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The price elasticity of residential district heating demand: New evidence from a dynamic panel approach

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ABSTRACT

We estimate the price elasticity of residential district heating demand in Denmark using the Blundell–Bond two-step generalized method of moments (GMM) estimator and a sample of 152,913 observations covering the period of 2015 to 2019. Moreover, we analyze the heterogeneity in the response to district heating price increases among various household groups and investigate the distributional consequences of policies that increase the price of district heating. To this end, we measure the effects of a price increase on district heating bills, consumption, and emissions. We find a short-run price elasticity of −0.530 and a long-run price elasticity of −0.638. Higher consumption levels are associated with dwelling age, dwelling size, homeownership, income, number of household members, and whether households receive heating allowances. We find significant evidence that price elasticity varies across household groups: Low-income households, intensive consumers, single households, and households in older and smaller dwellings are more responsive to price changes than their respective counterparts. We also demonstrate that a 10% increase in the price of district heating would increase expenditures in high-income and low-income households by 7.18% and 1.16% (ceteris paribus), respectively. Our findings therefore have important implications for the evaluation of price policies aimed at reducing emissions and the distributional impacts of such measures.

1. Introduction

Space and water heating account for roughly 80% of residential energy consumption in the EU (Eurostat, 2019), resulting in significant greenhouse gas (GHG) emissions. Consequently, reducing residential energy demand is key to achieving the ambitious climate targets of the EU – a reduction of overall GHG emissions by 55% until 2030 compared to 1990 (European Commission, 2021a).

Currently, in the EU there is an intense debate about policies that implicitly or explicitly price carbon to better match climate ambitions. As part of the European Green Deal, the European Commission has recently proposed to include the building and road transport sectors in its emissions trading system (European Commission, 2021a). At the same time, member countries ratchet up their national carbon prices. For instance, in Denmark, the government is considering to raise the carbon tax from DKK 177 (approx. EUR 24) per ton of CO_2 to DKK 1500 (approx. EUR 200) (Danish Ministry of Climate, Energy and Utilities, 2020), leading to an increase in the marginal costs of domestic fossil fuels used to generate energy (at rates that depend on a fuel's carbon content), which will—at least partially—be passed on to customers. However, these political initiatives build on the assumption that price increases lead to lower household consumption levels, and, especially in the context of Denmark and other Nordic countries, there is not enough evidence to support this assumption. Quantifying the consumer response, which is reflected in the magnitude of price elasticity of energy demand, is critical for determining the effectiveness of climate policies in reducing emissions associated with energy demand as well as distributional effects.

Among the various methods employed to distribute heat to end users, district heating is considered one of the most efficient and environmentally friendly and can thus play an important role in the mitigation of climate change (Connolly et al., 2014; Danish Energy Agency, 2017; Mazhar et al., 2018). Denmark provides an interesting case for the analysis of the price elasticity of residential heating demand as it has one of the world's highest implementation rates of district heating (Werner, 2017), supplying almost two-thirds of all households (Danish Energy Agency, 2020a). Despite being primarily produced by renewable energy, district heating still significantly relies on fossil fuels. This mix of energy

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sources is incompatible with Denmark's goal of becoming fossil-fuel free for its heating and total energy supply by 2035 and 2050, respectively (The Danish Climate Policy Plan, 2013; IRENA, 2017; Danish Ministry of Climate, Energy and Utilities, 2020; Kerr and Winskel, 2021). Moreover, the Russia-Ukraine conflict and sanctions against Russia are expected to trigger further increases in district heating prices, as Denmark is a large net importer of natural gas and biomass from Russia (Ea Energy Analyses, 2019; Danish Energy Agency, 2020b; Johansen and Werner, 2022), which have been heavily used for the district heating production in the last years (Danish Energy Agency, 2020a).

Against this backdrop, this paper investigates to which extent consumers respond to higher prices for district heating in the Danish residential sector. In this analysis, we exploit unique data possibilities in Denmark by using a large-scale longitudinal household-level data set of 152,913 observations covering the period of 2015–2019 and employing dynamic panel data models in the form of the Blundell–Bond two-step system generalized method of moments (GMM). In addition, we exploit the width of our data set and determine the heterogeneity in elasticity for different socioeconomic groups and discuss the distributional consequences of policies that increase the price of district heating.

There is a large literature that investigates how price changes, socioeconomic and dwelling characteristics, and weather conditions explain electricity demand (see Labandeira et al., 2017 for a meta-analysis). However, there is a much smaller literature analyzes the determinants of heating demand and most of them focus on natural gas (e.g., Alberini et al., 2011; Salari and Javid, 2016; Filippini and Kumar, 2021). Only few studies have specifically estimated the price elasticity of residential district heating demand. For instance, Hellmer (2013) uses cross-sectional data derived from 187 district heating plants in 2007 in Sweden. Moreover, Lim et al. (2021) investigates the household response of four hypothetical increases in district heating price, and Hansen (2018) investigates cross-sectional variation in response to district heating price levels in Denmark. Such studies have little or no control over socioeconomic and dwelling characteristics influencing district heating demand. Hence, building upon previous empirical research, this study contributes to the understanding of the reaction to changes in the price for district heating by exploiting a particularly rich longitudinal household-level (instead of aggregate) data set. This allows us to use dynamic panel models that capture the sluggishness of heating demand. Moreover, the width of the data set allows us to analyze heterogeneous effects to understand differences in the response to district heating prices across households.

This paper presents three main findings. First, we detect a short-run price elasticity of -0.530 and a long-run price elasticity of -0.638. To the best of our knowledge, this is the first estimate of price elasticity of residential district heating demand using a dynamic panel approach. Socioeconomic and dwelling characteristics as well as indicators of weather and location significantly contribute to explaining district heating demand. In particular, we find that higher consumption levels are driven by dwelling age, dwelling size, homeownership, income, number of household members, and whether households receive heating allowances.

Second, we establish that price elasticities significantly vary across household groups as a function of income and consumption levels, household size, dwelling age, and dwelling size. Specifically, we find that low-income households exhibit a higher price responsiveness than high-income households. Moreover, intensive consumers, single households, and households in older and smaller dwellings are more responsive to price changes than their respective counterparts.

Third, we quantify the impacts of a price increase on consumption, emissions, and district heating bills. We show that a 10% increase in prices would reduce consumption by 2194 terajoules (TJ) (thus avoiding 47,340 tons of related CO_2 emissions) and increase the district heating expenditures of low-income households by 1.16% (ceteris paribus). This kind of analysis allows us to outline implications for energy demand and emissions savings and to discuss the distributional consequences of an increase in the price of district heating.

The remainder of this paper is organized as follows: Section 2 briefly describes the Danish district heating sector. Section 3 reviews the literature on residential energy demand and price elasticity. Sections 4 and 5 describe the data and methods used for the Danish case study, respectively. Section 6 first discusses the empirical results obtained through the dynamic panel approach (Blundell–Bond two-step system GMM) for the entire data set, and then draws conclusions on specific household groups. Section 7 summarizes and concludes the paper.

2. The Danish district heating sector

Denmark is considered a global frontrunner in district heating supply (Sovacool and Martiskainen, 2020). The Danish Energy Agency (2017) estimates that in recent years, large-scale district heating deployments have significantly reduced energy dependence, greenhouse gas emissions, and waste-management problems in Denmark. In 2019, district heating alone accounted for 79% of total residential energy consumption, representing 11% of total Danish energy consumption and 35.8% of total CO_2 emissions in the power-generation sector (Danish Energy Agency, 2020a). Biomass represented the largest share of district heating production (57.6%), followed by natural gas (12.8%), non-renewable waste (10%), coal (9.2%), renewables other than biomass (such as solar, biogas, biomethane, heat pumps, and geothermal) (5%), surplus heat (3.3%), electricity (1.2%), and oil (0.8%) (Danish Energy Agency, 2020a).

The Danish district heating production and network companies are local, vertically integrated, natural monopolies. The main ownership model involves cooperatives owned by consumers (about 340) and municipalities (about 50), while the rest of the companies are privately owned (The Danish District Heating Association, 2016; Donnellan et al., 2018). There are six large central district heating areas located around the larger cities, in addition to about 400 small and medium decentralized district heating areas spread throughout the country (Danish Energy Agency, 2017).

Both production and network companies are regulated as non-profits to protect consumers against possible abuses of monopoly. The "non-profit principle" (or "principle of necessary costs"), combined with favorable financial-support schemes, has kept customer prices relatively low and free of commercial interests (Danish Energy Agency, 2017). Although the real effectiveness of the existing regulation in promoting cost optimization and lowering prices has recently been questioned (Gorrono-Albizu and de Godoy, 2021), the price of district heating mainly results from historical planning and infrastructure rather than regulatory mechanisms (Chittum and Østergaard, 2014). However, there are several other factors that influence the price of district heating, which vary substantially among consumers. This includes, for example, the utilities' operational efficiency, grid size, production costs, and especially the type of fuel (Hansen and Gudmundsson, 2018).

District heating companies are obliged to provide a report to the Utility Regulator (Forsyningstilsynet) outlining a number of indicators regarding the necessary costs that determine the tariff. The Utility Regulator can perform ex-post control of district heating prices upon a complaint from customers who are unsatisfied with the price set by their utility provider (Boscan and Söderberg, 2021; Energy Community, 2021).

3. Literature review

Several studies on residential energy demand have investigated the degree to which price changes, socioeconomic and dwelling characteristics, and weather conditions explain electricity demand (Blázquez et al., 2013; Fell et al., 2014; Boogen et al., 2017; Labandeira et al., 2017; Frondel et al., 2019), while only few studies have investigated the determinants of space heating (and hot water) demand (Hansen, 2016). As natural gas is one of the most common primary fuels used for heating

(Bertelsen and Vad Mathiesen, 2020; IEA, 2020), much of the literature has focused on estimating the price elasticity and determinants of gas demand, sometimes in combination with electricity demand. For the U. S., for example, Alberini et al. (2011) and Salari and Javid (2016) investigate residential gas and electricity demand using static and dynamic models for samples of about 98,772 and 432 observations, respectively. Alberini et al. (2011) employ household-level data covering the period of 1997–2007 and show that the short-run price elasticity for gas ranges from −0.693 to −0.566 and that the long-run price elasticity amounts to −0.647. Salari and Javid (2016) use household-level data covering the period of 2005–2013 and report a similar short-run price elasticity (−0.755, −0.557) but a higher long-run price elasticity (−1.094). From a methodological perspective, as with other empirical studies on energy demand (Blázquez et al., 2013; Fell et al., 2014; Frondel et al., 2019), both studies concluded that the two-step system GMM estimator proposed by Blundell and Bond (1998) provides more reliable price elasticity estimates than other models (for further discussion on this point, see Section 5).

For Switzerland, Filippini and Kumar (2021) use household-level panel survey data from 2010 to 2014 and an instrumental variable (IV) strategy to examine the determinants of gas demand for 958 households. In-line with Alberini et al. (2011) and Salari and Javid (2016), they use the average (rather than marginal) price and detect an inelastic gas demand in the short-run with a value of −0.73. Moreover, they demonstrate that gas demand increases with household size, thermal comfort, dwelling size and age, ownership, and heating degree days (HDD).

Other micro-econometric studies carried out in the Netherlands (Brounen et al., 2012), Denmark (Hansen, 2016), the Netherlands and Denmark (van den Brom et al., 2019), Germany (Braun, 2010), Greece (Sardianou, 2008), Ireland (Harold et al., 2015), and the EU (Karatasou et al., 2018) lack information about price variations and mainly focus on the socioeconomic and dwelling attributes that have the strongest influence on space heating demand. All these studies indicate that dwelling characteristics have larger impacts on space heating consumption than socioeconomic characteristics.

Few studies have specifically estimated the price elasticity of residential district heating demand. For Sweden, Hellmer (2013) use cross-sectional data derived from 187 district heating plants in 2007 to compare the price response of households living in single-family dwellings with those living in multi-family dwellings. He shows that households living in single-family dwellings are twice as responsive to price increases (−0.48) as households living in multi-family dwellings (−0.25). Using data from Korea, Park et al. (2019) scrutinize the benefits to consumers of switching from individual heating to district heating, while Lim et al. (2021) investigate the household response of four hypothetical increases in district heating price. They find a price elasticity ranging from −0.433 to −0.478 (Park et al., 2019; Lim et al., 2021). Yet, these studies have little or no control over socioeconomic and dwelling characteristics influencing district heating demand.

At the EU level, Ewald et al. (2021) use cross-country data for the period 1990–2018 and the two-step system GMM, Generalized Least Squared, and Least Square Dummy Variable estimators to provide EU-wide (long and short-run) price and income elasticities for both total energy demand and space heating energy demand, including district heating. Based on the authors' preferred estimator (two-step system GMM), the results indicate a short-run price elasticity of space heating demand of −0.067 and a long-run elasticity of −0.825. Compared to the total energy demand, the authors observe a larger price elasticity in the long run for space heating demand.[1]

In Denmark, one of the few attempts to model residential space heating demand and to investigate price elasticity was made by Leth-Petersen and Togeby (2001). They use a panel data set of about 36,403 observations covering the period of 1984–1995, containing information about technical characteristics and the energy consumption of Danish apartment blocks using district heating and oil. These authors emphasize the importance of building regulations for reducing energy consumption in new buildings and found a very small price elasticity for buildings using district heating (−0.02). According to the authors, the lack of individual metering in many of the apartment blocks analyzed might explain the low-price elasticity, which indicates a limited effect of fuel taxes on energy consumption. More recently, Hansen (2018) investigates district heating price elasticities of a large sample of Danish households living in single-family houses using static models. The study reports estimated short-run price elasticities for the period spanning from 2010 to 2014 that range from −0.199 to −0.441. Regarding heterogeneous effects, Hansen (2018) shows that the price response is stronger for high-income households and households living in newer houses.

Building on previous empirical research, this study (i) exploits a rich longitudinal household-level data set covering the period of 2015–2019 to further investigate the price elasticity of residential district heating demand in Denmark using dynamic panel modeling, (ii) analyzes heterogeneous effects to understand differences in the response to district heating prices across households, and (iii) provides recommendations for strengthening the design of future policy interventions aimed at reducing emissions while ensuring distributional fairness.

4. Data

For our analysis of the price elasticity of residential demand for district heating, we draw on annual price and consumption data from 289 utilities (out of about 400[2]) spanning the period of 2015–2019, which was provided by the Building and Housing Register (BBR). The gross data set comprises roughly 2,000,000 observations (Appendix, Table A1). To construct our relevant sample, we first restricted the data to single-family detached houses because these are individually metered, which is not the case for other dwelling types. Next, we eliminated observations for which we did not observe all the information relevant to the empirical analysis—namely, the district heating price and socioeconomic, dwelling, and geographical characteristics. The final unbalanced panel data set resulting from these pre-processing steps consists of 152,913 observations (Appendix, Table A1).

Yearly district heating-consumption data relates to the use of both space heating and domestic hot water over the period of 2015–2019. The district heating bill paid by households living in a single-family detached house is composed of a variable price component per kilowatt-hour (kWh) of consumption and a fixed price that includes capacity payment and an annual subscription fee (Danish Energy Agency, 2017). Fig. 1 shows the average yearly district heating price and consumption over the period of 2015–2019, indicating a trend of rising prices and declining consumption.

In our sample, from January 1, 2015 to December 31, 2019, the average district heating price was DKK 0.58 per kWh, corresponding to approx. EUR 0.078 per kWh, while the average district heating

[1] Ewald et al. (2021) emphasize the effectiveness of pricing policies in reducing total energy and space heating demand but also warn of the distributional challenges, especially in the short-run. Thus, lowering the costs of retrofitting energy systems and houses (through subsidies or tax breaks) is suggested to help ensure distributional fairness and protection, especially for low-income households.

[2] According to the Danish District Heating Association (2016).

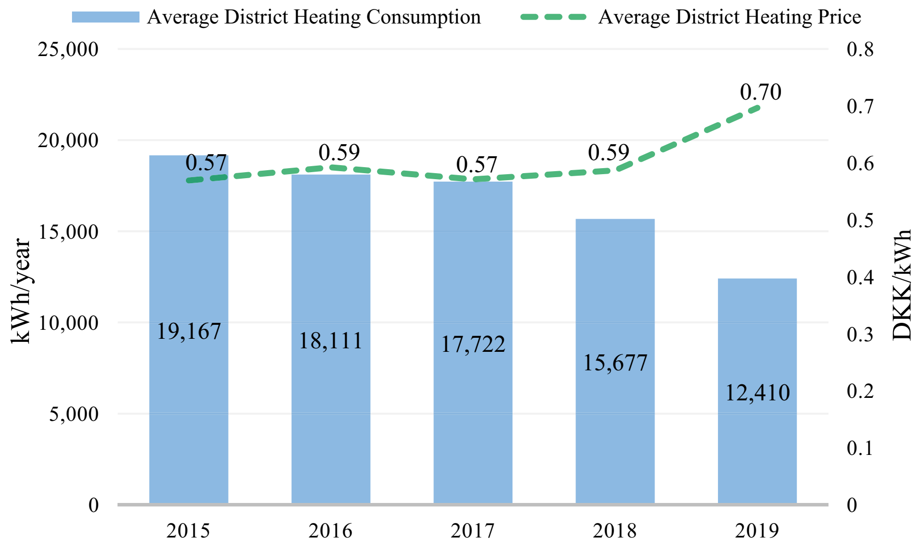

Fig. 1. Average yearly district heating price (DKK/kWh) and consumption (kWh/year) in single-family detached houses (2015–2019). Figures are based on sample data. N = 35,277 in 2015; N = 34,776 in 2016; N = 45,663 in 2017; N = 34,162 in 2018; N = 3085 in 2019.

consumption was 17,579 kWh per annum. Yearly district heating consumption of 17,579 kWh and a price of DKK 0.58 per kWh corresponds to a total bill of DKK 10,196 (approx. EUR 1371). However, both district heating prices and consumption vary significantly, ranging from DKK 0.21 to 1.22 per kWh and from 7361 to 47,657 kWh per annum, respectively.

We combined consumption and utility-level price data with socio-economic characteristics and dwelling attributes from Statistics Denmark. The linking of district heating consumption and price data with the administrative records is possible because all people living in Denmark are assigned a unique identification number (civil registration number), which public authorities use to register personal information on a regular basis. Access to anonymized micro data is heavily regulated and is only granted to Danish research environments through a secure server at Statistics Denmark (2014, 2017).

For our analysis, we mainly consider variables at the household level as energy used for space heating and domestic hot water depends on the practices of all household members rather than on one member alone. Table 1 shows that the mean annual disposable income of our sample households amounts to roughly DKK 532,000 (approx. EUR 71,500). About a sixth of the households are singles, while two-member households represent 44% of the sample. Accounting for 93% of total homes, the vast majority that use district heating are owned by the residing household, whereas only 7% are rented. Regarding geographical distribution, the largest share of households (38%) reside in Southern Denmark, and about 7% of households live within the region of the capital, Copenhagen.

The categorization of "dwelling year" reflects changes in the Danish Building Regulations (2015, 2018) and the energy labels typically linked to the year of construction.[3] While not entirely accurate, the building construction year has proven to be a reliable indicator of energy efficiency in the Danish context (Kristensen and Petersen, 2021).

The "heating allowance" variable refers to a supplement to heating costs granted to pensioners regardless of their income. Single-person households whose heating expenditure exceeds DKK 5400 per year (approx. EUR 726) and multi-person households whose heating expenditure exceeds DKK 8100 per year (approx. EUR 1090) are eligible to receive the allowance.[4] For houses supplied by district heating, the allowance covers 90% of the costs, up to DKK 22,500 (approx. EUR 3025); households with more than two adults can claim an additional DKK 6700 (approx. EUR 900) per person (18 years or older) living at the same address. The heating allowance is not taxable and is paid together with the pension.

Finally, to control for climate variations, we collected temperature data from the Danish Meteorological Institute and derived the number of HDD from each municipality's daily average temperature. We assumed 17 °C (62.6 °F) as the base temperature below which a dwelling needs heating. This temperature is typically used in Denmark to estimate HDD (Cox et al., 2015).

5. Empirical strategy

Household demand for energy, and thus for district heating, is considered a derived demand since energy is not consumed per se but to

[3] In particular, the energy label of dwellings built before 1961 ranges from D to G; for dwellings built between 1961 and 1972, the label ranges from D to F; for dwellings built during the periods 1973–1978 and 1979–1998, the label ranges from C to E; for dwellings built between 1999 and 2008, the label can be B or C; and for newer dwellings (built after 2008) the label is B or A. Each energy label relates to a threshold of expected energy consumption for a standard family. The official threshold for a typical A-labelled house of 100 m^2 is 69 kWh per m^2 per year, followed by the energy label B (69–92 kWh per m^2 per year), C (92–142 kWh per m^2 per year), D (142–192 kWh per m^2 per year), E (192–242 kWh per m^2 per year), F (242–305 kWh per m^2 per year), and G with an expected consumption higher than a threshold of 305 kWh per m^2 per year (Danish Energy Agency, 2015). https://sparenergi.dk/forbruger/boligen/skal-du-koebe-hus.

[4] https://www.borger.dk/pension-og-efterloen/tillaeg-til-folke–og-foertidspension/folkepension-varmetillaeg

Table 1
Descriptive statistics.

Variables	Mean	Std Dev	Min	Max	N
District heating energy consumption					
Average yearly district heating energy consumption (kWh) (January 1, 2015–December 31, 2019)	17,579	6,753	7,361	47,657	152,913
District heating price					
Average yearly district heating price (DKK per kWh) (January 1, 2015–December 31, 2019)	0.58	0.13	0.21	1.22	152,913
Socioeconomic and dwelling characteristics					
Household disposable income (DKK)	532,742	518,636	142,128	1,42e+08	152,913
Household size					
One member	0.17	0.37	0	1	25,367
Two members	0.44	0.50	0	1	66,818
Three members	0.13	0.34	0	1	20,635
Four or more members	0.26	0.44	0	1	40,093
Heating allowance					
Yes	0.06	0.25	0	1	9,730
No	0.94	0.25	0	1	143,183
Dwelling tenure					
Owned	0.93	0.25	0	1	142,631
Rented	0.07	0.25	0	1	10,282
Dwelling year					
Before 1961	0.23	0.42	0	1	34,569
1961–1972	0.23	0.42	0	1	35,530
1973–1978	0.16	0.36	0	1	24,041
1979–1998	0.21	0.41	0	1	32,854
1999–2008	0.12	0.33	0	1	18,678
After 2008	0.05	0.21	0	1	7,241
Living area (m^2)					
Less than 100 m^2	0.07	0.26	0	1	10,719
100–150 m^2	0.51	0.50	0	1	77,527
151–200 m^2	0.35	0.48	0	1	52,784
More than 200 m^2	0.08	0.27	0	1	11,883
Number of rooms					
Three rooms	0.08	0.27	0	1	12,518
Four rooms	0.31	0.46	0	1	46,920
Five rooms	0.32	0.47	0	1	49,419
Six or more rooms	0.29	0.45	0	1	44,056
Weather and geographical features					
Heating degree days (HDD) 17 °C	2,956.6	120.4	2,627.1	3,195.7	152,913
Government office region					
Capital Region of Denmark	0.07	0.25	0	1	10,001
Region of Southern Denmark	0.31	0.46	0	1	48,142
Central Denmark Region	0.38	0.48	0	1	57,389
Zealand Region	0.07	0.26	0	1	11,224
North Denmark Region	0.17	0.38	0	1	26,157

provide services, which are influenced by the complex interaction of many factors (Berndt and Wood, 1975; Flaig, 1990). As such, residential district heating demand can be based on the basic framework of household production theory (e.g., Muth, 1966). In our case, households acquire district heating energy that they use as input for providing different services such as a comfortable indoor temperatures and hot showers.

We investigated district heating demand in Danish households over the period of 2015–2019 while controlling for district heating prices,[5] household and dwelling characteristics, geographical differences, and weather conditions. A natural starting point to determine price elasticity would be the estimation of the following equation:

$$lnDH_{i,j,t} = \beta_0 + \beta_P lnP_{i,t} + \beta_{SD} SD_{i,t} + \beta_{WG} WG_{j,t} + \mu_i + \theta_t + \varepsilon_{i,j,t}, \tag{1}$$

where *DH* is the district heating consumption of household *i* in municipality *j* and year *t*, and *P* denotes the average price per kWh. $SD_{i,\ t}$ denotes socioeconomic and dwelling characteristics, such as household disposable income and dwelling year, while $WG_{j,\ t}$ controls for weather (HDD) in municipality *j* and for geography (government-office region). Moreover, μ_i and θ_t capture time-invariant household and year fixed effects, and $\varepsilon_{i,\ j,\ t}$ is the idiosyncratic disturbance term.[6] The consumption and price variables are logged such that the parameter of interest β_P can be interpreted directly as price elasticity.

However, this specification suffers from several shortcomings: Most importantly, the model assumes that households instantly adjust their behavior and infrastructure if the unit price or other control variables change (e.g., Alberini and Filippini, 2011). To overcome this shortcoming and thus to account for the interdependence of consumption decisions over time (e.g., sluggish appliance stock adjustments, energy-efficient retrofits, and utilization behavior), it is common to include the lagged consumption $DH_{i,\ t-1}$ on the right-hand side. The change in actual energy demand between two periods ($t-1$ and *t*) is some fraction (λ) of the difference between the logarithm of actual energy demand in period $t-1$ and the logarithm of the long-run equilibrium demand in period *t* (Alberini and Filippini, 2011). Formally,

$$lnDH_{i,t} - lnDH_{i,t-1} = \lambda \left(lnDH^{*}_{i,t} - lnDH_{i,t-1} \right). \tag{2}$$

Here, λ denotes the adjustment speed, which is bounded between 0 and 1 (if $\lambda = 0$, there is no adjustment; if $\lambda = 1$, the adjustment is immediate), and $DH_{i,\ t}^{*}$ is the long-run equilibrium demand in time period *t*. Given an optimum (albeit unobservable) level of energy demand, the demand will gradually converge to the optimal level between any two time periods (Alberini et al., 2011; Boogen et al., 2017). Therefore, the district heating demand function is specified as follows:

$$lnDH_{i,j,t} = \beta_0 + \beta_{DH} lnDH_{i,t-1} + \beta_P lnP_{i,t} + \beta_{SD} SD_{i,t} + \beta_{WG} WG_{j,t} + \mu_i + \theta_t + \varepsilon_{i,j,t}. \tag{3}$$

The inclusion of the lagged dependent variable in the explanatory variables violates the strict exogeneity condition, as it is correlated with the error term. Therefore, using pooled ordinary least squares (OLS), a random-effects (RE), or fixed-effects (FE) estimator would produce inconsistent and biased estimates (Wooldridge, 2010). Moreover, applying the FE estimator to Eq. 3 results in the so-called Nickell bias, which is characterized by a correlation between the regressors and the error term (Nickell, 1981).

[5] Standard economic theory suggests that households react to changes in prices by adjusting their energy demand and that price elasticities vary according to household type, dwelling characteristics, etc.

[6] The log–log functional form of the demand equation allows for a direct interpretation of the results, which means that changes in the variables can be interpreted as percent deviations. For categorical variables, the coefficient measures the difference in mean outcome with respect to the reference category.

To cope with endogeneity problems caused by reverse causality (or simultaneity) and unobserved heterogeneity, Anderson and Hsiao (1982) propose a simple IV estimator. The idea behind this estimator is to take the first-differences of Eq. 3 and use the lagged difference $\Delta DH_{i,t-2} = DH_{i,t-2} - DH_{i,t-3}$ as an instrument for $\Delta DH_{i,t-1}$. Arellano and Bond (1991) point out that this estimator is consistent but fails to take into account all available moment conditions and the differenced structure on the residual disturbances. Instead, these authors develop a generalized method of moments (GMM) estimator to first-difference the model (to remove unobserved heterogeneity) and then used the lagged levels of the dependent variables as instruments for the first-differenced variable ("difference" GMM estimator). However, as shown by Arellano and Bover (1995), Blundell and Bond (1998), and Alonso-Borrego and Arellano (1999), the "difference" GMM estimator proposed by Arellano and Bond (1991) can have a large finite sample bias and poor precision because lagged levels of the dependent variable are weak instruments for first-differences. Building upon Arellano and Bond (1991) and Arellano and Bover (1995), Blundell and Bond (1998) develop a system GMM estimator of two sets of equations that uses both lagged differences of the dependent variable to instrument for its levels and lagged levels of as instruments for differences. This allows the introduction of more instruments and improves efficiency. Another advantage of the system GMM estimator, as compared to the "difference" GMM estimator, is the possibility of including time-invariant regressors, which are orthogonal to the instruments for the first-differenced equation (Roodman, 2009a). In addition, the system of the Blundell and Bond GMM estimator is particularly suitable for panel data with large units of observations and small time periods (Roodman, 2009a), as in our case ($N = 152,913$; $T = 5$), and it is therefore employed in this study.

The validity of the GMM estimator relies on two specification tests: The Hansen test for over-identifying restrictions and the Arellano–Bond serial correlation test (Arellano and Bond, 1991; Arellano and Bover, 1995; Blundell and Bond, 1998). The Hansen test examines the validity of the instruments, employing the null hypothesis that all instruments as a group are exogenous. The serial correlation test examines the existence of first- and second-order serial correlation among error terms.

In our estimations, we use average district heating prices rather than marginal (or expected marginal) prices, as our price data were measured on an annual basis aggregated at the utility level and do not capture variations across the year. In addition, it is unrealistic to assume that consumers monitor cumulative district heating consumption and possess the information needed to understand and react to their actual marginal price. Moreover, the billing cycle for district heating, which is often only once a year, renders it even less likely to optimize consumption based on the marginal price. We treat the average district heating price as endogenous, and instrument it in a GMM style because it includes a fixed-fee component and is simultaneously determined by supply and demand. Finally, following Roodman (2009a, 2009b), we use orthogonal deviation to maximize the sample size and collapse instruments to reduce the finite-sample distortions. We also employ Windmeijer's (2005) finite-sample correction for standard errors to improve the accuracy of the inference. All analyses were performed using Stata MP 16.

6. Results and discussion

6.1. Estimation of the results of the dynamic panel model

Table 2 shows the results of the dynamic Blundell–Bond two-step GMM estimator of residential district heating demand over the period of 2015–2019. For comparison purposes only, we report the results of the Blundell–Bond one-step system GMM estimator and the static models (OLS, RE, FE) in Appendix Tables A2 and A3. The short-run elasticity amounts to −0.530, while the long-run price elasticity is −0.638. The long-run price elasticity is calculated as the ratio between the short-run elasticity (β = −0.530) and 1− the coefficient of the lagged district heating consumption variable (β = 0.170). Thus, district heating is an inelastic good, as are most other fuels and electricity (Hanemann et al., 2013).

Table 2
Results of the dynamic Blundell-Bond two-step GMM estimator of residential district heating demand (2015-2019).

Variables	Blundell–Bond two-step system GMM	
	Coeff.	Std. error
Lagged ln(DH consumption)	0.170***	(0.033)
Ln(DH price)	−0.530***	(0.059)
Ln(household income)	0.054***	(0.007)
Household size (Ref = One member)		
Two members	−0.003	(0.006)
Three members	0.004	(0.007)
Four or more members	0.013*	(0.007)
Living area (Ref = Less than 100 m^2)		
100–150 m^2	0.062***	(0.008)
151–200 m^2	0.137***	(0.011)
More than 200 m^2	0.243***	(0.017)
Number of rooms (Ref = Three rooms)		
Four rooms	0.007	(0.007)
Five rooms	0.028***	(0.008)
Six or more rooms	0.057***	(0.009)
Heating allowance	0.052***	(0.008)
Dwelling year (Ref = Before 1961)		
1961–1972	−0.058***	(0.006)
1973–1978	−0.096***	(0.008)
1979–1998	−0.144***	(0.010)
1999–2008	−0.163***	(0.011)
After 2008	−0.254***	(0.018)
Dwelling tenure (Ref = Owned)		
Rented	−0.021***	(0.008)
Government office region (Ref = Capital Region of Denmark)		
Zealand Region	−0.066***	(0.009)
Region of Southern Denmark	−0.147***	(0.015)
Central Denmark Region	−0.170***	(0.016)
North Denmark Region	−0.205***	(0.025)
Ln(HDD)	0.581***	(0.110)
Time dummies	Yes	
Constant	2.499***	(0.859)
Number of observations	20,245	
Number of instruments	33	
Arellano–Bond test for AR(1)	$z = -3.65$; $p = 0.000$	
Arellano–Bond test for AR(2)	$z = -0.78$; $p = 0.435$	
Hansen test for over-id. restrictions	$\chi^2(5) = 8.03$; $p = 0.155$	
Long-run price elasticity	−0.638***	(0.074)

Robust standard errors in parentheses. Standard errors of the estimate of long-run price elasticity obtained using the delta method.
Note: We use the average district heating price per kWh. This is calculated as the sum of annual variable and fixed price components divided by the annual consumption. The variable average district heating price is log-transformed.
** $p < 0.05$.
*** $p < 0.01$.
* $p < 0.1$.

The short-run price elasticity is significantly larger compared to the value reported by Leth-Petersen and Togeby (2001) and Hansen (2018) for Denmark, and larger than the values reported by Hellmer (2013) for Sweden and Park et al. (2019) and Lim et al. (2021) for Korea. Differences between these findings are likely due to various factors, such as the estimation method, model specification, time period of the analysis, and price variations during the period under investigation. Other differences relate to country specificity and framework conditions for district heating that impact price variations. For example, unlike Denmark, in Sweden and Finland, district heating prices are not regulated, and competition rules apply; in Norway, the district heating price is capped by electricity prices, including grid tariffs and electricity taxes (Sandberg et al., 2018). Compared to the other Nordic countries, the variation in district heating prices is larger in Denmark (Patronen et al., 2017). Our short-run and long-run price elasticities are comparable to those documented by Alberini et al. (2011) and Salari and Javid (2016), who investigate residential gas demand in the U.S. and employed the dynamic Blundell–Bond two-step GMM estimator.

Most of the control variables have the expected sign and contribute to explaining district heating demand (Table 2). District heating consumption increases by about 5% for every 10% increase in household disposable income. This income elasticity is broadly consistent with comparable studies on residential space heating demand (e.g., Hansen, 2018). Compared to single households, the consumption of households composed of four or more members is about 1.3% higher, while households who received heating allowance increased their consumption by about 5.2%.

Dwelling attributes have a more decisive influence on consumption than do socioeconomic characteristics. This result is consistent with previous studies (e.g., Braun, 2010; Hansen, 2016; Karatasou et al., 2018; van den Brom et al., 2019). District heating consumption increases with dwelling size and the number of rooms. For example, compared to households living in a dwelling of less than 100 m^2, the consumption of households living in a larger dwelling (more than 200 m^2) is about 24% greater. Rented dwellings exhibit somewhat lower consumption than owned dwellings. Moreover, consumption increases with the age of the dwelling, likely owing to less energy-efficient construction. Households living in dwellings built after 2008 (labelled between B and A) consume about 25% less than households living in dwellings built before 1961 (labelled between D and G).

The number of HDD has a strong and significant coefficient, indicating the impact of outdoor temperature on district heating consumption (Noussan et al., 2017; Rupp et al., 2021). Concerning location, households living in regions other than the Capital Region of Denmark exhibit lower district heating consumption. One possible explanation for this result might be that, in our sample, households living in regions other than the Capital Region of Denmark have lower disposable income levels (−24.1%) and, on average, live in relatively newer dwellings.

The Arellano–Bond test for AR(2) indicates the absence of second-order serial correlation in the error term (p-value = 0.435), while the AR(1) test indicates the appropriateness of including a first lag in the model specification. Moreover, the Hansen test does not reject the null hypothesis of joint invalidity of the instruments (p-value = 0.155).

6.2. Heterogeneity in the response to district heating prices

To quantify the heterogeneity in the response to district heating prices, we separately estimate the dynamic model (2) for various subgroups of our sample (Table 3). For the sake of easier interpretation, we choose two or three subsamples for the variables of interests. Specifically, low-income households fall below the 25th percentile, high-income households above the 75th percentile, and average-income households between the interquartile ranges. We use the same approach with respect to levels of district heating consumption. Concerning household size, we split the sample into single households (one member) and non-single households (two or more members). With respect to dwelling year (and associated energy labels), we split the sample into dwellings built before 1972 (labelled between D and G), dwellings built between 1973 and 1998 (labelled between C and E), and dwellings built after 1998 (labelled between C and A).

Our results reveal an inverse relationship between price elasticity and income level, as the price elasticity is higher at the lower end of the income distribution (25%) and lower among households in the top 25% of the income distribution. In this respect, we contribute to the mixed evidence in the literature. Some studies indicate that high-income households are more responsive to electricity and gas price increases than low-income households (Jamasb and Meier, 2010; Zhang, 2015; Schulte and Heindl, 2017), while other studies find that low-income households are more responsive to electricity, gas, and gasoline price increases. Generally, our result is consistent with, for instance, Wadud et al. (2009) and Schmitz and Madlener (2020), who estimate the gasoline demand elasticities in the U.S. and Germany, respectively, and Alberini et al. (2011), who estimate residential demand for electricity and gas in the U.S. One possible explanation of the inverse relationship between price elasticity of residential district heating demand and income level is that higher-income households are more likely to choose higher comfort levels and afford energy efficiency improvements than lower-income households (Ameli and Brandt, 2015; Ugarte et al., 2016). Moreover, higher-income households are more likely to possess higher

Table 3
Heterogeneity in the price response among different household groups.

	Short-run price elasticity Ln(DH price)		Long-run price elasticity		Number of observations
	Coeff.	Std. error	Coeff.	Std. error	N
Household disposable income					
Low-income household (≤DKK 329,535.9)	−0.607***	(0.158)	−0.804***	(0.191)	4,896
Average-income household (DKK 329,538–DKK 652,729.5)	−0.598***	(0.078)	−0.704***	(0.103)	9,174
High-income household (≥DKK 652,739.8)	−0.232*	(0.128)	−0.257*	(0.142)	3,928
District heating consumption					
Low consumption (≤12,800 kWh)	−0.513***	(0.161)	−0.548**	(0.220)	3,420
Average consumption (12,801 kWh– 20,858.23 kWh)	−0.405***	(0.075)	−0.471***	(0.146)	8,223
High consumption (≥20,858.24 kWh)	−0.726***	(0.205)	−0.798***	(0.258)	3,818
Household size					
Single household	−0.645***	(0.186)	−0.766***	(0.202)	3,247
Non-single household	−0.516***	(0.063)	−0.620***	(0.080)	16,921
Living area (m^2)					
≤150 m^2	−0.648***	(0.082)	−0.801***	(0.100)	11,487
≥151 m^2	−0.394***	(0.083)	−0.462***	(0.105)	8,647
Number of rooms					
≤4 rooms	−0.616***	(0.116)	−0.718***	(0.129)	7,837
≥5 rooms	−0.481***	(0.068)	−0.581***	(0.088)	12,319
Dwelling year					
Before 1972 (labelled between D and G)	−0.526***	(0.088)	−0.658***	(0.111)	8,896
Between 1973 and 1998 (labelled between C and E)	−0.648***	(0.085)	−0.745***	(0.101)	7,931
After 1999 (labelled between C and A)	−0.384**	(0.178)	−0.485**	(0.228)	3,341

Robust standard errors in parentheses. All models include socioeconomic and dwelling characteristics, geographical and weather features as well as year dummies. Standard errors of the estimate of long-run price elasticity obtained using the delta method.

*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

levels of "energy-related financial literacy," which is positively associated with the adoption of energy efficiency measures (Blasch et al., 2021) and contributes to explaining the energy efficiency gap (Kalmi et al., 2021). Therefore, in low-income households, a great deal of the response is likely caused by daily energy-saving activities (Trotta, 2018). This suggests that lower-income households are more likely to pay attention to price increases and adjust their heating behavior accordingly. However, for all income groups, district heating exhibits inelastic demand. Therefore, an increase in price leads to larger household expenditures. As low-income households spend a larger share of their budget on heating bills, rising prices lead to regressive distribution effects (for further discussion on this point, see Section 6.3).

With respect to the relationship between price elasticity and consumption levels, the results indicate that households that consume more tend to display greater responsiveness to price changes. This might be because higher-consumption energy users are more likely to indulge in discretionary consumption activities that can be avoided without sacrificing a lot of thermal comfort. For instance, higher-consumption households could easily reduce consumption by reducing the temperature by just one degree. However, both estimates are statistically indistinguishable at conventional significance levels.

With regard to household size, single-person households exhibit a greater responsiveness than non-single households. One possible explanation of this result is that for non-single households, especially those with children, it might be more difficult to adjust their behavior in response to price increases (Nicholls and Strengers, 2015). Moreover, this result might reflect the lower levels of domesticity of single-person households compared to non-single households. As the chance of not being at home decreases with household size, single-person households show greater responsiveness to price changes because they can reduce their space heating (and hot water) demand during their absence (Weber and Gill, 2016). In other words, the energy practices in single-person households might be more flexible. Similarly, households living in smaller dwellings, as captured by the variables "living area" and "number of rooms", exhibit a higher response to price increases.

With respect to dwelling year as a proxy for energy efficiency, the results indicate an "inverted U-shaped" relationship between price elasticity and the age of the dwelling. One would expect newer and more efficient dwellings to be associated with higher price elasticity. However, older dwellings are more likely to be renovated. This is because the variable "dwelling year" captures (the range of) the level of efficiency at the time of construction and not the potential energy-efficiency improvements that could have been made during the period under investigation.

6.3. Effects of district heating price increases on consumption, emissions, and bills

Table 4
Percentage (%) change in district heating consumption (and associated CO_2 emissions) and district heating bill for a 10% increase in price.

	District heating price +10%
% change in DH consumption and associated CO_2 emissions	−6.38%
% change in DH bill: Low-income household	+1.16%
% change in DH bill: Average-income household	+2.25%
% change in DH bill: High-income household	+7.18%
% change in DH bill: Single household	+1.1%
% change in DH bill: Non-single household	+3.17%

Based on our results from the previous section, we conduct a back-of-the-envelope calculation that quantifies the percentage reduction in district heating consumption (and associated CO_2 emissions) and the percentage increase in the bill of various household groups for a 10% (ceteris paribus) increase in the district heating price (Table 4).[7] To capture these effects, we use the estimated long-run price elasticities.

Overall, a 10% increase in the district heating price would reduce district heating consumption and related CO_2 emissions in single-family detached houses by 6.38%. In absolute numbers, when assessed against national official statistics (Danish Energy Agency, 2020a), this means a reduction of approx. 2194 TJ in district heating consumption of single-family detached houses and 47,340 tons of related CO_2 emissions.

With respect to the changes in district heating bills following a 10% increase in price, the largest increase in expenditure would occur in high-income households (+7.18%), followed by average-income households (+2.25%) and low-income households (+1.16%). Here, we assume that the district heating consumption by the sub-groups remains constant at the average level (from 2015 to 2019). Clearly, these results reflect the lower responsiveness of high-income households to district heating price increases (−0.257) as compared to average-income (−0.704) and low-income households (−0.804). In our sample, households in the lower- and higher-income tiers spent, on average, 3.7% and 1.24% of their disposable income to cover their space heating and hot water needs, respectively.

Following a 10% increase in price, low-income households would spend, on average, 4.15% of their income on district heating, while high-income households would spend 1.36% of their income. Recall in Table 3 that low-income households fall below the 25th percentile, while high-income households fall above the 75th percentile.[8] Concerning household size, non-single households would increase their expenditures by approx. 2 percentage points more than the increase for single households. In our sample, the share of household income spent on district heating energy for single households is 3.33%, on average, while it is 1.77% for non-single households.

7. Conclusion

Knowledge of household responsiveness to price changes and drivers of consumption is crucial for the assessment and design of energy and climate policies and for the evaluation of such measures' distributional consequences. Furthermore, insights into price elasticity and the determinants of energy consumption can inform future needs and trends in energy supply and demand, and thereby improve the design of targeted energy-efficiency policies.

By exploiting a longitudinal household data set of 152,913 observations covering 2015 to 2019, we used a dynamic panel data approach—Blundell–Bond two-step GMM estimator—to investigate the price elasticity of residential district heating demand in Denmark. Moreover, we analyzed the heterogeneity in price response across various household groups living in single-family detached houses to quantify the distributional consequences of policies that increase the price of district heating. Finally, we provided a back-of-the-envelope calculation of the effects of an increase in district heating price on consumption, emissions, and bills.

Overall, we found a short-run price elasticity of −0.530 and a long-run price elasticity of −0.638. These estimates are higher than those found in previous studies investigating residential district heating demand (Leth-Petersen and Togeby, 2001; Hellmer, 2013; Hansen, 2018; Park et al., 2019; Lim et al., 2021). Socioeconomic and (especially) dwelling characteristics as well as location and weather features significantly contribute to explaining district heating demand. In addition, we showed that households respond to price changes differently.

[7] This approach does not require any strong assumption about the changes in generation costs that are passed on to consumers.

[8] At the 10th percentile, the share of household income spent on district heating energy goes up to 4.74%, on average, while households belonging to the 90th percentile of the income distribution spent, on average, 1.02% of their income on district heating.

Specifically, low-income households, high-energy users, single households, and those living in older and smaller dwellings show greater responsiveness to price changes than their respective counterparts. We showed that a 10% increase in price would reduce consumption by 2194 TJ (and 47,340 tons of related CO_2 emissions) and increase the district heating expenditure in high-income and low-income households by 7.18% and 1.16%, respectively.

The higher price responsiveness of low-income households, as compared to high-income households, would only partially offset the increased portion of their incomes spent on district heating. Moreover, low-income households consume, on average, less than high-income households, and it might be more difficult for them to reduce consumption. Also, for low-income households, reducing thermal comfort via saving behaviors as a response to a price increase might pose serious threats to their mental and physical health (Ormandy and Ezratty, 2016).

In terms of policy implications, the results suggest that a higher carbon tax would likely be effective in reducing emissions associated with residential district heating demand. However, its impact would be unevenly distributed. To ensure distributional fairness, the results call for compensatory policies. Carbon tax revenues should be, at least in part, used to finance energy-efficient retrofit interventions targeted at lower-income households living in energy-intensive dwellings. Altogether, this could increase the public and political acceptability of such measures while also reducing costs for public health budgets.

An increase in district heating prices caused by a higher carbon tax (Danish Ministry of Climate, Energy and Utilities, 2020), the new EU ETS (Cambridge Econometrics, 2020; European Commission, 2021a), a misuse of the monopoly position from district heating companies (Gorrono-Albizu and de Godoy, 2021), the reduction or stop of Russian imports of energy products would thus make the economics and justification of energy efficiency more favorable. The district heating price responsiveness shown by lower-income households living in energy-inefficient dwellings is likely to be driven by (further) energy reductions. This group is most impacted by price and less likely to be able to invest in energy efficiency solutions. Relying only on the heating allowance granted to pensioners - regardless of their income - to help with the heating costs fails to address inequalities and provide long-term solutions. A recent French study (Bourgeois et al., 2019) examined the trade-off between fuel poverty alleviation, energy savings, and economic leverage for two carbon tax revenue-recycling options: a lump-sum payment and a subsidy for energy efficiency improvements (both targeted at low-income households). The authors found that the energy efficiency subsidy is superior to the lump-sum payment in all respects and offsets the regressive effect of the carbon tax from 2025 onwards.

Putting targeted energy efficiency measures at the top of the policy agenda would also ensure a better alignment with recent EU policy, legislation, and geopolitical developments. These include the treatment of energy efficiency as a crucial element in any policy-making and investment decision ("energy efficiency first" principle), the importance of the consideration of the multiple benefits of energy efficiency for the society (e.g., health benefits, improved energy security), and the empowerment and protection of vulnerable customers (European Commission, 2021).

CRediT authorship contribution statement

Gianluca Trotta: Conceptualization, Data curation, Methodology, Formal analysis, Validation, Writing – original draft, Writing – review & editing, Project administration. **Anders Rhiger Hansen:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Stephan Sommer:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

None.

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Appendix A

Table A1
Data pre-processing.

Variables	Sample	Yearly district heating energy consumption (kWh)			
	N	Mean	Std Dev	Min	Max
District heating energy consumption	2,005,414	50,354	746,675	0	100,010,120
District heating energy consumption; single-family detached house	1,079,173 (53.8%)	37,249	520,839	0	67,129,838
District heating energy consumption; single-family detached house; district heating price	683,685 (34.1%)	17,559	6,735	7,361	47,675
District heating energy consumption; single-family detached house; district heating price; socioeconomic and dwelling characteristics; weather and geographical features	152,913 (7.6%)	17,579	6,753	7,361	47,657

Note: The final sample (N = 152,913) accounts for duplicates, outliers, missing values, and other types of data-entry errors.

Table A2
Results of the dynamic Blundell-Bond one-step GMM estimator of residential district heating demand (2015-2019).

Variables	Blundell-Bond one-step system GMM	
	Coeff.	Std. error
Lagged ln(DH consumption)	0.171***	(0.033)
Ln(DH price)	−0.531***	(0.059)
Ln(household income)	0.054***	(0.008)
Household size (Ref = One member)		
Two members	−0.003	(0.006)

(*continued on next page*)

Table A2 (*continued*)

Variables	Blundell-Bond one-step system GMM	
	Coeff.	Std. error
Three members	0.004	(0.007)
Four or more members	0.013*	(0.007)
Living area (Ref = Less than 100 m2		
100–150 m^2	0.063***	(0.008)
151–200 m^2	0.137***	(0.011)
More than 200 m^2	0.243***	(0.017)
Number of rooms (Ref = Three rooms)		
Four rooms	0.007	(0.007)
Five rooms	0.027***	(0.008)
Six or more rooms	0.056***	(0.009)
Heating allowance	0.051***	(0.008)
Dwelling year (Ref = Before 1961)		
1961–1972	−0.058***	(0.006)
1973–1978	−0.096***	(0.008)
1979–1998	−0.143***	(0.010)
1999–2008	−0.163***	(0.011)
After 2008	−0.253***	(0.018)
Dwelling tenure (Ref = Owned)		
Rented	−0.021***	(0.008)
Government office region (Ref = Capital Region of Denmark)		
Zealand Region	−0.066***	(0.009)
Region of Southern Denmark	−0.148***	(0.015)
Central Denmark Region	−0.170***	(0.016)
North Denmark Region	−0.208***	(0.025)
Ln(HDD)	0.590***	(0.109)
Time dummies	Yes	
Constant	2.424***	(0.856)
Number of observations	20,245	
Number of instruments	33	
Arellano–Bond test for AR(1)	$z = -3.65$; $p = 0.000$	
Arellano–Bond test for AR(2)	$z = -0.87$; $p = 0.385$	

Robust standard errors in parentheses.

Note: The results of the Blundell–Bond one-step system GMM are similar to those of the Blundell–Bond two-step system GMM estimator. The one-step system GMM assumes the error term $\varepsilon_{i,j,t}$ to be independent and homoscedastic across households and time; in contrast, the two-step system GMM estimator uses an optimal weighting matrix, where the residuals of the first-step estimation are employed to estimate the variance–covariance matrix, and the assumptions about independency and homoscedasticity are not maintained (Blundell and Bond, 1998; Roodman, 2009a, 2009b).

** $p < 0.05$.

*** $p < 0.01$.

* $p < 0.1$.

Table A3

Estimation results of static models (OLS, RE, FE) of residential district heating demand (2015-2019).

Variables	OLS		RE		FE	
	Coeff.	Std. error	Coeff.	Std. error	Coeff.	Std. error
Ln(DH price)	−0.824***	(0.004)	−0.845***	(0.004)	−0.916***	(0.017)
Ln(household income)	0.043***	(0.002)	0.038***	(0.002)	0.016***	(0.008)
Household size (Ref = One member)						
Two members	−0.003	(0.003)	−0.002	(0.002)		
Three members	0.013***	(0.003)	0.014***	(0.003)		
Four or more members	0.015***	(0.003)	0.016***	(0.003)		
Living area (Ref = Less than 100 m2)						
100–150 m^2	0.074***	(0.003)	0.075***	(0.003)		
151–200 m^2	0.163***	(0.004)	0.164***	(0.004)		
More than 200 m^2	0.284***	(0.005)	0.286***	(0.005)		
Number of rooms (Ref = Three rooms)						
Four rooms	−0.007**	(0.003)	−0.007**	(0.003)		
Five rooms	0.022***	(0.003)	0.022***	(0.003)		
Six or more rooms	0.052***	(0.004)	0.053***	(0.004)		
Heating allowance	0.057***	(0.003)	0.051***	(0.003)		
Dwelling year (Ref = Before 1961)						
1961–1972	−0.070***	(0.002)	−0.069***	(0.002)		
1973–1978	−0.110***	(0.003)	−0.109***	(0.003)		
1979–1998	−0.165***	(0.002)	−0.165***	(0.002)		
1999–2008	−0.183***	(0.003)	−0.183***	(0.003)		
After 2008	−0.309***	(0.004)	−0.309***	(0.004)		
Dwelling tenure (Ref = Owned)						
Rented	−0.019***	(0.003)	−0.017***	(0.003)		
Government office region (Ref = Capital Region of Denmark)						
Zealand Region	−0.079***	(0.004)	−0.085***	(0.004)		

(*continued on next page*)

Table A3 (*continued*)

Variables	OLS		RE		FE	
	Coeff.	Std. error	Coeff.	Std. error	Coeff.	Std. error
Region of Southern Denmark	−0.208***	(0.004)	−0.220***	(0.003)		
Central Denmark Region	−0.237***	(0.004)	−0.237***	(0.004)		
North Denmark Region	−0.292***	(0.005)	−0.294***	(0.005)		
Ln(HDD)	0.749***	(0.037)	0.628***	(0.037)	0.761***	(0.104)
Time dummies	Yes		Yes		Yes	
Constant	2.944***	(0.293)	3.977***	(0.270)	3.001***	(0.837)
Observations	152,913		152,913		152,913	
R-squared	0.458		0.458		0.311	
R-squared within			0.462		0.466	
R-squared between			0.459		0.304	
Bruschen–Pagan LM test	15,591.24***	(0.000)				
Hausman test			882.92***	(0.000)		

Robust standard errors in parentheses, clustered at the household level.

Note: The short-run elasticities vary from −0.824 to −0.916, and most of the variables have the expected sign. As discussed in Section 5, biases in the magnitude of the coefficients are primarily due to reverse causality but are also due to measurement error and, in the case of OLS, to unobserved heterogeneity; these biases are mainly related (but not limited) to the price variable.

*** $p < 0.01$.

** $p < 0.05$.

* $p < 0.1$.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2022.106163.

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