Residential Energy Use and Conservation:
Economics, Demographics, and Standards

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Abstract

Energy consumption in the residential sector offers an important opportunity for conserving resources. However, much of the current debate regarding energy efficiency in the housing market focuses on the physical and technical determinants of energy consumption, neglecting the role of the economic behavior of resident households. In this paper, we analyze the extent to which the use of gas and electricity is determined by the technical specifications of the dwelling as compared to the demographic characteristics of the occupying household, using a unique set of microeconomic data for a sample of more than 300,000 Dutch homes. The results show that residential gas consumption is determined principally by structural dwelling characteristics, such as the vintage, building type and quality of the home, while electricity consumption varies more directly with household composition, in particular income and family composition. Combining these results with projections on future economic and demographic trends, we find that, absent price increases for residential energy, the aging of the population and their increasing wealth will mostly offset improvements in the energy efficiency of the building stock resulting from policy interventions and natural revitalization.

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Introduction

Energy efficiency in housing markets is again prominent in policy circles. During the late 1970s, in the aftermath of the oil crisis, concerns regarding energy dependency triggered a first wave of policies to improve the energy efficiency of residences. Forty years later, renewed attention to energy efficiency in housing is motivated by concerns about pollution, global warming, and fossil fuel depletion. About one-fifth of total global energy demand originates from the residential sector -- from the requirements to heat, cool, and light residential dwellings. Hence, the housing market has become an important target for policymakers and a prominent component of the Kyoto protocol.

Energy efficiency policies would be redundant if the private market for investments in energy efficiency functioned perfectly. But the long discussion about the "energy paradox," *i.e.*, the apparently irreconcilable contradiction between the profitability of energy-conserving technologies and the slow diffusion of these technologies (Adam B. Jaffe and Robert N. Stavins, 1994), suggests that the private market responds slowly. For example, it appears that consumers apply unreasonably high discount rates in valuing the monetary benefits of energy efficiency (Kenneth Train, 1985).[1]

Increased transparency in energy consumption may encourage energy conservation among private consumers. Recent experiments show that providing information to consumers on their current energy consumption can substantially reduce energy bills (Ian Ayers, Sophie Raseman and Alice Shih, 2009), and "energy certificates" may also enhance the awareness of energy consumption among consumers. These energy certificates convey information on energy efficiency relative to the market and could nudge consumers to opt for more energy efficient alternatives. Recent research suggests that homeowners value the energy efficiency signalled by energy labels (Dirk Brounen and Nils Kok, 2011). However, household discount rates for energy efficiency investments are still unclear.

As household energy bills rise due to increasing oil and gas prices, it is anticipated that energy efficiency will gradually be reflected in market pricing. In principle, future energy bills will be reflected in the transaction prices of homes, but only if energy efficiency is properly measured, understood and evaluated. Economic analysis of residential energy demand goes back at least sixty years to Hendrik Houthakker (1951); T.R. Lakshmanan and William Anderson (1980) provided an overview of the increased understanding of energy efficiency achieved during the energy crisis of the 1970s. Conservation policies in the US in

[1] In contrast, more recent research suggests that professional property investors recognize quite precisely the relative efficiency of commercial buildings (Piet M.A. Eichholtz, Nils Kok and John M. Quigley, 2010).

response to the first energy crisis -- subsidizing retrofits directly through state and federal tax codes and mandating technical standards for newly-constructed dwellings -- were studied extensively during the 1980s. (See, for example, Richard J. Gilbert, 1991, for a review.) The recent reawakening of concerns about energy use means that many of these same issues are being revisited with better data and techniques, for example, the efficiency of building codes in reducing energy consumption (Anin Aroonruengsawat and Maximillian Auffhammer, 2011, Grant D. Jacobsen and Matthew J. Kotchen, 2009).

Measuring or influencing occupant behavior is more complex, and has received less attention in policy debates.[2] David Fritzsche (1981) used the family life cycle construct to address the interactions between time variations in household income, family size and household age. Based upon detailed data from the Consumer Expenditures Survey, Fritzsche reported an inverted u-shaped curve in the energy expenditures of some 20,000 U.S. households, with energy expenditures lowest during the early and late stages of the life cycle. Fred van Raaij and Theo Verhallen (1983) introduced a detailed behavioral model to explain residential energy use, distinguishing between purchase, usage and maintenance-related behaviour. These models provided a framework which helped explain the interaction between household composition and energy demand (Peter C. Reiss and Matthew W. White, 2005), changes in residential electricity demand following energy shocks (Peter C. Reiss and Matthew W. White, 2008), and the energy consumption of households in relation to historical energy prices and changes in building codes (Dora L. Costa and Matthew E. Kahn, 2010).

This paper contributes to the re-emerging literature on energy efficiency in the built environment, in which a clear and integral analysis of household energy consumption has been lacking -- apart from one micro-economic study on the determinants of household electricity usage in Sacramento, California (Dora L. Costa and Matthew E. Kahn, 2011). Understanding the key determinants of residential energy consumption is important for the design and implementation of effective policies to reduce energy consumption (and thereby the carbon footprint) of the residential building sector. Importantly, the strong heterogeneity in the quality of the building stock in different countries around the world increases the need for international comparisons on the ingredients of successful policy design.

In this paper, we employ detailed micro-economic data on energy consumption, demographics and dwelling characteristics for more than 300,000 households and dwellings in the Dutch housing market. We focus on gas and electricity consumption and investigate

[2] There are some early discussions on the role of behavior and life-style in household energy consumption, but these studies are mostly descriptive rather than causal (Loren Lutzenhiser, 1993, Lee Schipper et al., 1989).

the impact of the physical structure of a home (*i.e.,* the hedonic characteristics) on variations in energy consumption. We then add a set of household demographic characteristics to measure the influence of household composition and behavior on the consumption of energy, conditional upon the vintage and structural characteristics of the dwelling.

The Dutch residential market offers an interesting research laboratory for the study of energy efficiency. Energy conservation is presumably important for Dutch residents, as the average energy bill of a Dutch household reached €152 per month in 2009 (€53 for electricity and €99 for gas), ranging from €105 for the most energy efficient homes, to €231 for the least energy efficient homes of similar size. In some cases, the energy costs represent almost half of total monthly housing expenses. This provides some indication of the economic relevance of the energy costs for the households in our sample, and more broadly, throughout Northern Europe.

Our results show that the cross-sectional variation in residential energy consumption is a function of both technical characteristics of the dwelling and the composition and background of the household. In case of gas consumption, the thermal attributes of the structure are dominant. For example, a well-maintained and insulated home consumes about four percent less natural gas as compared to the same home with a lower level of maintenance and insulation. With respect to residential electricity demand, we find that household composition is paramount. For instance, families with children consume almost one fifth more electricity than families without children, and this effect becomes stronger when the age of children increases.

The remainder of this paper is organized as follows. Section 2 describes the data and provides some descriptive information on energy consumption in our sample. Section 3 discusses the empirical results, relating energy consumption in a large cross-section, according to the technical characteristics of the dwelling, and to important household demographic conditions. Section 4 includes some projections of future household energy consumption and a brief conclusion.

2. Data

A. Sources and Baseline Characteristics

We analyze observations on some 300,000 dwellings in the Netherlands, gathered between January 2008 and December 2009. These dwellings have been registered by the National Association of Realtors (NVM), and provide information on address, the characteristics of the transaction, and a wide array of quality characteristics on each dwelling.[3] We focus on homeowners, as we lack critical information on rental units, such as dwelling characteristics, and the type of rental contract -- net or gross -- which may have a substantial influence on energy consumption, as emphasized by Arik Levinson and Scott Niemann (2004).

We merge information on each dwelling to detailed information from the Central Bureau of Statistics (CBS) on electricity consumption (kilowatt-hours, kWh) and gas consumption (cubic meters, m^3) of that dwelling for the year 2007. Note that we have annual data, not billing cycle data, and measures of energy consumption rather than energy bills. It is reasonable to assume that all households face similar average and marginal prices, as competition between utility companies in the Netherlands is fierce, and block-tier pricing systems currently do not exist. So, expenditures can be approximated by energy consumption, using average energy prices in 2007.

The Bureau of Statistics also provided detailed information on demographic characteristics of each individual household, such as age of the household head, number of persons in the household, family composition, ethnicity (and annual income for some of the occupants).

- Table 1 here -

Table 1 provides an overview of the data on individual dwellings -- 305,001 dwellings observed in 2008-2009. The average dwelling in the sample consumes some 1,900 cubic meters of natural gas and some 3,600 kilowatt hours (kWh) of electricity per year. This translates into an average utility bill of more than €2,000 on a yearly basis. But, of course, there is a wide variation in household consumption, which we explore in depth below.

About a third of the sample consists of duplex homes (“row” houses), followed by apartments in multi-family buildings. Detached homes are about 13 percent of the sample. The average size of dwellings is 125 square meters (some 1345 square feet), with five rooms. Homes in the Netherlands are relatively old: more than a quarter of the sample was constructed before World War II, and almost half of the sample was constructed before 1970. Less than one percent of the homes in our sample are officially qualified as “monuments,” or historic structures.

[3] The members of the NVM collectively cover approximately 70 percent of all housing transactions in the Netherlands.

Regarding thermal and quality characteristics, the data indicate that central heating is now the norm; it is included in 92 percent of all transacted homes.[4] Maintenance (interior as well as exterior) is generally categorized as "good," but the quality of insulation leaves some room for improvement -- only about half of the sample has more than two layers of insulation, which has direct implications for the energy efficiency of homes.

The average family size in our sample is 2.66 persons, which is slightly larger than the average household size in the Netherlands (2.23). One-family households are less likely to be homeowners, representing about 18 percent of the sample. Within the sample of families with children, the number of children is about one, on average, and the age of the oldest child is about 11 years. Elderly households (where the head of the household is at least 65 years or older) represent some 15 percent of the sample. Importantly, this number is expected to grow substantially in the decades to come, with an increase of 1.5 million people in the 65+ age-cohort until 2040.[5] Non-natives occupy about fifteen percent of the sampled homes. The Netherlands is known for its large fraction of foreign-born inhabitants, and this number is also expected to grow in the near future as well. The homeowners in our sample earn an average annual gross income of €35,455, which is ten percent higher than the national average, which also includes renters.

B. Dwellings, Households and Energy Consumption

Figures 1 and 2 illustrate the simple relationships between energy consumption, dwelling characteristics and household composition, both for gas use and for electricity consumption.

Figure 1A shows the variation in total average energy use by vintage. Demand for gas (*i.e.*, heating) is clearly lower for more recently constructed buildings, by some 1,000 cubic meters a year, as compared to very old homes, for example. This contrasts with electricity usage, which seems to be higher in more modern dwellings, presumably related to the presence of appliances and amenities in these homes. In Figure 1B, the effect of dwelling type on energy consumption is documented; both apartments and row houses consume substantially less energy, which may be related to the typically smaller size of these dwelling types. But of course, the exposed surface of apartments and row houses will be smaller than for (semi-) detached residences, requiring less heating for the same level of thermal comfort.

[4] Penetration of the national gas network has traditionally been quite extensive in the Netherlands: in 1962, 76 percent of households had access to natural gas, increasing to 90 percent by the end of the 1970s (Ecofys, 1998).
[5] Data retrieved from http://www.cbs.nl/nl-NL/menu/cijfers/statline.

In Figure 2A the relationship between family type (or household composition) and energy consumption is presented. Household composition is found to be an important determinant of demand for electricity, but this relation is less pronounced for gas consumption. Gas and electricity consumption are lower, on average, for single households, whereas families with children consume more gas and substantially more electricity. The relatively small variation in gas consumption across family types is well-documented in the literature and this is generally explained by household economies of scale (Brian C. O'Neill and Belinda S. Chen, 2002, Lee Schipper, et al., 1989). Figure 2A further shows that differences in gas consumption between the average household, female-headed households and non-native households are trivial. There are small differences in electricity consumption.

Figure 2B depicts how household energy consumption changes with each stage of the "family life cycle." Of course, income rises as households move through career paths, the size of the home increases with the growth of the family, and lifestyle changes again when households retire and spend more time at home. The averages suggest that children are important for energy consumption, and the age of children is a determinant of demand for heating and electricity as well. (It has, for example, been documented that teenagers shower more than younger children, Lee Schipper, et al., 1989).

- Figures 1 and 2 here -

3. Empirical Methods and Results

A. Energy Consumption and Dwelling Characteristics

We first examine the extent to which gas- and electricity consumption can be explained by the physical, technical, and engineering characteristics of dwellings. We estimate the following reduced-form equation:

$$\text{(1a)} \qquad \log(E) = \alpha + \beta_i \mathrm{X}_i + \sum_{P}^{p=1} \gamma_p p_p + \varepsilon_i$$

In the formulation represented by equation (1a), the dependent variable is the logarithm of gas consumption in cubic meters or electricity consumption in kilowatt hours of dwelling *i*. X_i is a vector of the hedonic characteristics of building *i*, including dwelling type, period of construction, and thermal and quality characteristics, such as heating system and maintenance. To control for locational variation in energy consumption, p_p is a dummy variable with a value of one if building *i* is located in province *p,* and zero otherwise. There are twelve provinces in Holland. ε_i is an error term, assumed i.i.d.

Table 2 presents the regression estimates for energy consumption. Standard errors are corrected for heteroskedasticity following Halbert White (1980). In the first three columns, total annual gas consumption, measured in cubic meters, is the dependent variable. Columns four to six repeat the analysis, relating electricity consumption (kWh) to physical characteristics of the dwelling.

Our basic models explain about a quarter to a third of total household gas consumption. This compares favorably with other studies (for example Katrin Rehdanz, 2007, who explains 17 to 27 percent of gas consumption for small panel of German homes). Dwelling size is a major determinant of gas consumption, with an elasticity of 0.50. After controlling for size, each additional room adds 0.5 percent to the total energy consumption[6]. Compared to corner dwellings, apartments and duplex homes use substantially less energy for heating -- the latter benefit from less exposed surface. In contrast, semi-detached and especially detached dwellings consume significantly more gas for heating.

In the second column, we add dwelling vintage to the model.[7] Relative to dwellings constructed in this century, we find that gas consumption increases with the ages of dwellings. The results seem to suggest that thermal building conventions (or standards) improved greatly after 1980 -- the 1970-1980 cohort uses 46 percent more energy, while the 1980-1990 cohort uses 26 percent more energy than the post-2000 cohort. This pervasive difference may well be the result of changes in building codes or building techniques. Research suggests that high energy prices have resulted the construction of more efficient homes in the US (Dora L. Costa and Matthew E. Kahn, 2010). In this case, the 1973 oil crisis led to large increases in oil- and gas prices around the globe, and this resulted in the largest home weatherization program in Dutch history. Initiated by the Dutch government, the National Insulation Program provided subsidies to improve the thermal quality of about one million homes, with an average expected saving of about 650 cubic meters of natural gas per dwelling (Bram G. Entrop and Jos H. Brouwers, 2007).

[6] Apart from the obvious cross correlations between dwelling size and the number of rooms, we also suspect that the low gas elasticity for the number of rooms may well be related to the fact that heating homes is mainly done in the living-, bath-, and dining rooms of the house. In most Dutch homes, bedrooms are typically not heated at night, which reduces the importance of number of rooms here. The particular importance of cultural backgrounds in relation to residential energy use are studied by for instance Harold Wilhite et al. (1996).

[7] The NVM data does not provide the exact year of construction, but rather the decade of construction. As such, we cannot link changes in building codes directly to changes in energy consumption.

For structures built before 1970, gas consumption increases monotonically with age, until 1930. Dwellings constructed between 1905 and 1930 use less gas than younger dwellings, *ceteris paribus*, and very old dwellings -- constructed before 1905 -- even use less gas than dwellings constructed more than half a century year later. The quality of now antique building techniques may explain this finding, but of course, older buildings are also much more likely to undergo renovation, which is not observable in these data.

Column (3) adds thermal and quality characteristics to the model. In line with expectations, dwellings with central heating have higher gas consumption -- about 1.3 percent. Homes that are well maintained use less energy, and better insulation also decreases energy usage, although the economic significance appears to be small. An additional layer of insulation leads to a one-percent reduction in the consumption of natural gas. Note that the relation between insulation and gas consumption is non-linear, so the effect of adding another layer of insulation to a dwelling that has already been insulated is smaller.

The results relating electricity consumption to dwelling characteristics are presented in columns (4) through (6). The explanatory power of our models is comparable to similar studies in other countries, for example Dora Costa and Matthew Kahn (2010), who explained about 27 percent of electricity consumption for a large panel which measured daily electricity consumption at the household level.

Dwelling size is again strongly related to total energy consumption, with an elasticity of 0.65, and an additional room adds 0.3 percent to total electricity consumption. The findings for dwelling vintage are quite different from those reported for gas consumption: relative to post-2001 constructed homes, the 1980-1990 and 1990-2000 cohorts consume 3.6 percent and 5.3 percent more electricity, respectively. However, older dwellings consume *less* electricity, which might imply greater efficiency. This contrasts with results documented by Dora Costa and Matthew Kahn (2010), who find “a distinctive non-monotonic [negative] relationship between a home’s year built and electricity consumption” in Sacramento, California. But of course, the climatic setting of that study differs markedly; homes in Sacramento require substantial cooling in the hot summers and hardly any heating during the mild winters. The average annual temperature in Sacramento is 16 degrees Celsius and 77 percent of the dwellings are air-conditioned. Holland has an average annual temperature of 10 degrees Celsius, homes have mostly gas-powered heating (and cooking) systems, and they require virtually no air-conditioning systems. The negative relation between property age and electricity consumption is unrelated to a dwelling’s thermal characteristics, but it may have more to do with unobserved wealth effects and the presence of more energy-intensive appliances in modern homes.

- Table 2 here -

As noted previously, we control for regional variation in energy demand by including fixed effects for the twelve Dutch provinces. Even though Holland can be considered a relatively small country, there are noticeable climatic differences between the regions closer to the North Sea, the landlocked south, and the north of the country. Figure 3A illustrates how average winter temperatures varied by province in 2007. Quite clearly, the northeast was colder than the southwest, by an average of 1.5 degrees Celsius. Figure 3B shows the relative gas consumption per province, based on the fixed effects for provinces estimated in Equation (1a). As compared to Flevoland, the central province in what was once the "Zuiderzee," dwellings in the colder northeastern provinces consume at least six percent more natural gas, on average (importantly, this is corrected for the physical and technical characteristics of the dwelling). Dwellings in the relatively warm southwestern province of Zeeland consume at least two percent less natural gas. Even in a country as small as Holland, variation in weather conditions has a noticeable influence on demand for energy.

- Figure 3 here -

Figure 4 provides further evidence on the effect of dwelling vintage and insulation quality on resource consumption, based on the partial derivates of the coefficients on interactions between period of construction and each dwelling type, estimated using equation (1). Keeping other dwelling characteristics constant, Figure 4A shows the non-monotonic relation between gas consumption and dwelling vintage. Dwellings constructed between 1930 and 1944 -- representing about 8 percent of the sample -- are least efficient and consume some 80 percent more gas than dwellings constructed post-2001. The effects reported here are much stronger than those reported in a recent study on the effect of "birth year" and electricity usage in a sample of homes in California (Dora L. Costa and Matthew E. Kahn, 2011). Part of this difference may be explained by climatic differences and the use of gas heating in Northern Europe rather than the use of electric air-conditioning in California. But the simple comparison also shows that dwelling vintage has a very strong effect upon energy efficiency in the Northern European residential housing market. More than 65 percent of the dwellings in our sample were constructed before 1980, and the dwellings in pre-1980 cohorts consume at least half as much energy as more recent constructions. Dwellings are long-lived (a third of our sample of 300,000 observations are more than a half century old) and the effects of less efficient construction in the past will continue to have an effect on current energy usage for decades to come. The vintage effects differ slightly by dwelling type, especially for older dwellings. Old corner homes are least efficient, whereas old detached homes are most efficient.

In Figure 4B, we analyze in more detail the effect of insulation quality on residential gas consumption for different cohorts of dwelling age.[8] Quite clearly, insulation matters for the usage of natural gas. Although economic effects are rather small, they differ strongly for different vintages, and the relation between the number of insulation layers and gas consumption is non-linear. For very old dwellings, constructed between 1905 and 1929, the difference in gas consumption between a non-insulated home and fully insulated home is about eight percent. For more recently constructed homes (1990-2000), this difference is less than two percent. To put this into perspective: recent experiments with OPOWER Home Energy Reports in the US -- providing households information on their past energy consumption as compared to their neighbors and providing energy conservation tips -- achieve energy reductions of about two percent as well (Hunt Allcott, 2009).

Figure 4C shows the effect of dwelling vintage on electricity consumption. Electricity consumption is not consistently related to a dwelling's vintage. Compared to recent construction, dwellings built after 1980 use slightly more electricity (some five percent more for dwelling constructed between 1990 and 2000), but dwellings constructed before 1980 consistently consume less electricity. This pattern confirms our prior finding that electricity consumption may be related to unobserved wealth effects and the presence of income elastic, energy-intensive appliances in modern homes, rather than to heating or cooling of the interior.

- Figure 4 here -

B. Energy Consumption and Household Demographics

While acknowledged as important, the social and demographic characteristics of households are often ignored in the engineering literature on energy efficiency, perhaps due

[8] We distinguish between age cohort rather than dwelling type, since insulation quality is strongly related to building age.

to a lack of detailed micro-economic data. For instance, family size and composition have a distinct influence on energy behavior and use. Table 3 relates the demographic composition of households to their consumption of gas and electricity. Supposedly, women have a preference for higher ambient temperatures than men, and non-natives have lifestyles that may lead to differences in energy consumption patterns.[9] The combination of age, marital status and family size represents the family life cycle. It has been documented that the ages and activities of family members offer some explanation for the cross-sectional variation in household energy consumption patterns (David J. Fritzsche, 1981).

We test more specifically for the implications of household type and composition on energy demand by replacing dwelling characteristics with household demographic measures in equation (1a):

$$\text{(1b)}\ \log(E) = \alpha + \beta_i X_i + \delta_i D_i + \sum_{P}^{p=1} \gamma_p p_p + \varepsilon_i$$

where D_i is a vector of demographic characteristics, including age of the head of the household, household composition, ethnicity, and income. We acknowledge that the annual energy consumption of the household is not only a function of the physical structure of the building and demographic composition, but it also depends on the choice of durable goods in the dwelling. However, the latter are unobserved and that we cannot further control for them directly.

Table 3 presents the results for four different specifications, estimated for both gas and electricity consumption. Location fixed effects are included in these specifications, but omitted from the table.[10] Column (1) shows that each additional person per household adds some 13 percent to total gas consumption. The age of the head of the household has no significant relation to gas consumption. Interestingly, demographic attributes also seem to influence demand for natural gas. Female-dominated households consume about two percent more natural gas, whereas non-native households consume slightly less. Anecdotally, we can explain these findings by gender differences in preferences on thermal comfort temperatures and differences between races regarding lifestyle (*i.e.*, cooking, bathing, etc.) and thermal preferences (Sami Karjalainen, 2007, Harold Wilhite, et al., 1996).

[9] There is a large body of mostly qualitative research on gender preferences on thermal comfort. See for example (Sami Karjalainen, 2007) There are also studies on cultural background and energy consumption. See for example (Harold Wilhite et al., 1996)

[10] Physical characteristics of the dwelling are excluded from this model, so results can be interpreted directly as the effect of household demographics on energy usage.

In Column (2), we decompose the household composition further into family type. Relative to households without children, single households consume about 22 percent less natural gas, but elderly households consume about 31 percent more. This difference may well be attributed to occupation intensity of the dwelling, which is likely to be lower among working singles than among retired households. Single elderly households demand substantially less heating than married seniors -- about 17 percent. Heating usage increases by about 18 percent per additional child, which contrasts existing evidence on economies of scale in household energy consumption.

We further investigate the influence of the family life cycle on gas consumption in Column (3). We find that energy consumption increases after the birth of children and then remains relatively stable until children are teenagers. (The behavior of young adolescents seems to be positively related to energy usage.)

In column (4), we add information on household income for a subset of the sample. The income elasticity of demand for natural gas is about 0.06. This is an indication that, if not controlled for dwelling size and amenities, thermal comfort requirements are substantially different across income classes (David J. Fritzsche, 1981).[11]

We relate electricity consumption to household demographics in Columns (5) through (8). As opposed to gas consumption, electricity usage is significantly lower in dwellings occupied by female or non-native households. This might be an unobserved wealth effect, but the results remain economically and statistically strong after controlling for income (See Column (8). The elasticity of electricity demand with respect to household size is even larger than for gas consumption: an additional person in the household increases electricity consumption by about 21 percent. Apparently, economies of scale are less powerful for electricity demand.

Even though the demand for heating increases with age, columns (5) and (6) show that age is not monotonically related to electricity consumption. The elderly may spend more time at home, but they seem to have fewer energy-consuming appliances -- elderly households consume about five percent less electricity than middle-aged married couples. The mild difference between single elderly households and elderly households with two or more people may result from the fact that all elderly households typically spend more time at their residence, which may reduce any economies of scale that are more common among families.

[11] We acknowledge that the differences in energy consumption are not proportional to the differences in economic well-being, as one can only use so much energy, no matter how wealthy the household.

Column (7) shows the relation between family life cycle and electricity usage. We document that the age of children has a significant influence on electricity consumption -- the "Nintendo-effect." Older children watch more television, use personal computers, and frequently have gaming devices. This has a substantial effect on energy consumption.

The income-elasticity of electricity demand is stronger than the elasticity of demand for heating. A one-percent increase in disposable income leads to a 12 percent increase in household electricity demand. This is a slightly stronger effect than results documented for a panel of households in Sacramento, California (Dora L. Costa and Matthew E. Kahn, 2010).

- Table 2 here -

Figure 5 provides a more detailed analysis of the sensitivity of energy demand to income, for different types of households. For all households, we here find that as soon as household income exceeds the national average of €32,000, energy bills increase monotonically with the monthly income households. For gas consumption, we document some interesting results for low-income households. It appears that the lowest income groups use more gas than the households with average income. This may well be a simple reflection of the large fraction of unemployed and disabled citizens that are present in this lowest income group, a group of citizens that spends more time at (a heated) home.

The energy demand of elderly lies substantially above the average of other family types, and is highly responsive to income (Figure 5A). The gas usage of middle-income elderly households is about thirty percent higher than that of other middle-income households, and the electricity consumption of middle and upper income elderly households is close to forty percent higher than that of other households. Presumably, the elderly spend more time in their dwellings; in any event they spend considerably more on heating and on the supply of electricity to their homes.

- Figure 5 here -

4. Conclusions and Discussion

In this analysis, we have relied upon a large sample of houses and their resident households in Holland, to investigate the linkage between the physical characteristics of dwelling units and their consumption of energy. At the same time, we investigate the relationship between household composition and demographics and households' consumption of gas for heating and electricity for lighting and other uses.

We document a strong relationship between the vintage of dwellings and their composition of energy. Dwellings constructed in this century use about forty percent less gas for heating than those constructed prior to World War II. We expect that this arises from secular improvements in construction technology and insulation, especially during the decade of the 1980s, the post-oil crisis era. Regarding electricity usage the variations among housing vintages and dwelling types are less pronounced. Electricity consumption is substantially larger in detached and semi-detached houses than in row houses or apartments, and we notice an increase in electricity usage in post-war buildings and especially those of recent construction.

When it comes to the demographics of the households, we find that families with children consume more gas than single households or couples, but elderly households consume more gas for heating than other household types. Households with children -- particularly teenagers -- consume much more electricity than other household units. We also document substantial differences in gas and electricity consumption by income; this is especially pronounced among elderly households who consume more energy and whose consumption is more responsive to income.

We can use these empirical observations to investigate, crudely to be sure, the effects of expected demographic changes in the Dutch population upon energy usage. Future changes in household size, age distribution, employment, and urbanization affect demand for natural resources. Importantly, demographic developments in the near future project the aging of Western societies and a further inflow of immigrants. In Holland for instance, the number of elderly (i.e. older than 65 years) will double by 2040.

Figure 6 reports the implications of the current forecasts of population change upon energy consumption in the Netherlands. As indicated in the figure, the aging of the Dutch society (and elsewhere in Europe, for that matter) can be expected to increase energy usage by a bit more than two percent over the next two decades. Forecasts of increased immigration from abroad add only a bit to the expected increase. In line with Brian C. O'Neill and Belinda S. Chen (2002), we find that the aging trend of society may lead to additional challenges for reducing future energy consumption. Our findings show that these developments will increase energy demand, and may offset technical improvements of the building stock.

By way of comparison, the figure also reports the implications for energy use if a home insulation program would be adopted in Holland. Assuming that half of the Dutch housing stock would be subject to a national insulation improvement program over the next two decades, we would expect only a marginal reduction in energy consumption, as insulation effects on residential energy use appear to be rather mild. We also investigate the effects of extrapolating the current Dutch trends in residential new construction and demolitions numbers over the coming decades. Assuming that 0.3 percent of the existing total stock (consisting mostly of older buildings) is demolished every year, while 0.8 percent of total existing stock is added as new (and energy efficient) construction, we anticipate that this increase in average housing quality is about twice as important as demographic considerations for future energy use.

Of course, these projections ignore the other important factors affecting energy usage, the price of gas and electricity and the evolution of household income in the years to come. The latter is incorporated in our simulations, by assuming average real income will grow at the same rate as the past two decades, which increases gas consumption with little over one percent over the next two decades.

- Figure 6 here -

Our paper has some implications for policy makers. The residential sector is potentially important in saving natural resources. Understanding the key factors that determine residential energy efficiency is crucial in the energy efficiency debate, but research and policies related to energy efficiency predominantly focus on the physical and technical structure of dwellings as determinants of energy consumption. The behavioral component is frequently underestimated or ignored in analyses of household energy use. A better understanding of demographics determinants of energy use can improve projections of energy demand, which are critically important to understanding and anticipating future resource requirements.

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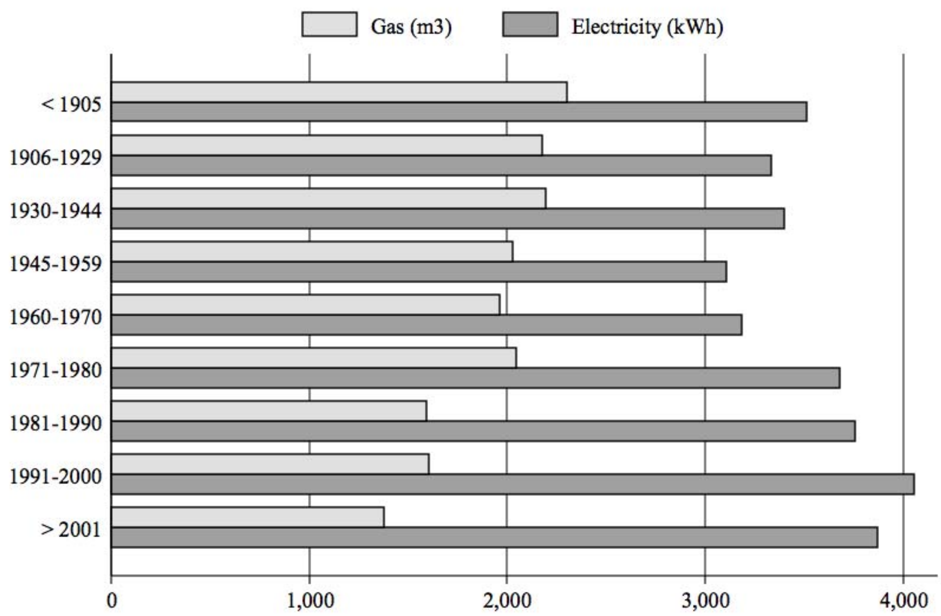
Figure 1
Energy Consumption and Dwelling Structure
(Electricity (kWh) and Gas (m^3) Per Dwelling)

A. Dwelling Age



B. Dwelling Type

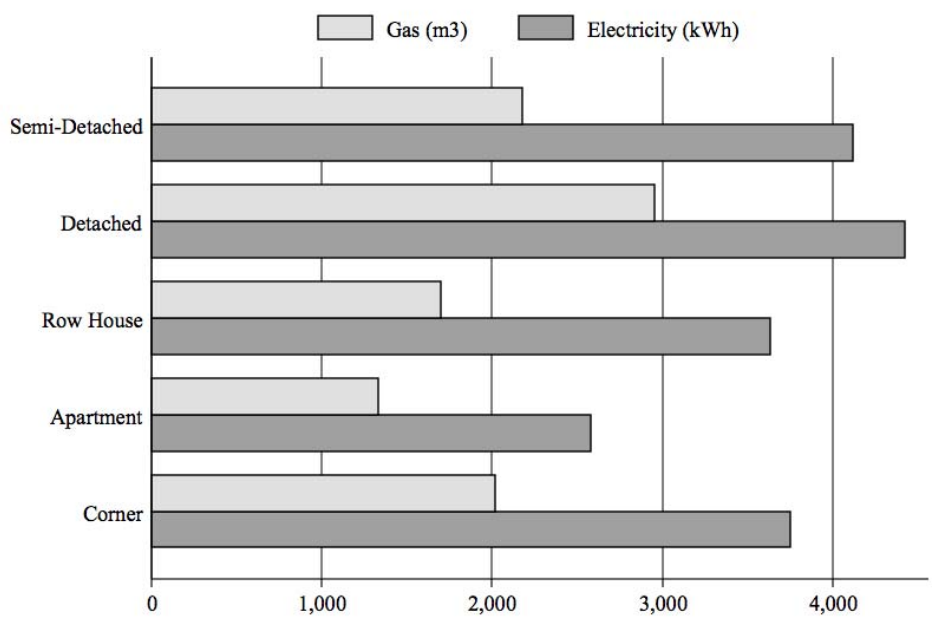
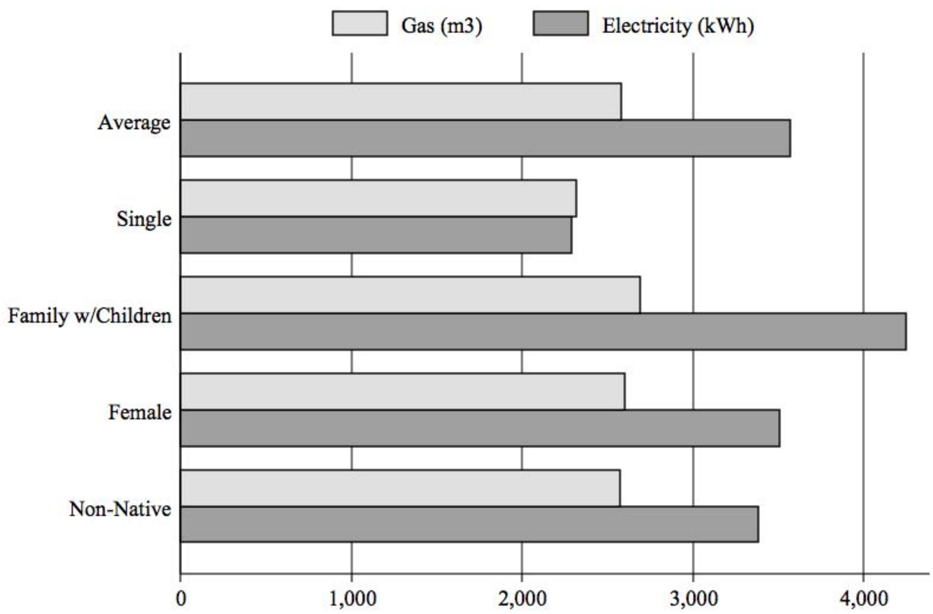


Figure 2
Household Energy Consumption
(Electricity (kWh) and Gas (m^3) Per Dwelling)

A. Family Type



B. Family Cycle

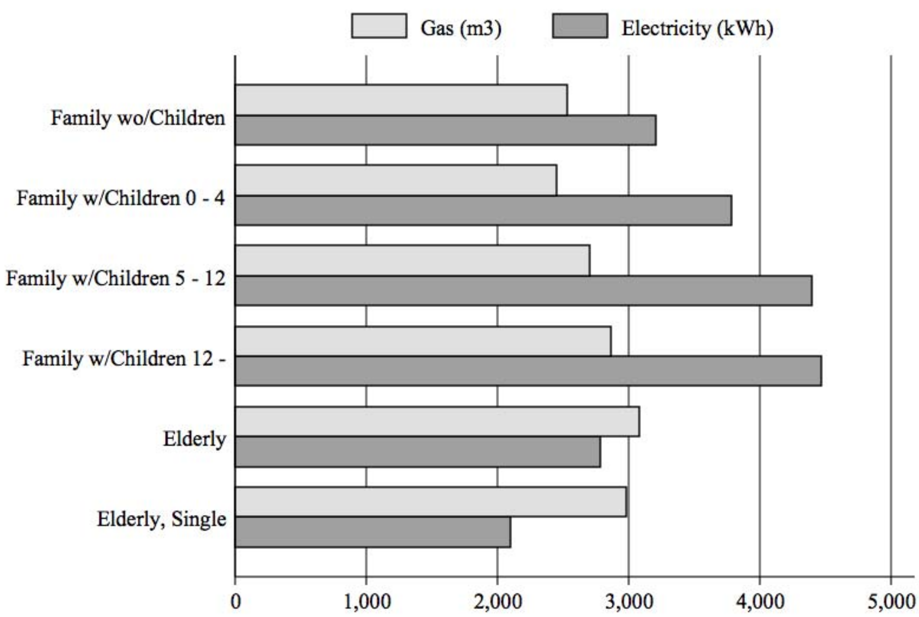
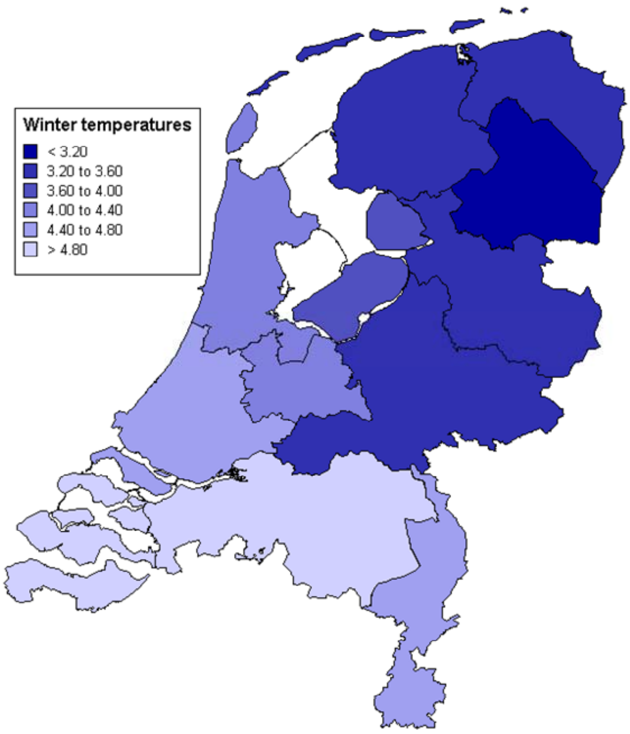


Figure 3
Regional Gas Consumption and Average Winter Temperature
(Gas (m^3) Per Dwelling Across Provinces)

A. Winter Temperature Across Provinces



B. Regional Gas Consumption

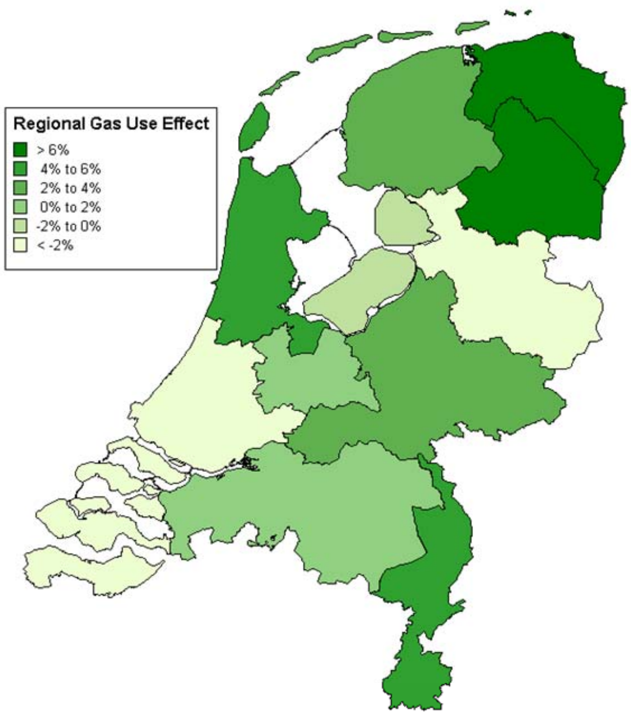
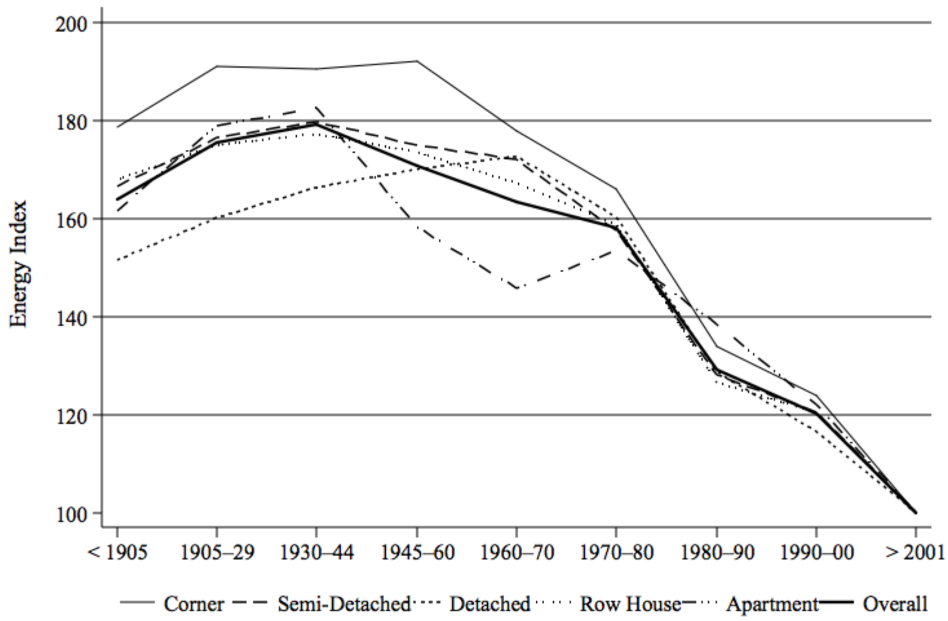
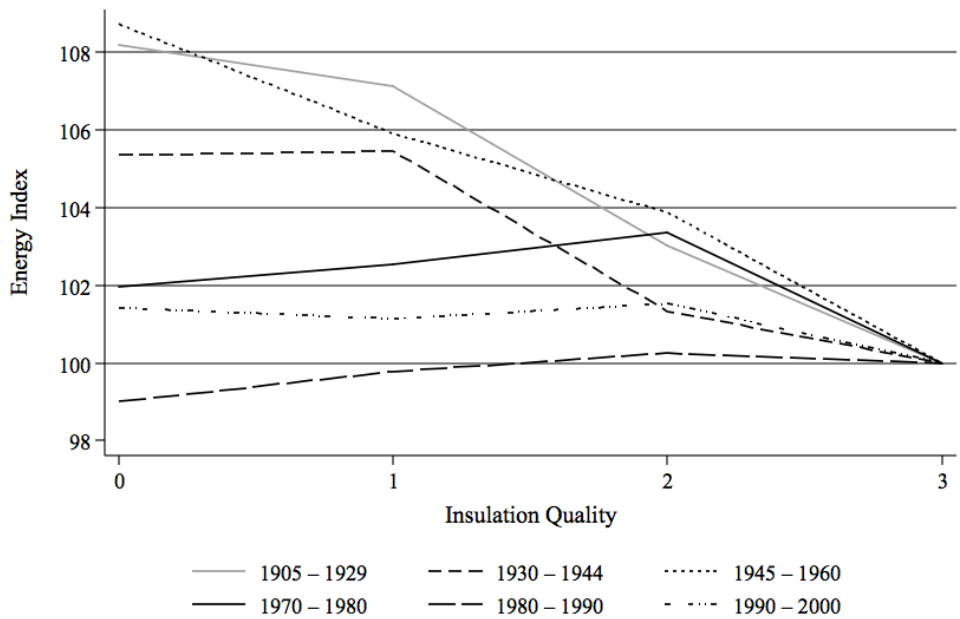


Figure 4
Energy Consumption and Dwelling Structure
(Electricity (kWh) and Gas (m^3) Per Dwelling)

A. Gas (Age - Dwelling Type Interactions)



B. Gas (Insulation – Age Interactions)



C. Electricity (Age – Dwelling Type Interactions)

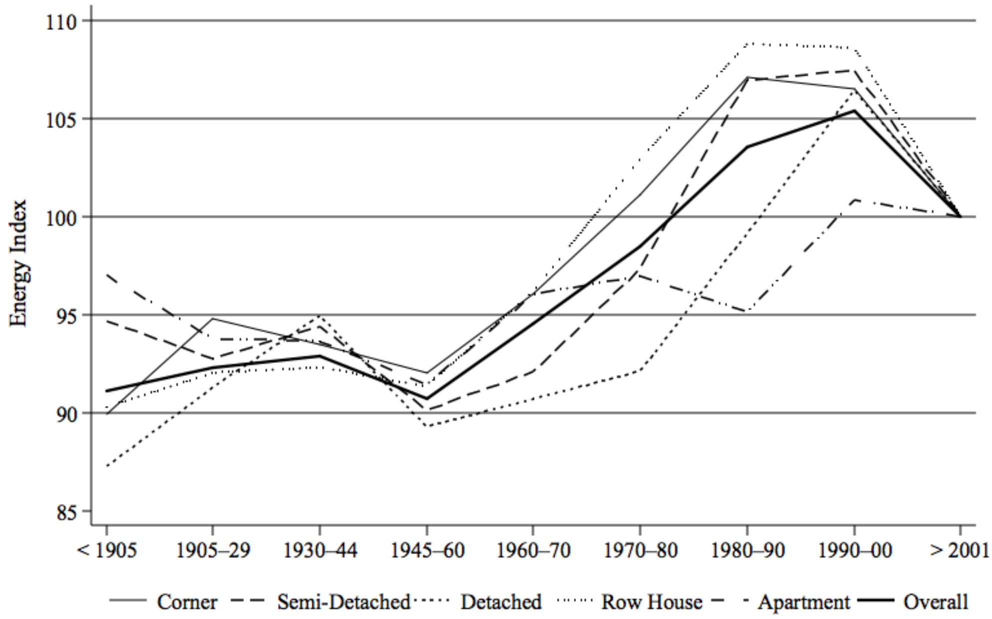
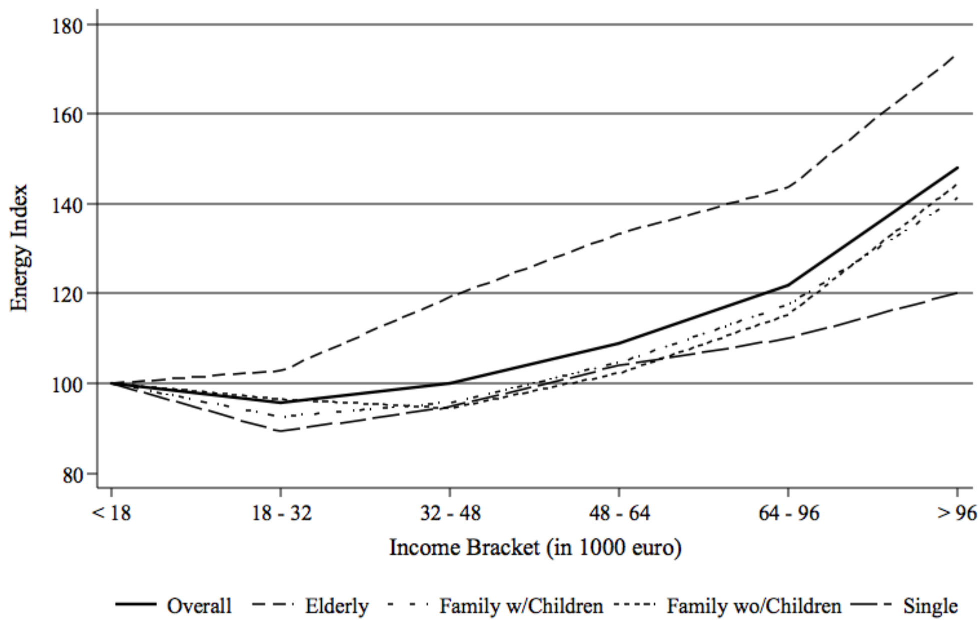


Figure 5
Household Energy Consumption
(Electricity (kWh) and Gas (m^3) Per Dwelling)

A. Gas (Income - Family Type Interactions)



B. Electricity (Income - Family Type Interactions)

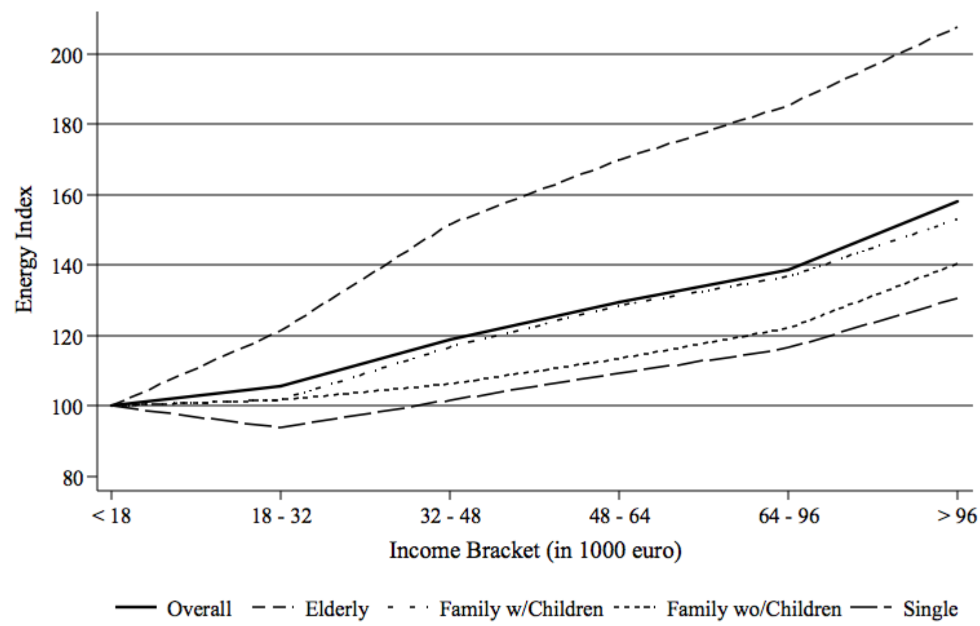
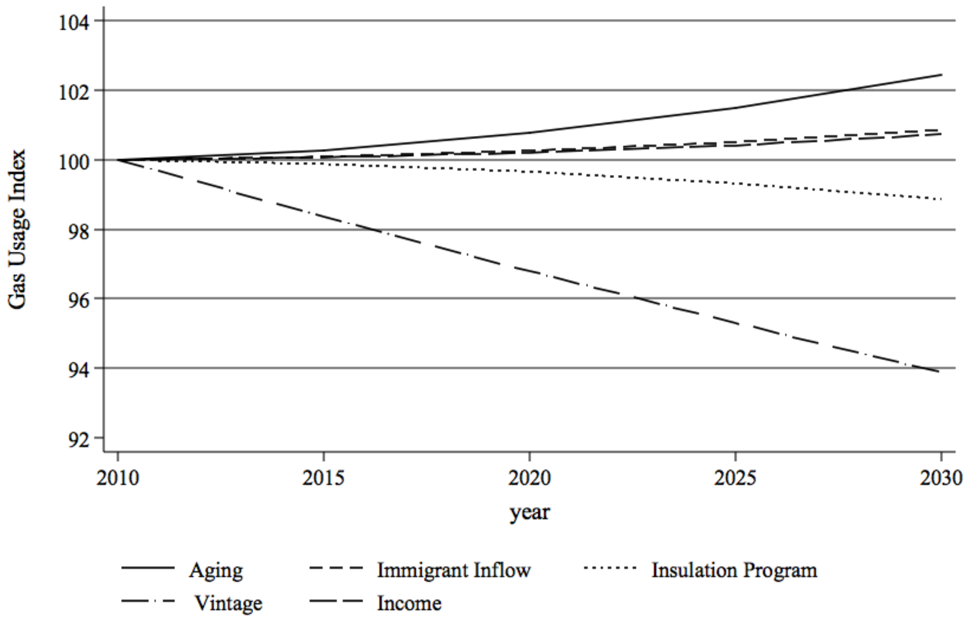


Figure 6
Simulated Future Energy Consumption

A. Gas (m^3) Per Dwelling



B. Electricity (kWh) Per Dwelling

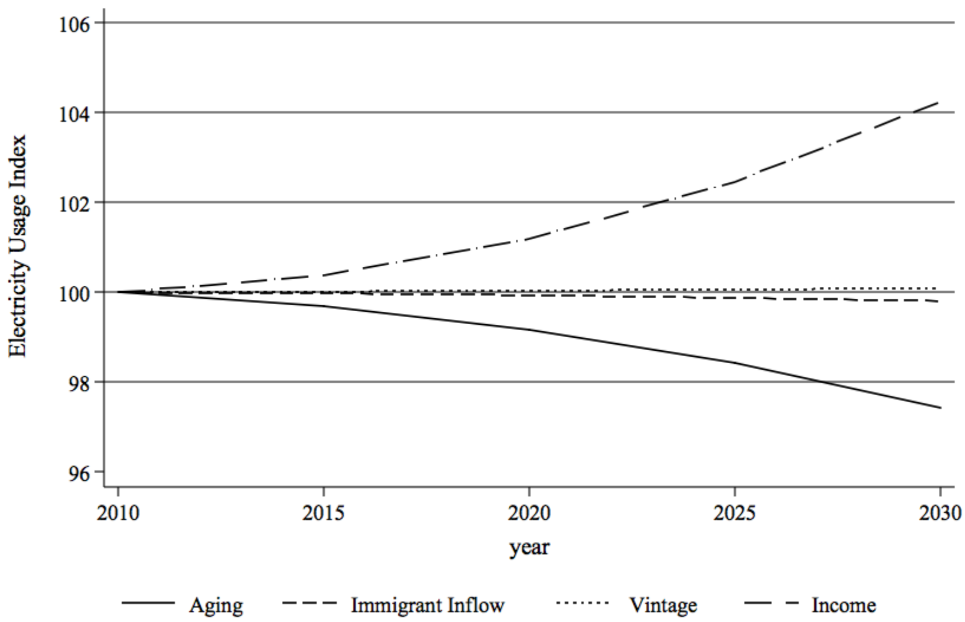


Table 1
Energy Consumption, Dwelling Structure, and Household Demographics
(305,001 dwellings observed between January 2008 and December 2009)

	Mean	Median	St. Dev.
Energy Consumption			
Gas (m^3)	1,897.77	1,724.00	1,012.43
Gas (€)	1,233.55	1,120.6	658.08
Electricity (kWh)	3,565.78	3,340.00	1,704.87
Electricity (€)	784.47	734.8	375.07
Dwelling Type (percent)			
Apartment	25.26	0.00	43.45
Row House	33.58	0.00	47.23
Semi-Detached	15.31	0.00	36.01
Detached	12.66	0.00	33.25
Corner	13.18	0.00	33.83
Period of Construction (percent)			
< 1905	5.16	0.00	22.13
1905 – 1929	11.98	0.00	32.57
1930 – 1944	8.13	0.00	27.32
1945 – 1960	7.44	0.00	26.24
1960 – 1970	15.40	0.00	36.10
1970 – 1980	17.27	0.00	37.80
1980 – 1990	13.65	0.00	34.33
1990 – 2000	14.29	0.00	35.00
> 2001	6.66	0.00	24.93
Historic Structure	0.73	0.00	8.54
Thermal and Quality Characteristics			
Dwelling Size (m^2)	124.55	120.00	53.20
Number of Rooms	4.53	5.00	1.82
Central Heating (Yes = 1)	91.75	100.00	27.51
Maintenance Interior (Good = 1)	89.20	100.00	31.04
Maintenance Exterior (Good = 1)	92.24	100.00	26.76
Insulation Quality	2.25	2.00	1.80
Demographic Characteristics			
Number of Persons in Household	2.66	2.00	1.26
Age of Head of Household (years)	40	38	22
Single Household (percent)	18.09	0.00	38.49
Household With Children (percent)	47.81	0.00	49.95
Number of Children	1.09	1.00	1.08
Age of Oldest Child (years)	10.67	9.00	8.70
Elderly Household (> 65 years, percent)	15.42	0.00	36.11
Fraction of Females in Household (percent)	50.54	100.00	50.00
Occupied by Non-Native (percent)	15.05	0.00	35.75
Household Income (€ thousands)	35.46	30.68	29.00

Table 2
Residential Energy Consumption and Dwelling Characteristics
Dependent variable: logarithm of gas consumption (m^3) and logarithm of electricity consumption (kWh)

	Gas			Electricity		
	(1)	(2)	(3)	(4)	(5)	(6)
Dwelling Size	0.513***	0.628***	0.629***	0.651***	0.618***	0.616***
(log)	[0.004]	[0.004]	[0.004]	[0.004]	[0.004]	[0.004]
Number of Rooms	0.005***	0.002***	0.002***	0.003***	0.004***	0.004***
	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]
Dwelling Type‡						
Apartment	-0.336***	-0.311***	-0.310***	-0.169***	-0.166***	-0.168***
	[0.004]	[0.004]	[0.004]	[0.003]	[0.003]	[0.003]
Row House	-0.166***	-0.154***	-0.154***	-0.018***	-0.020***	-0.021***
	[0.003]	[0.002]	[0.002]	[0.003]	[0.003]	[0.003]
Semi-Detached	0.020***	0.038***	0.038***	0.048***	0.046***	0.046***
	[0.003]	[0.003]	[0.003]	[0.003]	[0.003]	[0.003]
Detached	0.197***	0.153***	0.154***	0.001	0.024***	0.025***
	[0.003]	[0.003]	[0.003]	[0.004]	[0.004]	[0.004]
Period of Construction (percent)						
< 1905		0.496***	0.492***		-0.096***	-0.092***
		[0.006]	[0.006]		[0.006]	[0.006]
1905 – 1929		0.565***	0.561***		-0.083***	-0.080***
		[0.004]	[0.004]		[0.004]	[0.004]
1930 – 1944		0.586***	0.582***		-0.076***	-0.073***
		[0.005]	[0.005]		[0.005]	[0.005]
1945 – 1960		0.538***	0.534***		-0.099***	-0.097***
		[0.005]	[0.005]		[0.005]	[0.005]
1960 – 1970		0.494***	0.489***		-0.058***	-0.056***
		[0.004]	[0.005]		[0.004]	[0.004]
1970 – 1980		0.461***	0.456***		-0.016***	-0.015***
		[0.004]	[0.004]		[0.004]	[0.004]
1980 – 1990		0.257***	0.255***		0.036***	0.035***
		[0.004]	[0.004]		[0.004]	[0.004]
1990 – 2000		0.184***	0.183***		0.053***	0.053***
		[0.004]	[0.004]		[0.004]	[0.004]
Historic Structure		0.017	0.014		-0.017	-0.014
		[0.012]	[0.012]		[0.011]	[0.011]
Thermal and Quality Characteristics						
Central Heating			0.013***			0.034***
(Yes = 1)			[0.004]			[0.004]
Maintenance Exterior			-0.025***			0.043***
(Good = 1)			[0.004]			[0.004]
Insulation Quality			-0.010***			-0.018***
			[0.000]			[0.000]
Insulation Quality^2			0.001**			0.003***
			[0.000]			[0.000]
Constant	4.902***	4.090***	4.103***	5.001***	5.140***	5.082***
	[0.021]	[0.021]	[0.021]	[0.019]	[0.020]	[0.020]
Province-Fixed Effects	Y	Y	Y	Y	Y	Y
Observations	305,001	305,001	305,001	308,105	308,105	308,105
R-squared	0.251	0.325	0.326	0.231	0.240	0.241
Adj R^2	0.251	0.325	0.326	0.231	0.240	0.241

Table 3
Residential Energy Consumption and Household Composition
Dependent variable: logarithm of gas consumption (m^3) and logarithm of electricity consumption (kWh)

	Gas				Electricity			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Fraction of Females in Household	0.019***	0.009***	0.01***	0.001	-0.027***	-0.022***	-0.023***	-0.046***
(percent)	[0.002]	[0.002]	[0.002]	[0.004]	[0.002]	[0.002]	[0.002]	[0.003]
Occupied by Non-Native Head	-0.006**	-0.008***	-0.004*	0.009	-0.082***	-0.096***	-0.084***	-0.039***
(Yes=1)	[0.003]	[0.003]	[0.003]	[0.006]	[0.003]	[0.003]	[0.003]	[0.005]
Number of Persons in Household	0.130***				0.210***			
	[0.001]				[0.001]			
Age of Head of Household	0.006				0.001			
	[0.000]				[0.000]			
Single Household		-0.223***	-0.224***	-0.210***		-0.367***	-0.368***	-0.333***
(Yes=1)		[0.005]	[0.005]	[0.006]		[0.004]	[0.004]	[0.005]
Elderly Household		0.307***	0.305***	0.324***		-0.048***	-0.047***	-0.011**
(Yes=1)		[0.004]	[0.004]	[0.005]		[0.003]	[0.003]	[0.005]
Single Elderly Household		0.140***	0.142***	0.148***		-0.067***	-0.067***	-0.049***
(Yes=1)		[0.008]	[0.008]	[0.009]		[0.006]	[0.006]	[0.008]
Family with Children		0.182***				0.280***		
(Yes=1)		[0.003]				[0.002]		
Number of Children in Household			0.039***	0.036***			0.097***	0.093***
			[0.002]	[0.004]			[0.002]	[0.005]
Family with Children < 4 years			0.050***	0.054***			0.044***	0.042***
(Yes=1)			[0.004]	[0.007]			[0.004]	[0.008]
Family with Children 5 – 12 years			0.115***	0.116***			0.127***	0.124***
(Yes=1)			[0.005]	[0.009]			[0.005]	[0.010]
Family with Children > 12 years			0.176***	0.169***			0.183***	0.157***
(Yes=1)			[0.005]	[0.008]			[0.004]	[0.008]
Household Income				0.064***				0.115***
(€ thousands, log)				[0.003]				[0.003]
Constant	6.702***	7.207***	7.201***	6.399***	7.450***	8.061***	7.961***	6.767***
	[0.008]	[0.006]	[0.006]	[0.035]	[0.009]	[0.007]	[0.008]	[0.032]
Province-Fixed Effects	Y	Y	Y	Y	Y	Y	Y	Y
Observations	297,197	305,001	297,197	138,382	300,393	308,359	300,393	142,147
R-squared	0.090	0.087	0.096	0.112	0.213	0.209	0.236	0.238
Adj R^2	0.090	0.087	0.096	0.112	0.213	0.209	0.236	0.238

Appendix Table A1
Residential Energy Consumption, Dwelling Structure and Household Demographics
Dependent variable: log gas consumption (m^3) and log electricity consumption (kWh)

	Gas		Electricity	
	(1)	(2)	(3)	(4)
Dwelling Structure				
Dwelling Size	0.593***	0.584***	0.515***	0.511***
(log)	[0.004]	[0.006]	[0.004]	[0.006]
Number of Rooms	0.002***	0.002**	-0.000	-0.000
	[0.001]	[0.001]	[0.001]	[0.001]
Dwelling type				
Semi-Detached	0.033***	0.028***	0.049***	0.042***
	[0.003]	[0.004]	[0.003]	[0.005]
Detached	0.149***	0.146***	0.085***	0.089***
	[0.003]	[0.005]	[0.004]	[0.006]
Row House	-0.152***	-0.154***	-0.028***	-0.034***
	[0.002]	[0.004]	[0.003]	[0.004]
Apartment	-0.281***	-0.299***	-0.092***	-0.082***
	[0.004]	[0.005]	[0.003]	[0.005]
Period of Construction				
< 1905	0.494***	0.493***	-0.033***	-0.036***
	[0.006]	[0.009]	[0.006]	[0.009]
1906-1929	0.554***	0.555***	-0.030***	-0.038***
	[0.005]	[0.007]	[0.005]	[0.008]
1930-1944	0.568***	0.572***	-0.031***	-0.035***
	[0.005]	[0.007]	[0.005]	[0.008]
1945-1959	0.512***	0.513***	-0.026***	-0.031***
	[0.005]	[0.008]	[0.005]	[0.008]
1960-1970	0.467***	0.464***	0.007	0.003
	[0.005]	[0.007]	[0.005]	[0.007]
1971-1980	0.441***	0.440***	0.033***	0.029***
	[0.004]	[0.007]	[0.004]	[0.007]
1981-1990	0.243***	0.249***	0.048***	0.041***
	[0.004]	[0.007]	[0.005]	[0.007]
1991-2000	0.175***	0.176***	0.051***	0.053***
	[0.004]	[0.006]	[0.004]	[0.007]
Historic Structure	0.018	0.033*	-0.007	0.002
	[0.012]	[0.018]	[0.012]	[0.017]
Thermal and Quality Characteristics				
Maintenance Exterior	-0.018***	-0.023***	0.014***	0.013**
(Good=1)	[0.004]	[0.006]	[0.004]	[0.005]
Central Heating	0.022***	0.023***	0.019***	0.022***
(Yes=1)	[0.004]	[0.006]	[0.004]	[0.005]
Insulation Quality	-0.008***	-0.008**	0.010***	0.011***
	[0.002]	[0.004]	[0.002]	[0.000]
Insulation Quality^2	0.001	0.001	-0.002***	-0.002***
	[0.000]	[0.001]	[0.000]	[0.001]
Household Demographics				
Fraction of Females in Household	0.011***	0.017***	-0.018***	-0.032***
(percent)	[0.002]	[0.003]	[0.002]	[0.003]
Occupied by Non-Native Head	0.045***	0.048***	-0.041***	-0.013***
(Yes=1)	[0.003]	[0.005]	[0.003]	[0.004]
Single Household	-0.097***	-0.106***	-0.249***	-0.246***
(Yes=1)	[0.004]	[0.005]	[0.004]	[0.004]
Elderly Household	0.115***	0.118***	-0.139***	-0.119***
(Yes=1)	[0.003]	[0.004]	[0.003]	[0.004]
Single Elderly Household	0.103***	0.105***	-0.100***	-0.078***
(Yes=1)	[0.007]	[0.008]	[0.006]	[0.007]

Appendix Table A1 (continued)
Residential Energy Consumption and Household Demographics and Dwelling Structure

	Gas		Electricity	
	(1)	(2)	(3)	(4)
Family with Children < 4 years	0.066***	0.062***	0.047***	0.045***
(Yes=1)	[0.004]	[0.006]	[0.004]	[0.007]
Family with Children 5 – 12 years	0.065***	0.055***	0.076***	0.069***
(Yes=1)	[0.004]	[0.008]	[0.005]	[0.009]
Family with Children > 12 years	0.087***	0.067***	0.126***	0.095***
(Yes=1)	[0.004]	[0.007]	[0.004]	[0.008]
Number of Children in Household	0.003*	0.006**	0.064***	0.066***
	[0.002]	[0.003]	[0.002]	[0.004]
Household Income		0.009***		0.052***
(€ thousands, log)		[0.003]		[0.003]
Constant	4.220***	3.890***	5.499***	4.967***
	[0.022]	[0.040]	[0.022]	[0.039]
Province-Fixed Effects	Y	Y	Y	Y
Observations	297,197	138,382	300,393	142,147
R-squared	0.339	0.334	0.346	0.339
Adj R^2	0.339	0.334	0.346	0.339