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Performance gaps in energy consumption: household groups and building characteristics

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ABSTRACT
The difference between actual and calculated energy is called the 'energy-performance gap'. Possible explanations for this gap are construction mistakes, improper adjusting of equipment, excessive simplification in simulation models and occupant behaviour. Many researchers and governmental institutions think the occupant is the main cause of this gap. However, only limited evidence exists for this. Therefore, an analysis is presented of actual and theoretical energy consumption based on specific household types and building characteristics. Using a large dataset (1.4 million social housing households), the average actual and theoretical energy consumptions (gas and electricity) of different household types and characteristics (income level, type of income, number of occupants and their age) were compared for each energy label. Additionally, the 10% highest and lowest energy-consuming groups were analysed. The use of combinations of occupant characteristics instead of individual occupant characteristics provides new insights into the influence of the occupant on energy demand. For example, in contrast to previous studies, low-income households consume more gas per m^2 (space heating and hot water) than households with a high income for all types of housing. Furthermore, the performance gap is caused not only by the occupant but also by the assumed building characteristics.

KEYWORDS
big data; energy consumption; energy epidemiology; energy performance; household energy; occupant behaviour; performance gap

Introduction

In 2002, the European Union introduced the Energy Performance of Building Directive (EPBD). The EPBD requires buildings to have an energy performance certificate (EPC), or energy label, when sold or rented. In the Netherlands, the energy label is calculated based on both the building characteristics and modelled heating behaviour of occupants. Through a simplified heat-transfer calculation, a theoretical energy usage is determined that relates to an energy label. The theoretical energy usage for residential buildings contains building-related energy usage (*e.g.* energy for heating, hot water, ventilation, lighting in communal areas). Energy use for electrical appliances and lighting in private areas is excluded. The aim of this energy label is to show potential buyers or renters the energy efficiency of their dwelling in a simple and comprehensible way (Rijksoverheid, 2016a). Apart from this, the labelling system is used by policy-makers to set energy-saving targets and develop policies. For example, the Dutch social housing associations signed a covenant to renovate their building stock to reach an average energy label B by 2021, and thereby an energy reduction of 33% between 2008 and 2021 (Bzk, Aedes, Woonbond, & Vastgoed Belang, 2012).

The discrepancies between actual (measured by energy distribution companies) and theoretical energy consumption (as calculated by the energy label) were found by several researchers (Guerra-Santin & Itard, 2010; Majcen, Itard, & Visscher, 2013b; Menezes, Cripps, Bouchlaghem, & Buswell, 2012; Sunikka-Blank & Galvin, 2012). This set of discrepancies is known as the 'energy-performance gap'. Majcen et al. (2013b) showed that occupants of 'energy-inefficient' buildings consume less gas (for space heating and hot water) than expected, while occupants of 'energy-efficient' buildings consume more than expected. Apart from gas, there is also a gap between theoretical and actual electricity consumption.

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However, this gap for electricity is expected because theoretical energy consumption only incorporates building-related energy consumption and not other electricity consumption (*e.g.* electrical appliances and lighting). The performance gap for gas consumption is more difficult to explain because it primarily contains energy consumption for heating, which is dependent on multiple factors.

Several researchers found a significant influence of the occupant on residential energy consumption (Gram-Hanssen, 2012; Palmborg, 1986; Sonderegger, 1978; Steemers & Yun, 2009). Some even claim that the energy-performance gap is primarily caused by occupant behaviour (Aydin, Kok, & Brounen, 2013; Gram-Hanssen, 2011). This suggests that occupants in energy inefficient dwellings behave more energy efficiently than occupants in more energy-efficient dwellings. Additionally, occupants in energy-efficient dwellings are assumed to have a higher comfort level than occupants in less energy-efficient dwellings, which could be an explanation for the underestimation of high energy-efficient buildings. Guerra Santin (2013), for example, found that the average indoor temperature in energy-efficient dwellings is higher than in energy-inefficient dwellings. This can partly be explained by the so called 'rebound effect', which is defined by Herring and Sorrell (2009) as the increase of energy consumption in services for which improvements in energy efficiency reduce the costs.[1] The opposite of the rebound effect is also found to be true, also known as the 'pre-bound effect' (Sunikka-Blank & Galvin, 2012).

It is generally known that occupants influence residential energy consumption. However, researchers have so far only been able to use occupant behaviour to explain some of the variance. For example, Guerra Santin (2010) found evidence for 3.2–9.4% of the variance in energy consumption due to occupant behaviour, and Majcen (2016) for 9.1%. Despite limited evidence for the actual influence of occupant behaviour on residential energy consumption, several organizations and governments have implemented campaigns to change energy behaviours. A clear knowledge base of how inhabitants actually use energy is necessary to improve the effectiveness of energy-saving campaigns to help policy-makers set more realistic energy-saving targets, and to reduce the energy-performance gap. However, it is rather time-consuming and intrusive to gather actual occupant behaviour data. As there is relatively little explanation for the discrepancy in actual and theoretical energy use, better insight into the influence of the occupant on residential energy consumption is required.

The lack of available occupant data is probably one of the reasons researchers found only limited evidence for the influence of occupant behaviour on the performance gap. However, results from in-use building performance research (actual energy consumption) instead of pre-occupancy consumption (theoretical consumption) are essential for the development of energy-saving policy instruments (Bordass, Leaman, & Ruyssevelt, 2001; Visscher, Meijer, Majcen, & Itard, 2016b). Also, most studies that investigate actual energy consumption focus either on occupant behaviour or the building's characteristics. The rebound effect, however, suggests an interaction between behaviour and building characteristics. Understanding occupant behaviour is essential to predict the energy performance of buildings (Visscher, Laubscher, & Chan, 2016a). Therefore, the present study investigates the research question:

> Can analysing actual energy consumption by specific household types and building characteristics contribute to a better understanding of the role of the occupant in actual energy consumption and the energy-performance gap?

This research uses large databases. The first database is the SHAERE database from the umbrella organization of the Dutch social housing associations. It contains building characteristics and theoretical energy consumption data from 1.4 million social rented houses in the Netherlands. The other two databases contain occupant characteristics and annual energy consumption data from Statistics Netherland. By combining occupant characteristics and analysis per energy label, it is possible to use large databases to investigate the influence of the occupant on residential energy consumption (Hamilton et al., 2013) and identify clear patterns and trends.

This paper is structured as follows. The next section presents an overview of the literature on the influence of occupant behaviour on residential energy consumption along with an explanation of the Dutch energy label system. Then an overview of the databases and a description of the methods are provided. The findings are then described. The final two sections contain the discussion and conclusions.

Existing studies

This section describes findings of previous research regarding the influence of occupant behaviour on residential energy consumption. Findings that are not from the Netherlands are noted as such in the text.

Influence of actual behaviour on energy consumption

Residential energy includes energy for lighting and appliances, cooking, domestic hot water, and heating. In the Netherlands, heating consumes the largest share of a building's energy (Bosseboeuf, Gynther, Lapillonne, &

Pollier, 2015). It is widely recognized that building characteristics influence the actual energy consumption in terms of heating. For example, buildings with a high insulation level consume less energy for heating than buildings with a low insulation level. However, occupant behaviour is also found to have an effect on actual energy consumption for heating. For example, the hours that heating is at its maximum temperature explains 10.3% of the variance in actual energy consumption for heating. The number of hours the radiator is on in a certain room also explains a part of the variance of actual energy consumption for heating (living room 8.8%, bedroom 8.1% and bathroom 5.9%) (Guerra Santin, 2011).

Furthermore, in China the set-point temperature was found to influence significantly residential energy consumption (O'Neill & Chen, 2002). Lowering the set-point temperature by 1°C can result in a significant reduction in energy use, similar to roof insulation (Guerra Santin, Itard, & Visscher, 2009). The set-point temperature at night and in the evening has more impact on total energy use than the temperature setting during the day (Guerra Santin et al., 2009).

Appliances are the second main energy consumer in an average Dutch household (Bosseboeuf et al., 2015). Research in the UK found that 19% of energy is consumed by stand-by and continuous appliances (*e.g.* refrigerators) (Firth, Lomas, Wright, & Wall, 2007). In Denmark, 10% of household energy is used solely for stand-by appliances (Gram-Hanssen, Kofod, & Petersen, 2004). More frequent use of electrical appliances over previous years has resulted in an increase of electricity consumption. For example, more frequent use of dishwashers has caused a decrease of gas consumption for hand washing but increased electricity use (Dril, Gerdes, Marbus, & Boelhouwer, 2012).

Energy for domestic hot water is the third highest energy consumer in an average Dutch household (Bosseboeuf et al., 2015). The energy used for domestic hot water is, apart from the domestic hot water system, strongly related to the number of people per household (Gerdes, Marbus, & Boelhouwer, 2014). The majority of domestic hot water is used for showering or bathing. The frequency of showers has been stable in recent years (on average 12 times a week per household) (Gerdes et al., 2014).

Energy use for cooking has decreased in recent years. People go out for dinner more often, and delivery and takeaway meals are more common (Gerdes et al., 2014).

Influence of occupant characteristics on actual energy consumption

Several studies show a correlation between actual energy consumption and occupant characteristics. Occupant characteristic data are available on a larger scale than occupant behaviour data. Additionally, correlations between occupant characteristics and energy consumption are more usable for policy-makers than actual behaviour data. Therefore, many researchers focus on occupant characteristics instead of actual behaviour to study the influence of occupant behaviour on residential energy consumption. The text below describes the findings of previous research on the influence of occupant characteristics on gas and electricity consumption.

Incomes in England were found to be positively correlated with the actual energy consumption in a household (Druckman & Jackson, 2008; Steemers & Yun, 2009). A 1% increase in income increases the total energy consumption by 0.63%, according to Vringer and Blok (1995). The correlation for electricity ($r = 0.25$; $p < 0.01$) was found to be marginally stronger than for gas ($r = 0.23$; $p < 0.01$) (Druckman & Jackson, 2008). A larger number of household members also results in higher energy consumption, but it decreases the energy consumption per person (Chen, Wang, & Steemers, 2013; Druckman & Jackson, 2008; Guerra Santin et al., 2009; Guerra-Santin & Itard, 2010; Jeeninga, Uyterlinde, & Uitzinger, 2001; Kaza, 2010; O'Neill & Chen, 2002; Vringer & Blok, 1995; Yohanis, Mondol, Wright, & Norton, 2007; Yun & Steemers, 2011).

Age is found to be the most determining indirect effect on heating and cooling energy use in different countries (Guerra Santin, 2010; O'Neill & Chen, 2002; Pettersen, 1994; Yun & Steemers, 2011). Occupants between 40 and 50 years demand the highest comfort and also have the highest average net income (Yohanis, 2011; Yohanis et al., 2007). Households with young children ventilate less, whereas households with older children ventilate more (Guerra Santin, 2010).

Education level has only a very limited impact on residential energy consumption. Higher-educated people set their thermostat for fewer hours on the highest temperature set-point than lower-educated people (Guerra Santin, 2010).

Household size and the presence of teenagers in the house is found to have a significant effect on energy consumption for appliances (Brounen, Kok, & Quigley, 2012).

Finally tenants are found to have a higher rebound effect than homeowners (tenants 31–49% and homeowners 12–14%).

These results show that studying occupant characteristics is an effective way to investigate the influence of occupants on residential energy consumption. Additionally, studying occupant characteristics instead of actual behaviour data enables one to work with larger datasets.

Other explanations for the energy-performance gap

Although occupant behaviour is expected to be one of the main explanations for the energy-performance gap, other possible explanations should not be neglected. The insulation level of the building is seldom measured; in most cases it is estimated based on available building documents. As little or no data are available for older buildings, the insulation level of these buildings is determined based on the construction year of the building. Recent research by Rasooli, Itard, and Infante Ferreira (2016a) suggests that these assumptions could be an important explanation for a part of the energy-performance gap.

Several studies show that the thermal mass of a building contributes significantly to its heating energy demand. This could be another explanation for the performance gap (Aste, Angelotti, & Buzzetti, 2009; Bojić & Loveday, 1997). However, the thermal mass is not taken into account in the theoretical energy calculation of the Dutch EPC. Therefore, this could influence the discrepancy between actual and theoretical energy consumption.

Additionally, the theoretical energy-consumption calculation method used for the determination of the energy label only contains building-related energy consumption. However, the actual energy consumption data also include occupant-related energy consumption (*e.g.* use of electrical appliances).

Finally, the theoretical energy consumption is calculated with a steady-state model in this research. This model might be oversimplified. The most oversimplified aspects are assumed to be heat transfer between adjacent rooms with an identical air temperature, the definition of the combined radiative–convective heat-transfer coefficient, different definitions of solar gains (by surfaces or the air), and including/excluding solar gains by exterior surfaces such as roofs (Rasooli, Itard, & Infante Ferreira, 2016b). Time is not taken into account in the steady-state method, so the occupant behaviour is static in the Dutch energy label calculation. However, the relationships between behaviour patterns and occupant characteristics are found in previous research (Kane, Firth, & Lomas, 2015). The use of occupancy pattern models has significantly improved the accuracy of the estimation in space-heating energy use (Cheng & Steemers, 2011).

Dutch energy label

This section describes briefly how the theoretical energy consumption for Dutch dwellings is calculated and the energy label is determined. Additionally, it describes the assumptions made about the occupant in this calculation. The entire calculation and determination method of the energy label can be found in ISSO 82.3 (2011) (*energieprestatie advies woningen*).

As mentioned above, the theoretical energy is based on a simplified heat-loss calculation. The air tightness, insulation level and ventilation rate are taken into account to define the energy demand for heating. The energy consumption for domestic hot water is based on the assumed domestic hot water use in litres and the energy efficiency of the domestic hot water installation. The theoretical energy consumption only contains building-related energy usage, which is the sum of primary energy for heating, domestic hot water, pumps/fans and lighting in common areas minus the energy gained from solar panels and cogeneration. This is also important to consider when actual and theoretical energy consumption are compared. The theoretical energy consumption is calculated for a standard situation that assumes the following:

- average indoor temperature of 18°C
- average internal heat production due to appliances and people of 6 W/m^2
- 2620 degree-days (= 212 heating-days with an average outdoor temperature of 5.64°C)
- heating gains from the sun, vertical south orientation: 855 MJ/m^2
- ventilation rate based on floor area and type of ventilation system
- standard number of occupants based on floor area (Table 1)
- 0.61 showers per day per person
- 0.096 baths per day per person (if a bath is present).

$$Q_{total} = Q_{space\,heating} + Q_{waterheating} + Q_{aux.energy} + Q_{lighting} - Q_{pv} - Q_{cogeneration} \quad (1)$$

where Q_{total} = total theoretical primary energy consumption (MJ); Q_{space} heating = total theoretical primary energy consumption for space heating (MJ); $Q_{waterheating}$ = total theoretical primary energy consumption for domestic hot water (MJ); $Q_{aux.energy}$ = total theoretical primary energy consumption for pumps/ventilators (MJ); $Q_{lighting}$ = total theoretical

Table 1. Assumed number of occupants in the theoretical energy calculation (ISSO 82.3).

Floor area (m^2)	Assumed occupants
< 50	1.4
50–75	2.2
75–100	2.8
100–150	3.0
> 150	3.2

primary energy consumption for lighting (MJ); Q_{pv} = total theoretical primary energy gains from solar (MJ); and $Q_{cogeneration}$ = total theoretical primary energy gains from cogeneration (MJ).

Data

This section describes the data used for this research and its representativeness.

SHAERE database

The SHAERE (*Sociale Huursector Audit en Evaluatie van Resultaten Energiebesparing*; in English, social rental sector audit and evaluation of energy saving results) database is owned by AEDES (the umbrella organization for Dutch housing). Dutch social housing organizations own 31% of the total housing stock in the Netherlands. The SHAERE database contains 60% of social housing stock. Besides building characteristics (*e.g.* insulation, type of glazing, ventilation, heating and domestic hot water systems) the SHAERE database also contains a pre-label and the corresponding theoretical energy consumption and energy index. A pre-label is a label that has not been validated by the authorities but contains the same information as the validated one. The advantage of the pre-labels is that they are made as soon as the energy performance of a house is upgraded. The database is updated every year. For this research, the 2014 SHAERE database was used.

CBS (Statistics Netherlands Bureau) data

The theoretical energy consumption per dwelling is included in the SHAERE database, but to identify the performance gap the actual energy consumption is required. For this research, the authors had access to the actual annual energy consumption data of Dutch households provided by energy companies via the Statistics Netherlands Bureau (CBS). This database contains annual actual energy consumption at a household level. In addition, access was granted to occupant characteristics data at a household level from the same source. The occupant characteristics data include income, type of income (from work, benefits *etc.*), household composition, number of occupants, occupants above and below age 65 years, number of children, and age of children. This granularity of the data was available at the household level. This allowed the research team to link those databases and execute the analysis.

This is one of the first studies to have access to such a large and extensive database. Addresses and other personally identifiable data were encrypted to ensure the occupants' privacy. Furthermore, the data could only be accessed via a secured server from the CBS. The data can only be exported on an aggregated level of at least 10 households.

Cleaning data

The raw dataset was filtered before the analysis. First duplicate cases and cases that were not checked in 2014 were removed from the dataset (reduction of 240,330 cases). Next, unrealistic floor areas for social housing in the Netherlands (all dwellings smaller than 15 m^2 and larger than 300 m^2) were deleted (reduction of 20,734 cases). Also, all cases with a gas-powered heating system that had a gas consumption of zero were removed, as were the cases with an electricity consumption of zero. Finally, all cases with a primary energy use above 4000 MJ/m^2 were deleted. The final dataset contained 1,431,019 cases. A correction for climate was applied though the application of degree-days. As the energy consumption data of district and block heating were found to be unreliable, all cases with this type of heating system were removed from the dataset.

Household types

Based on occupant characteristic data, 18 household types were formed. These are based on income, household composition, type of income and age. These household types represent almost 80% of the total number of cases in the SHAERE database (Table 2).

Household types are not equally distributed among energy labels. Single households and retired couples appear to live more often in A- and B-label dwellings than in the less energy-efficient dwelling types. Single households that receive state benefits or have a low to average income live more often in dwellings with a low energy label. The same applies for couples with a low or average income and for receivers of state benefits. Households with a high income on average live more often in dwellings with a high energy label. Families with children and a high income live more often in dwellings with an energy label A. Families with a low or average income live less often in buildings with a high energy label (A and B) but also less often in buildings with a low energy label (F and G).

Representativeness of the dataset

This section compares the SHAERE database with the national situation. First, the database contains only rental dwellings data, which represents 55.8% of the housing stock (Rijksoverheid, 2016b).

Table 2. Household types.

	Household composition	Age (years)	Children	Age of children (years)	Work	Income
1	Single	≥65	No	n.a	Retired	n.a
2	Single	<65	No	n.a	State benefit	n.a
3	Single	<65	No	n.a	Employed	Low
4	Single	<65	No	n.a	Employed	Middle
5	Single	<65	No	n.a	Employed	High
6	Couple	>65	No	n.a	Retired	n.a
7	Couple	<65	No	n.a	State benefit	n.a
8	Couple	<65	No	n.a	Employed	Low
9	Couple	<65	No	n.a	Employed	Middle
10	Couple	<65	No	n.a	Employed	High
11	Family	<65	Yes	< 12	State benefit	n.a
12	Family	<65	Yes	< 12	Employed	Low
13	Family	<65	Yes	< 12	Employed	Middle
14	Family	<65	Yes	< 12	Employed	high
15	Family	<65	Yes	At least one > 12	State benefit	n.a
16	Family	<65	Yes	At least one > 12	Employed	Low
17	Family	<65	Yes	At least one > 12	Employed	Middle
18	Family	<65	Yes	At least one > 12	Employed	High

Note: n.a. = Not applicable.

Compared with the national housing stock in the Netherlands, the database contains fewer dwellings with an energy label A and B (RVO, 2014). Compared with the national housing stock, it contains more multi-family dwellings. Fewer buildings were constructed before 1965 and between 1992 and 2005 in the database than in the total national stock. More buildings were constructed between 1965 and 1991 in the database compared with the national stock.

The average number of household members in SHAERE (1.85) is lower than the overall national average in the Netherlands (2.20). A comparison between the assumed number of occupants in the energy performance calculation and that of the SHAERE database shows that the assumed number is always higher than the actual number.

The average income of the occupants in the database is lower than the average income of the total Dutch housing stock. The first to the fifth income percentiles are overrepresented and the higher income percentiles, sixth to 10th, are underrepresented in the database.

Occupants over 65 years occur more often in SHAERE than in the national database (28.9% SHAERE, 15% Dutch population). Particularly in dwellings with a better energy label, the number of people aged 65 years and older is higher in the SHAERE database.

Method

Gas and electricity consumption per m^2 are now studied. This metric was chosen to reduce the impact of variations in floor area. Two methods are used. First, the theoretical and actual average energy consumption for each household type per energy label are compared. The comparison is made on the energy label for two reasons. First, previous research found a relationship between occupant behaviour and the energy efficiency of the dwelling (Aydin et al., 2013; Sunikka-Blank & Galvin, 2012). Second, the data revealed that household types are unevenly distributed among the energy labels. The statistical significance of this comparison is checked with a linear regression.

The second method is a more in-depth analysis of the highest 10% and the lowest 10% energy-consuming groups of every energy label (Table 3). This approach was used because it is expected that the most relevant factors will be more clearly visible in the extreme groups than in the average group, where the factors will be less visible because there is more noise. The assumption is

Table 3. Households in the 10% high and lowest energy-consuming groups.

Energy label	Households
A	5018
B	18,076
C	30,703
D	22,003
E	11,413
F	6330
G	2442

that the observation of the extreme groups will distinguish the relevant parameters more quickly. Both groups are analysed for household type and other occupant characteristics as well as the building characteristics. The significance of the results is checked with a chi-square analysis. Analyses are conducted with IBM SPSS statistics 22 software.

Results

The results are divided into two parts: gas consumption and electricity consumption. For both, first the difference between actual and theoretical consumption is explained and then the highest and lowest energy-consuming groups are compared. When interpreting the results, it should be noted that the majority of the residential buildings in the Netherlands (as in this database) use gas for space heating and domestic hot water.

Gas consumption

Comparing actual and theoretical gas consumption per energy label reveals that supposedly energy-efficient buildings (energy labels A–B) consume more gas than expected. Buildings that are supposed to be inefficient (energy labels C–G) consume less gas than expected (Figure 1). These findings confirm the findings of Majcen et al. (2013b).

Household types are then added to the comparison between actual and theoretical gas consumption. This provides a better insight into their influence. Figures 2 and 3 show the results of this comparison. To keep the results section concise, only results for energy labels B and E are shown. The comparison results suggest that actual energy consumption is more influenced by household type than theoretical energy consumption. This is as expected because type of household is not taken into account in the theoretical energy calculation method.

Single households have the lowest and family households the highest gas consumptions for every energy label. This confirms previous research that a higher number of occupants results in higher gas consumption. Single and family households with a high income consume less gas in almost all cases compared with single and family households with a low income for every energy label. These findings are confirmed by the regression analysis (Table 4) for the majority of household types. This contradicts the findings of Vringer and Blok (1995). A possible explanation is the use of gas consumption per m^2 instead of total gas consumption.

It is expected that people with a high income live in houses with a larger area, which they do not heat constantly. However, if the same regression analysis is performed with the floor area of the dwelling, then a negative relationship exists between income and gas consumption, although the impact is smaller (Table 4). This suggests that the size of the floor area is only part of the explanation for why households with a high income are often in the low gas-

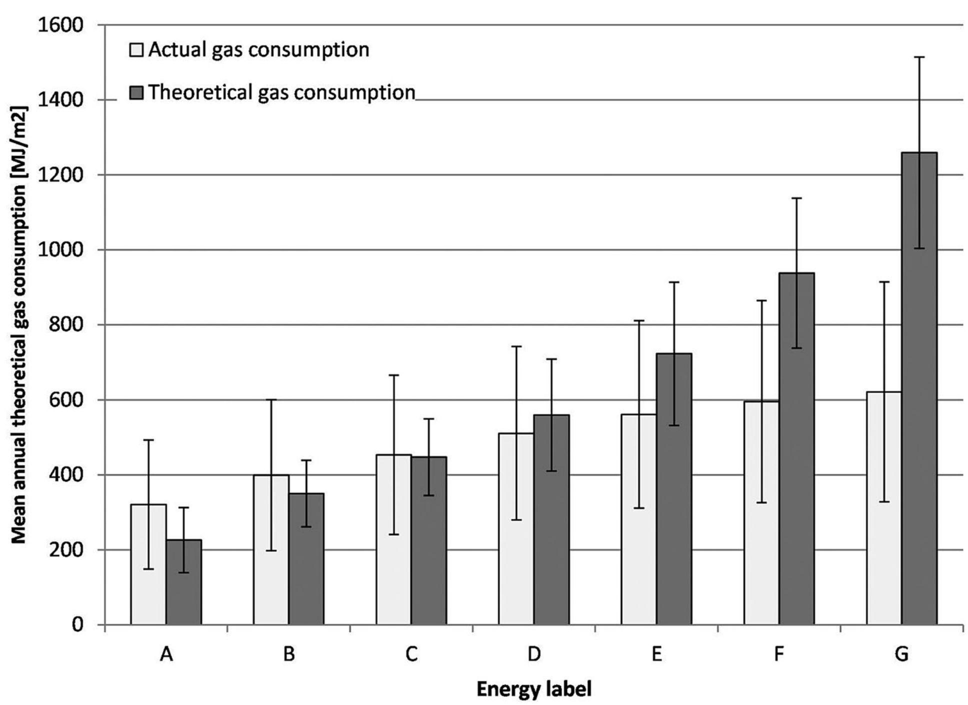

Figure 1. Comparison of actual versus theoretical gas consumption.

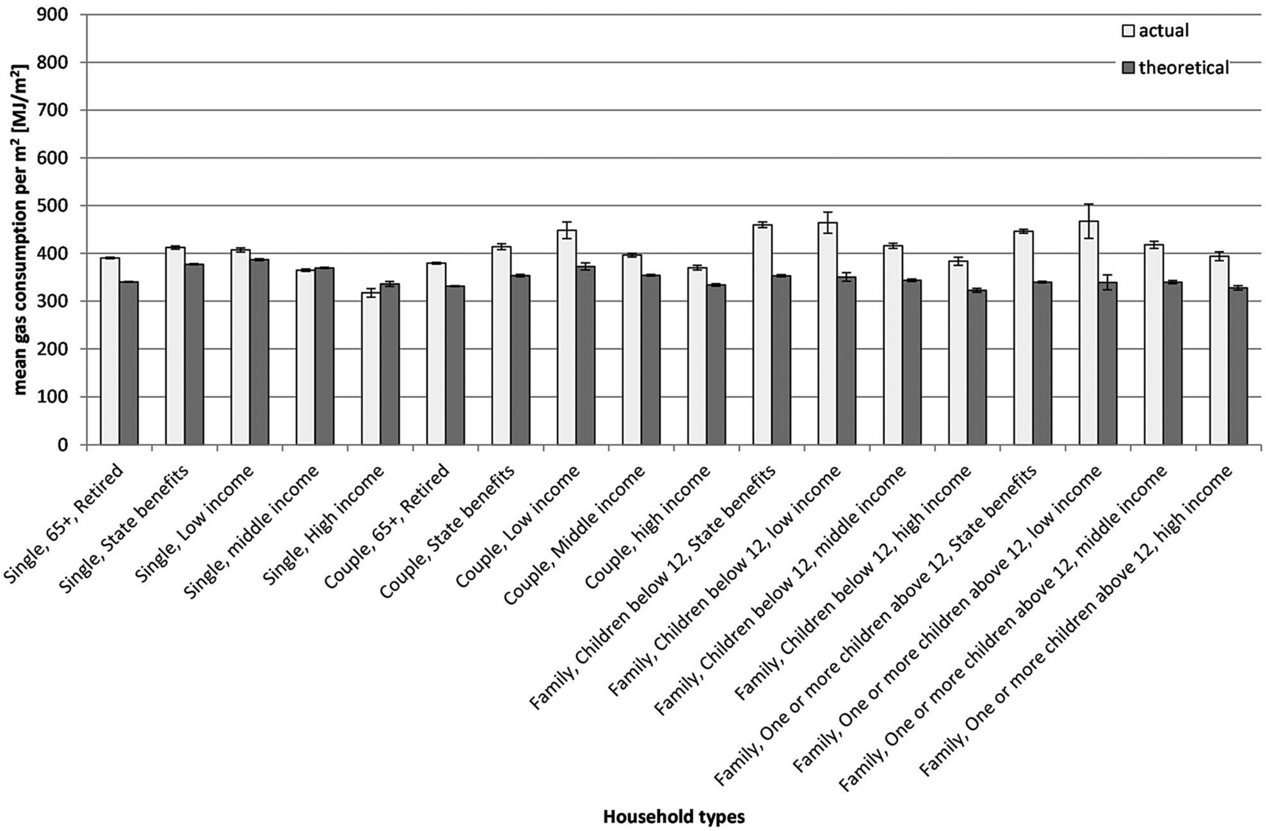

Figure 2. Comparison of mean actual versus theoretical gas consumption per household group – energy label B.

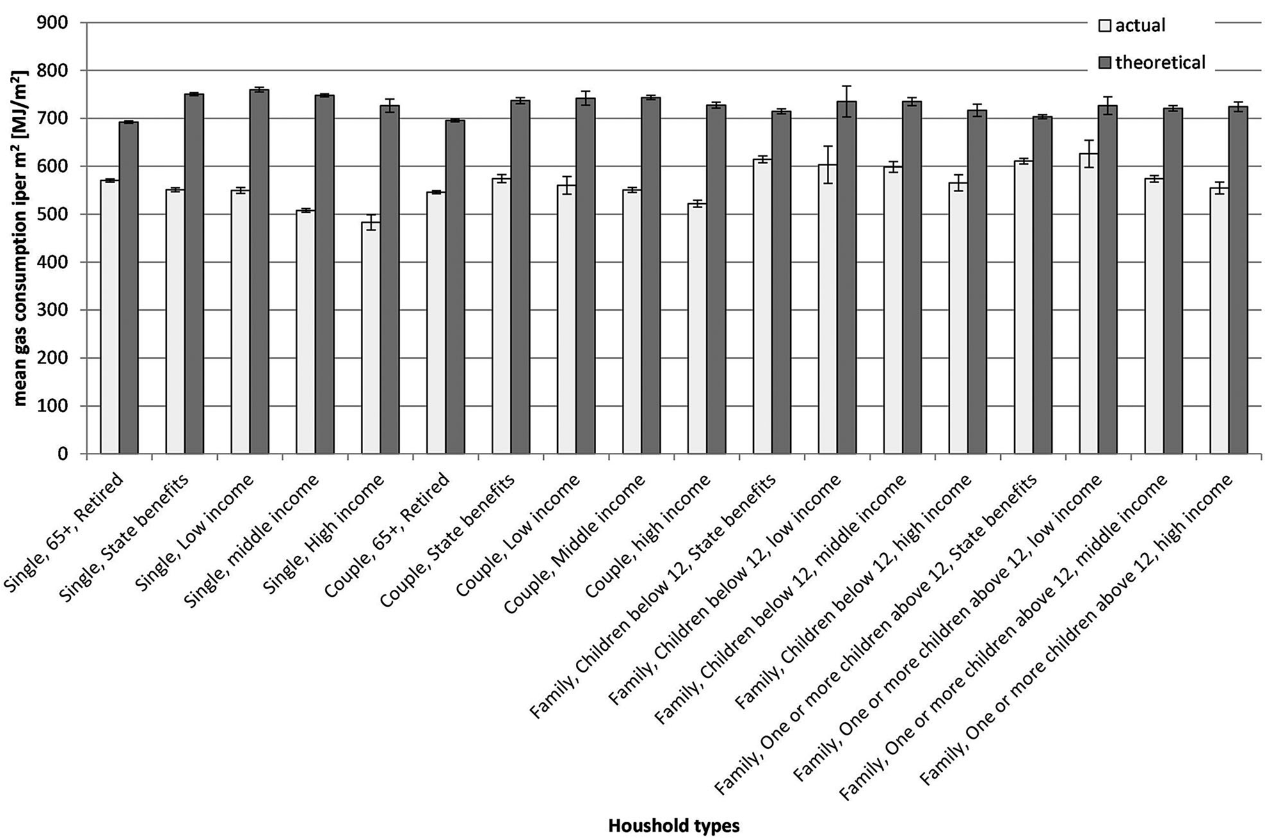

Figure 3. Comparison of mean actual versus theoretical gas consumption per household group – energy label E.

Table 4. Comparison regression analysis of gas-consumption energy (reference dummy variable = Single high income).

	Energy label B, $R^2 = 0.011$			Energy label B + area, $R^2 = 0.082$			Energy label E, $R^2 = 0.010$			Energy label E + area, $R^2 = 0.089$		
Household group	*B*	Standardized *B*	*p*	*B*	Standardized *B*	*p*	*B*	Standardized *B*	*p*	*B*	Standardized *B*	*p*
Constant	11.73		0.00	18.29		0.00	16.26		0.00	24.58		0.00
Single. 65+. Retired	−0.63	−17.67	0.00	−1.39	−0.10	0.00	−0.04	0.00	0.51	−0.24	−0.01	0.00
Single. State benefits	−0.01	−0.31	0.75	−1.24	−0.07	0.00	−0.59	−0.03	0.00	−1.78	−0.08	0.00
Single. Low income	−0.16	−0.01	0.01	−1.54	−0.06	0.00	−0.63	−0.02	0.00	−1.78	−0.05	0.00
Single. Middle income	−1.36	−0.07	0.00	−2.43	−0.12	0.00	−1.82	−0.08	0.00	−2.76	−0.11	0.00
Couple. 65+. Retired	−0.95	−0.06	0.00	−1.02	−0.06	0.00	−0.73	−0.03	0.00	−0.07	0.00	0.25
Couple. State benefits	0.04	0.00	0.69	−0.07	0.00	0.44	0.07	0.00	0.59	0.10	0.00	0.42
Couple. Low income	1.01	0.01	0.00	0.10	0.00	0.60	−0.32	0.00	0.23	−1.17	−0.01	0.00
Couple. Middle income	−0.46	−7.09	0.00	−0.69	−0.02	0.00	−0.61	−0.02	0.00	−0.68	−0.02	0.00
Couple. High income	−1.21	−14.23	0.00	−1.07	−0.03	0.00	−1.42	−0.03	0.00	−1.18	−0.03	0.00
Family. Children < 12. State benefits	1.37	0.04	0.00	1.21	0.03	0.00	1.22	0.03	0.00	0.88	0.02	0.00
Family. Children < 12. Low income	1.45	0.01	0.00	1.26	0.01	0.00	1.63	0.01	0.00	1.11	0.01	0.00
Family. Children < 12. Middle income	0.08	0.00	0.34	0.43	0.01	0.00	0.05	0.00	0.63	0.24	0.01	0.03
Family. Children < 12. High income	−0.85	−0.01	0.00	−0.07	0.00	0.64	−0.49	−0.01	0.02	0.04	0.00	0.83
Family. One or more children > 12. State benefits	−0.98	0.03	0.00	1.45	0.05	0.00	1.08	0.03	0.00	1.49	0.05	0.00
Family. One or more children > 12. Low income	1.52	0.01	0.00	1.91	0.01	0.00	1.19	0.01	0.06	1.83	0.01	0.00
Family. One or more children > 12. Middle income	0.13	0.00	0.30	0.86	0.02	0.00	0.71	0.01	0.00	1.24	0.02	0.00
Family. One or more children > 12. High income	−0.54	−0.01	0.00	0.49	0.01	0.00	−0.19	0.00	0.49	0.95	0.01	0.00
Floor area				−0.08	−0.28	0.00				−0.10	−0.29	0.00

consumption group than households with a low income. Another possible explanation is that households with a high income may spend less time at home than households with a low income and, therefore, consume less gas.

As expected, only a limited relationship was found between household type and theoretical energy consumption. The relationship can be traced back to household characteristics.

The largest difference between average actual and theoretical gas consumption in the total sample is found for single households that receive state benefits. The smallest difference is found for families with a high income from work. Analyses that take the energy labels into account show the smallest performance gap for family households in dwellings with a low energy label (D–G). Single households show the smallest gap for dwellings with an energy label between A and C. This means that there is no direct relationship between the performance gap and occupant characteristics or there are other factors that have a higher influence on the performance gap. Another explanation is that the average household type behaviour is dependent on the energy efficiency of the dwelling, *e.g.* household types behave more energy efficiently in energy-inefficient than in energy-efficient dwellings (the pre-bound effect).

Highest and lowest gas-consuming groups compared with the average

To get a better insight into the actual energy consumption, the households with the 10% highest and 10% lowest actual gas consumptions per energy label are analysed. The chi-square was used to test the statistical difference in the distribution of the three groups (10% highest energy consumers, 10% lowest energy consumers and 80% average energy consumers).

Figures 4 and 5 show the average actual and theoretical gas consumption per energy label, the mean lowest 10% and the mean highest 10% gas-consuming group. The difference between the highest, lowest and total theoretical gas-consuming groups provides evidence that building characteristics influence actual energy consumption. However, these differences are smaller compared with actual energy gas-consuming groups. This suggests that other factors also influence the actual energy consumption.

A comparison between the average actual and theoretical gas consumptions for the lowest 10% gas-consuming group shows an almost flat gas use for the actual gas consumption and (as expected) an increasing theoretical energy use as the label increases. The comparison of the actual and average theoretical gas consumption for the highest 10% gas-consuming group shows that even the average highest actual gas-consuming group consumes less gas than the predicted actual gas consumption.

To understand why residential buildings belong in the highest or lowest actual energy-consuming group, a more detailed comparison was made. This involved the comparison of the highest and lowest energy-consuming groups for both the building and occupant characteristics.

A comparison of the distribution of household types for the total, highest and lowest gas-consuming groups per energy label shows that the distribution of household types is different between groups (energy label B $\chi^2(34, N = 185{,}390) = 3747$, $p < 0.001$ and energy label E $\chi^2(34, N = 115{,}659) = 2287$, $p < 0.001$) Single households occur more frequently in the lower gas-consuming group than in the other groups, independent of label type. With the exception of the single retired household, this group occurs more often in the lower gas-consumption group for labels A–C, and more often in the higher gas-consuming group for labels F and G. This implies that the building characteristics have a larger influence on elderly people than on other household types. An explanation for this phenomenon could be that elderly people are more often at home and, therefore, heat their house for longer. However, this explanation cannot be confirmed by this research because actual occupant behaviour is not available. The comparison also shows that family households with children aged 12 years and above occur more often in the higher gas-consuming groups for every label type.

Specific occupant characteristics were also compared. In agreement with previous studies, the number of household members shows that households with one member occur more often in the lower gas-consumption group, and households with three or more members occur more often in the higher gas-consumption group. The difference in distribution is significant (energy label B $\chi^2(8, N = 185{,}390) = 1832$, $p < 0.001$ and energy label E $\chi^2(8, N = 115{,}659) = 1037$, $p < 0.001$).

Households without children occur more frequently in the low gas-consuming group and an increased number of children causes the household to occur more often in the higher gas-consuming group (Figure 6). The distribution difference between groups is significant (energy label B $\chi^2(8, N = 185{,}390) = 921$, $p < 0.001$ and energy label E $\chi^2(12, N = 115{,}659) = 491$, $p < 0.001$).

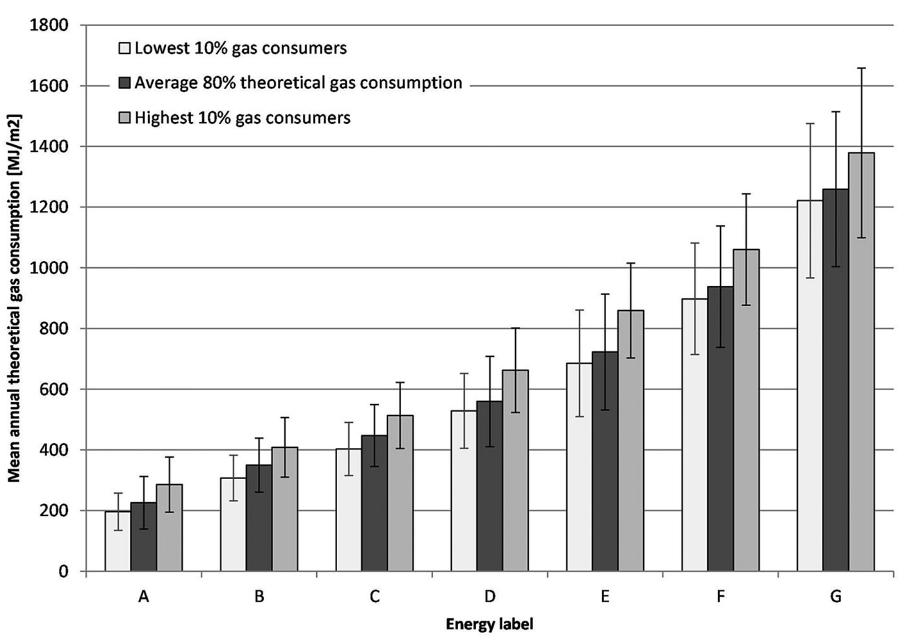

Figure 4. Comparison of highest, average and lowest mean theoretical gas consumption per energy label.

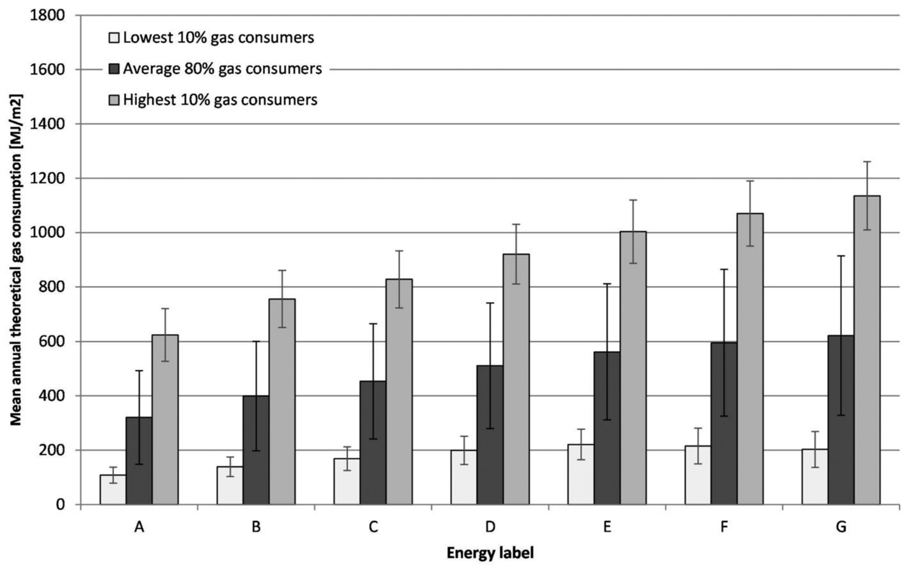

Figure 5. Comparison of highest, average and lowest mean actual gas consumption per energy label.

The chi-square test showed a significant difference of the distribution of household incomes between the high, low and average energy-consuming groups (energy label B $\chi^2(18, N = 185{,}390) = 1332$, $p < 0.001$ and energy label E $\chi^2(18, N = 115{,}659) = 838$, $p < 0.001$) Lower-income households occur more often in the extreme groups (high and low gas consumption) and higher-income households occur more often in the average group. In the previous comparison per occupant group, however, we found that higher incomes are related to lower gas consumption. A possible explanation is the household type was not taken into account in this comparison. Therefore, other household characteristics (*e.g.* number of household members) can therefore influence the results.

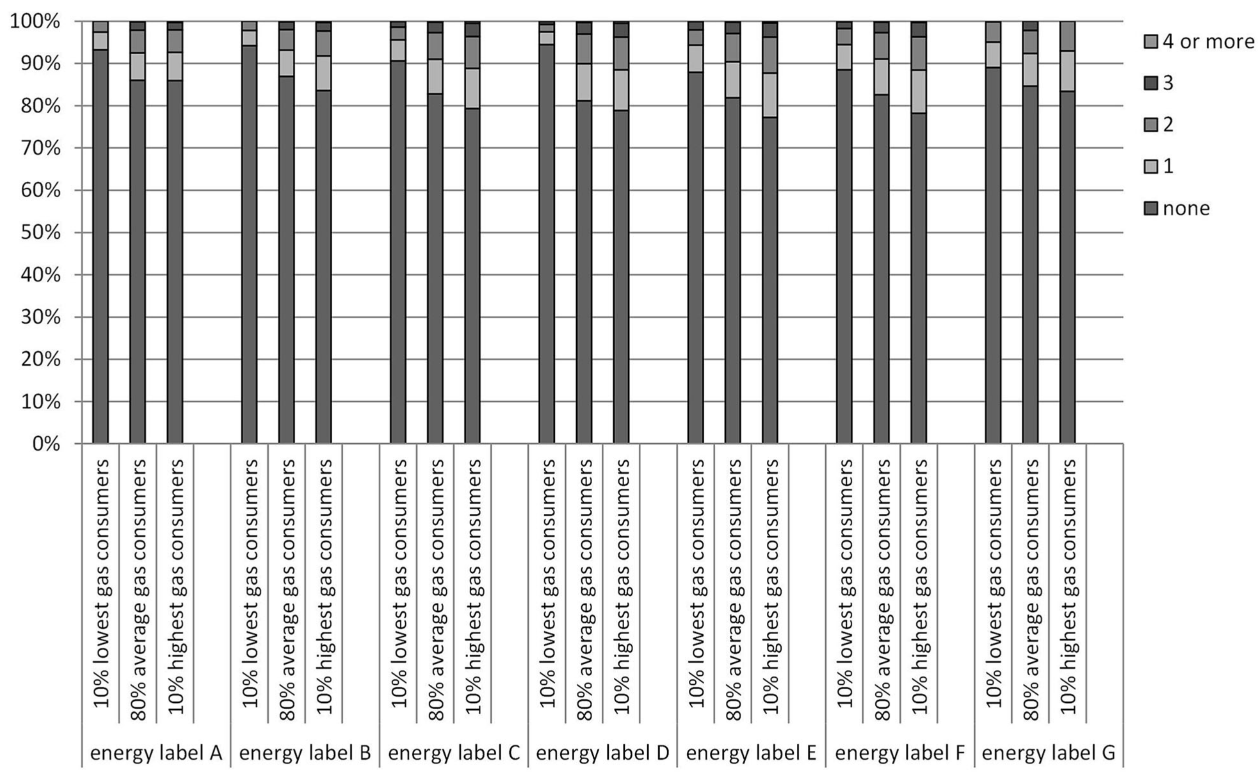

Figure 6. Comparison of the distribution of the number of children in a household for the highest, average and lowest gas-consuming group.

If there is at least one household member who is employed, the chance that this household belongs to the low energy-consuming group is higher than when no member is employed (energy label B $\chi^2(10, N = 185{,}390) = 430$, $p < 0.001$ and energy label E $\chi^2(10, N = 115{,}659) = 256$, $p < 0.001$). A possible explanation for this could be that the house is occupied fewer hours per day if someone works. Also other studies found that occupation time influences residential energy consumption (Guerra Santin et al., 2009; Majcen, Itard, & Visscher, 2015).

Apart from the occupant characteristics, Figure 4 suggests that building characteristics also influence whether a building belongs to the highest or the lowest gas-consuming group. Therefore, the distribution of certain building characteristics in the highest and lowest energy-consuming group are analysed per energy label group. The influence of heating systems could only be studied with some reservations because the condensing boiler is present in more than 90% of A–D dwellings; F and G dwellings have a higher mix of heating systems. Analysing the heating systems shows that the gas fire (an appliance that heats an individual room) occurs more frequently in the low energy-consuming group, despite a low energy-efficiency rating (energy label B $\chi^2(12, N = 185{,}390) = 213$, $p < 0.001$ and energy label E $\chi^2(14, N = 115{,}659) = 712$, $p < 0.001$). A possible explanation is that gas fires cannot heat the same floor area as buildings with a central heating system, a suggestion previously made by Majcen, Itard, and Visscher (2013a).

The distribution of housing type among the highest, lowest and average gas-consuming groups is also significantly different (energy label B $\chi^2(16, N = 185{,}390) = 4702$, $p < 0.001$ and energy label E $\chi^2(16, N = 115{,}659) = 2650$, $p < 0.001$). Single-family houses occur more often in the high-consuming groups, while apartments occur more often in the low gas-consuming groups. This can partly be explained by single-family houses having a larger building envelope than apartments.

As expected, buildings that are well insulated ($R_c > 3.86$) occur more often in the low-consuming group and buildings with poor or no insulation ($R_c < 2.86$) occur more often in the high-consuming group (energy label B $\chi^2(10, N = 185{,}390) = 2761$, energy label E $\chi^2(8, N = 115{,}659) = 164$). The results for energy label G were not conclusive. The average U-value of windows is lower for the low energy-consuming groups (energy label B $\chi^2(10, N = 185{,}390) = 630$ and energy label B $\chi^2(10, N = 115{,}659) = 197$).

Mechanical exhaust ventilation and natural ventilation occur more often in the high energy-consumption group from label A (Figure 7), while a balanced ventilation system occurs more often in the low energy-consumption group (energy label A $\chi^2(6, N = 185{,}390) = 2132$, $p < 0.001$, energy label B $\chi^2(9, N = 192{,}354) = 6779$, $p < 0.001$

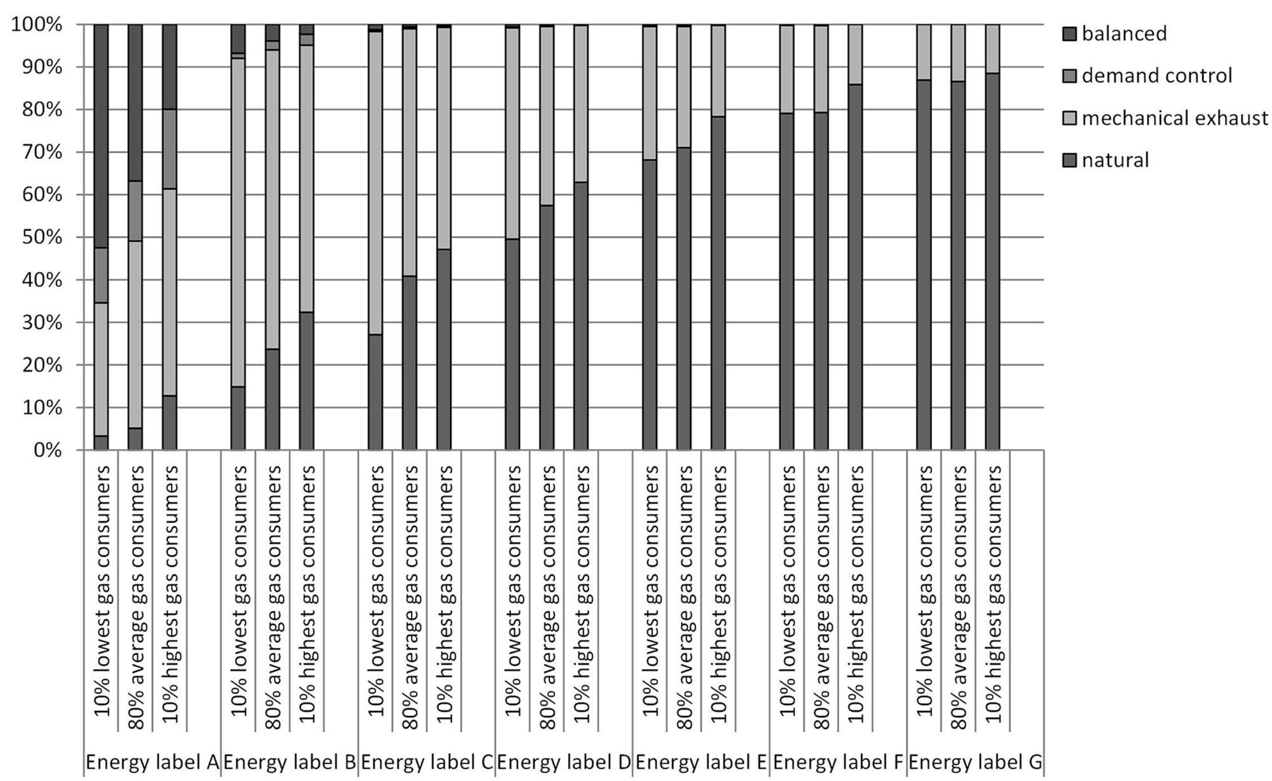

Figure 7. Comparison of the distribution of ventilation systems for the highest, average and lowest gas-consuming group.

and energy label C $\chi^2(6, N = 115{,}659) = 356$, $p < 0.001$). Labels B and C have a negligible number of balanced ventilation systems; therefore, mechanical exhaust ventilation occurs more often in the low energy-consuming group and natural ventilation in the high energy-consuming group. No conclusive results were found for the buildings with an energy label lower than C because they have a lower variety in ventilation systems.

Within the A label group, older buildings occur more often in the high gas-consuming group than newer buildings (Figure 8). It is highly unlikely that buildings built before 1991 had an energy label A from origin, because building regulations did not require it. It is expected, therefore, that the buildings with an older construction year in label-A dwellings are renovated. Our findings suggest that it is difficult for renovated buildings to reach the same energy-performance level as newer buildings. Fuel poverty could be another explanation. However, it is less probable because we found the amount of high-income households in this group is five times higher than the amount of low-income households.

These findings support the general idea that the input for theoretical energy calculations for buildings with a high energy label is more reliable than the input for buildings with a low energy label. More assumptions are likely made about the input for older buildings than for more recent buildings due to the availability of data.

Electricity

Comparisons of the average actual and theoretical electricity consumption per household type divided per energy label show a difference among household types (Figures 9 and 10). Single households consume the least electricity per m^2 of floor area. Families, especially those with children above 12 years of age, consume the most energy. Families that receive state benefits have a lower electricity consumption than people who have a high income from work. For couples, the electricity consumption for people with state benefits is a little higher than for employed people. Couples with a low income consume relatively the least electricity.

Highest and lowest electricity-consuming group compared with the average

The 10% highest and 10% lowest electricity consumer groups were analysed for electricity consumption. Little difference was found for the influence of household type per energy label. As a consequence, energy labels are not taken into account in this analysis. The distribution of household types between the high, low and average energy-consuming groups differs significantly ($\chi^2(34, N = 1{,}100{,}756) = 55{,}441$, $p < 0.001$). Single-occupant households occur more often in the lower-income

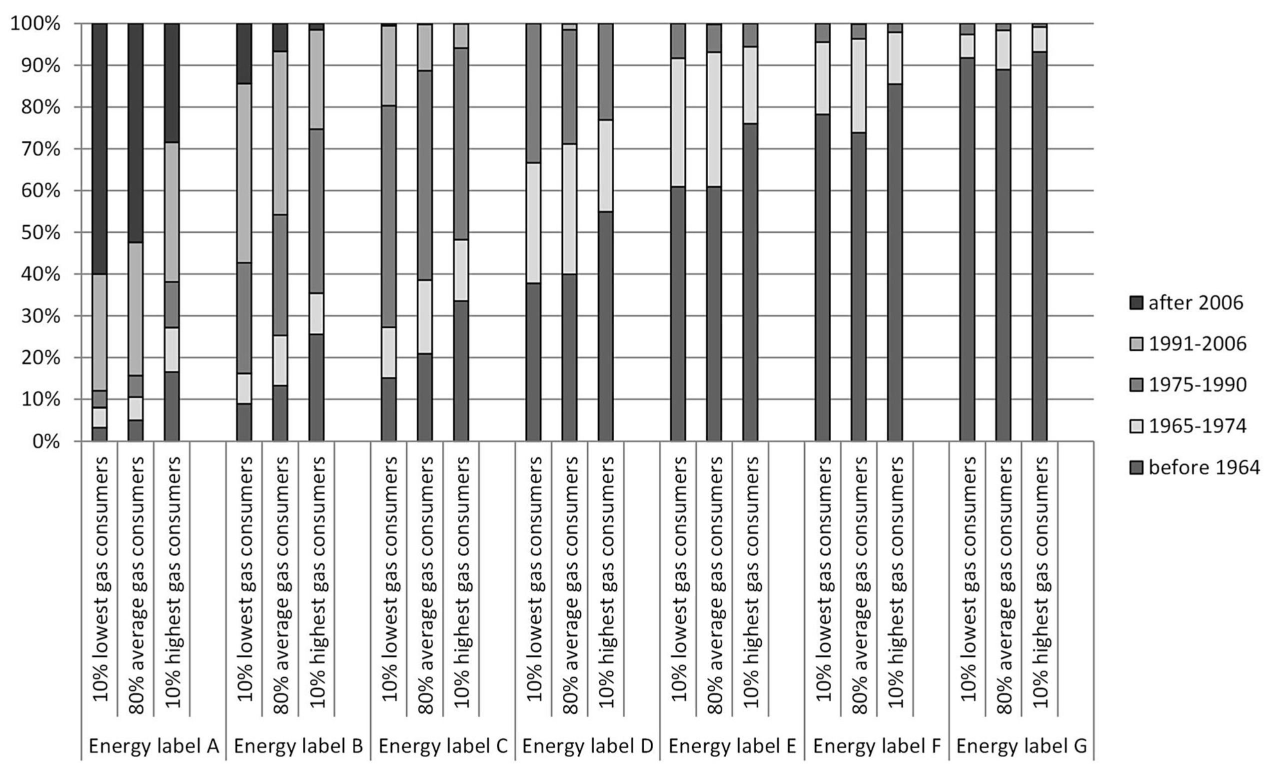

Figure 8. Comparison distribution of construction year for the highest, average and lowest gas-consuming group.

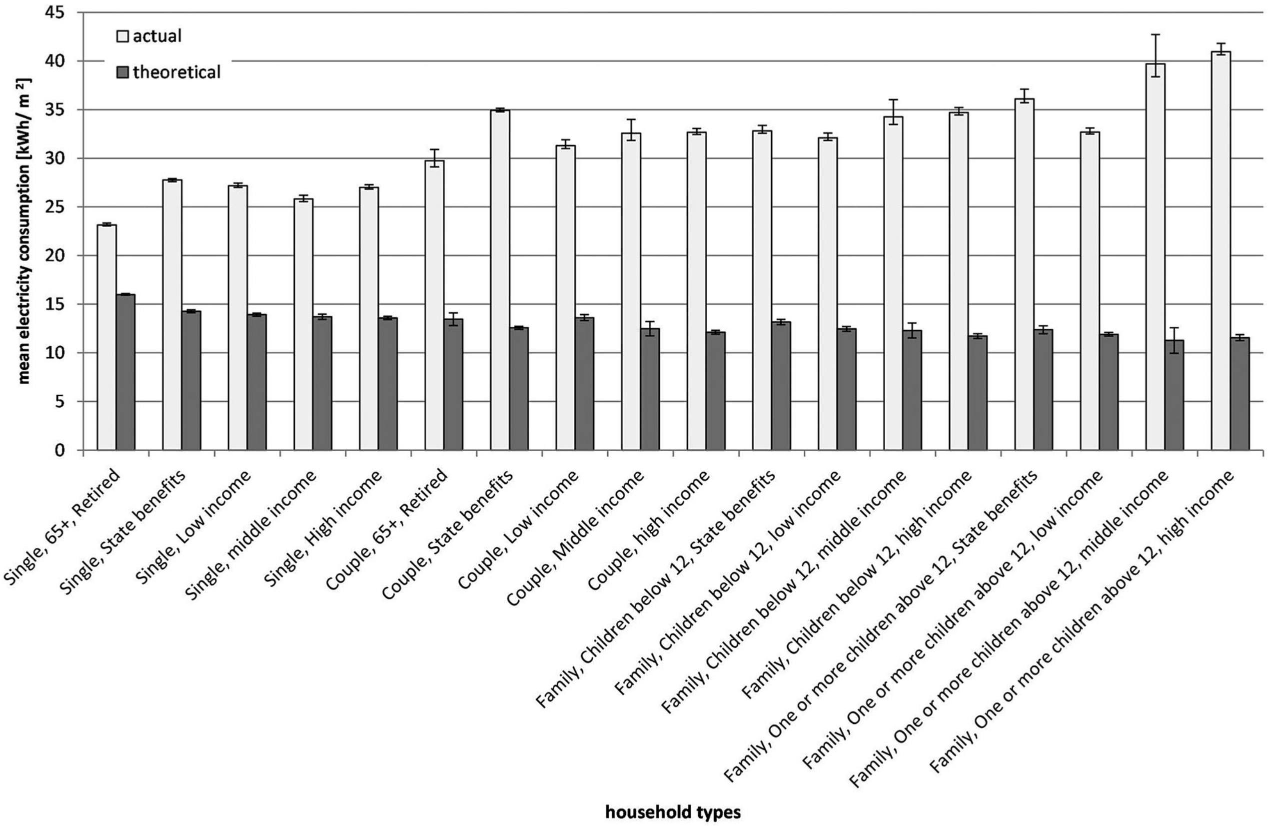

Figure 9. Comparison of mean actual versus theoretical electricity consumption per household group – energy label B.

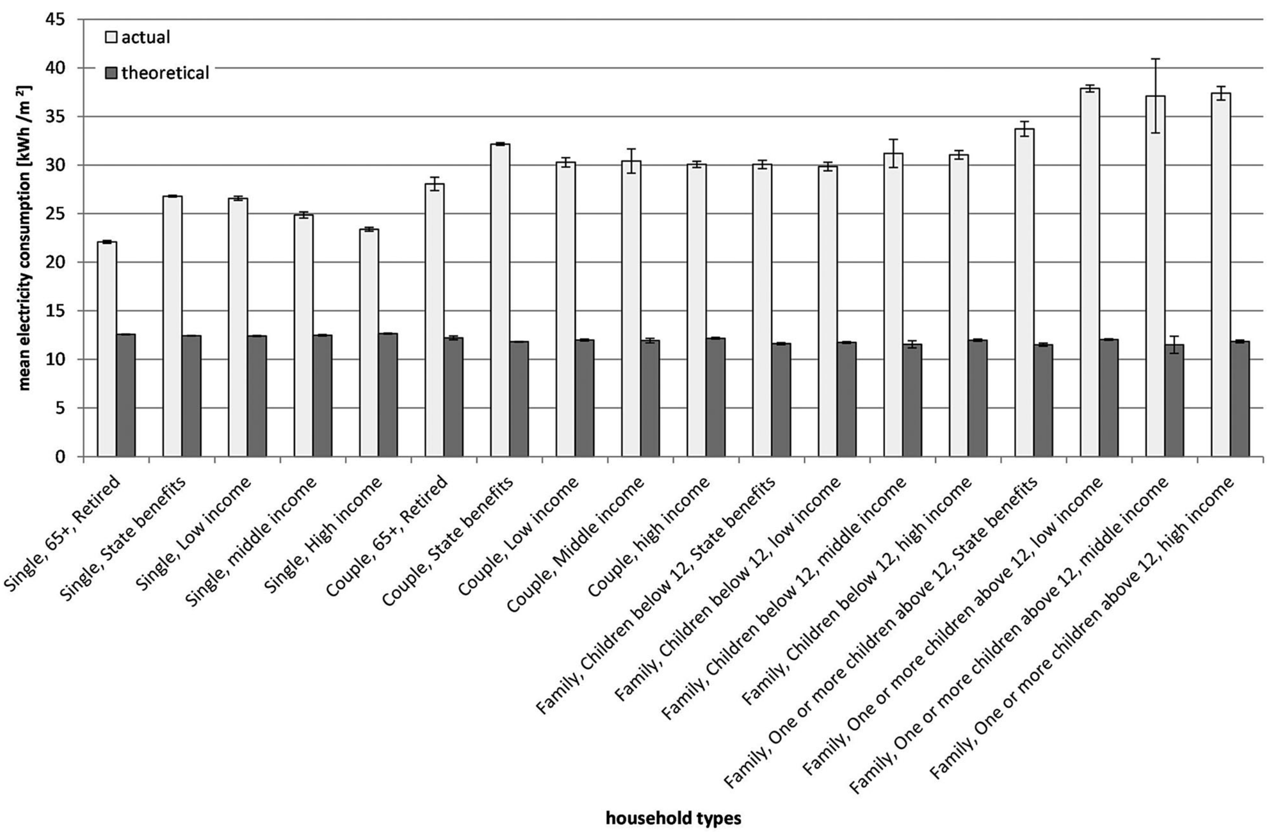

Figure 10. Comparison of mean actual versus theoretical electricity consumption per household group – energy label E.

groups than families. Single retired households occur most frequently in the lowest electricity-consuming group. In the higher electricity-consuming groups, families and couples occur most frequently, especially families with children older than 12 years.

Occupants with a high income occur more frequently in the higher electricity-consuming groups. Occupants with a low income occur more frequently in the low electricity-consuming groups ($\chi^2(18, N = 1{,}100{,}756) = 15{,}126$, $p < 0.001$).

Also, a significant difference was found for the distribution of the number of people per household ($\chi^2(8, N = 1{,}100{,}756) = 42{,}472$, $p < 0.001$). Single households occur more often in the low energy-consuming group and households with two or more members occur more often in the high energy-consuming groups.

Discussion

One of the strengths of this study is the extensive dataset, with 1.4 million dwellings. In contrast to most studies of occupants' influence on residential energy consumption, the present study takes both occupant characteristics and building characteristics into account. This sample only contains buildings owned by social housing organizations in the Netherlands, therefore all dwellings are rental dwellings. Studies in Germany and the Netherlands show that tenants behave differently from housing owners. For example, the rebound effect for tenants is found to be significantly larger than for homeowners (Aydin et al., 2013; Madlener & Hauertmann, 2011).

The main target group of Dutch housing associations are people with a low income and, therefore, the average income of the sample size is lower than that of the entire Dutch population. Additionally, the average number of household members is relatively low in the SHAERE database compared with the national average. This may have influenced our findings.

In the data-filtering process, several possible mistakes were found in both the SHAERE data and CBS datasets. Although the current authors tried to reduce the amount of incorrect data as much as possible, there could still be cases with incorrect data. Remaining sources of errors could be due to mistakes in the technical process, such as meter uncertainties, or translation mistakes from one database to the other, and human mistakes during the registering process of the houses in the SHAERE database, which is performed manually.

Housing organizations ought to update their databases each year, but it is not known how accurately or in how much detail they update the state of their building stock. Also, the accuracy of the actual energy consumption data from the CBS is not known. Additionally, energy companies are only required to report energy consumption every three years. This means that the data provided are not necessarily the actual data from 2014, but more likely to be data from 2012 or 2013. Although this is a serious limitation of the dataset, this is the best available data on such a large scale.

The theoretical energy calculation method is only a simplified version of reality. Therefore, it is not realistic to expect it to bridge the energy-performance gap at the level of individual households. However, it should be able to reduce the gap for average energy consumption. For this reason, this research focused mainly on average energy consumption. Although general conclusions can be drawn for specific socio-economic household types, it should be noted that each household is unique and, therefore, the occupants' behaviour can be different from the average.

The occupant characteristics data used in this research do not account for changes within household demographics during the year, *e.g.* domestic separations, the birth of children and becoming unemployed.

Despite these limitations, this research provides new insights into the influence of occupant characteristics on actual energy consumption and provides several indications for further research.

Conclusions

The findings of this research show that analysing specific household types and building characteristics contributes to a better understanding of the influence of the occupant on actual energy consumption and the energy-performance gap. The analysis of the highest and lowest 10% of consumers can help policy-makers to choose the right target groups for their energy-saving policies and campaigns. Energy-saving advice can also be tailored to specific household types.

The results imply that the building characteristics have a higher impact on the elderly than on younger people. This could be an incentive for policy-makers to prioritize building renovations for the elderly.

Single households with a high income are found to have the lowest average energy consumers. A possible explanation could be that they spend less time at home compared with other household types. Therefore, energy-saving campaigns focused on residential behaviour might be not the most effective strategy. However, families with a low income or those that receive state benefits could benefit from energy-saving campaigns focusing on the reduction of gas consumption. For the reduction of electricity consumption, this research suggests that focusing on families with high incomes would be most effective.

The analysis reveals a disparity between buildings in the same energy group. Buildings constructed more recently consume less energy than older buildings within the same energy-label grouping. The energy performance of a new building with energy label A is not the same as a renovated building with an energy label A. This suggests that although renovated buildings reach similar energy performances on paper, these are not achieved in practice. A consequence is that expectations (and financial and other formulations) will need to be different in order to reflect this reality.

The results of this research could also be beneficial for energy consultants and authorities responsible for providing EPCs. Additionally, the findings can help consultants to explain to their clients that energy consumption is not only dependent on physical factors but also on occupants' behaviour.

Although a reduction of the performance gap was not a goal, the findings can be used to interpret better the results of energy simulation. People who make building simulations can, for example, inform their clients about the differences between actual and theoretical energy consumption and the possible explanations for these differences. This can help clients understand why actual energy consumption is sometimes higher than expected and thus prevent disappointment.

Nevertheless, more research is required. In this research, relationships between certain occupant characteristics and actual energy consumption were found, but the causes of these relationships were not investigated. To explain these relationships, a similar study should be executed on more specific actual behaviour data. A smaller database should be sufficient for this follow-up research.

Note

1. An example of the rebound effect is when a home is retrofitted with insulation or a more efficient boiler. The expected efficiency gain is negated if people increase the hours of space heating and/or raise the internal (winter) temperature. This results in a higher energy use.

Disclosure statement

No potential conflict of interest was reported by the authors.

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