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RESIDENTIAL ENERGY USE AND CONSERVATION: ECONOMICS AND DEMOGRAPHICS

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Residential energy use and conservation: Economics and demographics

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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 residents. Our analysis is based on a sample of more than 300,000 Dutch homes and their occupants. The results indicate that residential gas consumption is determined principally by structural dwelling characteristics, such as the vintage, building type, and characteristics of the dwelling, 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, even absent price increases for residential energy, the aging of the population and their increasing wealth will roughly offset improvements in the energy efficiency of the building stock resulting from policy interventions and natural revitalization.

1. Introduction

Energy efficiency in housing markets is again prominent in policy circles. During the late 1970s, in the aftermath of the oil crisis, concerns about energy dependence triggered a first wave of policies intended 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 energy efficiency of the housing market has become an important target for policymakers and a promising tool for those seeking compliance with the Kyoto protocol.

Policies about the energy efficiency of dwellings would be redundant if the private market for real capital investment in energy efficiency functioned well enough. 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

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technologies (Jaffe and 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 (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 (Ayers et al., 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 signaled by energy labels (Brounen and 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 60 years to Houthakker (1951). Lakshmanan and 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 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, 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 (Aroonruengsawat and Auffhammer, 2011; Jacobsen et al., in press).

Measuring or influencing occupant behavior is more complex, and has received less attention in policy debates.[2] 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 US households, with energy expenditures lowest during the early and late stages of the life cycle. van Raaij and Verhallen (1983) introduced a detailed behavioral model to explain residential energy use, distinguishing between purchase, usage and maintenance-related behavior. These models provided a framework which helped explain the interaction between household composition and energy demand (Reiss and White, 2005), changes in residential electricity demand following energy shocks (Reiss and White, 2008), and the energy consumption of households in relation to historical energy prices and changes in building codes (Costa and 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 of the ingredients of successful policy design.

In this paper, we analyze detailed micro-economic data on energy consumption, occupant characteristics and dwelling specifications for more than 300,000 households and dwellings in the Dutch housing market. We focus on gas and electricity consumption and investigate the impact of the physical structure of a home (i.e., the physical and hedonic characteristics of dwellings) on variations in energy consumption. We compare the importance of these structural characteristics with the demographic characteristics of households in the consumption of energy by Dutch households.

The Dutch residential market offers an unusual research laboratory for the study of energy efficiency. Energy conservation is presumably important for Dutch residents, as the average annual energy bill of a Dutch household exceeded €1800 in 2009 (about €600 for electricity and €1200 for gas). This average ranges from €1200 for the most energy efficient homes, to €2800 for the least energy efficient homes of similar size. In some cases, energy costs represent about half of annual housing expenses. Variations in energy costs are important for the households in our sample, and more broadly, for households throughout Northern Europe.

Our empirical 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, residents living in a well-maintained and insulated home consume about 12 percent less natural gas as compared to the same home with a lower level of maintenance and insulation. Per capita gas consumption in dwellings constructed before 1980 is about 50 percent higher when compared to dwellings constructed during the past decade – importantly, the share of the pre-1980 cohort represents some 65 percent of the total Dutch housing stock.

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 (even though per capita consumption is lower), and this effect becomes stronger when the age of children increases. Per capita electricity consumption is also more sensitive to changes in income than gas consumption is.

[1] In contrast, more recent research suggests that professional property investors recognize quite precisely the relative efficiency of commercial buildings (Eichholtz et al., 2010, in press).

[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 (Lutzenhiser, 1993; Schipper et al., 1989).

Combining the empirical findings in this paper with forecasts of changes in household demographics, we document that the aging of an increasingly wealthy population will affect significantly the future demand for energy. Our findings have implications for policy makers; a better understanding of demographic determinants of energy consumption is needed to improve projections of energy demand. These projections are critical to anticipate future resource requirements and to achieve the carbon abatement necessary to comply with national goals and international agreements on emission reductions.

The remainder of this paper is organized as follows. Section 2 describes the data and provides some descriptive information on energy consumption for our sample of homeowners. Section 3 discusses the analysis, relating the energy consumption of a large cross-section of households to the technical characteristics of their dwellings, and to variations in their demographic conditions. Section 4 includes some projections of future household energy consumption and a brief conclusion.

2. Data

2.1. 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 information is provided on the address and a wide array of quality characteristics for each dwelling. 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 Levinson and Niemann, 2004).

We merge information on each dwelling to information made available by the Central Bureau of Statistics (CBS) on electricity consumption (kilowatt-hours, kW h) 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. However, all households face similar average and marginal energy prices; competition between utility companies in the Netherlands is fierce, and systematic block-tier pricing systems do not exist. So, expenditures are essentially proportional to energy consumption.

The Bureau of Statistics in the Netherlands 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 (for a subset of households) annual income.

Table 1 provides an overview of the data on individual dwellings – 305,001 dwellings observed in 2008–2009. The average household in the sample consumes some 1900 m^3 of natural gas and some 3600 kW h (kW h) of electricity per year – about 670 m^3 of and 1350 kW h of electricity per capita. This translates into an average annual utility bill of more than €2000.[3] But there is clearly a wide variation in household consumption, which we explore in depth below. As a comparison: per capita electricity consumption in the US was 11,641 kW h in 2009, on average, and 6691 kW h in California.[4] (Of course, these simple comparisons ignore substantial differences in the fuel-mix for heating and cooling, as well as climatic differences.)

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 m^2 (some 1345 square feet), with five rooms. Note that the housing stock in the Netherlands is 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.[5]

Regarding thermal and quality characteristics, the data indicate that central heating is the norm; indeed, 92 percent of the sample consists of dwellings with central heat.[6] 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 (out of five layers, or insulation areas). This has direct implications for the energy efficiency of homes.

The average family size in our sample of homeowners is 2.66 persons, which is slightly larger than the average household size in the Netherlands (2.23). Single-person 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 oldest child is about 11 years of age. 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 expected by 2040.[7] Foreign-born individuals occupy

[3] This estimate is based on average energy prices in 2007 – €0.22 per kW h of electricity and €0.65 per m^3 of gas.

[4] Source: http://www.eia.gov/consumption/residential/index.cfm.

[5] A dwelling may be classified as national “monument” if it is at least 50 years old and in public interest because of (1) its outer appearance, (2) its relevance to science, or (3) the cultural historic value (Article 1, Monument Law 1988). There are currently some 52,000 registered monuments in the Netherlands.

[6] 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).

[7] Source: http://www.cbs.nl/nl-NL/menu/cijfers/statline.

Table 1
Energy consumption, dwelling characteristics, and household demographics (305,001 owner-occupied dwellings observed between January 2008 and December 2009).

	Mean	Median	St. Dev.
Energy consumption			
Gas (m^3)	1897.77	1724.00	1012.43
Electricity (kW h)	3565.78	3340.00	1704.87
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=100)	91.75	100.00	27.51
Maintenance interior (Good=100)	89.20	100.00	31.04
Maintenance exterior (Good=100)	92.24	100.00	26.76
Insulation quality (1 through 5)	2.25	2.00	1.80
Demographic characteristics of residents			
Number of persons in household	2.66	2.00	1.26
Age of head of household (years)	40.00	38.00	22.01
Single person 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 (head's age > 65 years, percent)	15.42	0.00	36.11
Fraction of females in household (percent)	50.54	100.00	50.00
Occupied by foreign-born (percent)	15.05	0.00	35.75
Household income (€ thousands)	35.46	30.68	29.00

about 15 percent of the sampled homes. The Netherlands is characterized by a large fraction of foreign-born inhabitants, and this number is expected to grow in the near future as well. The homeowners in our sample earn an average annual gross income of €35,455 (about 10 percent higher than the national average of both renters and owners).

2.2. Dwellings, households, and energy consumption

Figs. 1 and 2 illustrate the simple relationships between energy consumption, dwelling characteristics and household composition, for gas use and for electricity consumption. Fig. 1(A) indicates the variation in total average energy use by vintage. Gas usage for heating is clearly lower for more recently constructed buildings, by as much as 1000 m^3 a year, as compared to very old homes. 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 Fig. 1(B), the effect of dwelling type on energy consumption is reported; 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.

In Fig. 2(A) and (B), the relationship between family type (or household composition) and energy consumption is reported. Household composition is found to be an important determinant of electricity consumption, 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 has been documented by others; this is generally explained by household economies of scale (O'Neill and Chen, 2002; Schipper et al., 1989). Fig. 2(A) 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.

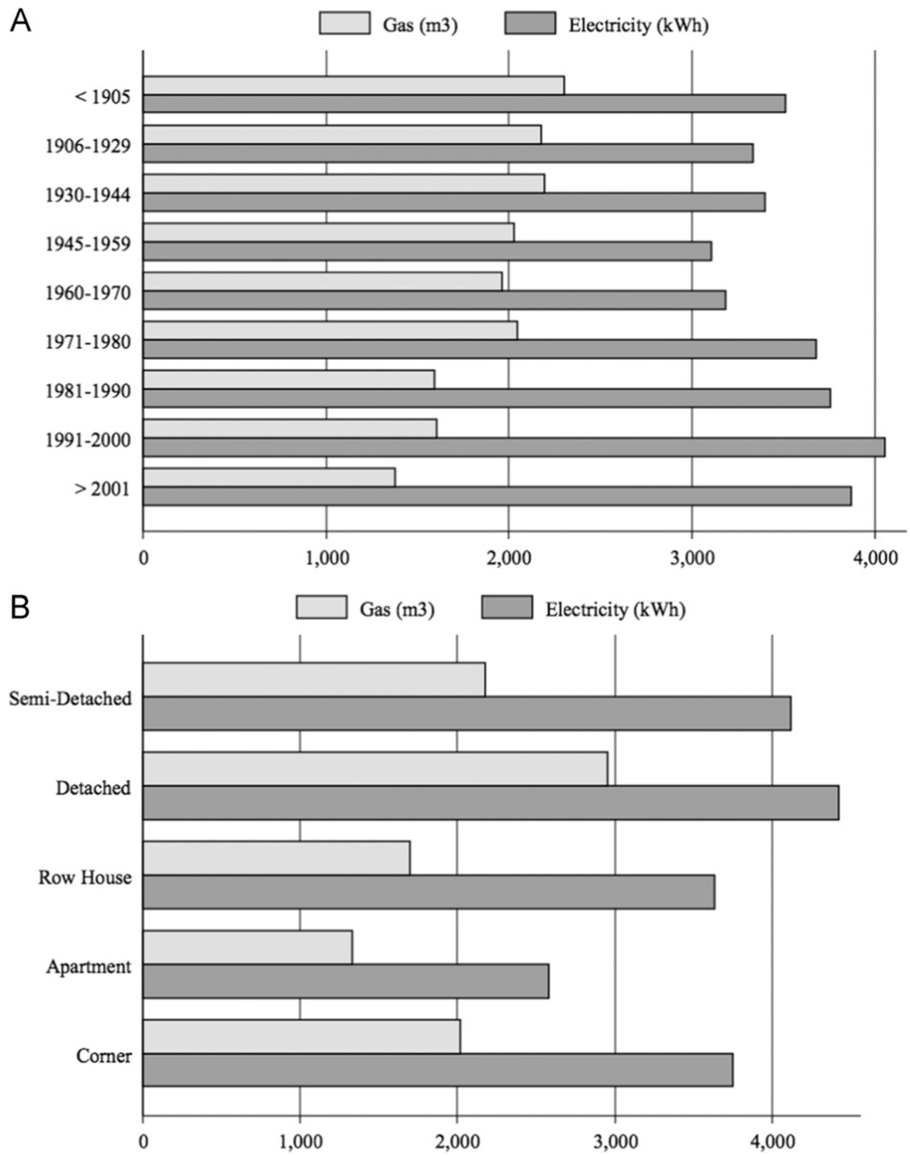

Fig. 1. Annual energy consumption and dwelling structure. (A) Year built and (B) dwelling type.

Fig. 2(B) 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 the number and ages of children are important for energy consumption, and the ages of children affect the consumption of heating and electricity as well.

3. Empirical methods and results

3.1. 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 equation:

$$\log(E_i) = \alpha + \beta_i X_i + \sum_{p}^{p=1} \gamma_p p_p + \varepsilon_i \tag{1a}$$

In Eq. (1a), the dependent variable is the logarithm of gas consumption per capita in cubic meters or electricity consumption per capita in kilowatt hours for dwelling *i*. X_i is a vector of the hedonic characteristics of building *i*, including

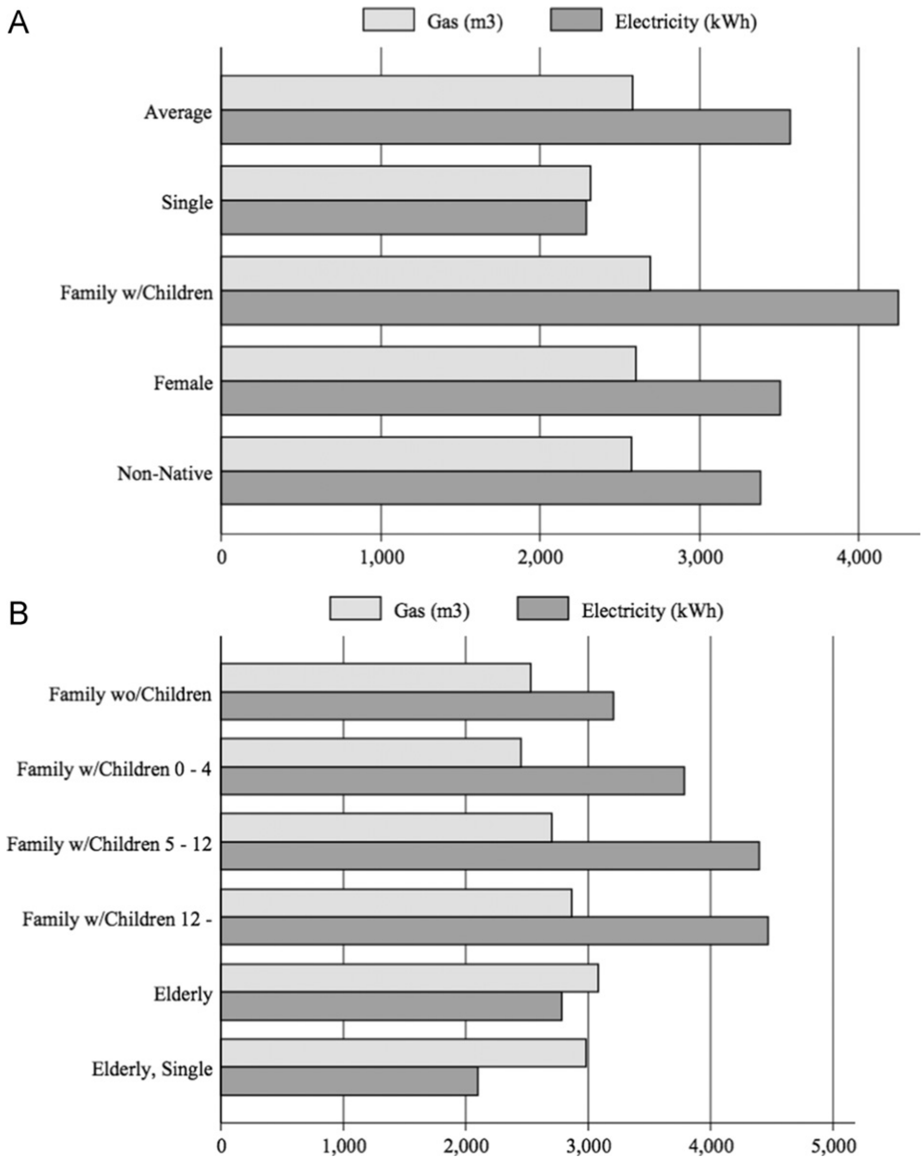

Fig. 2. Annual energy consumption and household composition. (A) Family type and (B) family cycle.

dwelling type, period of construction, and thermal and quality characteristics, including the 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 12 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 White (1980). In the first three columns, per capita annual gas consumption, measured in cubic meters, is the dependent variable. Columns (4) to (6) repeat the analysis, relating per capita electricity consumption (kW h) to physical characteristics of the dwelling.

The basic models explain about one-sixth of total household gas consumption. This is low compared to other studies (for example, Rehdanz (2007), and Meier and Rehdanz (2010), who explain 17 to 27 percent of gas consumption for panels of German and British homes), but standardizing energy consumption by household size absorbs much of the cross-sectional variation. Dwelling size is a major determinant of gas consumption, with an elasticity of 0.15. After controlling for size, each additional room decreases energy consumption by about a third of a percent.[8] Compared to corner dwellings,

[8] Apart from the correlations between dwelling size and the number of rooms, we also suspect that the negative correlation between gas consumption and 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

Table 2
Residential energy consumption and dwelling characteristics dependent variable: logarithm of gas consumption (m^3) per capita and logarithm of electricity consumption (kW h) per capita.

	Gas (m^3) per capita			Electricity (kW h) per capita		
	(1)	(2)	(3)	(4)	(5)	(6)
Dwelling size (m^2)	0.145***	0.292***	0.295***	0.285***	0.284***	0.284***
(log)	[0.006]	[0.006]	[0.006]	[0.004]	[0.004]	[0.004]
Number of rooms	−0.003***	−0.007***	−0.007***	−0.005***	−0.005***	−0.005***
	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]
Dwelling type						
Apartment	−0.111***	−0.079***	−0.079***	0.056***	0.061***	0.061***
	[0.005]	[0.005]	[0.005]	[0.004]	[0.004]	[0.004]
Row house	−0.183***	−0.167***	−0.167***	−0.038***	−0.037***	−0.037***
	[0.004]	[0.003]	[0.003]	[0.003]	[0.003]	[0.003]
Semi-detached	0.001	0.028***	0.029***	0.028***	0.036***	0.036***
	[0.004]	[0.004]	[0.004]	[0.003]	[0.003]	[0.003]
Detached	0.321***	0.266***	0.265***	0.135***	0.144***	0.144***
	[0.005]	[0.005]	[0.005]	[0.004]	[0.004]	[0.004]
Period of construction (percent)						
< 1905		0.625***	0.616***		−0.073	0.034***
		[0.008]	[0.008]		[0.056]	[0.006]
1905–1929		0.650***	0.641***		−0.104*	0.003
		[0.006]	[0.006]		[0.056]	[0.005]
1930–1944		0.644***	0.636***		−0.124**	−0.017***
		[0.006]	[0.006]		[0.056]	[0.005]
1945–1960		0.646***	0.636***		−0.101*	0.006
		[0.007]	[0.007]		[0.056]	[0.005]
1960–1970		0.583***	0.576***		−0.080	0.027***
		[0.006]	[0.006]		[0.056]	[0.005]
1970–1980		0.531***	0.526***		−0.052	0.055***
		[0.005]	[0.005]		[0.056]	[0.004]
1980–1990		0.256***	0.255***		−0.071	0.037***
		[0.005]	[0.006]		[0.056]	[0.004]
1990–2000		0.143***	0.144***		−0.096*	0.013***
		[0.005]	[0.005]		[0.056]	[0.004]
Historic structure		0.065***	0.053***		0.025**	0.024*
		[0.016]	[0.016]		[0.013]	[0.013]
Thermal and quality characteristics						
Central heating			0.001			0.009**
(Yes=1)			[0.005]			[0.004]
Maintenance exterior			−0.080***			−0.013***
(Good=1)			[0.005]			[0.004]
Insulation quality			−0.033***			−0.004*
			[0.003]			[0.002]
Insulation quality squared			0.005***			0.001
			[0.001]			[0.000]
Constant	5.749***	4.778***	4.871***	5.796***	5.882***	5.781***
	[0.028]	[0.028]	[0.028]	[0.021]	[0.060]	[0.023]
Province-fixed effects	Y	Y	Y	Y	Y	Y
Observations	297,197	297,197	297,197	300,143	300,143	300,143
R-squared	0.076	0.161	0.163	0.045	0.047	0.047
Adj R^2	0.076	0.161	0.163	0.045	0.047	0.047

Notes: Standard errors are in brackets. Significance at the 0.10, 0.05, and 0.01 levels are indicated by *, **, and ***, respectively.

apartments, and duplex homes use substantially less energy for heating – the latter benefit from less exposed surface. In contrast, detached dwellings consume significantly more gas for heating.

In the second column, we add dwelling vintage to the model.[9] 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 53 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

(*footnote continued*)
house. In most Dutch homes, bedrooms are typically not heated at night, which reduces the importance of count of rooms. The particular importance of cultural background in relation to residential energy use is studied by Wilhite et al. (1996), among others.

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

changes in building codes or building techniques. Research suggests that high energy prices have resulted in the construction of more efficient homes in the US (Costa and Kahn, 2010). In the Dutch case, the 1973 oil crisis led to large increases in energy prices (as it did around the globe), and this spawned 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 m^3 of natural gas per dwelling (Entrop and Brouwers, 2007).

For structures built before 1970, gas consumption increases with age, until 1944. Dwellings constructed between 1905 and 1944 use similar amounts of gas as compared to younger dwellings, *ceteris paribus*. Very old dwellings – constructed before 1905 – use even less gas than dwellings constructed more than half a century year later. The quality of now-antique building techniques may explain this finding (Chong, in press), but of course, older buildings are also much more likely to have undergone substantial renovations that are not observable in these data. Dwellings designated as "historic structures" have a 6.5 percent higher gas consumption, *ceteris paribus*. This may be related to restrictions on renovations (and thus thermal improvements) of these structures.

Column (3) adds thermal and quality characteristics to the model. Quite clearly, insulation matters for the usage of natural gas. Homes that are well-maintained consume less energy, and better insulation also decreases energy usage. Economic effects are, however, rather small. A one-unit increase in insulation (i.e., an additional "layer" of insulation) leads to a three percent reduction in the consumption of natural gas. To put this into perspective: recent experiments with Home Energy Reports in the US – providing households information on their past energy consumption as compared to their neighbors and providing energy conservation suggestions – achieve comparable energy reductions, about two percent (Allcott, 2009). 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 somewhat smaller.[10]

The results relating electricity consumption to dwelling characteristics are presented in Columns (4) through (6). The explanatory power of our models is again small compared to similar studies in other countries, for example Costa and Kahn (2010), who explained about 27 percent of electricity consumption for a large panel of Californian dwellings. Standardizing electricity consumption per capita decreases the explanatory power of models explaining residential energy consumption.

Dwelling size is strongly related to total energy consumption, with an elasticity of 0.29, but an additional room decreases electricity consumption by 0.5 percent. The findings for dwelling vintage are quite different from those reported for gas consumption (Column (6)). Relative to homes constructed post-2001, the 1980–1990 and 1990–2000 cohorts consume 3.7 and 1.3 percent more electricity, respectively. However, older dwellings consume *less* electricity, which might imply greater efficiency. This contrasts with results documented for California, which found "a distinctive non-monotonic [negative] relationship between a home's year built and electricity consumption" for dwellings (Costa and Kahn, 2010). But of course, the climatic setting of California differs markedly; these homes require substantial cooling in the hot summers and hardly any heating during the mild winters. The average annual temperature in Northern California is 16 °C, and 77 percent of the dwellings are air-conditioned. Holland has an average annual temperature of 10 °C, 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 the wealth of occupants and the availability of more energy-intensive appliances in modern homes.

As noted previously, we control for regional variation in energy consumption by including fixed effects for the 12 Dutch provinces. Although Holland is a relatively small country, there are noticeable climatic differences among the regions closer to the North Sea, the landlocked south, and the north of the country. Fig. 3(A) 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 °C. Fig. 3(B) reports the relative gas consumption by province, based on the fixed effects for provinces estimated in Eq. (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 dwellings.) 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 the consumption of residential energy.

Fig. 4 provides further evidence on the effect of dwelling vintage on resource consumption, based on the coefficients estimating the interactions between the period of construction and each dwelling type. (These estimates are derived from Eq. (1).) Keeping other dwelling characteristics constant, Fig. 4(A) shows the non-monotonic relation between gas consumption and dwelling vintage. Semi-detached dwellings constructed between 1930 and 1944 are least efficient and consume some 110 percent more gas than similar dwellings constructed post-2001.[11] More than 65 percent of the

[10] Further analysis shows that results differ strongly for different vintages: 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.

[11] The effects reported here are much larger than those linking vintage and electricity usage in a sample of homes in California. 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 shows clearly that dwelling vintage has a very strong effect upon energy efficiency in the Northern European residential housing market.

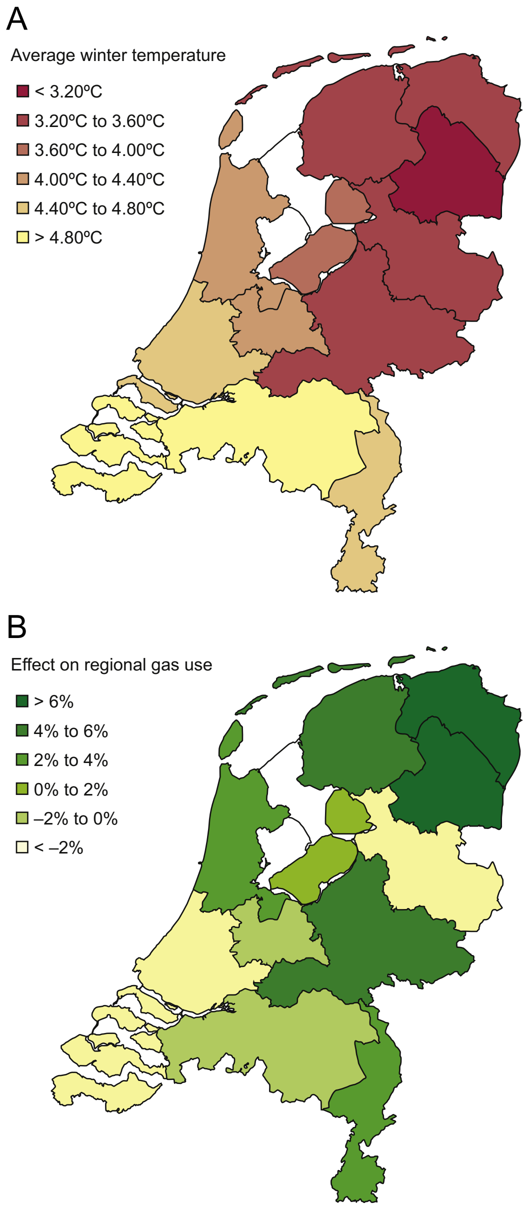

Fig. 3. Gas consumption in Holland and average winter temperature by province. (A) Winter temperature and (B) average gas consumption.

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 vintages. Dwellings are long-lived (a third of our sample of 300,000 observations are more than a half century old), and the less efficient construction of 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 apartments are most efficient.

Fig. 4(B) 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 somewhat more electricity (about 5 to 15 percent more than dwellings constructed between 1990 and 2000), but apartments constructed before 1970 consistently consume less electricity. This pattern again suggests that electricity consumption may be related to the presence of energy-intensive appliances and amenities in modern homes, rather than to the heating or cooling of the interior.

3.2. 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 to a lack of detailed micro-economic data. For instance, family

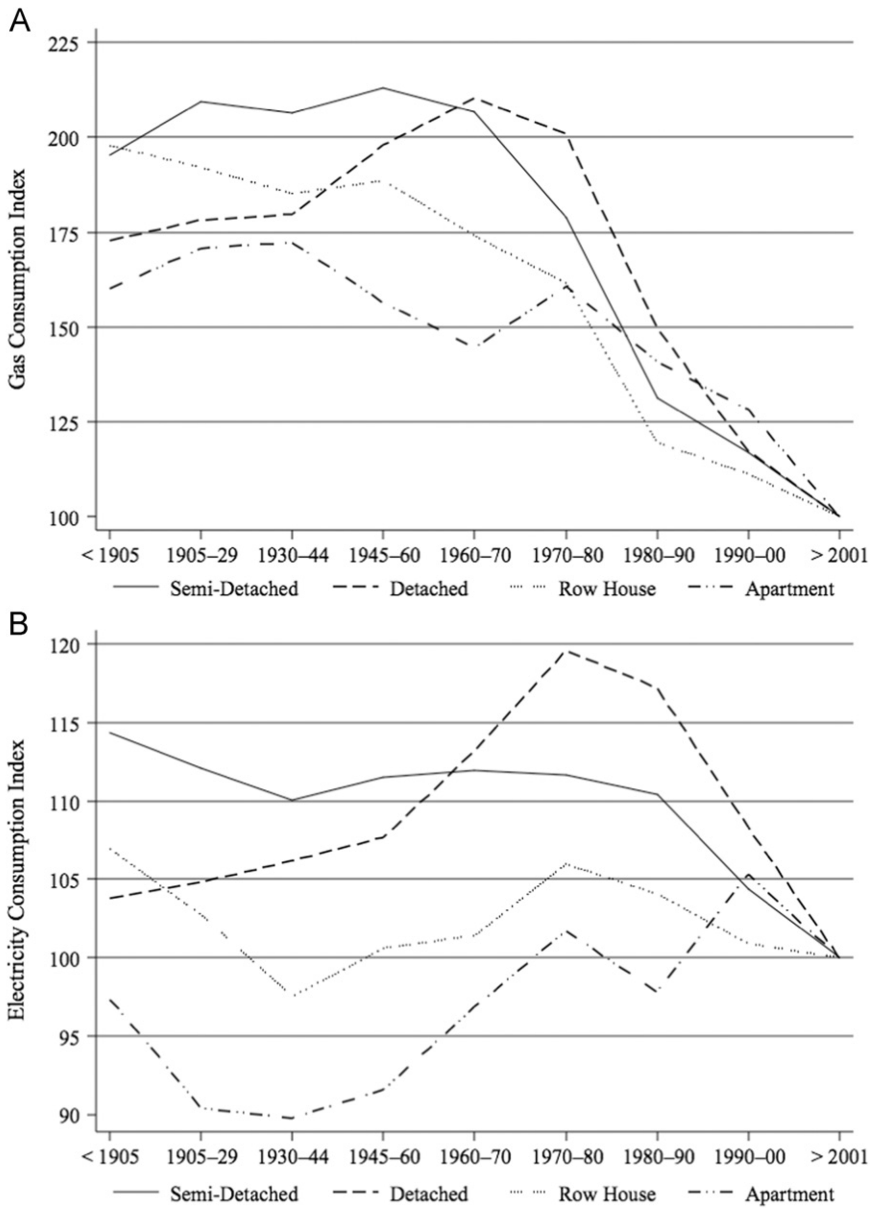

Fig. 4. Annual energy consumption, vintage, and dwelling type (electricity (kW h) and gas (m^3) per capita). (A) Gas (construction age – dwelling type interactions) and (B) electricity (construction age – dwelling type interactions).

size and composition have a distinct influence on energy behavior and use (see, for example, O'Neill and Chen, 2002). Supposedly, women have a preference for higher ambient temperatures than men, and different demographic groups may have lifestyles that lead to differences in energy consumption patterns.[12] The combination of age, marital status and family size represents the family life cycle. It has also been documented that the ages and activities of family members offer some explanation for the cross-sectional variation in household energy consumption patterns (Fritzsche, 1981).

We test more specifically for the implications of household type and composition on per capita energy consumption by replacing dwelling characteristics with household demographic measures in Eq. (1a):

$$\log(E_i) = \alpha + \delta_i D_i + \sum_{p}^{p=1} \gamma_p p_p + \varepsilon_i \quad (1b)$$

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

Table 3
Residential energy consumption and household composition dependent variable: logarithm of gas consumption (m^3) and logarithm of electricity consumption (kW h).

	Gas (m^3) per capita				Electricity (kW h) per capita			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Fraction of females in household (percent)	0.022***	0.016***	0.016***	0.016***	−0.024***	−0.017***	−0.017***	−0.032***
	[0.002]	[0.002]	[0.002]	[0.004]	[0.002]	[0.002]	[0.002]	[0.003]
Occupied by foreign-born head (Yes=1)	−0.002	−0.003	−0.008**	0.006	−0.079***	−0.084***	−0.087***	−0.042***
	[0.004]	[0.004]	[0.004]	[0.006]	[0.003]	[0.003]	[0.003]	[0.005]
Number of persons in household	−0.256***				−0.180***			
	[0.001]				[0.001]			
Age of head of household	0.007***				0.001***			
	[0.000]				[0.000]			
Single household (Yes=1)		0.488***	0.482***	0.489***		0.344***	0.338***	0.367***
		[0.005]	[0.005]	[0.006]		[0.004]	[0.004]	[0.005]
Elderly household (Yes=1)		0.336***	0.313***	0.330***		−0.020***	−0.039***	−0.005
		[0.004]	[0.004]	[0.005]		[0.003]	[0.003]	[0.005]
Single elderly household (Yes=1)		0.110***	0.133***	0.137***		−0.095***	−0.076***	−0.060***
		[0.008]	[0.008]	[0.009]		[0.006]	[0.006]	[0.008]
Family with children (Yes=1)		−0.381***				−0.272***		
		[0.003]				[0.002]		
Number of children in household			−0.230***	−0.249***			−0.174***	−0.194***
			[0.002]	[0.004]			[0.002]	[0.004]
Family with children < 4 years (Yes=1)			−0.073***	−0.044***			−0.076***	−0.054***
			[0.004]	[0.007]			[0.004]	[0.007]
Family with children 5–12 years (Yes=1)			0.017***	0.056***			0.034***	0.068***
			[0.005]	[0.009]			[0.005]	[0.009]
Family with children > 12 years (Yes=1)			0.115***	0.150***			0.127***	0.143***
			[0.005]	[0.008]			[0.004]	[0.008]
Household income (€ thousands, log)				0.055***				0.106***
				[0.003]				[0.003]
Constant	6.849***	6.485***	6.493***	5.789***	7.617***	7.248***	7.254***	6.148***
	[0.008]	[0.007]	[0.006]	[0.035]	[0.008]	[0.008]	[0.008]	[0.032]
Province-fixed effects								
Observations	297,197	297,197	297,197	138,382	300,393	300,393	300,393	142,147
R-squared	0.346	0.322	0.355	0.340	0.181	0.159	0.192	0.182
Adj R^2	0.346	0.323	0.355	0.340	0.181	0.159	0.192	0.182

where D_i is a vector of demographic characteristics, including age of the head of the household, household composition, ethnicity, and income.[13] 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 (i.e., appliances) in the dwelling. However, the latter are unobserved; we cannot further control for them directly.

Table 3 presents the results for four different specifications, relating the demographic composition of households to their consumption of gas and electricity. Fixed effects for provinces are also included in these specifications, but omitted from the table. Column (1) shows that each additional person per household decreases per capita gas consumption by about 26 percent. This reaffirms the well-documented economies of scale in residential energy consumption.

The age of the head of the household is significantly related to gas consumption. Interestingly, demographic attributes also seem to influence the consumption of natural gas. Female-dominated households consume about two percent more natural gas, whereas foreign-born households consume slightly less (though insignificantly so). These findings may arise from gender differences in preferences for thermal comfort temperatures and differences between races regarding lifestyle (i.e., cooking, bathing, etc.).

In Column (2), we decompose the household composition further into family type. Relative to households without children, single households consume about double the amount of natural gas per capita, whereas elderly households consume about 31 percent more. This difference may well be attributed to intensity of use (or occupation) of dwellings, which is likely to be lower among working singles than among retired households. Single elderly households consume substantially less heating than married seniors – about 23 percent. Per capita heating usage decreases by about 23 percent per additional child, which again confirms existing evidence on economies of scale in household energy consumption.

[13] One reviewer raised the issue of interdependence of household demographics and dwelling characteristics. Households with children may sort in larger dwellings, *etc.* Our cross-sectional dataset does not allow for time series analysis, for example by analyzing households moving in and out of the same dwelling. As a robustness check, we combined both sets of variables into a single model. Results reported in Appendix Table A1 show that the explanatory power of the models increases, but coefficients do not change substantially.

We further investigate the influence of the family life cycle on gas consumption in Column (3). We find that per capita energy consumption is low 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 (Fritzsche, 1981).

We relate electricity consumption to household demographics in Columns (5) through (8). As compared to gas consumption, per capita 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 consumption with respect to household size is smaller than for gas consumption; an additional person in the household increases electricity usage by about 21 percent. Apparently, economies of scale are less powerful for electricity usage.

Even though the consumption of gas 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 two to four percent less electricity than middle-aged married couples do. The small 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 in their residence, which obviates any economies of scale that are more common among families.

Column (7) shows the relation between family life cycle and electricity usage. It is clear that the age of children has a significant influence on electricity consumption. Older children watch more television, use personal computers, and are frequent users of gaming devices, which has a substantial effect on energy consumption – we describe this phenomenon as the "Nintendo-effect."

The effect of income on electricity consumption is stronger than the effect upon gas for heating. A one-percent increase in disposable income is associated with an 11 percent increase in household electricity usage.

Fig. 5 provides a more detailed analysis of the sensitivity of energy consumption to variations in household composition. The energy consumption of the elderly lies substantially above the average of other family types, and it is highly responsive to thermal quality of homes as reflected in period of construction (Fig. 5(A)). The gas usage of elderly households is about 30 percent higher than that of other households. However, the per capita electricity consumption of elderly households is consistently lower than that of other households (Fig. 5(B)). 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.

4. Conclusions and discussion

Energy consumption in the residential sector offers an important opportunity for conserving resources, and understanding the key determinants of residential energy consumption is important for the design and implementation of effective policies aiming to increase the energy efficiency of the building stock. Importantly, the strong heterogeneity in the quality of the building stock and climatic circumstances in different countries around the world increases the need for international comparisons of the ingredients of successful policy design.

In this paper, we have relied upon a large sample of dwellings, 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 households' demographic composition and households' consumption of gas for heating and electricity for other uses. Given the relatively cold climate, variations in energy consumption are important for the households in the Netherlands, and more broadly, for households throughout Northern Europe.

We document a strong relationship between the vintage of dwellings and their resource consumption. Dwellings constructed in this century use about 65 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 regime. The variations among housing vintages and dwelling types are less pronounced with regard to electricity usage. 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 per capita consumption is lower. 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.

In Fig. 6, we provide an indication of the effects of expected demographic changes in the Dutch population upon energy usage; we combine these empirical observations with the available forecasts on the Dutch demographic outlook for the next two decades. We combine the estimates of the full model reported in Appendix Table A1 (including both dwelling characteristics and household demographics)[14] with the current forecasts for the age structure of the population,

[14] We note that the explanatory power of the models combining household demographics and dwelling characteristics is quite strong, explaining about 50 percent and 30 percent of the variation in per capita gas and electricity consumption, respectively.

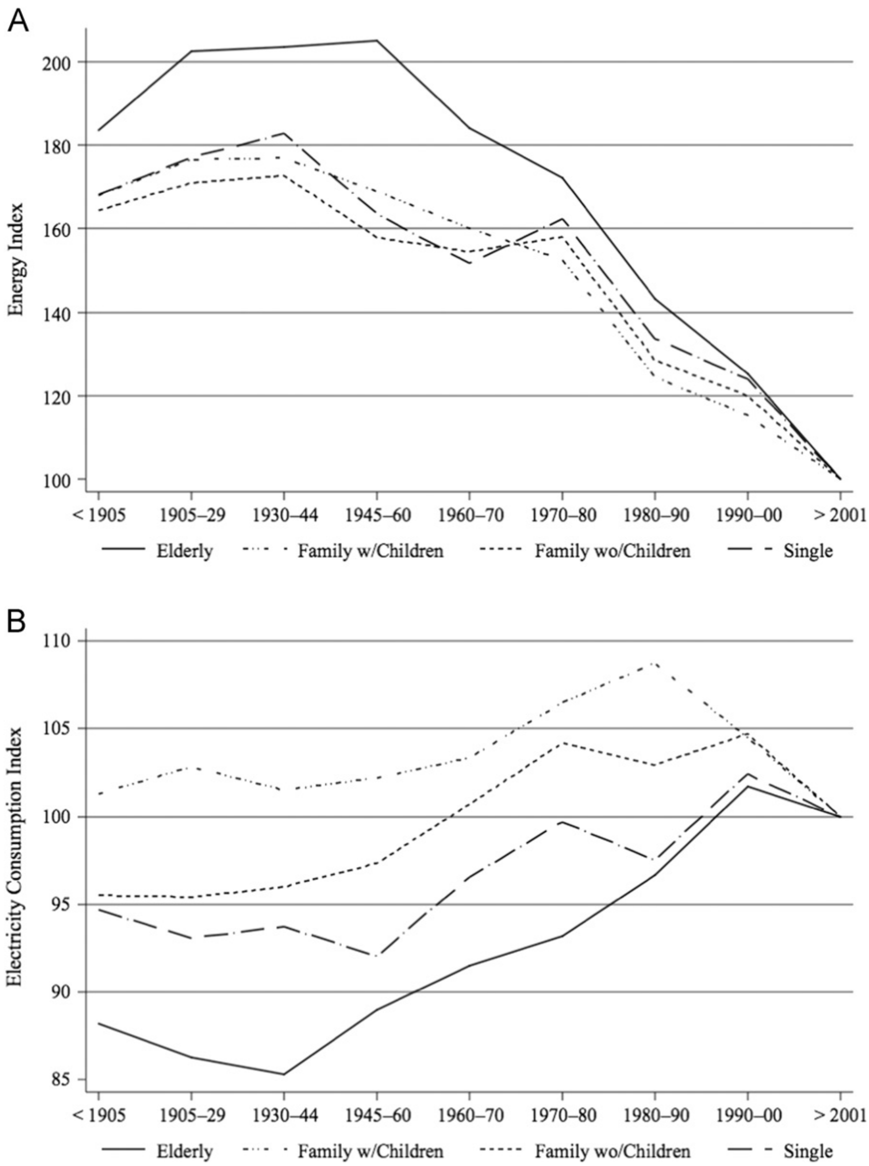

Fig. 5. Household Energy Cconsumption (electricity (kW h) and gas (m^3) per capita). (A) Gas (construction age – family type interactions) and (B) electricity (construction age – family type interactions).

immigration flows, insulation efforts, new construction volumes, and future income levels. 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) is expected to double by 2040.

Fig. 6 reports the implications of these 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 the developed world, for that matter) can be expected to increase energy usage of owner-occupied households by a bit more than two percent over the next two decades. Forecasts of increased immigration from abroad add only a little to the expected increase in gas consumption. As postulated by O'Neill and Chen (2002), our results also suggest that the aging trend of society will create additional obstacles to reducing future energy consumption. Our findings show that these developments will increase energy usage, and may even offset technical improvements of the building stock.

By way of comparison, the figure also suggests the implications for energy use if a home insulation program were adopted in Holland. Assuming that half of the Dutch housing stock were subject to a national insulation improvement program over the next two decades (adding two layers of insulation on a scale of six), we would expect only a marginal reduction in energy consumption. The effects of home insulation on residential energy use appear to be rather mild, resulting in an aggregate reduction of gas consumption of around one percent in the next 20 years. We also investigate the

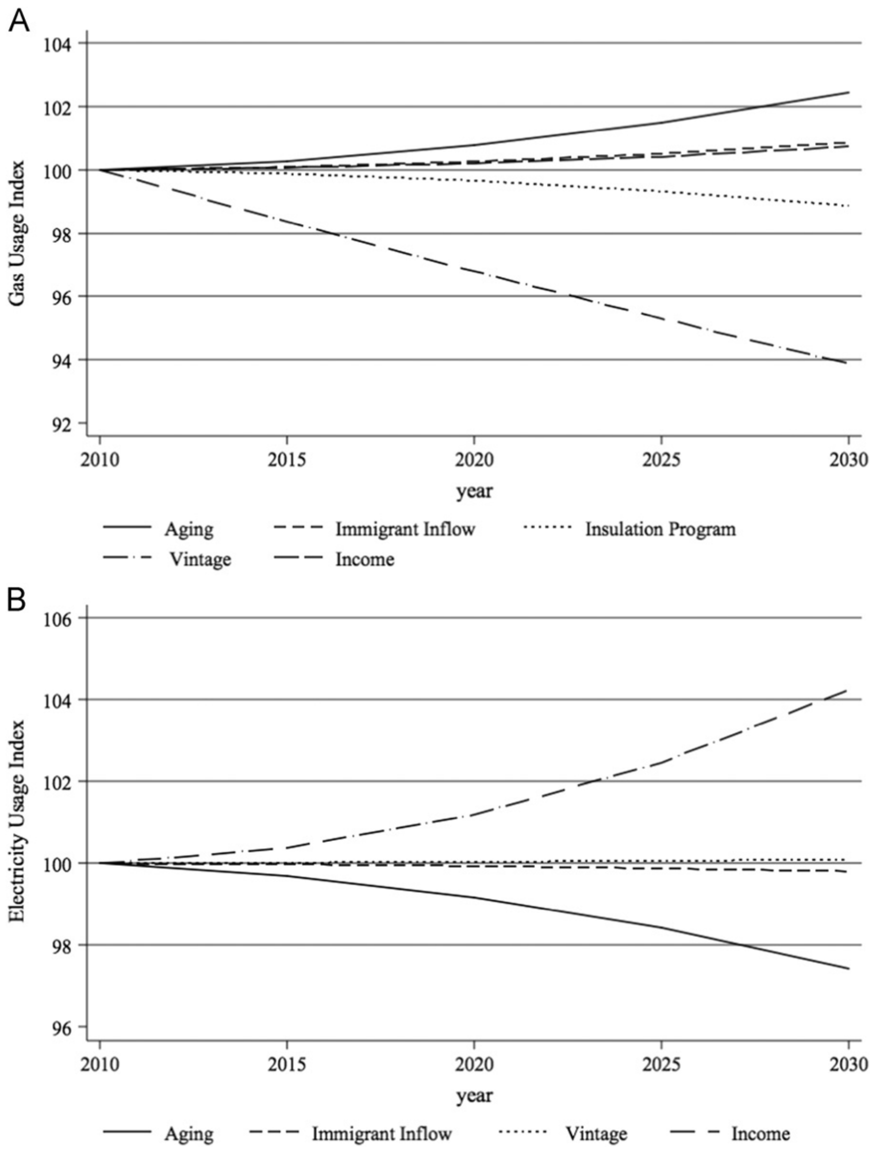

Fig. 6. Simulated future energy consumption. (A) Gas (m^3) per dwelling and (B) electricity (kW h) per dwelling.

effects of extrapolating the current Dutch trends in residential new construction and demolition over the coming two 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 would be about twice as important as demographic considerations for future energy use. In other words, new construction will have a pervasive impact on the total energy efficiency of the future housing stock by reducing gas consumption with around six percent in the next two decades.

Of course, these projections ignore the other crucial 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 incomes will grow at the same rate as the past two decades; this increases gas consumption with little over one percent over the next two decades.

The results documented in this paper have 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 the economic and demographic 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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