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Will energy transition in Poland increase the extent and depth of energy poverty?

Lilia Karpinska [a,*], Sławomir Śmiech [b]

[a] Cracow University of Economics, Department of Microeconomics, Rakowicka 27 St., 31-510, Cracow, Poland
[b] Cracow University of Economics, Department of Statistics, Rakowicka 27 St., 31-510, Cracow, Poland

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ABSTRACT

The clean energy transition in Poland means replacing coal with natural gas in the household sector, resulting in an increase of heating costs. The aim of this article is to examine the impact of changing the energy source on the extent and depth of energy poverty in Poland. In the study, we use a definition of hidden energy poverty and simulate theoretical energy expenditures in two scenarios. The first scenario assumes the status quo, and the second one – the transition to natural gas. The result shows that the rate of energy poverty increases from 16.5% in the first to 19.3% in the second scenario. Furthermore, the transition to gas translates into an increase on average by 22.9% per household. The results obtained indicate that shielding policies for energy poor households are necessary.

1. Introduction

Reducing coal consumption has two dimensions in Poland. One is linked to the energy sector, as coal remains the main source of electricity (more than 70% in the mix; see PSE, 2021). The other is related to the residential sector. Coal remains the primary source of heat for a large proportion of households (40.5% in 2018) and most houses (70% in 2018[1]). Burning coal in domestic boilers causes smog, which is responsible for premature deaths in Poland (EEA, 2020; IQ Air, 2021). The transition to energy in the household sector is a major challenge in energy policy challenge. In 2018, the Polish government launched the Clean Air program, which focused on thermal modernization of single-family buildings, replacement of solid fuel heat sources by modern low-carbon heat sources that meet the highest efficiency standards, and connecting households to the heating or gas network (NFEP&WM, 2021). The program aims to improve air quality in Poland and is planned for the next decade (2018–2029). This program can be classified as one of a number of European policy actions enabling the transition to a low-carbon economy (Bouzarovski et al., 2021). Coal-fired boilers are being replaced by less polluting energy sources, of which gas boilers are the most common (45% share, see NFEP&WM, 2021). At the same time, Polish provinces are announcing antismog programmes, which oblige house owners to replace their dirty energy sources with less emitting ones. This change in the energy source is not living-costs neutral. Gas is a more expensive fuel than coal or wood. Poor households can become energy poor as a result of switching to less polluting energy sources.

Energy poverty, i.e., the lack of essential energy services necessary for a household or an individual to live a dignified life (EPOV, 2021), remains a serious problem in Poland. Various studies report that energy poverty affects up to 18.6–24% of households (Karpinska and Śmiech, 2020; Sokołowski et al., 2020).

We identify two gaps in the literature that need to be bridged. The first is the depth of energy poverty, which is understudied not only in Europe (Meyer et al., 2018; Hills, 2011), but also worldwide, where it is often referred to as the energy affordability gap (Fisher et al., 2013; Brown et al., 2019). In the European context, the energy poverty depth is mostly based on the Low Income High Cost (LIHC) threshold (Szpor and Lis, 2016; Hills, 2012), which imposes certain limitations on the data availability and methodology. In our study, we rely on the data gathered by the Central Statistical Office in Poland and acquired in other EU countries. Not only does our study offer an estimate of the depth of energy poverty in Poland, but it could also be extended to countries that collect the same statistics.

The second gap is related to the impact of the energy transition in the household sector on the rate and depth of energy poverty. Direct emissions by private households in EU countries exceed 830 MT of carbon

* Corresponding author.
E-mail addresses: karpinsl@uek.krakow.pl (L. Karpinska), smiechs@uek.krakow.pl (S. Śmiech).

[1] Survey on Fuels and Energy Consumption in Households (EGD) 2018.

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dioxide equivalents in 2019 (Eurostat). The need to reduce emissions in this sector raises the question of social costs borne by households. It is therefore poorly known what costs would have to be incurred to lift individual households out of energy poverty.

To fill this gap, we analyze the depth of energy poverty in Poland in two scenarios. In the first scenario, we calculate the existing energy poverty gap. In the second scenario, we predict what will happen if households in Poland have to abandon dirty energy sources and switch to gas in the immediate future. To identify energy poor households, we will use the concept of hidden energy poverty introduced by Karpinska and Śmiech (2020a, 2020b), whose idea is to estimate expected energy expenditure, taking into account household and dwelling characteristics. This approach allows, in particular, to identify households that under-consume energy for economic reasons.

We base our analysis on the latest available Survey on Fuels and Energy Consumption in Households (EGD) and the Household Budget Survey (HBS) 2018. The EGD is collected by Statistics Poland (2021) every three years following the requirements on sample selection and data collection. This survey contains the most comprehensive set of questions on household energy usages. There are 12 sections with a total of 22 questions, including energy consumption by type and purposes; heating, air conditioning, mechanic ventilation, cooking, and water heating equipment; ownership of electric appliances; availability of smart meters; information on biomass fuels, solar collectors, and heat pumps; consumption of motor fuels; energy audit; behavioral practices and awareness of renewable energy and energy saving awareness.

Our study contributes to the literature on energy poverty in two dimensions. First, we calculate the prevalence and depth of energy poverty in Poland. In this way, we show how severe the problem of energy poverty is, which allows us to estimate the costs of escaping deprivation. The simple headcount ratio is complemented with the respective indices to provide insight into inequality in the energy-poor group. Thanks to the decomposition properties of the Foster-Greer-Thorbecke measure, we demonstrate the distribution of the energy poverty inequality and severity in population subgroups divided by the economic activity and the household type. Analysis by subgroups allows us to identify the most affected ones in the second part described below.

Second, we show the consequences for the extent and depth of energy poverty of a switch from dirty fuels to gas in the household sector. In this way, we show the social costs, for the poorest groups in the society, of improving the air quality. However, our study does not undermine the idea of a clean energy transition as the whole society also pays for the costs of low stack emissions. One of the practical implications of the study is the ability to find the optimal (in terms of energy efficiency and future costs) alternative to solid fuel heat sources currently being replaced within the Clean Air program.

The study is divided into two parts. The goal of the first part is to assess the prevalence of energy poverty and the shortfall of households from the energy poverty threshold. We identify energy-poor households as those with annual disposable income after energy costs that is less than 60% of the national median (Karpinska and Śmiech, 2020a). The after-energy-costs disposable income is equivalised according to the OECD-modified scale to account for a household size. What is specific for the measurement of implicit energy poverty is that we do not use the declared but modeled energy consumption. With this approach, we classify as energy poor households that use self-restricted coping strategy and under-consume energy. To measure the intensity and the severity of energy poverty in a country, we rely on Foster-Greer-Thorbecke indices (Foster et al., 1984) that satisfy, among others, the requirements for decomposability.

The goal of the second part is to compute the costs of gas switching in terms of the energy poverty rate and the energy poverty gap increases. The prices of dirty fuels, such as coal, brown coal, coke, firewood, and biomass,[2] are converted to gas prices and energy expenditures are estimated on their basis. We compare the energy poverty rate and depth to the results obtained in the first part. The energy-poverty gap index (EPGI) and the energy-poverty-severity index (EPSI) allow us to compute the costs of the energy-poverty alleviation policy with perfect targeting and with no targeting as well as to assess the disparities among the energy poor.

The remainder of the study is organized as follows. Section two reviews the subject literature. Section three describes the data and provides descriptive statistics. Section four justifies the choice of statistical tools. Section five discusses the results, and Section six concludes.

2. Review of the literature

This study estimates the immediate impact on the prevalence and depth of energy poverty in some state programs that force the issue of air improvement in the country. Rising energy poverty may jeopardize policy efforts, which stirs a debate about socially acceptable energy choices in Poland (Bogacz, 2021). Although the social costs of carbon emissions are widely presented in the literature, the social costs of CO2 reduction are a relatively new aspect of the problem. Not to mention, energy poverty has not been discussed in a similar vein. In this study, we discuss the topic of social costs of energy transition recognized as a knowledge gap in the recent review of energy poverty research (Primc et al., 2021). Our study contributes to the limited literature on hidden energy poverty and its depth, with emphasis on households transition to clean energy in Europe (Feenstra et al., 2021). Three strands of literature need to be considered here.

The first strand focuses on hidden energy poverty. Meyer et al. (2018) point to deficiencies in the policy that does not distinguish energy poverty linked to self-restrained energy needs. Papada and Kaliampakos (2020) consider the compression of energy consumption an important and unfairly ignored manifestation of energy poverty. Abnormally low energy costs characterize households and individuals deprived in other dimensions, for example, those living on a low income (Betto et al., 2020). Self-disconnections, staying in bed during the day, wrapping up, etc. – these are methods of coping with cold (Anderson et al., 2012). We believe that households living in hidden energy poverty in Poland cut their energy bills by consuming cheap dirty energy or under-consuming energy (Karpinska and Śmiech, 2020a). As a result, the scale and depth of energy poverty in Poland are underestimated.

The second strand covers the depth of energy poverty depth. The depth of energy poverty is defined in the literature as the amount of financial support needed to escape the predicament (Rademaekers et al., 2016). Depending on the measure of energy poverty, the gap could be income necessary to reach the energy poverty line (UK Government, 2021) or the difference between the actual energy costs and the maximum affordable energy costs (Meyer et al., 2018). Following the LIHC approach to calculating energy poverty, a double threshold can be applied here, i.e. 60% of the national median income and the median required energy costs (Hills, 2011). As an alternative to measuring the energy poverty gap as a shortfall from the established line, Sareen et al. (2020) suggest assessing the depth of energy poverty on Likert scales. Although the depth of energy poverty in Poland is crucial for policy considerations, it is still an understudied area (Szpor, 2016).

Our analysis of the depth and severity of energy poverty is based on the respective poverty measures described in the seminal work by Foster et al. (1984). The authors presented a measure of poverty with a strong decomposability property and a parameter that indicates aversion to inequality. The Foster-Greer-Thorbecke family of indicators satisfies the monotonicity and transfer axioms formulated by Sen (1976) in regard to

[2] The carbon neutrality of biomass remains disputable (Catuti et al., 2020) and the full production lifecycle should be considered.

poverty measures and is suitable for energy poverty analysis. When providing the outcomes of the EPGI, we think of policies with perfect and proxy targeting. Perfect targeting is achieved in a situation in which each energy poverty gap is covered separately. Perfect targeting implies horizontal equity, i.e., the equally poor receive the same amount of benefits (Kakwani and Son, 2005). In most cases, welfare transfers are made based on some proxy information about a recipient. The decomposition of energy poverty indices by subpopulation is useful in this regard. To our knowledge, this study is also the first in which the Foster-Greer-Thorbecke poverty measures are used in the analysis of energy poverty.

The last strand studies energy poverty in relation to the energy transition. Most of the research on this topic is dedicated to the developing world (Sovacool, 2012; Ma et al., 2019). However, the problem of household emissions is also acute in many developed countries, including Poland, even though these countries are less frequently mentioned in this regard. According to the WHO (2012, 2007), energy poverty-related housing risks include indoor dampness and mold, cold, smoke from solid fuels and biomass, while health outcomes attributable to the risks include asthma, tuberculosis, winter mortality, and obstructive pulmonary diseases. Household energy practices are responsible for both outdoor and indoor emissions, the latter being the subject of a special guideline (WHO, 2014). Apart from studies on the energy transition (Damette et al., 2018), consumer behavior (Vainio et al., 2020; Gaspari et al., 2021), there are only a few researches that deal with the issue of energy poverty and CO2 reduction (Bonatz et al., 2019; Zhao et al., 2021). We intend to provide some empirical support to a social disapproval of current policies devoted to energy transitions in the residential sector in Poland. Other European countries with a similar energy mix might experience the same problems.

3. Data description

The study is based on the cyclical module of the Polish HBS dedicated to fuels and energy consumption in households. The survey is conducted every three years, and the latest available version contains data from 2018. The total sample size of the HBS in 2018 is equal to 36,166 households; the EGD contains information on 4081 households, which is about 11.3% of the HBS sample. The EGD sample has a minimum sample size that represents about 14.4 million Polish households. In a cleaning procedure, we remove about 13% of the data. The questionnaire is collected in a paper during on-site visits of officers from statistical offices. The EGD covers aspects such as the thermal condition of buildings, energy consumption by purpose and type of energy, heating appliances, air conditioning, lighting, household appliances and electronics, measuring and regulating devices, additional information on biomass fuels, solar collectors, heat pumps, passenger cars, energy saving and self-generation.

In the analysis, we combine data on the same households from the EGD and the HBS. HBS variables convey additional information on living conditions, income, and types of households. In total, 12 variables are used in the regression analysis. The variables represent building parameters and housing adequacy, characteristics of households, poverty, and regional division. Inclusion of the variables allows for the capture of multiple aspects of energy usage, the technical attributes of the houses, as well as behavioral patterns of Polish households. Table 1 provides further justification for the choice of the variables and gives reference to the literature, in which similar variables are used in the analysis of energy poverty.

The respective statistics for all categorical and continuous variables are presented in Tables A1 and A2. In brief, households living in single- and multifamily buildings are almost equally represented in the sample. On average, buildings were constructed between 1961 and 1980, and the space each household occupies was about 85 m^2 or three rooms. Most of the buildings (62.04%) are insulated. According to subjective evaluation, 91.22% of the properties are in good condition and 86.85% of them provide thermal comfort to their owners. Almost half of the respondents live in a rural area, only 8.77% of households reside in large agglomerations with more than 500,000 inhabitants. Mazowieckie and Śląskie voivodeships have the largest representation. Among all types of households, the shares of couples without children (27.88%) and one-person households (20.12%) are the largest.

The average annual disposable income is PLN 56,520 (about EUR 12,280) per household; 50% of households report neither good nor bad financial condition. Average annual energy expenditures constitute about 7% of disposable income. Energy expenditures comprise the costs of electricity, district heating, natural gas, LPG, heating oil, coal, brown coal, coke, firewood, and biomass. The share of the respective energy sources is shown in Fig. 1. Electricity, gas, including liquid gas, and coal are the most widely used energy commodities in Poland. Some households (at 31%) still rely on firewood; district heating and hot water

Table 1
Variables included in modelling of hidden energy poverty.

Variables	Comments
Type of building	The type of accommodation decides on the energy needs and sources of energy available to its inhabitants. For example, single-family homes require more energy to heat.
Year of construction	This variable denotes thermal characteristics of a dwelling, i.e. modern buildings are built according to a higher standard of energy efficiency.
The total useable floor area of the apartment	This parameter indicates how many square meters should be heated to maintain thermal comfort. Living in large apartments or houses usually increases energy needs.
Number of rooms	The large number of rooms also imposes an additional burden on the energy budget. Some households adopt a coping strategy and heat only one room.
Subjective evaluation of a building	One of the subjective indicators that allows households to assess technical characteristics of a building, including water supply, heating installation, etc.
Thermal comfort of a building	One of the most popular subjective energy poverty indicators, which classifies households as energy poor or non-energy poor based on their own opinion.
Subjective perception of a household's financial condition	Similarly to the previous subjective indicators, this survey question gives households the possibility to describe their material situation in a range from 'good' to "bad".
Urban and rural areas	In less urbanized areas, households usually have limited choice of energy sources, e.g. there might be no access to gas grid or district heating.
Household type	The composition of households is an important factor in the precariousness of households. For example, single-family households composed of elderly retired people, as well as households with dependent children, are considered to be more vulnerable.
Voivodeship	Regions as large administrative units usually differ in terms of climate conditions and socioeconomic development. The capacity and infrastructure of a region play a decisive role in the mitigation of energy poverty.
Insulation in buildings	Insulation increases the thermal performance of a building and hence deceases the energy needs of a household ceteris paribus.
Income	Household income is a decisive factor in determining the level of vulnerability and the ability to pay for energy services.
Energy costs	The actual energy costs are used to model the required energy expenditures, which are considered in LIHC indicator among others.

Sources: Based on Belaïd (2018); Robinson et al. (2019); Fizaine and Kahouli (2018); Karpinska and Śmiech (2020a); Gouveia et al. (2019); Sokołowski et al. (2020); Libor and Bouzarovski (2018); Ziółkowska et al., 2018; BRE, 2020; Thomson and Snell (2013); European Commission (2013).

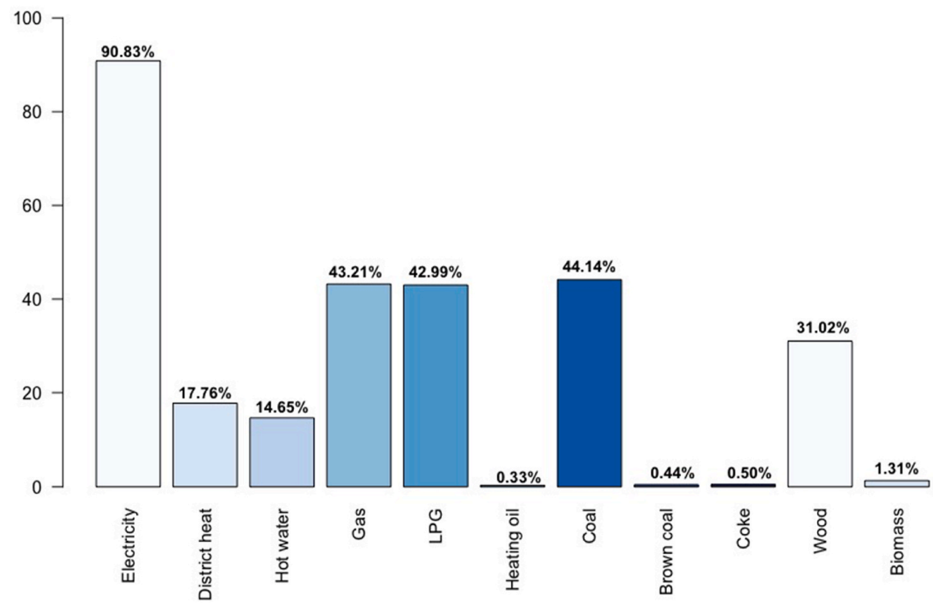

Fig. 1. Share of households that report the costs of energy sources.

supply are common to agglomerations.

Fig. A1 presents the frequency distribution of energy sources in different types of buildings. We divide energy sources into two groups: dirty and clean energies. All households are assigned a dirty-clean energy indicator, depending on whether a household spends or does not spend money on dirty energy, such as heating oil, coal, brown coal, coke, firewood, or biomass. Statistics indicate that about 53.7% of households in Poland report spending on dirty energy sources. The chi-square test reveals a significant level of association between types of building and energy sources. As shown in Fig. A1, clean energy positively correlates with multifamily buildings, whereas dirty energy is mostly associated with free-standing residential buildings, which is also true for other buildings.

4. Methodology

This study examines the effects of switching to gas on the depth and rate of energy poverty in Poland. We carry out the analysis in two steps. First, we assess the current level of energy poverty and the corresponding energy poverty gap accounting for the estimated energy expenditures. Second, we estimate the level of energy poverty and the gap in case households choose to abandon dirty fuels and use gas instead.

The study extends the methodology for estimating the hidden aspect of energy poverty presented by Karpinska and Śmiech (2020). We propose to consider multiple linear regression to compute the energy expenditures necessary to maintain comfortable thermal comfort and satisfy the other basic energy needs. To avoid the correlation between variables and improve the predictive power of the model, we utilize the lasso technique. The most regularized lasso model serves as a robustness check of the multiple linear regression results. The analysis is performed in R. Fig. 2 visualizes our methodology.

In the first step, we compute the expected energy costs following the general linear regression framework. The respective model is given by:

$$Y = X\beta + \varepsilon$$

where $\varepsilon = (\varepsilon_1, \ldots, \varepsilon_m)$ is a vector of i.i.d. random error with mean zero and variance σ^2, Y is an $n \times 1$ vector of a response variable, β is an m-dimensional vector of parameters or coefficients, $X = (X_1, \ldots, X_m)$ is an $n \times m$ matrix of predictors. To retain the most informative variables, we apply the lasso (the least absolute shrinkage selection operator) procedure (Tibshirani, 1996). Within the lasso model, we obtain the optimal set of predictors with the lowest prediction errors by minimizing the sum of squares of residuals as follows:

$$\min(\| Y - X\beta\|_2^2 + \lambda \| \beta\|_1)$$

where $\| \|_1$ is ℓ_1-norm, $\| \|_2$ is ℓ_2-norm and $\lambda \geq 0$ is a tuning parameter. In the most regularized version, many variables are set to zero, and only the most influential ones are kept. The tuning parameter λ is computed in the cross-validation procedure. We compare multiple linear regression and lasso specifications to find the optimal model to predict energy costs.

We identify the group of those affected by energy poverty by subtracting the necessary energy costs from disposable income and setting the threshold at 60% of the national median value. The disposable income after energy costs is adjusted to households' composition based on the OECD-modified equivalence scale, where 1 is assigned to the first adult, 0.5 is assigned to an additional adult and child aged 14 and older, 0.3 is assigned to a child under 14.

The energy poverty gap measures how much of the after-energy-costs disposable income is needed to get out of energy poverty, i.e. to cross the energy poverty line. To quantify the energy-poverty indices (EPI), we adopt the existing Foster-Greer-Thorbecke poverty measure (Foster et al., 1984) given by:

$$EPI = \frac{1}{N}\sum_{j=1}^{H}\left(\frac{z - y_i}{z}\right)^{\alpha}$$

where z is the threshold for energy poverty, N is the total number of households, H is the total number of energy poor households, y_i is the disposable income after energy costs of an energy poor household i, alpha ($\alpha \geq 0$) is a parameter that takes different values and equals 1 in the case of EPGI. The alpha parameter captures poverty aversion, i.e., the greater parameter, the more sensitive the measure is to the position of the poor in the group of the poor. If $\alpha = 2$, we obtain the squared EPGI or EPSI, which accounts for the inequality among the energy-poor group. The gap is considered zero for households above the energy poverty line.

In the second step, we analyze the changes in the prevalence and depth of energy poverty in case households shift from dirty energy to gas, ceteris paribus. The energy poverty threshold is kept at the level established in the first step. Table 2 shows the prices of energy commodities. We use EUR/GJ to express units of measure and calculate

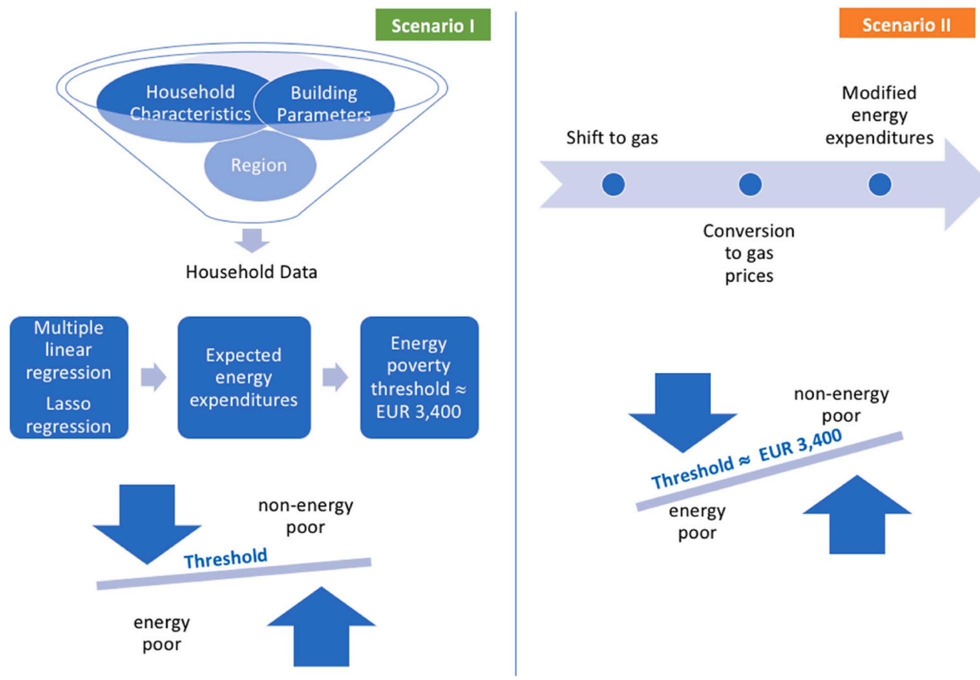

Fig. 2. Flow chart of our methodology.

Table 2
Energy prices for different energy commodities, EUR/GJ.

Energy	Price	Coefficient of conversion*
Electricity	39.2	
District heating	11.7	
Hot water	24.5	
Natural gas	**15.4**	
LPG	20.2	
Heating oil	18.5	
Coal	6.1	2.52
Brown coal	9.0	1.72
Coke	7.2	2.12
Firewood	3.5	4.42
Biomass	3.3	4.56

Based on: Statistics Poland (2019). Energy consumption in households in 2018, Warsaw. *Own calculations.

coefficients of price conversion. The price of natural gas is the reference value. The costs of coal, brown coal, coke, firewood, and biomass are multiplied by the respective coefficients to obtain the respective value for gas. The converted energy costs are higher than the initial ones.

The possible consequences of switching to gas include an increase in both the level and the depth of energy poverty. After estimating the new level and the depth of energy poverty in Poland, we show the average shortfall of households from the energy poverty threshold and compare the results with the first scenario. The energy poverty gap indicates the extent to which households fall below the threshold as a consequence of the switch to gas from dirty energy.

Also, statistical tools utilized in the study include the Chi-square test of independence as a measure of association between categorical variables (Fisher, 1922), the adjusted Rand index as a measure of similarity between classifications (Wagner and Wagner, 2007), etc.

5. Results and discussion

We examine the role played by switching to gas in the prevalence of energy poverty and the shortfall of households from the energy poverty thresholds in Poland. The energy poverty rate is calculated based on the modeled energy costs. We account for multiple aspects of energy consumption and include variables from both the EGD and the HBS.

First, we model energy costs. The results of multiple linear regression as well as lasso estimates, are presented in Table A3. Our results reveal a positive statistically significant impact on energy costs of factors such as: single-family buildings, total useable floor area, the number of inhabitants in an area, income, households with at least one dependent child, and a lack of insulation. Living in a particular region of Poland is associated with either with lower energy costs, i.e., in Lubelskie and Podlaskie voivodeships, or higher energy costs, i.e., Wielkopolskie and Śląskie voivodeships. One-person households, lack of installation in a house, and recent year of construction are among the factors that reduce energy costs.

In lasso analysis, we rely on the most regularized model.[3] The number of retained variables is reduced as much as possible. The lasso model consists only of 12 factor levels compared to 62 factor levels in the multiple linear regression model. The most significant predictors include the type of building, the total useable floor area, the number of rooms, population density, type of household, income, voivodeships, and insulation. The sign of lasso estimates suggests the same positive or negative correlations revealed in the multiple linear regression model. The energy poverty rate is 16.49% and 16.77% according to, respectively, multiple linear regression and lasso. The adjusted Rand index (0.96) points to a high similarity between the two classifications. The results of multiple linear regressions are robust to alternative (lasso) techniques. In the later part of the analysis, we rely on multiple linear regression results opting for a simpler tool of statistical analysis.

Fig. 3 presents a density plot for the energy expenditures modeled in the study. The plot shows a distribution shape of actual and modeled energy costs over a continuous interval. The peaks of the linear fitted values display where the actual expenditures are lower than those estimated in the models.

Second, we convert the prices of dirty fuels to a gas price and estimate energy poverty in a scenario where households abandon dirty fuels. The important condition is that an alternative source of energy, in

[3] We use the most regularized parameter, i.e. the parameter lambda.1se identified in the cross-validation procedure.

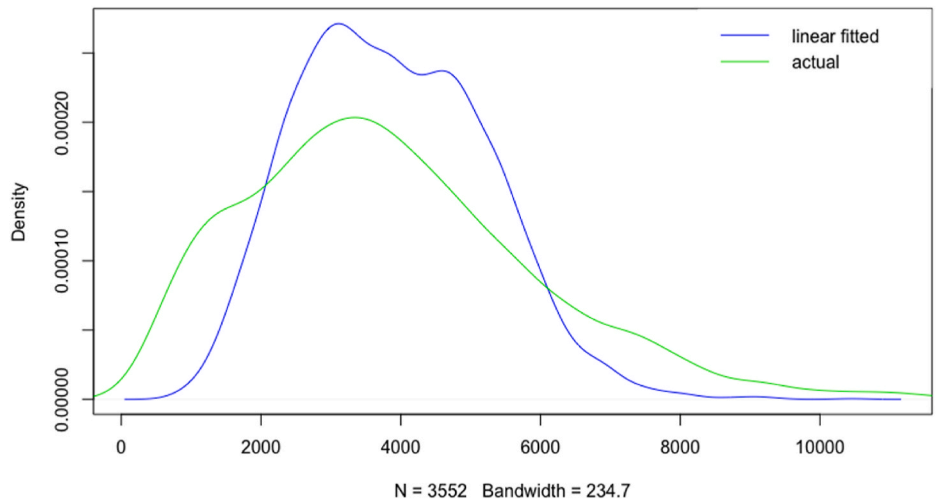

Fig. 3. Density of actual and modeled energy expenditure.

our case natural gas, is available to a household with no additional costs.[4] We use the energy poverty threshold set in the previous step. Gas is the only viable alternative[5] available to most households abandoning coal, brown coal, coke, firewood, and biomass in Poland. Our goal is to assess the impact of price switching on the energy poverty situation of households assuming the consumption patterns do not change. The new energy poverty rate identified in the second scenario is about 19.28%.

The rate of energy poverty computed in the second scenario increases by 2.79 p.p. compared to the first scenario. In other words, more households fall into energy poverty as a result of the shift to gas from dirty fuels. The distribution of energy poverty per income decile in two scenarios is presented in Fig. 4. Energy poverty mostly affects the first three and up to six income deciles in the first and the second scenarios, respectively. Even households with moderate income are pushed into energy poverty after switching to gas, ceteris paribus. This could be attributed to the fact that dirty fuels are cheaper than gas, which allows a number of households in Poland to save on energy expenditures. In the lower-income deciles, households apply different coping strategies to save on energy costs, such as self-restricting, among others.

To understand the change in the intensity of energy poverty, we estimate the shortfall of energy poor households from the threshold. Two indices, i.e. EPGI and EPSI, are valuable in this regard. The energy poverty line adopted in this study equals 60% of a national median after-energy-costs equivalised disposable income. The threshold produced in the first scenario is PLN 15,652.16 (about EUR 3400). Multiplied by the number of affected households, this threshold indicates the maximum policy costs, i.e., the costs with no targeting, of eliminating energy poverty in Poland.

Table 3 provides the descriptive statistics of the energy poverty gap obtained in the first and second scenarios. On average, energy-poor households lack annual equivalised after-energy-costs disposable income in the amount of PLN 4465 (about EUR 970) in the first scenario and PLN 5792 (about EUR 1250) in the second scenario to get out of the predicament. The interquartile range is quite high, especially in the second scenario, pointing to inequality among the energy poor. Some households are just below the line; others need substantial financial help to reach the energy poverty line. Extreme outliers are observed in the second scenario. Szpor and Lis (2016) who estimated the energy poverty gap based on the LIHC indicator provided estimates comparable to ours, that is, in 2014 EUR 76.00 per household in a month was needed to reach the energy poverty line.

The sum of all energy-poverty gaps reveals the minimum cost of eradicating energy poverty with perfect targeting, i.e., each household receives the amount sufficient to cover its gap. In the second scenario, households are pushed well below the line, and the minimum value of the energy poverty gap is much lower than in the first scenario. Facing higher energy costs, households have to decide whether to change the consumption behavior and keep the energy costs unchanged or whether further burden the budget.

The energy poverty rate increases from 16.49% in the first scenario to 19.28% in the second scenario. EPGI indicates the mean proportion of the energy-poverty gap to the threshold in the sample, where non-energy-poor households are assigned zero values. The EPGI is 0.047 in the first scenario and 0.080 in the second scenario. EPSI provides information on the position of energy poor households in the group of the energy poor, which means that a transfer from a more energy-poor household to a less energy-poor household increases the index. EPSI accounts for the transfer principle (Dalton, 1920). Households further below the energy-poverty line have a higher gap-to-threshold ratio than households marginally below the line. EPSI equals 0.023 in the first scenario and 0.048 in the second scenario.

The properties of EPGI and EPSI measures satisfy decomposability requirements and can be used in the analysis of energy poverty distribution by population subgroups. We divide the total sample into several collections of households by household types and economic activity statuses of the heads of the households.[6] Table 4 and Table 5 present the results obtained in the first and second scenarios respectively. In our study, a high energy poverty rate in a group is accompanied by a greater severity of the predicament.

In both scenarios, households led by inactive or retired heads demonstrate about three times higher incidence and depth of energy poverty compared to households with economically active heads. It is worth mentioning that the subgroup of households with children is the most affected among working groups. In one-person households, energy expenditures are not shared and fall on a single budget, which makes these households more vulnerable to energy poverty.

In the second scenario, we observe a higher incidence and depth of energy poverty compared to the first scenario. The most severely affected subgroups are one-person households with inactive or retired

[4] This is an optimistic scenario that assumes no further investments should be made to energy installation and connection to a gas grid.

[5] Gas is about two to three (depending on the tariff) times cheaper than electricity.

[6] All personal attributes, such as education, age, economic activity, marital and tenure statuses etc. reported in the HBS and the EGD belong to heads of households.

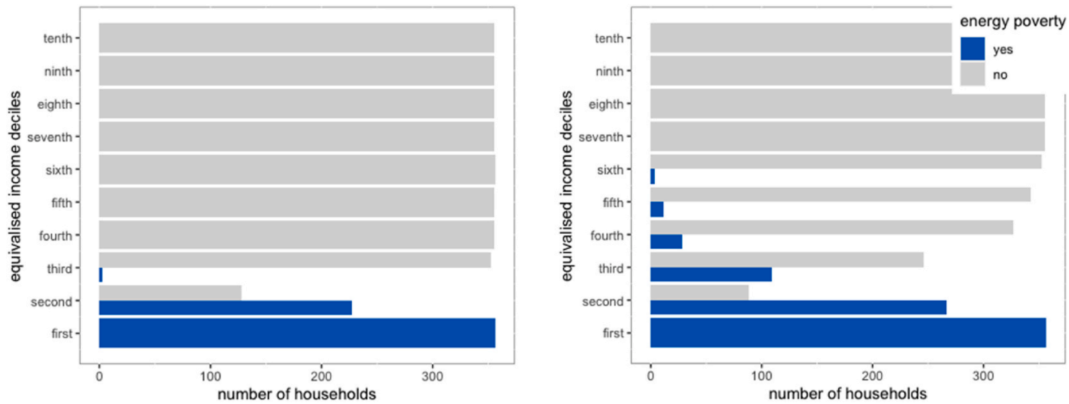

Fig. 4. Distribution of energy poverty across income deciles (scenario 1 – left panel, scenario 2 – right panel).

Table 3
Descriptive statistics of the energy poverty gap, EUR.

	min	1st Qu.	median	mean	3rd Qu.	max
Scenario 1	−4058.69	−1360.65	−743.04	−970.65	−335.65	−1.80
Scenario 2	−6167.39	−1860.21	−1043.04	−1259.13	−498.26	−1.56

Table 4
Incidence and depth of energy poverty by household types and economic activity (scenario 1).

Household type	Economic activity					
	Retired/inactive			Working		
	EP	EPGI	EPSI	EP	EPGI	EPSI
One-person	34.89%	0.090	0.037	7.73%	0.031	0.024
With children	31.03%	0.090	0.044	9.29%	0.028	0.016
Without children	15.08%	0.036	0.015	9.18%	0.023	0.010
Other	40.34%	0.131	0.063	6.44%	0.022	0.013

Table 5
Incidence and depth of energy poverty by household types and economic activity (scenario 2).

Household type	Economic activity					
	Retired/inactive			Working		
	EP	EPGI	EPSI	EP	EPGI	EPSI
One-person	45.96%	0.176	0.102	11.04%	0.056	0.046
With children	35.34%	0.128	0.077	12.18%	0.042	0.025
Without children	22.95%	0.077	0.045	14.55%	0.043	0.022
Other	47.21%	0.188	0.107	7.73%	0.031	0.019

heads, and a subgroup without children within a working category.

The transition to gas from dirty fuels has the greatest impact on households represented by retired or inactive heads. The rate of energy poverty grows in this subgroup by up to 11.07 p.p. The energy poverty gap measured by EPGI and EPSI increases significantly in a group of one-person households led by heads in inactive or retired status. The second vulnerable category is a one-person working subgroup that exists on a single budget.

The energy poverty indices indicate that the higher incidence of energy poverty in a particular population subgroup in Poland corresponds to the higher energy poverty gap and the greater severity of the predicament. The model captures household types falling well below the energy poverty line, such as one-person households, pensioners living alone, households represented by an inactive or retired head of household, and households with children. On the contrary, households with an economically active head of household are less affected by energy poverty. Shared energy costs make it easier for large households to cope with the challenges of energy consumption.

Poor insulation causes an excessive amount of consumed energy. To lower the costs of clean energy transitions, the policy must be accompanied by thermal modernization of residential buildings, which includes, among others, insulation of the outer walls, renovation of the window and door frames, installation of solar batteries, raising public awareness of energy efficiency and clean energy usage. At the moment, the level of thermal modernization in the country is estimated at 26% (maximum), while the number of gas connections varies between 68.7% and 11.9% (Bogacz, 2021).

It should be remembered that some of the houses are in poor technical condition and there is no economic justification for expensive thermo-modernization. For the group of households that live in such houses, it should be considered to maintain existing energy sources and, if necessary to provide a social support. It is also important to reduce the size of vulnerable groups by increasing their activity in the labor market and giving them the possibility to earn more income.

6. Conclusions

The study examines the prevalence and depth of energy poverty in Poland in two scenarios. In the first scenario, the modeled energy costs are used to estimate both the depth and the rate of energy poverty. In the second scenario, we assume that households switch from dirty fuels to gas ceteris paribus and estimate the impact of this decision on the prevalence and depth of energy poverty.

The main findings can be summarized as follows. First, currently about 16.5% of households in Poland are in hidden energy poverty. Energy poor households belong to the first three income deciles. The average energy poverty gap is estimated at PLN 4465 (approximately EUR 970) per household.

Second, replacing coal with gas in the household sector results in higher hidden energy poverty (19.3%). In this scenario, energy poverty affects up to six income deciles. The average energy poverty gap increases to PLN 5792 (about EUR 1250) per household. The annual cost of eliminating energy poverty per household with no targeting, that is, all households receive enough money to bring their annual equivalised after-energy-costs disposable income to the energy poverty line, equals PLN 15,652.16 (about EUR 3400).

Third, switching to gas results in a higher rate of energy poverty rate and a greater depth and severity of energy poverty in almost all subgroups. However, the retired and inactive one-person households subgroup is most at risk of increasing hidden energy poverty. In this group, the indices of energy poverty gap and energy poverty severity grow by 0.086 and 0.065 accordingly.

The energy transition is a huge but necessary challenge facing Europe and the world. Our study highlights the risks imposed on households associated with this transition. In particular, it points to the negative impact of this transition on vulnerable households, such as the higher level and depth of hidden energy poverty. Therefore, it is necessary to propose policies that protect vulnerable groups but also reduce the size of these groups, for example, by increasing labor force participation.

Our analysis of the energy poverty depth can be replicated as long as the assumptions of the hidden energy poverty model are maintained and microlevel data on the energy consumption in households are available. A similar questionnaire to the one we used in the study is collected in other EU countries, e.g., Latvia, Estonia, etc. The data that make it possible to estimate LIHC also provide a good basis for estimating the depth of energy poverty.

A certain limitation of the study is attributed to the specificity of the energy sources used by households in Poland, where coal and wood have the largest share in the heating of the space heating of single-family buildings. The predominance of solid fuels in the residential sector makes the transition to clean energy transition in Poland an important issue that has a strong impact on vulnerable groups. Meanwhile, the residential sector in other European countries differs in the composition of energy sources. In some countries, switching from higher-emitting to lower-emitting sources may not increase the burden on household budgets. All of this makes the replication of our study in other countries not straightforward and requires a detailed analysis of the characteristics of the energy sources used in the household sector.

In addition, our scenario does not account for the costs of gas connection, which are hard to estimate at the household level. However, the poorly developed natural gas pipeline network and a low level of building insulation in Poland create additional obstacles to the clean energy transition and the mitigation of energy poverty mitigation in the household sector. Accounting for the infrastructural costs of the clean energy transition in the assessment of energy poverty is a new scenario to be considered in future research.

Finally, in the second scenario, we assume that the transition does not involve improvements in residential energy efficiency. In other words, we assume the worst-case scenario from the point of view of household budgets. We do this to emphasise that the energy transition should be comprehensive and inclusive, because only then will it be accepted and have a chance to succeed.

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CRediT authorship contribution statement

Lilia Karpinska: Data curation, Writing – original draft, Visualization, Investigation, Software, Validation, Writing – review & editing, Conceptualization, Methodology. **Sławomir Śmiech:** Conceptualization, Methodology, Supervision, Visualization, Investigation, Software, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

Table A1
Variables from the EGD and the HBS

Variable	Category	Frequency
Type of building		
	Blocks of flats	46.32
	Single-family	47.30
	Other	6.36
Year of construction		
	before 1946	19.31
	in 1946–1960	12.21
	in 1961–1980	33.60
	in 1981–1995	19.87
	in 1996–2011	12.52
	after 2011	2.46
The total useable floor area of the apartment		
	up to 50 m^2	26.40
	50–100 m^2	46.63
	100–200 m^2	24.21
	above 200 m^2	2.74
Number of rooms		
	1 room	7.37
	2 rooms	30.46
	3 rooms	30.96
	4 rooms	14.82
	more than 4 rooms	16.36
Subjective evaluation of a building (has appropriate technical and sanitary conditions - efficient wastewater, water, electricity, gas, and heating installations; good condition of the roof, walls, floors, windows)		
	Yes	91.22
	No	8.77
Thermal comfort of a building (warm in winter and cool in summer)		
	Yes	86.85
	No	13.14

(*continued on next page*)

Table A1 (*continued*)

Variable	Category	Frequency
Subjective perception of a household's financial condition		
	Good	20.23
	rather good	21.07
	neither good nor bad	50.02
	rather bad	6.75
	Bad	1.90
Urban and rural areas		
	more than 500,000 inhabitants	8.77
	200,000–499,000 inhabitants	8.77
	100,000–199,000 inhabitants	7.53
	20,000–99,000 inhabitants	17.06
	less than 20,000 inhabitants	11.32
	Village	46.52
Household type		
	a couple, no dependent children	27.88
	a couple with one dependent child	9.05
	a couple with 2 dependent children	8.57
	a couple with 3 dependent children	1.96
	a couple with 4 and more dependent children	0.28
	mother with dependent children	1.73
	father with dependent children	0.19
	a couple with at least one dependent child and other adults	9.72
	mother with dependent children and other adults	2.04
	father with dependent children and other adults	0.22
	other households with dependent children	0.67
	one-person household	20.12
	Other	17.51
Voivodeship		
	Dolnośląskie	8.38
	kujawsko-pomorskie	5.80
	Lubelskie	6.86
	Lubuskie	2.94
	Łódzkie	7.17
	Małopolskie	6.86
	Mazowieckie	13.34
	Opolskie	2.41
	Podkarpackie	5.35
	Podlaskie	3.55
	Pomorskie	5.91
	Śląskie	10.39
	Świętokrzyskie	3.95
	warmińsko-mazurskie	4.56
	Wielkopolskie	8.40
	Zachodniopomorskie	4.06
Insulation in buildings		
	yes, entirely	62.04
	yes, partially	8.84
	No	27.95
	don't know	1.15

Notes: values are truncated up to two decimal points.

Table A2
Summary statistics for continuous variables, EUR

	Min	1st quartile	Median	Mean	3rd quartile	Max
Energy costs	19.5	508.6	782.6	845.4	1100.2	5343.4
Income	41.7	6521.7	10,434.7	12,286.9	15,334.7	131,847.8

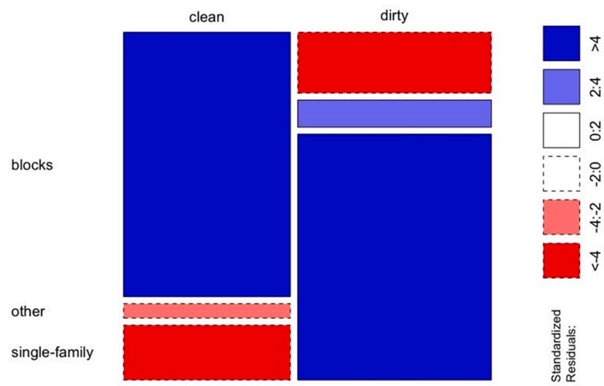

Fig. A1. Clean/dirty energy sources versus types of building distribution. Chi-square test of independence.

Table A3
Multiple linear regression and lasso regression results

Coefficients	Estimate	Std. Error	t value	Pr(>|t|)	Lasso estimate
(Intercept)	1564.641	247.994	6.309	0.000 ***	1949.493
Type of building: single-family	1109.558	103.596	10.710	0.000 ***	829.815
Type of building: other	931.341	142.765	6.524	0.000 ***	354.516
Year of construction: 1946–1960	−296.541	115.220	−2.574	0.010 *	.
Year of construction: 1961–1980	−182.836	97.713	−1.871	0.061.	.
Year of construction: 1981–1995	−115.037	108.247	−1.063	0.288	.
Year of construction: 1996–2011	−158.122	126.272	−1.252	0.211	.
Year of construction: after 2011	−664.203	216.790	−3.064	0.002 **	.
Total useable floor area	9.576	1.089	8.792	0.000 ***	10.810
Number of rooms	107.344	34.417	3.119	0.002 **	103.903
Building evaluation: no installation	−291.501	118.538	−2.459	0.014 *	.
Thermal comfort of a building: no	73.763	95.747	0.770	0.441	.
Financial condition: rather good	−119.714	95.841	−1.249	0.212	.
Financial condition: neither good nor bad	−98.046	87.902	−1.115	0.265	.
Financial condition: rather bad	−181.004	147.221	−1.229	0.219	.
Financial condition: bad	−378.757	237.696	−1.593	0.111	.
Urban and rural areas: 200,000–499,000 inhabitants	692.883	162.760	4.257	0.000 ***	.
Urban and rural areas: 100,000–199,000 inhabitants	363.598	167.282	2.174	0.030 *	.
Urban and rural areas: 20,000–99,000 inhabitants	645.154	134.709	4.789	0.000 ***	.
Urban and rural areas: less than 20,000 inhabitants	877.842	148.356	5.917	0.000 ***	.
Urban and rural areas: village	564.219	138.288	4.080	0.000 ***	.
Household type: a couple with one dependent child	−56.890	117.939	−0.482	0.630	.
Household type: a couple with 2 dependent children	145.121	121.864	1.191	0.234	.
Household type: a couple with 3 dependent children	356.910	228.609	1.561	0.119	.
Household type: a couple with 4 and more dependent children	1202.726	574.386	2.094	0.036 *	.
Household type: mother with dependent children	23.233	237.224	0.098	0.922	.
Household type: father with dependent children	−447.986	683.374	−0.656	0.512	.
Household type: a couple with at least one dependent child and other adults	454.790	118.645	3.833	0.000 ***	203.357
Household type: a mother with dependent children and other adults	410.129	219.218	1.871	0.061.	.
Household type: a father with dependent children and other adults	320.366	642.204	0.499	0.618	.
Household type: other households with dependent children	215.907	373.218	0.579	0.563	.
Household type: one person household	−410.569	92.207	−4.453	0.000 ***	−380.693
Household type: other	33.597	94.651	0.355	0.723	.
Income	0.089	0.011	8.056	0.000 ***	0.066
Voivodeship: kujawsko-pomorskie	288.640	168.211	1.716	0.086.	.
Voivodeship: lubelskie	−705.418	165.048	−4.274	0.000 ***	−236.276
Voivodeship: lubuskie	−275.489	207.107	−1.330	0.184	.
Voivodeship: łódzkie	198.856	160.125	1.242	0.214	.
Voivodeship: małopolskie	220.546	162.411	1.358	0.175	.
Voivodeship: mazowieckie	−80.033	140.955	−0.568	0.570	.
Voivodeship: opolskie	−160.754	224.528	−0.716	0.474	.
Voivodeship: podkarpackie	−250.287	174.886	−1.431	0.152	.
Voivodeship: podlaskie	−718.838	198.492	−3.621	0.000 ***	−165.810
Voivodeship: pomorskie	−402.707	169.775	−2.372	0.018 *	.
Voivodeship: śląskie	452.860	149.979	3.019	0.003 **	83.608
Voivodeship: świętokrzyskie	18.985	191.207	0.099	0.921	.
Voivodeship: warmińsko-mazurskie	79.528	179.801	0.442	0.658	.
Voivodeship: wielkopolskie	406.491	151.257	2.687	0.007 **	85.848
Voivodeship: zachodniopomorskie	−59.203	188.727	−0.314	0.754	.

(*continued on next page*)

Table A3 (*continued*)

Coefficients	Estimate	Std. Error	t value	Pr(>|t|)	Lasso estimate
Insulation: yes, partially	123.362	113.750	1.085	0.278	.
Insulation: no	290.289	80.452	3.608	0.000 ***	55.802
Insulation: don't know	95.858	285.873	0.335	0.737	.

Notes: Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.
Residual standard error: 1789 on 3500 degrees of freedom.
Multiple R-squared: 0.3619, adjusted R-squared: 0.3526.
F-statistic: 38.92 on 51 and 3500 degrees of freedom, p-value: < 0.00000000000000022.

Data statement

The research is based on micro-data from the Survey on Fuels and Energy Consumption in Households (2018) and the Household Budget Survey (2018). The data is provided by the Central Statistic Office in Poland (GUS). The data is confidential and is available at GUS upon request.

To obtain the data please visit https://stat.gov.pl/en/questions-and-orders/data-request-form/and fill in the request form.

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