findings is that while energy requirements in household consumption increase with income, they do so at a marginally decreasing rate. That is, as households become richer their environmental impact grows but the energy required per unit of consumption decreases. Table 1

[6] Note that it is likewise conceivable that households treat both energy domains as complements. For instance, households' direct energy demand is likely to increase as a reaction to increasing the stock of energy-consuming durables such as electronic appliances. In this case, policy measures targeting at one of the sub-domains of direct energy (i.e. electricity, heating and mobility) may also decrease demand for energy-consuming durables and thus embodied energy. In general, substitution and complementarity mechanisms may co-exist. However, which mechanism dominates is an open empirical question.

provides an overview of the main estimates of income- and expenditure elasticities found in previous research.[7]

Table 1: Income and expenditure elasticities of total energy requirements [8]

Country	Year	Reference	Net income elasticity	Expenditure elasticity
USA	(1960-1961) (1972-1973)	(Herendeen & Tanaka, 1976) (Herendeen et al., 1981)		0.87 0.81
Norway	(1973)	(Herendeen, 1978)		0.72
New Zealand	(1980)	(Peet et al., 1985)		0.40
The Netherlands	(1990)	(Kees Vringer & Blok, 1995)	0.63	0.83
Australia	(1993-1994) (1998-1999)	(Lenzen, 1998) (Lenzen et al., 2006)	0.59	0.74 0.78
India	(1993-1994) (1997-1998)	(Pachauri, 2004) (Lenzen et al., 2006)		0.67 0.86
Denmark	(1995) (1999)	(Wier et al., 2001) (Lenzen et al., 2006)	0.48	0.90 0.86
Brazil	(1995-1996) (1999)	(C. Cohen et al., 2005) (Lenzen et al., 2006)		[1.1 ; 0.9] [9] 1.00
Japan	(1999)	(Lenzen et al., 2006)		0.64
Ireland	(2004-2005)	(Leahy & Lyons, 2010)		0.32 [10]

In reference to Environmental Kuznets Curve (EKC) hypothesis (Grossman & Krueger, 1991), a number of studies have additionally evaluated changes in income elasticities of total energy demand with increasing income. For instance, Lenzen et al. (2006) pool data from 10 different countries collected between 1961 and 1998 and find that the relationship between income and total energy demand seems follow an inversely U-shaped relationship although the identified turning point substantially exceeds observed income values. This finding is in line with a majority of results from the empirical literature on the EKC focusing on the emission of specific pollutants such as CO_2 or fine particles (for recent reviews see Dinda, 2004; Kijima et al., 2010; Stern et al., 2017). While this literature also tends to identify an inversely U-shaped relationship between most pollutants and wealth, estimated pollution turning points commonly exceed observed income by several orders of magnitude.

Despite a general agreement on the importance of some socio-economic variables for determining household energy requirements, there are a number of unresolved issues. For one, while the effect

[7] As noted by Vringer & Blok (1995) the remarkable differences between income and expenditure elasticities arise from the fact that saving rates increase with income, such that richer households tend to use a smaller share of their income for consumption purposes.
[8] This table combines and builds upon similar representations from (Pachauri, 2004; Wier et al., 2001).
[9] These values depend on the particular income class considered.
[10] Although (Leahy & Lyons, 2010) compare this expenditure elasticity with other estimates from studies on total energy requirements, their work does not seem to address *total* household energy demand, but only *direct* energy use.

of income and wealth on energy requirements has been extensively studied, analyses of the functional form best describing this relationship are rare in the literature on household energy requirements. Yet, clearly understanding the structure of this relationship is essential for predicting changes in energy requirements from either economic growth or policy changes such as adaptations of taxation regimes.

Second, as criticized by Wiedenhofer et al. (2013), many studies investigating household energy requirements tend to stay at the descriptive level or rely on univariate methods with income as the sole predictor. This is problematic as it may not only fail to identify other influential determinants, but may also lead to bias in the estimated income elasticities if the omitted variables are correlated with income. To deal with these issues we will estimate multivariate models simultaneously controlling for a range of socio-economic controls. Moreover, we will follow the EKC literature and include higher-order polynomials of income in order to identify the functional relationship between income and energy requirements in both domains best describing our data.

Third, a question that has received similarly little attention revolves around the effects of household attitudes, values and preferences on energy requirements. While an increasing number of studies have investigated the effects of these factors on household direct energy demand and savings (Brandon & Lewis, 1999; Martinsson et al., 2011; Volland, 2017), few have addressed their relevance for explaining either total or indirect energy demand. Notable exceptions are the contributions by Abrahamse & Steg (2009), Gatersleben et al. (2002) and Vringer et al. (2007), who all find that such psychological attributes improve model predictions for energy use in both domains. For instance, Gatersleben et al. (2002) show that concern about the state of the environment, increased frequency of self-reported recycling and purchase of environmentally sound food products decreased household direct energy use. Vringer et al. (2007) study the univariate relationships between household values and energy requirements showing that different values may have opposite effects on different energy domains. In the present contribution we extend this nascent literature by focusing on the effects of preferences over risk and social outcomes, which have been found to influence direct energy demand in a number of recent papers (Fischbacher et al., 2015; Torgler et al., 2009; Volland, 2017).

Finally, to the best of our knowledge, there are no studies that explicitly investigate the relationship and interactions between direct and indirect energy requirements at the household level[11]. Despite a growing body of literature that has addressed the effect of socio-economic

[11] The need to test the "separability" between direct and embodied energy demand has been emphasized by Leth-Petersen (2002) in his analysis of direct energy demand in Denmark. To the knowledge of the authors, this study is the only one addressing in a straightforward way the dependence between sub-domains of household energy requirements.

determinants on direct and indirect energy requirements separately (e.g., Abrahamse & Steg, 2009; Lenzen et al., 2004; Reinders et al., 2003; Wiedenhofer et al., 2013), the question whether demand in the two domains is related above and beyond the effect of joint determinants is an open empirical question. Yet, as outlined in the introduction to this manuscript, interactions between direct and indirect energy requirements have important implications for the effectiveness of policies aiming to reduce overall energy demand by the domestic sector. In the present paper we therefore test directly for the presence and magnitudes of these interactions.

3. Data and descriptives

3.1 Datasets and basic assumptions

To obtain an encompassing picture of household energy requirements in Switzerland, this study follows previous research and links individual expenditure data with energy content of consumption items obtained from Life-Cycle Analysis and Input-Output-Analysis (Bullard & Herendeen, 1975; Lenzen et al., 2006; Pachauri & Spreng, 2002).

The primary data set used in the current study is the Swiss Household Budget Survey, a cross-sectional survey of expenditures by private households in Switzerland. In particular, we use information from the 2011 wave of the SHBS, which was latest available wave at the time of writing. The data set contains a total of 3087 households of whom 3070 report non-negative disposable income and are therefore retained for further analysis. Another four households were removed because they reported zero overall energy expenditures.[12] Thus, estimations are based on 3066 observations of individual households.

Aside from standard socio-economic characteristics, the SHBS dataset collects detailed data on consumer expenditures of these households at the four-digit COICOP level. Expenditure information is collected using diaries which are kept by each household for the period of one month. For 25 percent of commodities, information on the physical quantities obtained by the household is additionally provided in the SHBS. Expenditures on 281 commodities, encompassing 80% of expenditure categories surveyed in the SHBS provide the basis for computing energy requirements by these households. Expenditures on these categories account for 63% of discretionary expenditures, i.e. expenditures after subtracting compulsory outlays, such as health, unemployment and disability insurances, or payments to pension schemes. Since households hold

[12] Note that households consuming only self-produced energy from renewable sources would be characterized by zero energy expenditures in the SHBS data. However, in the absence of any expenditure information, a reliable imputation of their direct energy consumption is unfeasible. For this reason, we prefer to exclude these observations.

little to no discretionary scope over the energy contents of these expenditures and assigning energy intensities to these categories involves a substantial degree of uncertainty and ambiguity (c.f. Herendeen, 1978), we consider it prudent to exclude them from the analysis. For similar reasons, we omit categories such as fees, insurances, financial services, donations, lottery games, rents and mortgages or gifts and monetary transfers.

Energy intensities of household expenditures are measured by the means of Life-Cycle Assessment (LCA) and Environmentally-Extended Input-Output Tables (EEIOT) for Switzerland. LCA data are derived from the ecoinvent life-cycle inventory, version 2.2 (ESU-services Ltd. & Niels Jungbluth, 2015). It contains information on average energy intensity measured in Megajoules (MJ) per physical unit of consumption of the expenditure items collected in the SHBS. Unfortunately, LCA measurements were not available for 85 out of the 281 commodities retained from the SHBS. For these items energy intensities were therefore computed based on EEIOT as provided by the Swiss Federal Office of Energy (ESU-services Ltd. & Niels Jungbluth, 2015; FOEN, 2011). A drawback of these tables is that energy intensities are given for limited number of categories corresponding to higher level COICOP divisions. Consequently, commodities for which we lack detailed LCA data, are assigned the EEIO-based intensities of the corresponding 2-digit or, where available, 3-digit COICOP level. Similar combinations of LCA and EEIO datasets have been used in in previous studies on household energy requirements in Switzerland (FOEN, 2011; Girod & De Haan, 2010) and beyond (Chitnis & Sorrell, 2015; Druckman & Jackson, 2008; Wiedmann et al., 2007).[13]

3.2 Measuring direct and indirect energy requirements

Following the literature on the analysis of the energy requirements (e.g., Abrahamse & Steg, 2009; Chitnis & Sorrell, 2015; Reinders et al., 2003) and environmental footprints of households (e.g., Girod & De Haan, 2010; Munksgaard et al., 2000; Steen-Olsen et al., 2016; Vringer & Blok, 1995), we compute household energy requirements, E^{η}, for direct and indirect energy, $\eta \in \{direct, indirect\}$, as a product of the expenditures on the corresponding categories and their respective energy intensities. Thus:

$$E^{\eta} = (\boldsymbol{x}^{\eta})^{T} \Omega^{\eta} \boldsymbol{m}^{\eta}, \qquad (1)$$

[13] Appendix 2 provides an extensive discussion of several additional datasets we had to use in order to assign energy intensities to a number of composite consumption categories such as package holidays or energy use in secondary houses.

where, $\boldsymbol{x}^{\eta}$ is a $k^{\eta} \times 1$ vector of expenditures in CHF on the k^{η} commodities considered in each domain of household energy demand, $\eta.\boldsymbol{m}^{\eta}$ is a corresponding $k^{\eta} \times 1$ vector of energy intensities per physical unit of each commodity as derived from the LCA data. The diagonal $k^{\eta} \times k^{\eta}$ matrix Ω^{η} then provides the framework for translating expenditures into physical units of consumption. Elements on the main diagonal of Ω^{η} therefore give the inverse of individual prices for each expenditure category. To construct Ω^{η}, we use average commodity prices for each SHBS item drawing on data initially collected by the Federal Office of Statistics for the construction of the 2011 consumer price index (Rappo, 2015). In the case where physical units can be directly obtained from the SHBS, we abstain from price-based translation such that the corresponding element of vector $\boldsymbol{x}^{\eta}$ gives physical units instead of expenditures and the corresponding element of the main diagonal of Ω^{η} takes a value of one.[14]

Direct energy demand is derived from expenditures on electricity and heating for primary and secondary residences, as well as on fuels for private transport (gasoline and diesel). Moreover, to account for the fact that at least in larger residential units some energy expenditures are shared by households,[15] we disaggregate reported shared expenditures by households based on a simple imputation scheme described in Appendix 1. Altogether, we thus compute direct energy requirements of Swiss households based on six expenditure categories, implying that $k^{direct} = 6$. Notably, energy use on these direct energy commodities are measured based on LCA intensities and therefore include the embodied energy used during their extraction, production and transport. Indirect energy demand is subsequently computed using expenditures and energy intensities of the remaining 275 non-energy commodities from the SHBS ($k^{indirect} = 275$). This distinction between direct and indirect energy thus closely traces the common convention of defining direct energy as the *"energy carriers purchased by the household itself, in order to cater for energy services"* (Weber & Perrels, 2000), and indirect energy as the energy contained in all other non-energy goods and services (Druckman & Jackson, 2008; Munksgaard et al., 2000; Reinders et al., 2003).

3.3 Independent variables

In defining our independent variables we draw on the broad literature in economics and psychology on the determinants of direct and embodied energy requirements (Abrahamse & Steg, 2009; Lenzen et al., 2006; Reinders et al., 2003; Kees Vringer et al., 2007). Following the economic literature, our main control of interest is household disposable income. This variable comprises

[14] Our approach thus is a hybrid between the household consumption model based on expenditures (Kees Vringer & Blok, 1995) and the one based on physical units (c.f. Girod & De Haan, 2010; Hertwich, 2005).

[15] For example, the energy used to light and heat jointly used spaces, such as basements or corridors.

all revenues from employment, freelance activities and rents of all household members after the deduction of taxes and mandatory insurance premia. Sporadic incomes are not included in this measure. We standardize disposable income with respect to the median disposable income of our sample in order assess the impact of deviations from the 'typical income' on household energy requirements.

Further controls contain the age, sex, nationality and marital status of the household reference person, as well as the composition of the household in terms of members and the share of those gainfully employed. We also include a set of binary variables capturing dwelling ownership, whether households report shared costs, and if the household has been used as a basis for disaggregating these shared expenditures. Moreover, we control for the stock of energy-consuming durables such as the number of cars, and the private ownership of electronic appliances like television sets, personal computers, dishwashers, or tumble driers. To account for unobservable regional and temporal differences (e.g., heating degree days and prices), we likewise include a set of dummy controls for the geographic location within Switzerland and the month in which the household completed the expenditure diary[16].

Finally, we focus on three psychological characteristics that figure prominently in the increasing stream of literature on the psychological determinants of household energy demand. For one, environmental attitudes, that is the psychological tendency to view the natural environment as a positive feature worth protecting (Kaiser et al., 1999; Milfont & Duckitt, 2010) has been related to both energy use (e.g., Lange et al., 2014; Volland, 2017) and energy savings (Abrahamse & Steg, 2009). Second, attitudes towards risk taking have been linked with both investment in energy-efficient durables (e.g., Farsi, 2010; Qiu et al., 2014) and energy consumption (Fischbacher et al., 2015; Volland, 2017). Third, since one's energy consumption affects environmental quality and via this channel the welfare of others, social preferences have been linked with pro-environmental behaviours and attitudes (Torgler et al., 2009) including investment into energy-efficient durables (Fischbacher et al., 2015) and in-home energy use (Fischbacher et al., 2015; Volland, 2017).

Since the SHBS is a standard consumption survey, direct measures for these characteristics are absent from the data. As a consequence, we draw on the extensive literature about the effect of these characteristics on every-day consumption decisions in order to derive corresponding proxies based on observed expenditure behaviour. In particular, we rely on household insurance coverage and donations for different purposes to establish these proxies. We, thus, measure pro-environmental attitudes using a dummy indicating whether the household donated to

[16] Summary statistics for all the variables used in this analysis are given in Table X, Appendix 3

environmental organizations during the month of observation[17]. The assumption is that giving to such organizations is a sign for the household's agreement with their aims and thus a reflection of its preference structure. Indeed, research in environmental psychology has repeatedly demonstrated the existence of a link between individual's pro-environmental values and their donations or donation intentions to such organizations (de Groot & Steg, 2008; Yen et al., 1995). Roughly 10% of all households in the SHBS donate to pro-environmental organizations, and thus qualify as holding pro-environmental preferences. In the same vein, we proxy a household's social preferences by whether it reported expenditures on donations to other non-governmental organizations. Endorsement of pro-social values as measured in questionnaire-based surveys and the extent of social preferences as elicited from experimental set-ups have both been associated with charitable giving in economics and sociology (Bekkers & Wiepking, 2011; Kamas & Preston, 2010). Based on this measure just over 20% of households in the SHBS exhibit other-regarding preferences. Finally, we obtain a measure for the household's risk aversion by using information on the household's expenditures for legal protection insurance. More precisely, we assume that a household is risk averse if it has any such expenditures and risk tolerant otherwise. Inferring risk preferences from insurance data is a natural choice as risk aversion is among the main reasons for the existence of insurance markets (Cohen & Einav, 2007). Consequently, empirical research demonstrates that risk averse individuals tend to have higher insurance coverage (Barsky et al., 1997; Chiappori et al., 2000). About 34% of respondent's qualify as risk averse based on our criteria.[18]

Notably, measuring preference patterns using observed (and dichotomized) expenditure behaviour is a noisy and inefficient operationalization for the underlying psychological concept. Hence, caution is clearly advised when relying on such measures. However, as pointed out above, there is convincing evidence for strong relationships between our proxies and the underlying preference structure. In this sense, our proxies have the advantage of capturing revealed behaviours, in contrast to stated preference measures pre-dominant in the preceding literature (Abrahamse & Steg, 2009; Kees Vringer et al., 2007)

---

[17] The creation of these controls is possible because the underlying expenditures have been excluded from the computation of embodied energy due issues of uncertainty concerning their energy content.

[18] Results using expenditures on facultative, complementary health insurance give identical results. They are available from the authors upon request.

3.4 Descriptive statistics

Based on the combination of datasets described in the previous section, Table 2 presents basic descriptive statistics for our main dependent variables. They suggest that an average Swiss household uses about 37 gigajoules (GJ) of total energy per month. This value closely traces previous estimates for Switzerland (Dürrenberger et al., 2001) and falls well into the range of 20 GJ to 69 GJ estimated for other developed economies (Bin & Dowlatabadi, 2005; Park & Heo, 2007; Reinders et al., 2003). Its spread is substantial with an inter-quartile range of just over 23 GJ, suggesting that energy requirements vary considerably across Swiss households. More importantly, results from Table 2 give a first impression on the relative importance of direct and indirect energy requirements by these households. It shows that on average Swiss household uses 13.5 GJ of direct compared to 23.3 GJ of indirect energy, suggesting that almost two-thirds of the total energy consumption of Swiss households stems from the energy embodied in non-energy commodities and services they consume. Again results almost perfectly resemble findings from previous studies likewise demonstrating that indirect energy makes up the lion share of total energy consumption in most developed economies, including Switzerland (Bin & Dowlatabadi, 2005; Dürrenberger et al., 2001). Hence, clearly household choices over non-energy commodities have a larger effect on their total energy requirements and environmental impact than their use of primary fuels, which is commonly the focus of energy policies. The finding therefore underscores the policy relevance of studying common determinants for and interactions between these two domains of household energy demand.

Table 2: Descriptive statistics

	Mean	Sd	min	max	p50
Total energy demand (MJ)	36,796.60	20,094.89	3,266.13	283,922.50	33,129.17
Direct energy demand (MJ)	13,498.73	7,419.60	1,225.42	67,659.34	12,031.40
Embodied energy demand (MJ)	23,297.86	16,550.56	1,081.78	264,336.28	19,498.46
Energy int. per CHF (MJ/CHF)	4.18	1.47	0.54	17.55	3.97
Observations	3066				

Table 2 also summarizes the energy intensity of household expenditures as measured in MJ per CHF. It shows that an average Swiss Franc spent by a household buys roughly 4.2 MJ of energy. Again spread is substantial. The household with least energy-intensive expenditure pattern obtains as little as 0.54 MJ per CHF, while the household with the most energy-intensive expenditure pattern buys as much as 17.55 MJ per CHF. Several reasons contribute to this considerable variation. For one, as expenditures are collected using a diary kept over a given month, the purchase of energy-intensive consumer durables like electronic appliances during that month has a significant impact on the measure of average energy intensity. Similarly, seasonal effects like the purchase of heating oil or summer holidays including air travel will substantially affect average energy intensity measured over that period. This is primarily due to the fact that the amount of energy that can be bought with a Swiss franc varies substantially across expenditure categories. Figure 1 plots these intensities for a group of 17 aggregate expenditure categories against their share in total / discretionary expenditures.[19] The vertical line denotes average energy intensity over expenditure categories (15.81 MJ/CHF). Hollow dots represent the categories that go into the calculation of direct energy requirements, while filled dots denote the categories that form indirect requirements. Differences across categories are substantial, with one CHF buying as little as 1.05 MJ when purchasing personal apparel and as many as 52.42 MJ when spent on electricity.

In general, carriers of direct energy such as electricity or heating fuels show substantially higher per CHF energy-intensities than other, non-energy commodities like household appliances or furniture. This may be little surprising, as direct energy sources are commonly one in many inputs that are used in the production of non-energy commodities, such that intensities are likely to reflect the value added by these primary energy sources. Figure 1 highlights that the overall impact of a consumption category on a household's energy requirement is the product of this intensity and the category's relative importance in the consumption basket of the household. As a consequence, categories that accumulate only a small share of expenditures can nevertheless exhibit a major effect on total energy requirements. For instance, air travel makes up less than 0.6 % of discretionary expenditures but is responsible for approximately 5 % of energy requirements due to its energy-intensity of 50 MJ/CHF. Conversely, food and beverage consumption shows an average energy intensity of 9.34 MJ/CHF, but is responsible for about19 % of energy requirements due to its comparatively high share in discretionary expenditures (11.5 %). More generally, results demonstrate that residential energy requirements (in-home energy use, 23.22 %), transport requirements (21.33 %) and food-related requirements make up more than 60 % of the total energy requirements.

The marked difference in energy intensities per CHF between energy and non-energy commodities also has important implications for energy policy. For one, it indicates that a reduction in expenditures on direct energy carriers reduces total energy demand of a household considerably more than an identical reduction in expenditures elsewhere. For instance, reducing expenditures on car fuels by 10 CHF would reduce household total energy demand by 250 MJ, whereas the same reduction in expenditures on personal apparel would decrease energy demand

[19] Discretionary expenditures are measured as total expenditures less mandatory expenditures such as health, unemployment and disability insurances, or payments to pension schemes. Due to the comprehensive welfare state in Switzerland, mandatory expenditures make up about 36% of total expenditures of the average household in the SHBS.

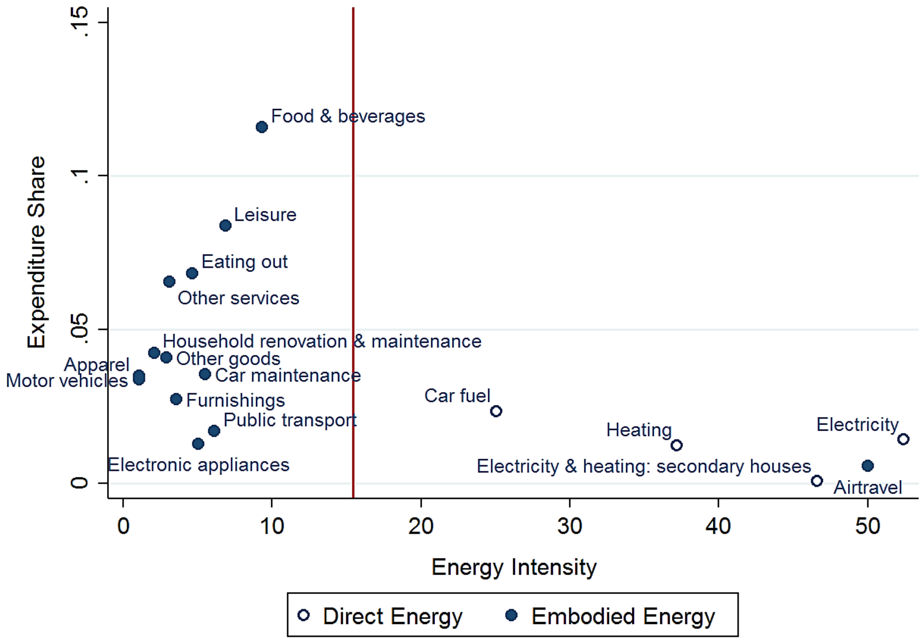
by only 10.5 MJ. This suggests that, despite the relative importance of indirect energy in total energy requirements, tax-based policies are likely to be most effective when targeting direct energy commodities, like car fuels or electricity.

Moreover, due to the difference in energy intensities per CHF across expenditure categories, shifts in consumption patterns and changes in income can be predicted to have a substantial impact on total energy requirements. Both effects essentially depend on the sensitivity of household demand for individual commodities to changes in the budget constraint. If these income elasticities are positively correlated with the amount of energy a CHF can buy, total energy requirements are likely to increase over-proportionally as households become richer, while the opposite is likely to be the case if this correlation is negative. Hence, understanding how sensitive household energy requirements are with respect to changes in income, provides a ready way to judge the environmental effects of redistributive policy measures.

It also sheds some light on the risks associated with the implementation of policies that focus on improving the energy-efficiency in the domestic sector. Since such improvements imply monetary savings, they are tantamount to relaxing the budget constraint of the affected households. The subsequent increase in consumption will inevitably affect energy requirements and thus yield a divergence between the technically possible energy savings from the efficiency improvement and the energy savings realized by the household. This phenomenon is commonly known as the *'rebound effect'* (Alcott, 2005; Binswanger, 2001; Sorrell & Dimitropoulos, 2008). The major differences in energy intensities per CHF, evidenced in Figure 1, show that the net effect on household energy requirements strongly depends on how arising savings are re-distributed over expenditure categories. In particular, it suggests that if households re-invest such savings into (other) energy commodities, efficiency improvements may completely fail to deliver energy savings expected from them. To the contrary, if households re-spent savings largely on non-energy commodities, total energy requirements may reduce substantially, despite rebound.
For example, an average car-owning household in the SHBS spends about 125 CHF per month on gasoline. If this household would acquire a car with a 20% more efficient combustion engine, technically possible energy savings would amount to 625 MJ. Yet, if the arising savings were completely re-spent using the new car, e.g. by driving more often, faster or longer distances, energy use before and after the efficiency-improvement would be identical (implying a direct rebound of 100%). Even more problematic, would be the case where savings were spent for heating, air travel or the use of electronic appliances, in which case energy requirements following the improvement would exceed requirements prior to the efficiency improvement. Alternatively, if all savings were spent on personal apparel, energy requirements of the household would drop by 600 MJ, implying a modest indirect rebound effect of 4 %.

Thus, clearly the net effect of any energy efficiency improvement on the total energy requirement of a household depends how corresponding savings are re-spent. This, in turn, depends to a considerable degree on how reactive demand for direct and indirect energy is with respect to changes in disposable income.[20]

Figure 1: Energy intensities (MJ/CHF) and expenditure shares per consumption category

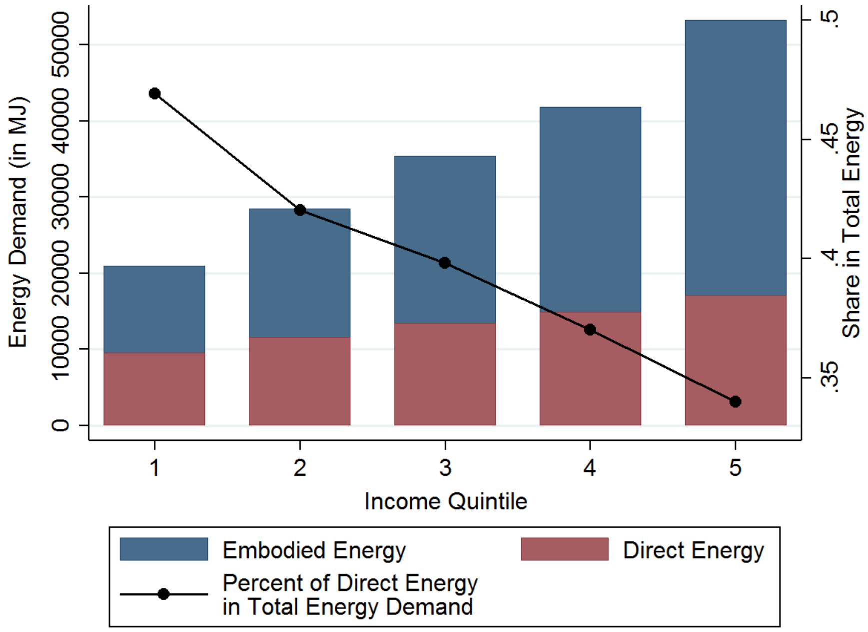


We can use our decomposition of total household energy requirements to obtain a first impression of this sensitivity. For this purpose, Figure 2 plots the evolution of direct and indirect energy requirements as well as the share of direct in total energy consumption over increasing quintiles of household disposable income. The graph shows that total energy demand rises substantially across the income range, more than doubling from about 21 GJ per month among the poorest 20% of households to more than 53 GJ among the richest fifth. Total energy demand in each successive quintile is larger than the demand of the previous poorer quintile. This suggests that, at least at this descriptive level, we do not find any indication for a reduction of environmental pressure among high income households as might have been expected based on the environmental Kuznets curve literature. Moreover, there is no indication for such an abatement at high income levels for any of the two components of total energy demand. That is, demand for both direct and indirect energy demand increase with household income. Yet, clearly at diverging rates. As a consequence,

[20] It is important to stress that rebound effects are not only driven by the impact of efficiency improvements on income, but also by the implicit reduction in the relative price of the energy service in question (Binswanger, 2001; Sorrell & Dimitropoulos, 2008). Hence, focusing on income elasticities would lead to an underestimation of the increase in consumption of the cheaper energy service (i.e., the direct rebound effect). Nevertheless, focusing on income effects is common in studies simultaneously addressing direct and indirect rebound (for a review see Chitnis & Sorrell, 2015).

the share of direct energy consumption in total household energy demand decreases steadily from about 47% for households in the lowest income quintile to slightly less than 35% for the highest income households in our sample.

Figure 2: Direct and embodied energy demand for income quantiles



4. Econometric strategy

To further investigate the relationship between income and household energy requirements and to evaluate the impact of various basic socio-demographic controls we use the following basic econometric model:

$$ln(E_i^\eta) = \beta_0^\eta + \sum_{k=1}^{m} \beta_k^\eta (\ln I_i)^m + \sum_{l=m+1}^{n} \beta_l^\eta \left(X_{li}^\eta\right) + \varepsilon_i^\eta \quad (2),$$

where E_i^η with $\eta \in \{direct, indirect\}$ is the monthly direct or embodied energy consumption of household i. I_i^m represents its normalized disposable income for the same period of time to the power of the integer m. To allow for a possible non-linear relationship between energy demand and income (Ferrer-i-Carbonell & van den Bergh, 2004; Lenzen et al., 2006; Stern et al., 2017; Volland, 2017), we use a set of different specifications with m ranging from one to four, and evaluate whether increasing polynomials improve model fit by comparing information criteria. The double log form, which has been widely used in similar energy research (Pachauri, 2004), has the advantage of reducing the impact of outliers and heteroscedasticity, but also of providing a direct interpretation of regression coefficients as income elasticities. Hence, in all specifications,

β_1 gives the income elasticity of energy requirements, ϵ^{η}_{EI}, at the median income. In the absence of non-linearities, this elasticity extends to all values of the observable income range, such that $\beta_2 = \beta_3 = \cdots = \beta_m = 0$. Otherwise elasticities change systematically across the income range, such that a linear approximation to the income elasticity at income level I is given by:

$$\epsilon^{\eta}_{EI} = \frac{\partial\, ln(E^{\eta})}{\partial lnI} = \beta_1 + \sum_{k=2}^{m} k\beta_k (ln\, I)^{k-1} \quad (3).$$

X^{η}_{li} is a set of energy category specific control variables. They contain the socio-demographic, geographical and temporal controls discussed above. In addition, estimations on direct energy include several controls aiming to capture household heterogeneity in terms of the stock of electronic durables, such as washing machines, computers or TV sets.

To account for the fact that consumption decisions over direct and indirect energy may be taken jointly by the household, model (2) is estimated using a seemingly unrelated regression estimator (SURE), as introduced by Zellner & Theil (1962).[21] This estimator allows the error terms, ε^{η}_{i}, of the two equations to be correlated, and thus provides a possibility to measure the existence and relevance of unobserved common determinants. The estimator has been widely used to analyze household expenditures over several energy commodities (Bartels et al., 1996; Dubin et al., 1986; Fiebig et al., 1991; Henley & Peirson, 1994). For more reliable results, we base the statistical inference on bootstrapped standard errors.[22]

[21] We use Stata 14's *sureg* and the user-written *cmp* (Roodman, 2009) commands.

[22] When following the more common procedure and clustering standard errors over geographic regions or cantons, we obtain confidence intervals that are slightly smaller than the ones presented below. Yet, since in all cases the number of clusters is small (< 15), these results may overstate precision (Cameron & Miller, 2015) which is why we have opted for the more conservative bootstrap approach.

5. Results

We proceed by discussing our findings in two main steps. Section 5.1 examines the impact of common factors on direct and embodied energy requirements, and the cross-equation correlations of residuals from our SUR estimation. Section 5.2 discusses the conditional correlations between direct and indirect energy (and vice-versa), as well as related endogeneity issues.

5.1 Determinants of households' direct and embodied energy demand

Table 3 provides results from a set of SUR estimations on household direct and indirect energy demand, with increasing polynomials of the income measure. With respect to direct energy, findings across all specifications reflect a number of well-documented phenomena from the substantial body of literature focusing on household heating energy and electricity demand (see, among others, (Alberini et al., 2011; Baker et al., 1989; Ferrer-i-Carbonell & van den Bergh, 2004; Meier & Rehdanz, 2010). In particular, we find that direct energy demand increases under-proportionally in the number of individuals in the household, suggesting that co-habitation creates substantial scale economies (Ferrer-i-Carbonell & van den Bergh, 2004; Schröder et al., 2015). In fact, results suggest that as households increase in size, direct energy demand rapidly levels off with a 2-person household using only 14% more direct energy than a single household, and a 3-person household requiring just 3% more than a 2-person household. We also find the common inversely U-shaped evolution of energy demand across the life-cycle of a household (Baker et al., 1989; Ferrer-i-Carbonell & van den Bergh, 2004; Kees Vringer & Blok, 1995). Estimates suggest that direct energy demand increases up to an age of about 44 years and then starts declining again. As income and household size are controlled for separately, this is likely to reflect changes in energy-related requirements over the household life-cycle, such as increased heating needs due to the presence of young children. Finally, our findings underline the importance of household possession of energy-consuming durables for driving energy requirements. Households owning more electronic devices, such as computers or dish washers show substantially higher direct energy use[23]. Likewise, car ownership increases direct energy demand substantially. Households owning a single car require about 47% more direct energy than

[23] The SHBS collects data on the number of washing machines, freezers and dishwashers only when they are *owned* by the household. However, this is not the case for the majority of tenants who live in multi-family buildings where these appliances are shared. Therefore, the coefficients concerning the three electronic devices mentioned above should be interpreted cautiously.

an otherwise comparable household without a car, while households possessing two or more cars use even 76% more direct energy.

A remarkable result is that we find clear evidence for a non-linear relationship between income and direct energy use at the household level with higher-order polynomials being significantly different from zero up to the third-order polynomial. Notably the cubic specification of income also outperforms alternative specifications in terms of model fit, when judged by information criteria, McElroy's adjusted R squared values, and standard log-likelihood ratio tests. For the best-fitting model M3, we obtain positive and significant coefficients of both disposable income and its squared term, while its cubic term displays a significant but negative coefficient, implying a sigmoid relationship between income and direct energy demand. This suggests that direct energy requirements react stronger to changes in income at medium income levels, while such responses are less pronounced for (very) high and low values of disposable income. More precisely, coefficient estimates suggest that income elasticities are highest for incomes that exceed the median income in our sample by about 55 % (i.e., monthly disposable income of CHF9'763), corresponding roughly to the 90^{th} percentile of the empirical income distribution.

Table 3: Determinants of Swiss households' direct (D.) and embodied (E.) energy consumption, 2011

	M1		M2		M3		M4	
	D. (ln)	E. (ln)	D. (ln)	E. (ln)	D. (ln)	E. (ln)	D. (ln)	E. (ln)
Normalized disposable income (ln)	0.1122***	0.4654***	0.1365***	0.4970***	0.1650***	0.5825***	0.1620***	0.5894***
	(0.02120)	(0.02650)	(0.02034)	(0.02455)	(0.02483)	(0.03355)	(0.02540)	(0.03137)
Normalized disposable income (ln) ^{2}			0.0614***	0.0823***	0.0434***	0.0281	0.0373	0.0422
			(0.01337)	(0.02357)	(0.01592)	(0.02176)	(0.02760)	(0.04241)
Normalized disposable income (ln) ^{3}					-0.0201**	-0.0607***	-0.0173	-0.0673***
					(0.00879)	(0.01864)	(0.01138)	(0.01774)
Normalized disposable income (ln) ^{4}							0.0022	-0.0051
							(0.00654)	(0.01435)
Owner	0.0054	0.1108***	0.0015	0.1039***	0.0017	0.1032***	0.0018	0.1028***
	(0.02755)	(0.02858)	(0.02759)	(0.02843)	(0.02748)	(0.02845)	(0.02752)	(0.02848)
Dwelling with shared costs	0.0620**	0.0107	0.0638**	0.0136	0.0646**	0.0158	0.0645**	0.0161
	(0.02894)	(0.03057)	(0.02872)	(0.03028)	(0.02873)	(0.03042)	(0.02871)	(0.03042)
Used for disaggregation	0.0872***	0.0186	0.0882***	0.0201	0.0867***	0.0155	0.0868***	0.0152
	(0.03227)	(0.03311)	(0.03236)	(0.03301)	(0.03242)	(0.03317)	(0.03241)	(0.03313)
2 HH memb.	0.1434***	0.2569***	0.1401***	0.2524***	0.1337***	0.2310***	0.1338***	0.2307***
	(0.02901)	(0.03557)	(0.02886)	(0.03545)	(0.02919)	(0.03573)	(0.02917)	(0.03580)
3 HH memb.	0.1755***	0.2561***	0.1702***	0.2485***	0.1617***	0.2207***	0.1621***	0.2196***
	(0.03385)	(0.04658)	(0.03395)	(0.04634)	(0.03455)	(0.04663)	(0.03452)	(0.04658)
>3 HH memb.	0.1632***	0.3844***	0.1542***	0.3713***	0.1441***	0.3387***	0.1449***	0.3366***
	(0.04117)	(0.05074)	(0.04108)	(0.05084)	(0.04167)	(0.05115)	(0.04163)	(0.05117)
Age of ref. person	0.0084*	0.0263***	0.0078*	0.0255***	0.0076*	0.0247***	0.0075*	0.0248***
	(0.00443)	(0.00458)	(0.00440)	(0.00452)	(0.00440)	(0.00449)	(0.00440)	(0.00452)
Age of ref. person ^{2}	-0.0001**	-0.0003***	-0.0001**	-0.0003***	-0.0001**	-0.0002***	-0.0001**	-0.0002***
	(0.00004)	(0.00004)	(0.00004)	(0.00004)	(0.00004)	(0.00004)	(0.00004)	(0.00004)
Gender of ref. person: female	0.0045	0.0431*	0.0058	0.0448*	0.0089	0.0547**	0.0092	0.0542**
	(0.02030)	(0.02318)	(0.02032)	(0.02320)	(0.02039)	(0.02331)	(0.02041)	(0.02337)
Nationality of ref. person: foreign	0.0439*	-0.0151	0.0444*	-0.0144	0.0458*	-0.0098	0.0458*	-0.0097
	(0.02424)	(0.03045)	(0.02422)	(0.03047)	(0.02415)	(0.03013)	(0.02416)	(0.03008)
% of gainfully working HH members	-0.0004	-0.0004	-0.0004	-0.0004	-0.0005	-0.0007*	-0.0005	-0.0007*
	(0.00031)	(0.00037)	(0.00031)	(0.00037)	(0.00031)	(0.00037)	(0.00031)	(0.00037)
HH with more than one cell phone per HH head ≥12 y.o	0.0487		0.0449		0.0448		0.0445	
	(0.03472)		(0.03435)		(0.03431)		(0.03430)	
HH with more than one laptops per HH head ≥12 y.o	0.1391***		0.1325***		0.1340***		0.1343***	
	(0.04817)		(0.04786)		(0.04825)		(0.04812)	
HH with (at least one) desktop computer	0.0212		0.0207		0.0202		0.0204	
	(0.01910)		(0.01901)		(0.01900)		(0.01902)	
HH with (at least one) TV	0.0128		0.0115		0.0104		0.0104	

	(0.03078)		(0.03097)		(0.03098)		(0.03101)	
HH with (at least one) freezer	-0.0130		-0.0101		-0.0102		-0.0102	
	(0.01996)		(0.01982)		(0.01983)		(0.01985)	
HH with (at least one) washing machine	0.0608***		0.0571***		0.0572***		0.0573***	
	(0.01985)		(0.01984)		(0.01982)		(0.01980)	
HH with (at least one) dish washer	0.0963***		0.0971***		0.0956***		0.0957***	
	(0.02384)		(0.02403)		(0.02412)		(0.02406)	
HH with one car	0.3812***		0.3845***		0.3836***		0.3831***	
	(0.02823)		(0.02825)		(0.02827)		(0.02848)	
HH with two or more cars	0.5643***		0.5628***		0.5614***		0.5613***	
	(0.03388)		(0.03373)		(0.03381)		(0.03381)	
Pro-environmental attitude proxy	0.0603**	0.1065***	0.0568**	0.1015***	0.0556**	0.0985***	0.0555**	0.0988***
	(0.02723)	(0.03060)	(0.02706)	(0.03032)	(0.02701)	(0.03040)	(0.02703)	(0.03035)
Philanthropic attitude proxy	-0.0157	0.0832***	-0.0170	0.0817***	-0.0180	0.0793***	-0.0180	0.0794***
	(0.02158)	(0.02189)	(0.02153)	(0.02143)	(0.02147)	(0.02113)	(0.02148)	(0.02117)
Risk aversion proxy: legal protection insurance	0.0599***	0.0760***	0.0613***	0.0783***	0.0601***	0.0740***	0.0601***	0.0742***
	(0.01756)	(0.01921)	(0.01757)	(0.01900)	(0.01756)	(0.01879)	(0.01757)	(0.01879)
Constant	8.3852***	8.8725***	8.3878***	8.8748***	8.4072***	8.9288***	8.4087***	8.9255***
	(0.11652)	(0.12536)	(0.11645)	(0.12473)	(0.11794)	(0.12476)	(0.11815)	(0.12587)
Marital status	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Month	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3066		3066		3066		3066	
AIC	8331.91		8297.23		8273.46		8276.83	
BIC	8832.25		8809.62		8797.91		8813.33	
McElroy's adj. R^2	0.3695		0.3743		0.3775		0.3774	
Cross-equation correlation of residuals	0.1125		0.1066		0.1042		0.1043	

Standard errors in parentheses
* p<0.10, ** p<0.05, *** p<0.010

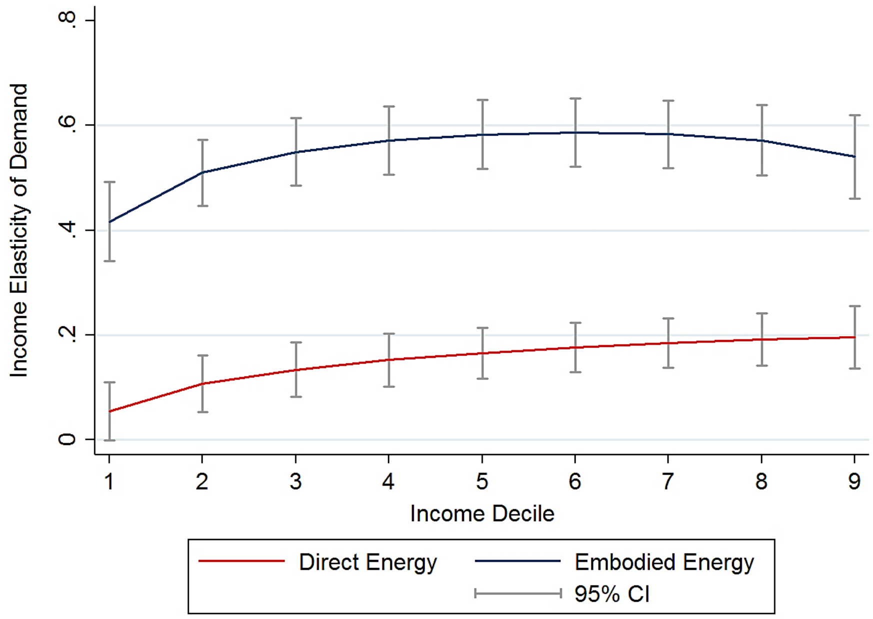
To obtain a more comprehensive impression of the change of income elasticities over the observable income range, Figure 4 plots the corresponding evolution for direct (and indirect) energy demand with increasing income deciles. It clearly shows that income elasticities for direct energy are below 0.3 across all deciles, demonstrating that direct energy is a staple good over the entire range of observable income. At median values of income (CHF 6289.14), elasticity is about 0.17and thus close to results from previous studies on in-home energy demand (Berkhout et al., 2004; Filippini, 2011; Meier & Rehdanz, 2010; Volland, 2017) but smaller than income elasticities from studies on energy demand for private mobility (see e.g., surveys by Espey (1998) and Graham & Glaister (2002), and for Switzerland Baranzini & Weber, (2013)). Moreover, Figure 4 shows that the median income elasticity is only slightly smaller than maximum income elasticity (0.2559) and highly similar to the estimated elasticity at the 90th percentile of the distribution (0.1961), suggesting that despite the estimated functional form income elasticities seem to be constant across the top half of the empirical income distribution. Conversely, elasticities increase markedly over the bottom half of the income distribution. Households at the 10th percentile have an estimated income elasticity of 0.0549 and thus react more than three times less sensitively to changes in the budget constraint than households at the median. A set of ensuing Wald tests demonstrates that this difference is statistically significant at standardly accepted levels of error ($p < 0.0001$).

Viewed over the entire income distribution, results clearly suggest that income elasticities tend to increase with income. This finding is in line with previous research by Volland (2017), who likewise finds increasing income elasticities for household energy demand in a British data set. As pointed out there, there are a number of potential explanations for this phenomenon. First, it is well-documented that households with similar levels of wealth tend to cluster in the same areas (Watson, 2009). A phenomenon that in Switzerland is additionally driven by heterogeneity in local taxation regimes (Morger et al., 2013; Schmidheiny, 2006). Correspondingly, it is perceivable that suppliers adjust their pricing schemes to neighbourhood wealth, such that wealthier households tend to pay higher prices.[24] An alternative explanation is that despite being a necessary good, there could be certain *"luxury"* features to energy. For instance, a rise in income may induce better-off households to spent more on activities that require higher direct energy input, such as purchasing bigger cars, driving them further, faster and more often, or heating up more spacious

[24] Aside from issues of price discrimination, price differences across incomes may arise from differences in the quality of goods obtained by households. That is, rich households may be more inclined to buy high-quality versions of commodities, which are also more expensive. Since differences in quality are not observable in the SHBS data, expenditures cannot be adjusted for these quality differences, such that we may systematically overestimate energy requirements for high-income households (Girod & De Haan, 2010). Yet, as quality variations can be conjectured to be limited in direct energy commodities, this explanation pertains primarily to the results for indirect energy, discussed below.

dwellings to higher temperatures. Since we compute energy requirements based mainly on expenditures rather than use, we cannot distinguish between these two hypotheses. An interesting avenue of future research would therefore be to investigate whether the finding that income elasticities increase with income can be replicated in further data sets, and whether these differences can be traced to differences in consumption or differences in prices.

Figure 4: Direct and embodied income elasticities for income quantiles



Note that the negative coefficient on the third-order polynomial indicates that for very high levels of income, income elasticities would eventually turn negative implying that further increases in income would yield a decrease in household's direct energy requirements. However, caution is advised when taking this result as support for the EKC hypothesis. The income level at which this turn in predicted requirements occurs exceeds median income in our sample by a factor 12.48 (i.e., for a monthly disposable income of CHF 78'454.93). Since there are no observations in our sample that exceed this value, predicting decreases in direct energy requirements as a result of rising income stands on shaky empirical grounds.

With respect to indirect energy requirements, results from model three (M3) in Table 3 are largely comparable to the ones for direct energy. In particular, we observe that the substantial scale economies reported for direct energy demand also extend to indirect energy requirements. Compared to a single household, a 2-person household consumes about 26 % more indirect energy, implying that per-capita requirements are about 37 % lower than that of the individual living in a single household. Similarly, a household consisting of more than three persons consumes only about 40 % more indirect energy than a single household, indicating that each person living in that household gets along with no more than a third of the indirect energy requirements of the single household resident. This suggests that Switzerland's projected demographic transition towards smaller households, will pose a substantial challenge to attaining the goals of the Energy Strategy 2050. In fact, official statistics predict that the share of single and 2-person households will each increase by 4% until 2030, while the share of 3-person households and households with more than three members will decline by 3% and 5%, respectively (Kohli et al., 2015). Simple back-of-the-envelope calculations based on our results suggest that as an effect of this demographic transition alone direct energy requirements per person will increase by about 1.53 %, while indirect energy requirements can be predicted to go up by roughly 1.40 %. We also observe a concave relationship between the age of the household's main respondent and its indirect energy requirements, peaking at the age of 50 and thus slightly higher than the estimated peak in direct energy demand. Similarly, the functional relationship between income and indirect energy demand, closely resembles that of its direct energy counterpart. That is, we observe positive coefficients for both disposable income and its square term (albeit only the prior is statistically significant) and a negative and significant coefficient for the third-order polynomial. Coefficient estimates indicate that income elasticities for indirect energy requirements are highest at a disposable income of about CHF 7301, corresponding roughly to the 70th percentile of the empirical income distribution. At this income level, estimated elasticity is0.5868, which compares to 0.5827 at the median. To ease further interpretation, the corresponding evolution of elasticity estimates is likewise plotted in Figure 4. This plot shows that income elasticities for indirect energy change in a similar pattern across the income distribution as elasticities for direct energy requirements. That is, income elasticity of indirect energy demand increases from 0.4168 at the 10th percentile of the income distribution to 0.609 at the 60th percentile, and then declines to 0.5403 at the 90th percentile. A series of ensuing Wald tests shows that differences in elasticities are significant when comparing elasticity estimates for low and median incomes, but not when comparing high and median incomes. Hence, results suggest that – like in the case of direct energy requirements – income elasticities of indirect energy demand increase over the lower half of the income distribution and remain constant over the top half.

In general, income elasticities of indirect energy requirements are substantially larger than elasticities for direct energy. For instance, at median income, demand for indirect energy reacts roughly three times as sensitively to changes in the budget constraint as demand for direct energy. This, may be little surprising as computations of indirect energy requirements are based on expenditures on all non-energy commodities, and thus contain a substantial number of goods whose income elasticities of demand are likely to be larger than unity (Lenzen, 1998; Wiedenhofer et al., 2013). However, it clearly highlights that with rising income the environmental impact of household consumption is increasingly determined by these latter type of goods and services. Since the variation in energy content within many of these commodities can be conjectured to be substantially larger than in any direct energy good, the scope for behavioral changes is likely to be considerable. Consequently, despite its low average energy-content, policies aiming at energy reduction in final household consumption may be easy to implement in this domain. Interestingly, Figure 4 also shows that income elasticities for indirect energy requirements are well below unity across the entire range of observable incomes, implying that just like direct energy requirements, indirect requirements are a *"staple"* good. Hence, even though total energy requirements increase with income, the energy content per Swiss franc of income is decreasing.

The congruence in the effects of determinants across the two energy demand domains also extends to the psychological controls. We find that, contrary to our expectations, households that donate to environmental organizations tend to use about 6% more direct and almost 10% more indirect energy. One reason for this finding could be that a large share of individuals who donate to environmental organizations do this not primarily because of environmental concern, but as a form of "warm-glow giving" (Andreoni, 1989). That is, they give to environmental organizations in order to enhance their self-image as environmentally benign persons, rather than as an expression of their environmental attitudes. Menges et al. (2005)have demonstrated experimentally that such motivations play an important role in donating to an environmentally relevant public good. Alternatively, households may perceive donations to environmental organizations as a form of indulgence for environmentally damaging behaviours, meaning they believe to be able to off-set their impact on the environment by this form of giving. Girod & de Haan (2009) and Schütte & Gregory-Smith (2015), for instance, present cursory evidence that individuals indeed tend to engage such forms mental accounting and "neutralization" when justifying consumption behaviours with high environmental impacts. Similarly, our control for risk attitude, proxied by the possession of insurance covering legal expenses, shows that risk-averse households consume more direct energy. This finding is in line with previous results showing that risk averse individuals are less likely to invest in energy efficient technologies (Christie et al., 2011; Farsi, 2010, Qiu et al 2014). Interestingly, risk aversion also has a significant positive impact on indirect energy demand. This result may be imputed to the accounting method for dwelling renovations. In fact, expenditures for wall or roof insulation, double glazing, heat pump or solar panels are defined by the SHBS nomenclature as investments, in contrast with consumption expenditures, and are therefore are accounted for only up to a maximum amount of 2418 Swiss francs, as long as they have been carried out the last five months prior to the interview and their amount is above 300 Swiss francs. This means that households who take the financial risk to invest (higher amounts) in energy efficiency measures, are likely to be automatically assigned a lower use of embodied energy, whereas the opposite is true for risk-averse ones. Finally, households that are classified as philanthropic tend to require insignificantly less direct but significantly more embodied energy. A negative impact of altruistic attitude on direct energy is previously observed by Volland (2017) and by Asensio & Delmas (2015), whereas Steg et al. (2005) fail to detect a significant relationship between altruistic attitude and the acceptability of energy policies.

In summary, we find that both direct and indirect energy requirements in Switzerland are overwhelmingly driven by the same determinants, with effects being identical, at least in terms of direction. This suggests that energy requirements in both domains is highest among households sharing a set of common socio-economic characteristics. In particular, it is highest among high-income households, residing in owner-occupied single households. Consequently, these households compose a natural target group for energy conservation policies. Moreover, it suggests that a policy measure like a decrease in disposable income due to a general environmental tax will affect energy requirements in both domains similarly rather than inducing a trade-off between them. It thus provides a first, albeit tentative, indication that requirements for direct and indirect energy demand are positively correlated among Swiss households. That is, that those households using a lot of direct energy are also the households that have the highest environmental impact in terms of the indirect energy contained in their consumption basket of non-energy commodities. This conclusion is further supported by looking at the correlation structure of the error terms from the two SUR estimations, presented at the bottom of Table 3. Estimated cross-equation correlation coefficients are significant in all models and take values in the neighbourhood of 0.11. While this clearly indicates that there are unobserved common determinants – for instance, dwelling size, prices or preferences over energy efficiency – it also shows that, at least on average, these unobserved variables affect indirect and direct energy demand in a similar fashion.

5.2 Complementarity vs. substitutability of direct and indirect energy demand

Estimations from the preceding section(s) suggest that indirect and direct energy are driven by the same determinants and that the effect of these determinants is similar on both domains of energy requirements. A first implication of this finding is that any change in these determinants will lead to a similar change in demand for direct and indirect energy. For instance, the introduction of an additional environmental income tax would reduce demand for direct and indirect energy demand alike. Similarly, it suggests that the energy intensity of household consumption practices in both domains can be predicted from more easily observable socio-economic features like income or household size. A final implication is that in the absence of any further information, household consumption in one domain of energy can be used to predict household consumption in the other. That is, a household with high direct energy requirements is likely to also have high indirect requirements (and vice versa). In this sense and at this descriptive level, energy requirements in both domains can be conjectured to be complementary.

However, based on such univariate predictions it is impossible to state whether the observed relationship is structural or arises spuriously due to endogeneity. Yet, as stated earlier, the nature of the relationship in demand between the two domains of energy is important for evaluating the full set of consequences of any policy targeting one of them. For instance, an environmental tax on direct energy sources like car fuels will have a different impact on total household energy consumption if households consume direct energy and indirect energy jointly than if households react to increasing prices by shifting demand to services containing more indirect energy.

There are a number of reasons to believe that both mechanisms co-exist simultaneously[25]. For one, as demonstrated in Table 3, household direct energy demand is a function of the household's stock in energy-consuming durables like tumble driers or dish washers. Hence changes in this stock (and thus changes in the consumption of indirect energy) will lead to changes in the demand for direct energy services. Inversely, changes in demand for direct energy services can influence household decisions over the acquisition, replacement or retirement of the energy-consuming devices it holds. For example, increasing fuel prices, may induce households to retire rather than replace a second car. In this sense, the relationship between direct and indirect energy requirements can be described as complementary.

On the other hand, it is perceivable that households react to such changes in price patterns by shifting demand from direct energy consumption to indirect energy demand. That is, indirect energy is treated as a substitute for direct energy demand. For instance - as noted in the beginning – households may react to increasing prices for car fuels by reducing trips with their own car and rely on air travel, public transport or delivery services instead. While under many conditions this may lead to favorable environmental outcomes, one has to recall that a similar increase in the price of car fuels also decreases the relative price of air travel and thus increases its demand. Hence, the net environmental effect is an empirical question. Moreover, it is clear that to some extent these substitutive relationships are structural. That is, one can either go on holidays by plane or by car, but not both at the same time. Similarly, one can shop online and have products

[25] Additional examples of sources of endogeneity in household energy demand are provided by Leth-Petersen (2002).

delivered or go to town and obtain them oneself. But again, it is unlikely that a household does both.

While economic analysis commonly defines complementarity based on positive cross-price elasticities, the essential implication is that both goods experience joint demand. Since, we do not observe prices for demand of the two energy domains under investigation, we analyze the nature of the demand relationship between them by directly regressing one on the other simultaneously controlling for joint determinants.

Columns (1) and (2) in Table 4 give OLS estimates for these regressions. Goodness-of-fit measures at the bottom of the table show that additionally including the energy requirements from the other domain substantially improves model fit. Results for most controls closely trace the findings presented in Tables 3. For instance, we still find that owners report higher requirements for indirect energy, or that the increase in requirements with increasing number of individuals is disproportionally small. More importantly, controlling for these covariates we find that there is a significant positive relationship between both domains of energy consumption, suggesting that all else being equal a household with a 1% higher requirements in one domain will also have about 0.1% higher energy use in the other.

A caveat of this empirical approach using OLS is that point estimates in this set-up are susceptible to endogeneity bias arising from reverse causality or unobserved variables jointly determining demand in the two domains of energy. In fact, results from the preceding sections yielded positive and significant correlations in error terms across equations, and thus demonstrate the existence of important omitted determinants simultaneously affecting both requirements. As a consequence, OLS coefficients are likely to be biased estimates for the impact of one domain of energy demand on the other.

To evaluate to which extent these issues affect the results obtained by OLS, we instrument energy requirements in the two domains using information from domain-specific energy use by neighboring households filling in their expenditure diary during the same season. Neighborhood is broadly defined by living in the same larger Swiss region.[26] The argument behind the use of this instrument is that households living in the same region and completing the diary at the same time are likely to face similar policy environments and thus are likely to show similar demand patterns. At the same time a household's energy demand in one domain should not to influence energy

[26] Due to the absence of information on fine-grained geographic location in the data, information on the household's placement within Switzerland is derived by combining information on cantons, language regions and larger geographic regions available in the data set. In doing so, we obtain 16 geographical units that are similar but not identical to cantonal borders.

demand of its neighbors in the other. Similar identification strategies have been applied by Miller & Alberini (2016) and (Volland, 2017) in instrumenting energy prices and energy efficiency in estimations of household direct energy demand. One problem with these sets of instruments is that variation of energy requirements within geographic units is very limited, which dramatically affects the efficiency of the estimation. To check in how far this problem affects results, we run additional estimations substituting regional fixed effects by a set of average regional and seasonal outcomes.[27]

Results from these exercises are given in columns (3) to (6) of Table 4. By accounting for endogeneity in both estimations we no longer find evidence for a causal effect of direct energy demand on indirect energy requirements, while we observe a substantial increase in the effect of changes in indirect energy requirements on direct energy demand. In short, instrumental variable estimations reveal a causal effect of indirect on direct energy demand, and not the other way round. As evidenced by first stage instrument coefficients and F-statistics, neighborhood energy requirements can be considered as a relevant instrument for direct energy demand, whereas second-stage estimates suggest that results obtained by OLS are subject to substantial bias. From a policy perspective these results are important for a number of reasons. First and most importantly, they suggest that any policy targeting direct energy demand is unlikely to lead to major adjustments of indirect energy demand by private households in Switzerland. That is, there is no evidence that such policies will be (partially) off-set by a compensatory increase of indirect energy demand. Second, the possibility of a substantial significant causal link running from indirect to direct energy demand, further highlights the importance of addressing long-term energy-related investment decisions of households. However, we draw this conclusion cautiously, for additional studies commanding more detailed information and using different instrument sets are needed to confirm the current findings.

[27] More precisely, this control set encompasses average household size, average disposable income and the average number of cars owned by households in a region. Moreover, it contains the average age of the household reference person, as well as the share of households in a region with working head, female head, and head with foreign nationality.

Table 4: Separability of direct (embodied) and embodied (direct) energy demand

	OLS		IV 1		IV 2	
	(1)	(2)	(3)	(4)	(5)	(6)
	D. (ln)	E. (ln)	D. (ln)	E. (ln)	D. (ln)	E. (ln)
Direct (ln)		0.1460***		-0.0480		0.0140
		(0.02041)		(0.21485)		(0.16058)
Embodied (ln)	0.0914***		0.3902		0.4980*	
	(0.01659)		(0.31221)		(0.29980)	
Normalized disposable income (ln)	0.1118***	0.5475***	-0.0527	0.5928***	-0.1195	0.5838***
	(0.02698)	(0.03336)	(0.17395)	(0.06217)	(0.16934)	(0.05034)
Normalized disposable income (ln) ^{2}	0.0409***	0.0225	0.0324	0.0331	0.0294	0.0263
	(0.01577)	(0.02050)	(0.02008)	(0.02300)	(0.02024)	(0.02145)
Normalized disposable income (ln) ^{3}	-0.0145*	-0.0559***	0.0020	-0.0605***	0.0107	-0.0620***
	(0.00773)	(0.01758)	(0.01897)	(0.01983)	(0.01960)	(0.01832)
Owner	-0.0076	0.0879***	-0.0346	0.1047***	-0.0409	0.1031***
	(0.02812)	(0.02756)	(0.03447)	(0.03524)	(0.03495)	(0.03188)
Dwelling with shared costs	0.0632**	0.0071	0.0606*	0.0162	0.0481	0.0177
	(0.03000)	(0.02958)	(0.03097)	(0.03271)	(0.03154)	(0.03058)
Used for disaggregation	0.0852***	0.0050	0.0804**	0.0183	0.0774**	0.0149
	(0.03249)	(0.03390)	(0.03435)	(0.03829)	(0.03588)	(0.03614)
2 HH memb.	0.1126***	0.1968***	0.0585	0.2450***	0.0393	0.2262***
	(0.02989)	(0.03394)	(0.06743)	(0.06047)	(0.06405)	(0.05003)
3 HH memb.	0.1415***	0.1819***	0.0929	0.2379***	0.0657	0.2200***
	(0.03656)	(0.04410)	(0.06857)	(0.07294)	(0.06694)	(0.06076)
>3 HH memb.	0.1132***	0.3021***	0.0288	0.3550***	-0.0089	0.3401***
	(0.04231)	(0.04840)	(0.10082)	(0.07198)	(0.09883)	(0.06137)
Age of ref. person	0.0053	0.0228***	-0.0007	0.0256***	-0.0030	0.0238***
	(0.00410)	(0.00451)	(0.00801)	(0.00546)	(0.00760)	(0.00510)
Age of ref. person ^{2}	-0.0001	-0.0002***	-0.0000	-0.0003***	0.0000	-0.0002***
	(0.00004)	(0.00004)	(0.00008)	(0.00005)	(0.00007)	(0.00005)
Gender of ref. person: female	0.0039	0.0574**	-0.0156	0.0506**	-0.0265	0.0605**
	(0.02029)	(0.02388)	(0.02905)	(0.02462)	(0.03181)	(0.02429)
Nationality of ref. person: foreign	0.0467*	-0.0134	0.0503*	-0.0110	0.0486*	-0.0144
	(0.02489)	(0.03019)	(0.02642)	(0.03103)	(0.02776)	(0.03055)
% of gainfully working HH members	-0.0004	-0.0007*	-0.0002	-0.0007*	-0.0001	-0.0006*
	(0.00031)	(0.00036)	(0.00040)	(0.00037)	(0.00041)	(0.00036)
HH with more than one cell phone per HH head ≥12 y.o	0.0446		0.0184		0.0079	
	(0.03377)		(0.04399)		(0.04477)	
HH with more than one laptops per HH head ≥12 y.o	0.1339***		0.1180**		0.0968*	
	(0.04901)		(0.05423)		(0.05572)	

HH with (at least one) desktop computer	0.0201		0.0072		0.0005	
	(0.01759)		(0.02352)		(0.02449)	
HH with (at least one) TV	0.0104		0.0210		0.0201	
	(0.03019)		(0.03234)		(0.03388)	
HH with (at least one) freezer	-0.0102		-0.0199		-0.0172	
	(0.01949)		(0.02180)		(0.02228)	
HH with (at least one) washing machine	0.0572***		0.0618***		0.0600***	
	(0.01927)		(0.02072)		(0.02132)	
HH with (at least one) dish washer	0.0954***		0.0652*		0.0578*	
	(0.02312)		(0.03466)		(0.03501)	
HH with one car	0.3834***		0.3470***		0.3391***	
	(0.02698)		(0.04281)		(0.04328)	
HH with two or more cars	0.5612***		0.5144***		0.4963***	
	(0.03241)		(0.05604)		(0.05750)	
Pro-environmental attitude proxy	0.0466*	0.0933***	0.0172	0.0977***	0.0035	0.0976***
	(0.02705)	(0.02929)	(0.04167)	(0.03100)	(0.04193)	(0.03007)
Philanthropic attitude proxy	-0.0252	0.0862***	-0.0514	0.0858***	-0.0573*	0.0778***
	(0.02135)	(0.02224)	(0.03710)	(0.02443)	(0.03441)	(0.02319)
Risk aversion proxy: legal protection insurance	0.0534***	0.0568***	0.0388	0.0773**	0.0291	0.0742***
	(0.01738)	(0.01952)	(0.02481)	(0.03241)	(0.02604)	(0.02663)
Constant	7.5915***	7.6746***	4.8992*	9.4376***	3.6831	9.5188***
	(0.19564)	(0.22056)	(2.80393)	(1.85509)	(3.00284)	(1.53000)
Marital status	Yes	Yes	Yes	Yes	Yes	Yes
Region	Yes	Yes	No	No	No	No
Month	Yes	Yes	No	No	Yes	Yes
Refined regions	No	No	Yes	Yes	No	No
Season	No	No	Yes	Yes	No	No
HH with working head: average value of refined region	No	No	No	No	Yes	Yes
Age: average value of refined region	No	No	No	No	Yes	Yes
Disposable income: average value of refined region	No	No	No	No	Yes	Yes
N of HH members: average value of refined region	No	No	No	No	Yes	Yes
N of cars: average value of refined region	No	No	No	No	Yes	Yes
N of HH with female HH head: average value of refined region	No	No	No	No	Yes	Yes
N of HH with foreign HH head: average value of refined region	No	No	No	No	Yes	Yes
Observations	3066	3066	3066	3066	3066	3066
Adjusted R^2	0.357	0.450	0.281	0.428	0.212	0.443
AIC	3680.38	4540.72	.	.	.	.
BIC	3975.76	4781.84	.	.	.	.
First-stage regression F-statistic	.	.	7.16	25.86	8.76	44.89

Standard errors in parentheses
* p<0.10, ** p<0.05, *** p<0.010

6. Conclusions and limitations

This paper adopts a holistic approach to household energy demand by investigating the socio-economic and psychological drivers of and the interactions between direct and indirect energy requirements. For this purpose it combines expenditures data from the Swiss Household Budget Survey 2011 with life-cycle and input-output analyses. Using a seemingly-unrelated regression model, we observe that energy requirements in both domains are largely driven by the same socio-economic and psychological determinants. In particular, we find that the relationship between income and energy demand in both domains seems to follow a sigmoid relationship with changes in requirements tracing income changes most closely for medium to high income levels. Results, also show that income elasticities for both domains of energy requirements are well below unity across the entire range of observable incomes, implying both are *"staple"* goods indicating that even though total energy requirements increase with income, the energy content per Swiss franc of income is decreasing. We, thus, find little evidence for an environmental Kuznets curve effect in Swiss direct or indirect energy demand. While the estimated functional relationship between income and energy requirements indicates that theoretically one may expect a turning point after income surpasses a certain level, these points are either very high (indirect energy, 7 times observed median income) or completely out-of-sample (direct energy, 12.5 times observed median income). Moreover, we find that energy demand for both indirect and direct energy demand is subject to considerable scale economies arising from cohabitation, indicating that projected future changes in the household composition of Switzerland pose a challenge to achieving the envisioned energy savings. Furthermore, our results underline previous findings suggesting that basic psychological characteristics like social and risk preferences, play a non-negligible role in determining household energy requirements (Abrahamse & Steg, 2009; Fischbacher et al., 2015; Lange et al., 2014; Volland, 2017).

These findings, along with the positive cross-equation correlation of residuals from our SUR estimation, provide a strong evidence that indirect and direct energy demand are driven by the same determinants, such that the environmental impact of a household in one domain can be predicted from the other, or that both can be derived from more easily observable socio-economic variables. The significative positive coefficients from the conditional correlation between direct (embodied) and embodied (direct) confirm these results. Yet, when investigating the causal relationship between the two we find evidence only for an impact of indirect on direct energy demand but not vice versa. It is however important to note that the instruments on which our identification relies suffer from limited variance, yielding substantial efficiency problems. From a policy perspective, the previous findings are important as they suggest that the wide-spread policies targeting direct energy consumption are unlikely to cause a substantial shift in household energy demand from the direct to the indirect domain.

A note of caution regarding our results is clearly advised as our computations of household energy requirements rest on a substantial number of potentially problematic assumptions. First and foremost, although we have information on the energy intensities for about 80% of final consumption items in the SHBS, these account for only 63% of discretionary and 44% of total expenditures. In particular, we were not able to obtain credible intensities for many economically important expenditure categories like taxes, fees and rents, which were therefore treated as if they did not imply energy use. While this is a common problem in the literature on household energy requirements (Herendeen, 1978; Randolph, 2008; Reinders et al., 2003; Kees Vringer & Blok, 1995), it suggests that additional investigations incorporating these consumption categories into household energy requirements or relying on higher-order categories may help to clarify the consequences of this treatment on the results found in this study. Another, potentially more critical caveat of our approach is that we use expenditures rather than physical units of consumption as the basis for computing energy requirements. As a consequence, we cannot distinguish between differences in the quality of consumption items purchased by households. This is problematic as previous literature has suggested that it may lead to an upward bias in estimated income elasticities (Girod & De Haan, 2010; K Vringer & Blok, 1997). However, while this literature in general has found that estimated differences in income elasticities are significant they also tend to be small,[28] suggesting that all in all the problem may be limited. Moreover, since direct energy sources are a substantially more homogenous, problems regarding quality differences are likely to play a much smaller role here than for indirect energy demand.

[28] For instance, Vringer and Blok (1997) using data from the Dutch Budget Survey find that income elasticities of indirect energy demand based on physical units decreases elasticities based on expenditures only slightly – from 0.63 to between 0.56 and 0.60. One reason could be – as pointed out by (Girod & De Haan, 2010)– that energy inputs into production may also increase with quality.

Appendix 1

According to the SHBS 2011 "*For an important number of tenants, a part of the energy costs (e.g. heating and hot water) is included in the category non-apportioned expenditures* [shared expenditures]*.*" (SHBS, 2011, p.28). This category includes lighting and heating of common spaces, elevator costs, cleaning, gardening, maintenance, and janitor costs. We apply the following disaggregation method in order to extract direct energy costs:

1) Owners with expenditures (425 obs.) in the domains of electricity, heating and shared expenditures are exclusively kept, because they are more likely to know their specific energy expenditures. They are used as a reference population for the disaggregation.

2) We find the average share of electricity, heating and shared expenditures for these observations i.e. the mean of. We hence obtain three ***general weights*** applicable to all households (except to the previous reference population of 425 owners).

3) We estimate ***personal weights*** for all households (3066 obs.). They are defined as the part of shared expenditures in the household's total energy expenditures (incl. shared costs).

4) We create ***final weights*** by multiplying general weights with personal weights. Thus, the disaggregation is more important for households with an important relative amount of shared costs (by definition more shared costs capture a more important part of the direct energy costs of the household).

5) We use the final weights in order to find the expenditure amount of electricity use, heating consumption and common expenditures contained in the mother category shared expenditures. This method is applied to all households, except for the ones used for the disaggregation. These amounts are then multiplied with their corresponding energy intensities. We consider that shared expenditures, which now consist of non-energy services only, have the same energy intensity as the category household reparation and maintenance (MJ/CHF=0.8317). Thus, we obtain additional energy consumptions for direct energy (electricity, heating) and embodied energy (shared expenditures).

Appendix 2

1) In order to match expenditures from the SHBS 2011 with energy intensities from LCA, we use average prices form the Swiss Federal Office of Statistics (Rappo, 2015). Prices are based on data used in the calculation of the Consumer Price Index (CPI) and follows closely the expenditure categories defined by the SHBS 2011. However, prices are not available for all categories. For instance, prices are missing for the category *"622: Transport services".* Therefore, data from the ational Microsensus on mobility and transports for 2010 (SFOE, 2012) which provides us with average annual person-kilometers (pkm) per type of transport. We then combine pkm data with expenditures from the SHBS 2011 in order to obtain unit prices. Our estimation of prices for transport services are close to the ones obtained by Girod & De Haan (2010) for Switzerland.

2) Because of the different energy intensities of the constituent sub-categories of *holiday packages*, we proceed to the disaggregation of this category. In order to be able to do that, we use the *Swiss National Accounts on Tourism* (SFOS, 2011) which provide information on tourism expenditures for Swiss residents. We estimate how these expenditures are distributed between different domains. Based on this data, we estimate that on average Swiss households spend 19.03% on hotels, private rooms and housing in general; 22.29% on eating out; 21.58% on transport services; 18.8539% on airplane tickets; and 18.25% on leisure activities. Using these parts, we calculate the constituent expenditure amounts of holiday packages, which we then multiply by their corresponding average energy intensities.

3) We encounter a similar disaggregation problem with the category e*nergy use of secondary houses*. However, since in this case we do not dispose of any disaggregation criterion, we only attribute a weighted average energy intensity to this category (weighted average of the energy intensities of electricity and heating.

4) In order to estimate average prices per physical unit for furniture and various household appliances, we use an extensive list of average 2005 weights (e.g. in kilograms) established by the *Furniture Re-use Network*, UK, currently known as the FRN Product Weight Protocol (FRN, 2011, 2015)

Appendix 3

Table 5: Descriptive statistics

	mean	sd	min	max
Owner	0.49	0.50	0.00	1.00
Tenant	0.51	0.50	0.00	1.00
Dwelling w/o shared expenditures	0.23	0.42	0.00	1.00
Dwelling with shared expenditures	0.77	0.42	0.00	1.00
Disaggregated	0.86	0.34	0.00	1.00
Used for disaggregation	0.14	0.34	0.00	1.00
1 HH memb.	0.27	0.45	0.00	1.00
2 HH memb.	0.38	0.49	0.00	1.00
3 HH memb.	0.14	0.35	0.00	1.00
>3 HH memb.	0.21	0.41	0.00	1.00
Age of ref. person	53.07	15.21	19.00	95.00
% of gainfully working HH members	53.77	39.61	0.00	100.00
Gender of ref. person: male	0.70	0.46	0.00	1.00
Gender of ref. person: female	0.30	0.46	0.00	1.00
Nationality of ref. person: Swiss	0.87	0.34	0.00	1.00
Nationality of ref. person: foreign	0.13	0.34	0.00	1.00
Marital status: Single	0.19	0.39	0.00	1.00
Marital status: Married	0.61	0.49	0.00	1.00
Marital status: Widowed	0.07	0.26	0.00	1.00
Marital status: Divorced	0.13	0.34	0.00	1.00
HH with one or less cell phone per HH head ≥12 y.o.	0.95	0.21	0.00	1.00
HH with more than one cell phone per HH head ≥12 y.o.	0.05	0.21	0.00	1.00
HH with one or less laptops per HH head ≥12 y.o	0.98	0.15	0.00	1.00
HH with more than one laptops per HH head ≥12 y.o.	0.02	0.15	0.00	1.00
HH without desktop computers	0.43	0.49	0.00	1.00
HH with (at least one) desktop computer	0.57	0.49	0.00	1.00
HH without a TV	0.06	0.25	0.00	1.00
HH with (at least one) TV	0.94	0.25	0.00	1.00
HH without a freezer	0.30	0.46	0.00	1.00
HH with (at least one) freezer	0.70	0.46	0.00	1.00
HH without a washing machine	0.38	0.49	0.00	1.00
HH with (at least one) washing machine	0.62	0.49	0.00	1.00
HH without a dish washer	0.20	0.40	0.00	1.00
HH with (at least one) dish washer	0.80	0.40	0.00	1.00
HH without a car	0.17	0.38	0.00	1.00
HH with one car	0.57	0.49	0.00	1.00
HH with two or more cars	0.26	0.44	0.00	1.00
No environmental attitude proxy	0.90	0.30	0.00	1.00
Pro-environmental attitude proxy	0.10	0.30	0.00	1.00
No philanthropic attitude proxy	0.80	0.40	0.00	1.00
Philanthropic attitude proxy	0.20	0.40	0.00	1.00
Risk tolerance proxy: legal protection insurance	0.66	0.47	0.00	1.00
Risk aversion proxy: legal protection insurance	0.34	0.47	0.00	1.00
Region: Zurich	0.17	0.38	0.00	1.00
Region: Ticino	0.09	0.29	0.00	1.00
Region: Central Switzerland	0.10	0.30	0.00	1.00
Region: North-West Switzerland	0.13	0.34	0.00	1.00
Region: East Switzerland	0.12	0.33	0.00	1.00
Region: Leman	0.15	0.36	0.00	1.00
Region: Mittelland, French-speaking	0.06	0.23	0.00	1.00
Region: Region: Mittelland, German-speaking	0.17	0.38	0.00	1.00
Month: January	0.08	0.27	0.00	1.00
Month: February	0.08	0.27	0.00	1.00

Month: March	0.08	0.28	0.00	1.00
Month: April	0.09	0.28	0.00	1.00
Month: May	0.08	0.27	0.00	1.00
Month: June	0.09	0.28	0.00	1.00
Month: July	0.08	0.28	0.00	1.00
Month: August	0.08	0.27	0.00	1.00
Month: September	0.09	0.29	0.00	1.00
Month: October	0.08	0.27	0.00	1.00
Month: November	0.09	0.28	0.00	1.00
Month: December	0.08	0.27	0.00	1.00
Observations	3066			

References

Abrahamse, W., & Steg, L. (2009). How do socio-demographic and psychological factors relate to households' direct and indirect energy use and savings? *Journal of Economic Psychology*, *30*(5), 711–720.

Alberini, A., Gans, W., & Velez-Lopez, D. (2011). Residential consumption of gas and electricity in the U.S.: The role of prices and income. *Energy Economics*, *33*(5), 870–881.

Alcott, B. (2005). Jevons' paradox. *Ecological Economics*, *54*(1), 9–21.

Andreoni, J. (1989). Giving with Impure Altruism: Applications to Charity and Ricardian Equivalence. *Journal of Political Economy*, *97*(6), 1447–1458.

Asensio, O. I., & Delmas, M. A. (2015). Nonprice incentives and energy conservation. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(6), E510-5.

Baker, P., Blundell, R., & Micklewright, J. (1989). Modelling Household Energy Expenditures Using Micro-Data. *The Economic Journal*, *99*(397), 720.

Baranzini, A., & Weber, S. (2013). Elasticities of gasoline demand in Switzerland. *Energy Policy*, *63*, 674–680.

Barsky, R. B., Juster, F. T., Kimball, M. S., & Shapiro, M. D. (1997). Preference Parameters and Behavioral Heterogeneity: An Experimental Approach in the Health and Retirement Study. *The Quarterly Journal of Economics*, *112*(2), 537–579.

Bartels, R., Fiebig, D. G., & Plumb, M. H. (1996). Gas or Electricity, which is Cheaper? An Econometric Approach with Application to Australian Expenditure Data. *The Energy Journal*, *Volume17*(Number 4), 33–58.

Bekkers, R., & Wiepking, P. (2011). A Literature Review of Empirical Studies of Philanthropy. *Nonprofit and Voluntary Sector Quarterly*, *40*(5), 924–973.

Berkhout, P. H. G., Ferrer-i-Carbonell, A., & Muskens, J. C. (2004). The ex post impact of an energy tax on household energy demand. *Energy Economics*, *26*(3), 297–317.

Bin, S., & Dowlatabadi, H. (2005). Consumer lifestyle approach to US energy use and the related CO2 emissions. *Energy Policy*, *33*(2), 197–208.

Binswanger, M. (2001). Technological progress and sustainable development: what about the rebound effect? *Ecological Economics*, *36*(1), 119–132.

Brandon, G., & Lewis, A. (1999). Reducing Household Energy Consumption: A Qualitative and Quantitative Field Study. *Journal of Environmental Psychology*, *19*(1), 75–85.

Bruvoll, A., & Fæhn, T. (2006). Transboundary effects of environmental policy: Markets and emission leakages. *Ecological Economics*, *59*(4), 499–510.

Bullard, C. W., & Herendeen, R. A. (1975). The energy cost of goods and services. *Energy Policy*, *3*(4), 268–278.

Cameron, C., & Miller, D. L. (2015). A Practitioner's Guide to Cluster-Robust Inference. *Journal of Human Resources*, *50*(2), 317–372.

Chiappori, P., Salanie, B., Chiappori, P.-A., & Salanié, B. (2000). Testing for Asymmetric Information in Insurance Markets. *Source: Journal of Political Economy*, *108*(1), 56–78.

Chitnis, M., & Sorrell, S. (2015). Living up to expectations: Estimating direct and indirect rebound effects for UK households. *Energy Economics*, *52*, S100–S116.

Christie, L., Donn, M., & Walton, D. (2011). The "apparent disconnect" towards the adoption of energy-efficient technologies. *Building Research & Information*, *39*(5), 450–458.

Cohen, A., & Einav, L. (2007). Estimating Risk Preferences from Deductible Choice. *American Economic Review*, *97*(3), 745–788.

Cohen, C., Lenzen, M., & Schaeffer, R. (2005). Energy requirements of households in Brazil. *Energy Policy*, *33*(4), 555–562.

Cole, M. A. (2004). Trade, the pollution haven hypothesis and the environmental Kuznets curve: examining the linkages. *Ecological Economics*, *48*(1), 71–81.

de Groot, J. I. M., & Steg, L. (2008). Value Orientations to Explain Beliefs Related to Environmental Significant Behavior. *Environment and Behavior*, *40*(3), 330–354.

Dinda, S. (2004). Environmental Kuznets Curve Hypothesis: A Survey. *Ecological Economics*, *49*(4), 431–455.

Druckman, A., & Jackson, T. (2008). Household energy consumption in the UK: A highly geographically and socio-economically disaggregated model. *Energy Policy*, *36*(8), 3177–3192.

Dubin, J. A., Miedema, A. K., & Chandran, R. V. (1986). Price Effects of Energy-Efficient Technologies: A Study of Residential Demand for Heating and Cooling. *The RAND Journal of Economics*, *17*(3), 310.

Durrenberger, G., Patzel, N., & Hartmann, C. (2001). Household energy consumption in Switzerland. *International Journal of Environment and Pollution*, *15*(2), 159.

Espey, M. (1998). Gasoline demand revisited: an international meta-analysis of elasticities. *Energy Economics*, *20*(3), 273–295.

ESU-services Ltd., & Niels Jungbluth. (2015). *ESU life cycle inventory data on demand*

Documentation for the ESU database. Margrit-Rainer-Strasse 11c, CH-8050 Zürich.

Farsi, M. (2010). Risk aversion and willingness to pay for energy efficient systems in rental apartments. *Energy Policy*, *38*(6), 3078–3088.

Ferrer-i-Carbonell, A., & van den Bergh, J. C. J. M. (2004). A Micro-Econometric Analysis of Determinants of Unsustainable Consumption in The Netherlands. *Environmental and Resource Economics*, *27*(4), 367–389.

Fiebig, D. G., Bartels, R., & Aigner, D. J. (1991). A random coefficient approach to the estimation of residential end-use load profiles. *Journal of Econometrics*, *50*(3), 297–327.

Filippini, M. (2011). Short- and long-run time-of-use price elasticities in Swiss residential electricity demand. *Energy Policy*, *39*(10), 5811–5817.

Fischbacher, U., Schudy, S., & Teyssier, S. (2015). Heterogeneous preferences and investments in energy saving measures.

FOEN. (2011). Environmental Impacts of Swiss Consumption and Production. Retrieved April 7, 2017, from https://www.bafu.admin.ch/bafu/en/home/topics/economy-consumption/economy-and-consumption--publications/publications-economy-and-consumption/environmental-impacts-consumption-production.html

FRN. (2011). Furniture Re-use Network, Product Weight Protocol. Retrieved April 7, 2017, from http://www.frn.org.uk/product-weight-protocol.html

FRN. (2015). Furniture Re-use Network, Product Weight Protocol. Retrieved April 7, 2015, from http://www.frn.org.uk/product-weight-protocol.html

Gatersleben, B., Steg, L., & Vlek, C. (2002). Measurement and Determinants of Environmentally Significant Consumer Behavior. *Environment and Behavior*, *34*(3), 335–362.

Girod, B., & de Haan, P. (2009). *Mental rebound. Rebound Research Report Nr.3*. *report EMDM1522*. Zürich. https://doi.org/10.3929/ethz-a-006224327

Girod, B., & De Haan, P. (2010). More or Better? A Model for Changes in Household Greenhouse Gas Emissions due to Higher Income. *Journal of Industrial Ecology*, *14*(1), 31–49.

Graham, D. J., & Glaister, S. (2002). The Demand for Automobile Fuel: A Survey of Elasticities. *Journal of Transport Economics and Policy (JTEP)*, *36*(1), 1–25(25).

Grether, J.-M., Mathys, N. A., & de Melo, J. (2012). Unravelling the worldwide pollution haven effect. *The Journal of International Trade & Economic Development*, *21*(1), 131–162.

Grossman, G., & Krueger, A. (1991). *Environmental Impacts of a North American Free Trade Agreement*. Cambridge, MA. https://doi.org/10.3386/w3914

Henley, A., & Peirson, J. (1994). Time-of-use electricity pricing. *Economics Letters*, *45*(3), 421–426.

Herendeen, R. (1978). Total energy cost of household consumption in Norway, 1973. *Energy*, *3*(5), 615–630.

Herendeen, R., Ford, C., & Hannon, B. (1981). Energy cost of living, 1972–1973. *Energy*, *6*(12), 1433–1450.

Herendeen, R., & Tanaka, J. (1976). Energy cost of living. *Energy*, *1*(2), 165–178.

Hertwich, E. G. (2005). Life Cycle Approaches to Sustainable Consumption: A Critical Review.

Jopson, B. (2011). High petrol prices fuel jump in US online shopping. *Financial Times*. New York.

Kaiser, F. G., Wolfing, S., & Fuhrer, U. (1999). ENVIRONMENTAL ATTITUDE AND ECOLOGICAL BEHAVIOUR. *Journal of Environmental Psychology*, *19*.

Kamas, L., & Preston, A. (2010). What can social preferences tell us about charitable giving? Evidence on responses to price of giving, matching, and rebates (pp. 165–199).

Kijima, M., Nishide, K., & Ohyama, A. (2010). Economic models for the environmental Kuznets curve: A survey. *Journal of Economic Dynamics and Control*, *34*(7), 1187–1201.

Kohli, R., Bläuer Herrmann, A., Perrenoud, S., & Babel, J. (2015). *Szenarien zur Bevölkerungsentwicklung der Schweiz*. Neuchâtel.

Kuik, O., & Gerlagh, R. (2003). Trade Liberalization and Carbon Leakage on JSTOR. *The Energy Journal*, *24*(3), 97–120.

Lange, I., Moro, M., & Traynor, L. (2014). Green hypocrisy?: Environmental attitudes and residential space heating expenditure. *Ecological Economics*, *107*, 76–83.

Leahy, E., & Lyons, S. (2010). Energy use and appliance ownership in Ireland. *Energy Policy*, *38*(8), 4265–4279.

Lenzen, M. (1998). Energy and greenhouse gas cost of living for Australia during 1993/94. *Energy*, *23*(6), 497–516.

Lenzen, M., Dey, C., & Foran, B. (2004). Energy requirements of Sydney households. *Ecological Economics*, *49*(3), 375–399.

Lenzen, M., Wier, M., Cohen, C., Hayami, H., Pachauri, S., & Schaeffer, R. (2006). A comparative multivariate analysis of household energy requirements in Australia, Brazil, Denmark, India and Japan. *Energy*, *31*(2), 181–207.

Leth-Petersen, S. (2002). Micro Econometric Modelling of Household Energy Use: Testing for Dependence between Demand for Electricity and Natural Gas. *The Energy Journal*, *23*(4), 57–84.

Martinsson, J., Lundqvist, L. J., & Sundström, A. (2011). Energy saving in Swedish households. The (relative) importance of environmental attitudes. *Energy Policy*, *39*(9), 5182–5191.

Meier, H., & Rehdanz, K. (2010). Determinants of residential space heating expenditures in Great Britain. *Energy Economics*, *32*(5), 949–959.

Menges, R., Schroeder, C., & Traub, S. (2005). Altruism, Warm Glow and the Willingness-to-Donate for Green Electricity: An Artefactual Field Experiment. *Environmental & Resource Economics*, *31*(4), 431–458.

Milfont, T. L., & Duckitt, J. (2010). The environmental attitudes inventory: A valid and reliable measure to assess the structure of environmental attitudes. *Journal of Environmental Psychology*, *30*(1), 80–94.

Miller, M., & Alberini, A. (2016). Sensitivity of price elasticity of demand to aggregation, unobserved heterogeneity, price trends, and price endogeneity: Evidence from U.S. Data. *Energy Policy*, *97*, 235–249.

Morger, M., Brändle, T., Daepp, M., Jeitziner, B., Moes, A., Peters, R., … Stadelmann, D. (2013). Heterogeneity in Income Tax Capitalization and Its Effects on Segregation within Switzer-land Heterogeneity in Income Tax Capitalization and Its Effects on Segregation within Switzerland. *Eidgenössische Steuerverwaltung ESTV A Bteilung Grundlagen* .

Munksgaard, J., Pedersen, K. A., & Wien, M. (2000). Impact of household consumption on CO2 emissions. *Energy Economics*, *22*(4), 423–440.

Pachauri, S. (2004). An analysis of cross-sectional variations in total household energy requirements in India using micro survey data. *Energy Policy*, *32*(15), 1723–1735.

Pachauri, S., & Spreng, D. (2002). Direct and indirect energy requirements of households in India. *Energy Policy*, *30*(6), 511–523.

Park, H.-C., & Heo, E. (2007). The direct and indirect household energy requirements in the Republic of Korea from 1980 to 2000—An input–output analysis. *Energy Policy*, *35*(5), 2839–2851.

Peet, N. J., Carter, A. J., & Baines, J. T. (1985). Energy in the New Zealand household, 1974–1980. *Energy*, *10*(11), 1197–1208.

Qiu, Y., Colson, G., & Grebitus, C. (2014). Risk preferences and purchase of energy-efficient technologies in the residential sector. *Ecological Economics*, *107*, 216–229.

Randolph, J. (2008). Comment on Reid Ewing and Fang Rong’s “The impact of urban form on U.S. residential energy use.” *Housing Policy Debate*, *19*(1), 45–52.

Rappo, V. (2015). Interview with Vincent Rappo on Unit Prices for the Items of the SHBS, 13.01.2015. Espace de l'Europe 10 CH-2010 Neuchâtel: Swiss Federal Office of Statistics, Section Prix.

Reinders, A. H. M. E., Vringer, K., & Blok, K. (2003). The direct and indirect energy requirement of households in the European Union. *Energy Policy*, *31*(2), 139–153.

Roodman, D. (2009). Estimating fully observed recursive mixed-process models with cmp.

Sapci, O., & Considine, T. (2014). The link between environmental attitudes and energy consumption behavior. *Journal of Behavioral and Experimental Economics*, *52*, 29–34.

Schmidheiny, K. (2006). Income segregation and local progressive taxation: Empirical evidence from Switzerland. *Journal of Public Economics*, *90*(3), 429–458.

Schröder, C., Rehdanz, K., Narita, D., Okubo, T., Y., Y., B., M., & M., H. (2015). The decline in average family size and its implications for the average benefits of within-household sharing. *Oxford Economic Papers*, *67*(3), 760–780.

Schütte, L., & Gregory-Smith, D. (2015). Neutralisation and Mental Accounting in Ethical Consumption: The Case of Sustainable Holidays. *Sustainability*, *7*(6), 7959–7972.

SFOE. (2012). *Statistique globale suisse de l'énergie 2011*. Section Analyses et perspectives 3003 Bern.

SFOS. (2011). Compte satellite du tourisme 2011, Consommation du tourisme interne, par produits et groupes ad hoc de visiteurs résidents, 2011, CST-TABLEAU 2, Swiss Federal Office of Statistics (SFOS). Retrieved April 7, 2017, from https://www.bfs.admin.ch/bfs/fr/home/statistiques/tourisme/aspects-monetaires.gnpdetail.2015-0180.html

Sorrell, S., & Dimitropoulos, J. (2008). The rebound effect: Microeconomic definitions, limitations and extensions. *Ecological Economics*, *65*(3), 636–649.

Steen-Olsen, K., Wood, R., & Hertwich, E. G. (2016). The Carbon Footprint of Norwegian Household Consumption 1999-2012. *Journal of Industrial Ecology*, *20*(3), 582–592.

Steg, L., Dreijerink, L., & Abrahamse, W. (2005). Factors influencing the acceptability of energy policies: A test of VBN theory. *Journal of Environmental Psychology*, *25*(4), 415–425.

Stern, D. I., David, B., & Stern, I. (2017). The environmental Kuznets curve after 25 years. *J Bioecon*, *19*, 7–28.

Torgler, B., Frey, B. S., & Wilson, C. (2009). Environmental and Pro-Social Norms: Evidence on Littering. *The B.E. Journal of Economic Analysis & Policy*, *9*(1).

Volland, B. (2017). The role of risk and trust attitudes in explaining residential energy demand: Evidence from the United Kingdom. *Ecological Economics*, *132*, 14–30.

Vringer, K., Aalbers, T., & Blok, K. (2007). Household energy requirement and value patterns. *Energy Policy*, *35*(1), 553–566.

Vringer, K., & Blok, K. (1995). The direct and indirect energy requirements of households in the Netherlands. *Energy Policy*, *23*(10), 893–910.

Vringer, K., & Blok, K. (1997). Do Higher Incomes Pay More?: The Effect of Price-income Relations on the Direct and Indirect Energy Requirement of Households in the Netherlands. *Vakgroep Natuurwetenschap En Samenleving*.

Watson, T. (2009). Inequality and the Measurement of Residential Segregation By Income in American Neighberhoods. *Review of Income and Wealth*, *55*(3), 820–844.

Weber, C., & Perrels, A. (2000). Modelling lifestyle effects on energy demand and related emissions. *Energy Policy*, *28*(8), 549–566.

Wiedenhofer, D., Lenzen, M., & Steinberger, J. K. (2013). Energy requirements of consumption: Urban form, climatic and socio-economic factors, rebounds and their policy implications. *Energy Policy*, *63*, 696–707.

Wiedmann, T., Lenzen, M., Turner, K., & Barrett, J. (2007). Examining the global environmental impact of regional consumption activities — Part 2: Review of input–output models for the assessment of environmental impacts embodied in trade. *Ecological Economics*, *61*(1), 15–26.

Wier, M., Lenzen, M., Munksgaard, J., & Smed, S. (2001). Effects of Household Consumption Patterns on CO_2 Requirements. *Economic Systems Research*, *13*(3), 259–274.

Yen, S. T., Boxall, P. C., & Adamowicz, W. (1995). An Econometric Analysis of Donations for Environmental Conservation.

Zellner, A., & Theil, H. (1962). Three-Stage Least Squares: Simultaneous Estimation of Simultaneous Equations. *Econometrica*, *30*(1), 54.