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Over- and underconsumption of residential heating: Analyzing occupant impacts on performance gaps between calculated and actual heating demand

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Abstract. Previous research estimates that building physics and occupant practices equally contribute to the explanation of variations in residential heating consumption. However, the so-called performance gap, where calculated heating demand diverge from actual heating consumption, indicates that the relation between occupant practices and building physics vary across energy efficiency of the building. In this paper, using data from 2019 to 2021, we investigate such interactions 1) by comparing the *calculated* heating demand with *actual* energy consumption for residential space heating and domestic hot water (DHW) across energy performance certificates (A to G), and 2) by investigating variations in over- and underconsumption (deviance from *calculated* to *actual*) across socio-economic characteristics of households. In line with previous studies, we find that households living in energy inefficient houses tend to have lower heating demand than expected. Moreover, we find that lower-income households and households living in rural area has less overconsumption, indicating that they have more frugal heating practices.

1. Introduction

The impact of occupant practices on residential heating demand is well-described in socio-technical studies [1–4], and a recent study estimates that occupants and building physics approximately equally explain variations in heating demand across households [5]. Although this simple division provides important insights, for example to emphasize user practices in developing new building technologies, design, and regulations [6], it risks simplifying the complex interaction between occupant behavior, physical surroundings, and societal norms, which constitute variation in energy consumption [7]. The interaction between occupant energy practices and building physics clearly shows in studies of the so-called performance gap [8,9], referring to estimated discrepancies between calculated heating demand and actual heating demand, which is also referred to as rebound [10–13] and pre-bound effects [14].

Whilst the performance gaps and rebound effects are well-established, the occupant variation of these are understudied. Previous studies have found that several occupant characteristics, such as household income, correlate with higher heating consumption [1–4], but do these correlations also apply (to the same extent) for households living in more or less energy efficient houses?

In this paper, we start by comparing calculated heating demand and actual consumption of energy for space heating and domestic hot water (DHW) in Danish households. Compared to previous studies, the analysis is based on updated and improved data, as it is based on around 100,000 households with metered data for three years (2019-2021). Next, we estimate correlations between household characteristics, such as income and family composition, and the difference between calculated heating demand and actual heating consumption (calculated-actual/calculated). This analysis provides novel and nuanced findings on the interaction between occupant practices, measured by variables like household income, and building physics, for example using energy performance certificate information. Performance gap analysis are in the discussion linked to discussions on energy poverty [15] as well as other social aspects of consuming more or less.

2. Data, variables, and methods

The analysis is based on data from three sources. First, the Danish Property Assessment Agency provided data on the amount of energy used for space-heating and domestic hot water in Danish single-family houses. The data was further restricted to heating supply of gas or district heating. Second, the Danish Energy Agency (DEA) provided information from the Danish Energy Performance Certificate (EPC) database, where the primary information was calculated heating performance, called 'residential building heating requirement' by DEA, and energy performance certificate. Third, information on households and houses were provided by Statistics Denmark. Data from the three data sources was merged, prepared, and analyzed using Statistic Denmark's research servers. Access to these servers is provided to researchers through double control, why it is not possible to provide access to the dataset.

The analysis was based on data on approximately 100,000 households with heating consumption data for one to three years in the period 2019 to 2021. These households had a valid energy performance certificate (energy label) attached to their house, which were calculated in the period 2014 to 2019. The sample was restricted to single-family houses to ensure individual metering of the specific households' occupant practices and households that had not moved during the period of registrations. Further, the highest and lowest one per cent of heating consumption were removed to avoid bias of extreme outliers.

The first part of the analysis compared calculated heating demand and actual consumption, and because it used data for three years, where most of the sampled households appeared multiple times, we estimated standardized means to avoid interdependence within households. Thus, to take account of serially correlated errors [16], we applied 'empty' panel regression models only with the energy label as independent variable and the calculated or actual heating demand as dependent variables. We used the Stata function *xtreg* with the specification for the between estimator (*be*), which can be interpreted like an ordinary least square estimator where estimates are averaged over time within households [17]. The second part of the analysis used the same method but included a range of household characteristics as independent variables and building characteristics as control variables.

3. Results

The first part of the result section addresses the relation between calculated and actual heating demand across energy labels. The second part of the analysis investigates the impact of socioeconomic characteristics of occupants on over- and underconsumption related to the performance gaps.

3.1 Calculated heating demand compared to heating consumption across energy labels

Figure 1 presents means of calculated heating demand and actual heating consumption across energy labels. For the energy labels E, F, and G, the mean for calculated heating demand is higher than the mean for actual heating consumption, especially in the G-labelled houses. For the energy labels A to D, the mean for actual heating consumption is higher than the mean for calculated demand, and especially for the labels A2015 and A2020, the actual heating consumption appears considerable higher than the calculated heating demand. In the following, we will term it *overconsumption* when *actual* is higher than *calculated* and *underconsumption* when *actual* is lower than *calculated*.

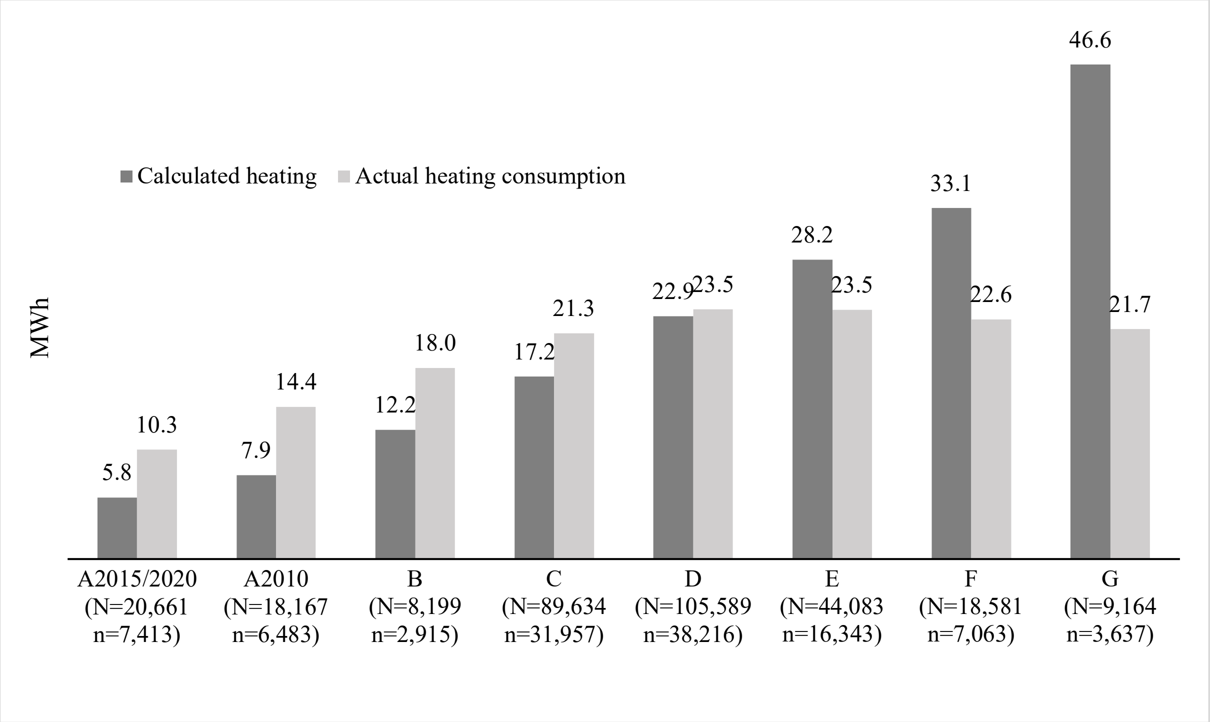


Figure 1. Comparison of means of calculated heating demand and actual heating consumption in houses in MWh for 2019 to 2021 across labels. N=314,078 observations. n=114,022 households.

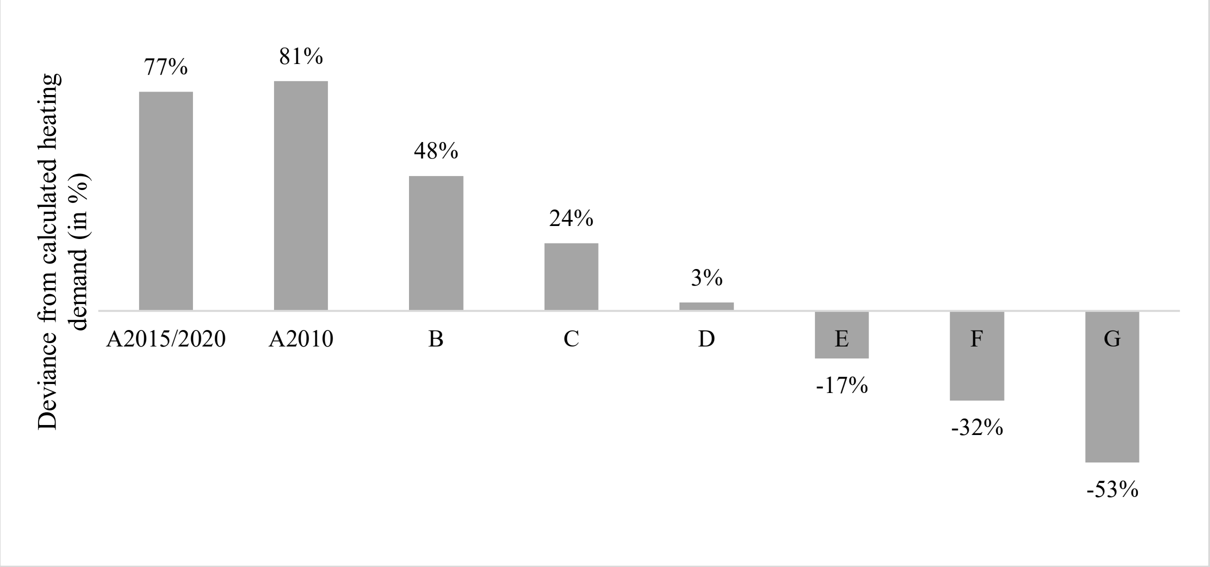


Figure 2. Percentage deviance from calculated heating demand (calculated-actual/calculated) across energy labels based on numbers from Figure 1.

To better understand the variation across energy labels, Figure 2 shows the percentage deviance from the calculated heating demand across labels based on numbers from Figure 1. Figure 2 shows a similar pattern as in Figure 1, but it further illustrates the high relative overconsumption in A-labelled houses.

3.2 Household variation of performance gaps across energy labels

In this second part of the analysis, we focus on the over- and underconsumption (i.e., the deviance in MWh between calculated heating demand and actual heating consumption) in energy efficient (ABC) and energy inefficient (EFG) houses and analyze correlations with household characteristics indicating variations in household energy practices.

Table 1. Panel regression models on data from 2019 to 2021 with deviance in MWh from calculated heating demand as outcome variable. Predicted over/underconsumption reflects marginal effects of regression coefficients. Standard errors in paranthesis (*** p<0.01, ** p<0.05, * p<0.1).

y = deviance from calculated heating demand to actual heating consumption (over- and underconsumption)	***1) Labels: A2020, A2015, B, C)***		***2) Labels: E, F, G***	
	Regression coefficients	*Predicted overconsumption*	*Regression coefficients*	*Predicted underconsumption*
Family composition				
Couple	Ref.	5.0	Ref.	-8.0
Single	-0.470*** (0.142)	4.6	-0.860*** (0.344)	-8.9
Youngest child in the household				
No child	Ref.	4.0	Ref.	-9.6
Pre-school child (0-6y)	1.232 *** (0.140)	5.2	2.071*** (0.387)	-7.6
Young child (7-12y)	0.633*** (0.164)	4.6	1.045** (0.473)	-8.6
Teenager (13-19y)	0.549*** (0.208)	4.5	1.388** (0.562)	-8.3
Oldest member in the household				
18 to 40 years	Ref.	4.5	Ref.	-8.7
41 to 60 years	0.057 (0.124)	4.6	0.123 (0.342)	-8.6
61 years or older	0.683*** (0.179)	5.2	-0.132 (0.488)	-8.8
Area				
Urban area	Ref.	6.0	Ref.	-6.3
Urban area outside largest cities	-3.210*** (0.119)	2.8	-3.236*** (0.344)	-9.5
Rural areas closer to larger cities	-2.757*** (0.122)	3.3	-6.145*** (0.409)	-12.4
Rural areas, incl. smaller islands	-4.161*** (0.150)	1.9	-6.953*** (0.409)	-13.2
Household disposable income				
Less than 300,000 DKK	Ref.	2.5	Ref.	-11.4
300,000 to 399,999 DKK	0.000 (0.261)	2.5	1.772*** (0.560)	-9.6
400,000 to 499,999 DKK	-0.081 (0.247)	2.4	1.675*** (0.566)	-9.7
500,000 to 599,999 DKK	0.523** (0.246)	3.0	2.461*** (0.599)	-8.9
600,000 to 699,999 DKK	1.858*** (0.254)	4.3	3.584*** (0.658)	-7.8
700,000 to 799,999 DKK	2.706*** (0.267)	5.2	4.263*** (0.747)	-7.1
800,000 DKK or higher	5.384*** (0.245)	7.8	6.145*** (0.613)	-5.3
Unemployed in the household				
No	Ref.	4.5	Ref.	-8.4
Yes	0.370*** (0.120)	4.9	-0.709** (0.327)	-9.1
Highest attained education				
High school or lower	Ref.	4.7	Ref.	-8.3
Vocational	0.125 (0.173)	4.8	-0.526 (0.416)	-8.8
Uni college	-0.324* (0.175)	4.4	-0.786* (0.444)	-9.0
University	0.042 (0.186)	4.7	-0.011 (0.496)	-8.3
Building control variables	*Included but not reported*		*Included but not reported*	
Number of observations	130,687		66,234	
Number of households	46,636		24,577	
Avg. Obs. Per household	2.8		2.7	

Table 1 presents two models with deviance in MWh from calculated heating demand to actual heating consumption as outcome variable, where Model 1 includes energy efficient labels (A2020, A2015, B, C) and Model 2 includes energy inefficient labels (E, F, G). Both models included control variables on heating supply, building year, heating area, major renovation year, basement and attic floor. To ease the interpretation, we show the marginal effects based on the regression estimates, and present these as predicted deviance from the calculated heating demand in negative or positive direction, interpreted as respectively under- and overconsumption. In the energy efficient houses (ABC), it seems that single households and households without children tend to have less overconsumption, and for the energy inefficient houses (EFG), single households and households without children tend to have more underconsumption. In energy efficient houses (ABC), the older households (60 years or older) tend to have more overconsumption than younger households and unemployed households also tend to have more overconsumption. This might reflect being more at home, which could especially influence DHW use. In energy inefficient houses (EFG), the unemployed households tend to have more underconsumption compared to households without any unemployed members. There does not seem to be much difference related to educational groups. However, household disposable income and location seem to reflect substantial differences in deviance from calculated heating demand. Figure 3 and 4 illustrates these differences by showing the trends from urban towards rural areas and for lower income towards higher income households related to over- or underconsumption.

Figure 3 shows that households living in urban areas tend to have higher consumption compared to rural households no matter if they live in efficient or inefficient houses. This means that in energy efficient houses (ABC), there seems to be higher overconsumption in urban areas as well as less underconsumption. Figure 4 shows that higher-income households in efficient homes (ABC) tend to have much higher overconsumption, whereas they also tend to have less underconsumption in energy inefficient houses (EFG). However, it is equally important to notice that in any case, for lower and higher income as well as for rural and urban areas, the deviance in all cases show underconsumption in inefficient houses and overconsumption in efficient houses.

Figure 3. Comparison of over- and underconsumption in MWh for urban to urban areas.

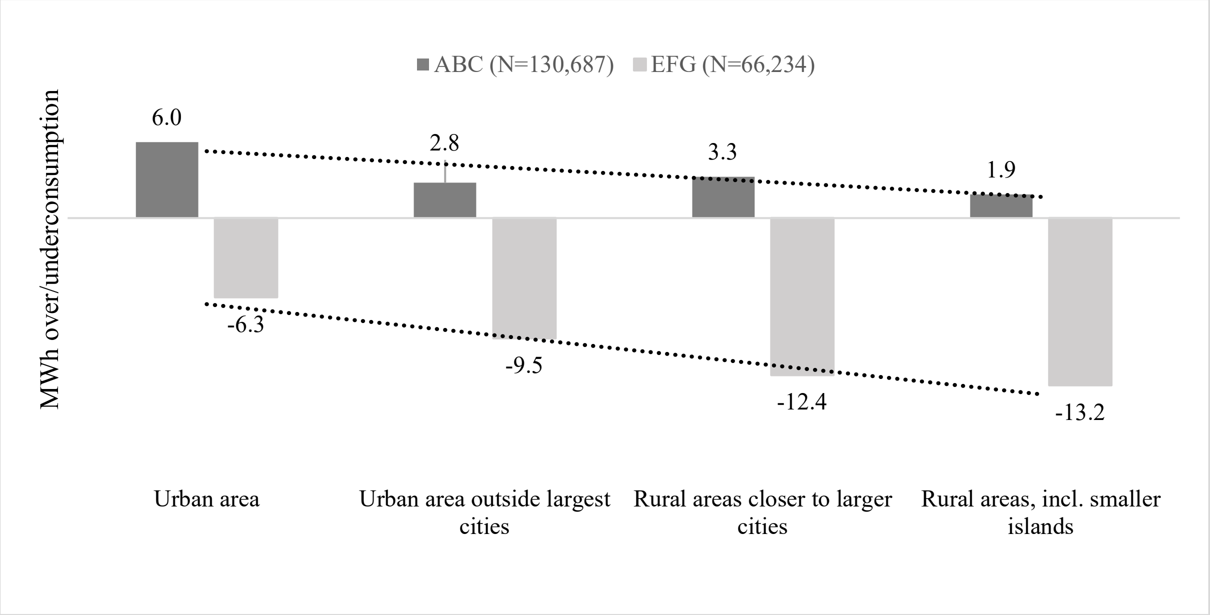
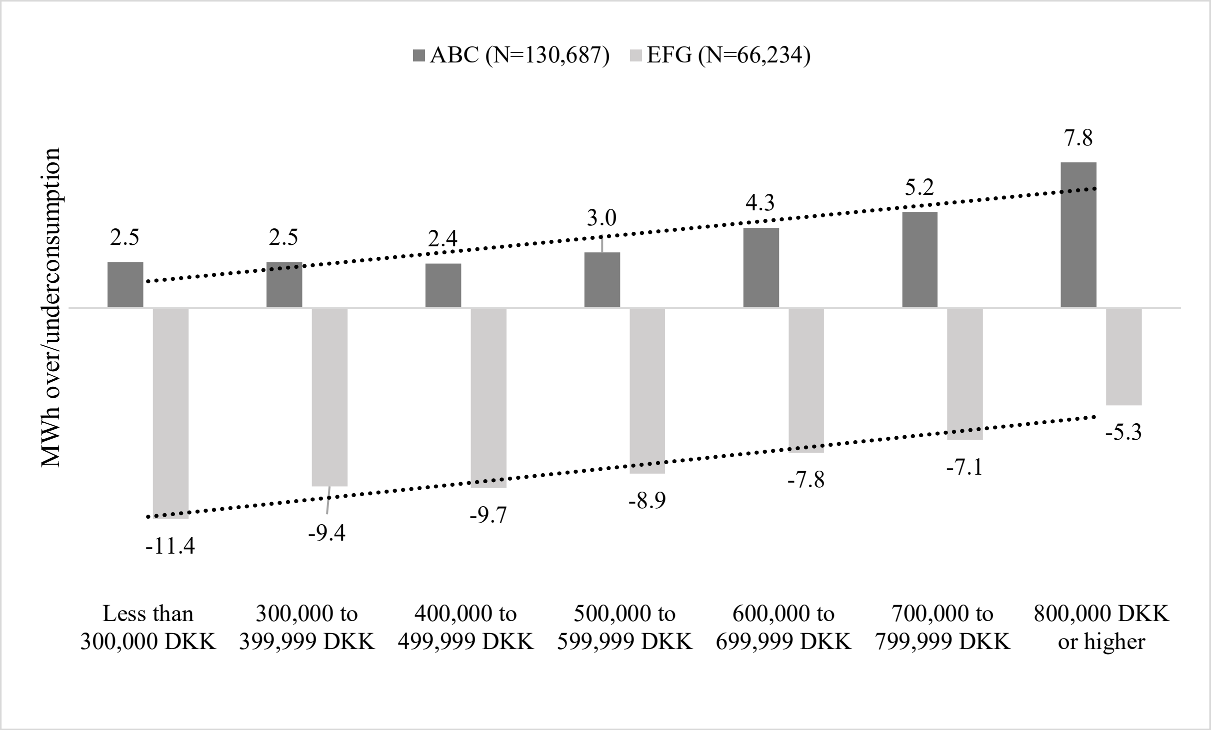


Figure 4. Comparison of over- and underconsumption in MWh from lower to higher income households.



4. Discussion and conclusion

The results in this paper are in line with previous results finding discrepancies between calculated and actual energy consumption [9,18]. The analysis shows larger numeric discrepancies in the less efficient houses compared to more efficient houses, which is slightly different from a previous Danish study [9], but more in line with a previous Dutch study [18]. However, when discrepancies in the present study are seen as percentages of over- and underconsumption, it seems that the largest (relative) discrepancies are found in energy efficient houses.

In this paper, we have been interested into what extend underconsumption in inefficient houses should be considered as a social problem, indicating that lower-income households cannot afford to have a decent and healthy indoor climate, or to what extend this should be understood as people choosing to have lower temperatures even if they could afford to do otherwise. The relative overconsumption in energy efficient houses could assume that overconsumption in newbuilt houses was mainly related to an effect of economic capacity of households understood as a form of luxury for those who can afford it, whereas underconsumption in inefficient homes mainly could be seen as households who cannot afford to heat their poor homes to an adequate standard. However, in this analysis, where consumption data is combined with information on socioeconomics, dismantle this straightforward assumption, and shows how the efficiency of the house has an explanation of its own, and in many cases that households living in older homes with underconsumption, and thus presumably lower temperatures, probably is not a matter of deprivation.

Still, we do find that especially lower-income households and households living in rural area tend to have less resource-intensive energy practices. In other words, these households seem to have lower overconsumption in more energy efficient houses (ABC) as well as higher underconsumption in more energy inefficient houses (EFG). This suggests that lower-income and rural households tend to perform more frugal heating practices. According to income differences, this is in line with studies showing that higher income correlates with higher heating consumption [1,2]. A potential explanation for the results could be that lower income and rural area here reflect adopted or inherited energy practices, for example where less-intensive energy practices are inherited by parents [19] or acquired over a life course influenced by experience from childhood home and form of heating supply [20].

This paper underpins the importance of income and location as crucial predictors for variation in energy practices. Income variables reflects other household practices than (just) the ones related to economic decision-making, and location to some degree reflect different cultural aspect. Thus, it seems that household income and location are indicators of several (unknown) factors that drives heating consumption upwards. This discussion could benefit from further analysis of such differences in energy practices between different types of households.

This analysis is a reminder to recognize that there is (complex) occupant variation, and that this cannot be ‘solved’ or ‘fixed’. Rather, we should try to understand energy practices in various kind of households and houses, and focus on intervening in the most critical cases, for example when ‘underconsumption’ might lead to health issues, when poor households in leaky houses cannot afford any renovations, or when ‘overconsumption’ becomes normalized.

This paper has focused on explanations for the performance gap related to occupant practices. However, several other potential explanations are important to consider. First, the procedure of assigning energy labels. For example, the practice of the energy consultant, who inspects the house, might vary across contexts. Second, the quality of the technical calculation of the energy performance and thermal loss of the building envelope might vary across different types of buildings [21], for example when highly insulated envelopes are not as efficient in practice as in technical calculations [22]. Fourth, this analysis was based on data only on single-family houses, which are predominantly owner-occupied, but it would be relevant to investigate whether similar patterns of performance gaps exist in other forms of housing, for example in apartment buildings.

Moreover, the variations over time in heating demand might be an influential factor for understanding performance gaps. The years 2019 to 2021, which data for this analysis is based on, was characterized by several lockdowns following Covid-19 pandemic, and the average temperature was slightly lower with 2,887 degree days on average compared to 2,955 degree days for a 10-year period (2012 to 2021) (www.dmi.dk). Finally, the difference between practices related to DHW and space heating might influence the performance gap across energy labels, for example as DHW use seems to constitute larger shares in newer buildings compared to older buildings [23] and as DHW use patterns seem to differ across household types [24].

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