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Predictors of fuel poverty and the equity of local fuel poverty support: secondary analysis of data from Bradford, England

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Abstract:

Aims
Addressing fuel poverty is a critical public health issue given its recent rise in prevalence across Europe. Although previous research identifies national risk markers of fuel poverty, evidence is lacking on whether these are consistent across local geographies, and the equity of local interventions. In the UK's current economic climate, it is more crucial than ever that services benefit households in greatest need.
This study aimed to determine significant predictors of fuel poverty among households in Bradford, England, comparing them to national-level predictors, and evaluate if households possessing significant fuel poverty predictors were equitably referred to a local fuel poverty service (Warm Homes Healthy People (WHHP)).

Methods
A multivariate logistic regression model determined significant fuel poverty predictors in Bradford using household-level data from the Energy Saving Trust and the Low Income High Costs fuel poverty definition. Statistical testing highlighted significant differences in predictors of fuel poverty between households referred to WHHP and all Bradford households.

Results
Significant ($p<0.05$) predictors of fuel poverty included: living in an area with lower average household incomes and higher proportion of ethnic minority individuals, and living in a property with a lower energy-efficiency rating. Households living in a detached or older property, and homeowners were more likely to be fuel poor. Differences in the direction of the relationship with fuel poverty were identified between some national and local predictors. Most predictors were significantly ($p<0.05$) overrepresented among WHHP households, suggesting equitable service reach. Ethnic minorities, younger people, and multi-person households were underrepresented.

Conclusions
Local fuel poverty predictors were similar to many national-level predictors, but identified differences in the direction of the relationship between some national and local predictors reaffirms the value of locally-focused research. WHHP successfully targeted households possessing key predictors, but should ensure that ethnic minorities, younger people and multi-person households are equitably referred.

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Predictors of fuel poverty and the equity of local fuel poverty support: secondary analysis of data from Bradford, England

Plain Language Summary

- The study aimed to identify features among households in Bradford, England, that increase risk of fuel poverty, and if households were fairly referred to a local fuel poverty service.
- Features increasing risk of fuel poverty among households in Bradford were similar to those nationally, including: low income, ethnic minority groups, homeowners, less energy-efficient homes, detached homes, and older homes.
- The service **effectively reached** households at greatest risk of fuel poverty, but **was less effective in reaching** ethnic minorities, younger people, and households containing more than one person. **This implies the service was broadly equitable, but some groups benefitted to a lesser extent.**
- Local-level research is useful to discover particular features that increase risk of fuel poverty among local populations rather than relying on national research. This approach should be repeated in other local areas so fuel poverty services can accurately target households most at risk of fuel poverty.

For Peer Review

Abstract

Aims

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Significant ($p<0.05$) predictors of fuel poverty included: living in an area with lower average household incomes and higher proportion of ethnic minority individuals, and living in a property with a lower energy-efficiency rating. Households living in a detached or older property, and homeowners were more likely to be fuel poor.

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Differences in the direction of the relationship with fuel poverty were identified between some national and local predictors. Most predictors were significantly ($p<0.05$) overrepresented among WHHP households, suggesting equitable service reach. Ethnic minorities, younger people, and multi-person households were underrepresented.

Conclusions

Local fuel poverty predictors were similar to many national-level predictors, but identified differences in the direction of the relationship between some national and local predictors reaffirms the value of locally-focused research. WHHP successfully targeted households possessing key predictors, but should ensure that ethnic minorities, younger people and multi-person households are equitably referred.

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Introduction

Fuel poverty, also known as energy poverty[1], is defined as a household's inability to afford to keep adequately warm to achieve a healthy standard of living at a reasonable cost[2]. Fuel poverty is a critical issue for public health, given its association with a multitude of health and socioeconomic consequences for households and wider society. In much of Europe, fuel poor households are at greater risk of damp, cold, and mouldy homes, leading to development or exacerbation of respiratory health issues (including asthma and infections such as influenza) and cardiovascular conditions (including strokes and heart attacks)[3,4]. Fuel poverty negatively impacts mental health[5] due to stress, anxiety and worry about finances and living conditions. Groups more vulnerable to fuel poverty include those

already living with these health conditions, older people, households with young children, and low income households[6]. People living in fuel poverty are more likely to have days off work and school, which can impact household finances and educational attainment[7,8]. There are also knock on effects for health care. For example, in England, annual NHS treatment costs related to illnesses caused by cold homes are estimated to be around £1.3 billion[9].

Three main drivers of fuel poverty widely discussed in the literature are income, energy efficiency, and energy prices[7], with recent research highlighting the complexity of interaction between these drivers and additional factors, including demographic and physical housing characteristics, and national and local policies that impact on energy prices and household expenditure[10,11].

Existing literature highlights key risk markers of and vulnerabilities to fuel poverty[11-16]. In England, most research on this topic is nationally focused, with significant characteristics influencing whether a household is living in fuel poverty grouped into three main categories: household income and employment[5,8,17], occupant demographics[10,18], and housing characteristics[5,18,19]. Energy consumption habits are also important to consider[20] but it is notable that these will not impact whether a household is deemed fuel poor according to current UK government definitions[21].

Yet while research identifies national risk markers of fuel poverty, evidence is lacking on whether these are consistent across local geographies. This information is crucial to enable locally-based intervention services to be aware of and equitably engage with populations most at risk of fuel poverty. Previous evaluations of fuel poverty initiatives in Europe highlight issues with targeting and reaching fuel poor homes[12-13,22]. There is a significant research gap in evaluating the equity of local

interventions. This is a particular concern in the UK given long-term cuts to local authority budgets and the ongoing cost-of-living crisis[17,23]: more than ever there is a need to ensure local funding and fuel poverty programmes benefit those who most need help.

This study aimed to address these gaps in the literature. Firstly, through determining significant predictors of fuel poverty in one local geography and exploring if and/or how these differ to national findings; and, secondly, by evaluating if households with significant local predictors of fuel poverty have been equitably referred into a local fuel poverty service, and thus if they are benefiting households in most need.

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Intervention site

Bradford, a district in West Yorkshire, England, with over half a million residents[24] was selected as an appropriate intervention site to explore risk markers of fuel poverty at a smaller geographic level as it has a different demographic structure and housing stock to the national average: a younger, more deprived population; higher proportion of ethnic minority individuals; an older housing stock, and higher proportion of privately rented homes compared to the national average. Bradford has higher than average rates of fuel poverty**, with 19.2% of households living in fuel poverty in 2021, compared to 13.1% nationally,** as measured by using the UK government's Low Income Low Energy Efficiency definition[25-28].

Furthermore, Bradford has a fuel poverty service - Warm Homes Healthy People (WHHP) - that has been operating for over a decade, with data from which it was possible to evaluate the equity of referrals. Initially funded by the Department of Health, but now commissioned by Bradford Council, WHHP aims to address the

impacts and underlying causes of fuel poverty by focusing on prevention and early intervention. **Multiple WHHP service providers work in partnership across Bradford, including the lead provider Groundwork, Bradford AgeUK, Inn Churches, and the HALE Project[29].**

WHHP provides services including energy supplier switching advice, installation of simple energy efficiency measures, and support for energy bills, debt, and benefits checks[29]. To be referred into WHHP, households must fit into one or more eligibility criteria (Table 1) to capture those most vulnerable to fuel poverty, based on national evidence[7]. **Referrals are via organisations including health and social care, voluntary sector, and educational establishments, or self-referral.**

Table 1 – Eligibility criteria for the WHHP service[29]

Household member(s) aged over 65
Household income below £16,190
Household member(s) with long term health condition
Household member(s) with a mental health condition
Household member(s) living with dementia
Household member(s) with a learning disability
Children under 5 in the household
Pregnant household member
Asylum seeker or refugee
In receipt of benefits
Accommodation in disrepair / not adequately heated
Experiencing/fleeing domestic abuse

Methods

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A retrospective, observational, cross-sectional design using secondary analysis was used. Measuring fuel poverty is challenging because it is a multi-dimensional concept[30]. **Since 2021 in England, fuel poverty has been measured using the 'Low Income Low Energy Efficiency' (LILEE) indicator. To be considered fuel poor using LILEE, a household's disposable income (after housing costs and energy needs, equivalised to account for the number of occupants) must be below the relative poverty line (60% below the median national household income) and they must live in a property with a Standard Assessment Procedure (SAP) Band of D or below. LILEE superseded the 'Low Income High Cost' (LIHC) indicator, which deemed a household to be fuel poor if it exceeded both a national income threshold (determined using the same methodology as LILEE) and a fuel cost threshold (weighted median of fuel costs of all households to keep at an adequate standard of warmth, equivalised to account for the number of occupants)[31].**

For this study, the LIHC indicator was used because it includes households living in more energy efficient homes (ie. SAP Band A to C properties), who cannot be classed as fuel poor using the LILEE indicator[31]. This was considered more appropriate as the WHHP service provides a range of interventions beyond energy efficiency improvements which could benefit any household living in fuel, regardless of SAP Band rating.

Ethical approval was not required as this secondary research study used anonymised datasets containing no identifiable information, in accordance with the [redacted] Ethics Committee policies. The datasets were used in accordance with a data sharing agreement agreed prior to the project. The raw datasets are compliant to GDPR regulations.

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All data cleaning and analysis was performed in R Studio version 4.2.1.

Aim 1: to determine significant local-level predictors of fuel poverty

The Home Analytics Database was used to determine significant predictors of fuel poverty among households in Bradford, provided to the West Yorkshire Combined Authority, including Bradford Council, by the Energy Saving Trust[32]. This dataset contains detailed information on every home across Bradford District as of November 2021, resulting in a raw sample size of 226,696 properties. It is a complete dataset with no missing values. The variables are a mixture of property-specific variables, and estimated variables based on small geographies in which the property is situated including census output areas (COA's), Lower-Level Super Output Areas (LSOA's), and Middle-Level Super Output Areas (MSOA's). If a **variable likely to be a predictor of fuel poverty was not present in the Home Analytics Database**, **an estimated value for each household was sourced from publicly-available datasets** (for example 2021 Census data) to ensure a comprehensive set of fuel poverty predictors could be included in the analysis. There were 22 variables eligible for inclusion in the final logistic regression model (Table 2).

The dependent variable was estimated fuel poverty status (fuel poor or not fuel poor), calculated by ranking homes by their relative fuel poverty probability, estimated by the Energy Saving Trust using the LIHC definition, and determining the top 19.2% homes (Bradford's estimated 2021 fuel poverty rate[25]) as those estimated to be living in fuel poverty.

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Table 2 – List of independent variables eligible to be included in the logistic regression model.

Variable name	Variable type	Geography	Source and year of data collection	Description
Individuals claiming benefits (%)	Continuous	Census Output Area	Energy Saving Trust, 2020[32]	The proportion of individuals in the area claiming at least one of the following benefits: Employment and Support Allowance, Universal Credit, Jobseekers Allowance, Disability Living Allowance, Income Support, Pension Credit. As reported by the Department for Work and Pensions.
Dependent children households (%)	Continuous	Census Output Area	UK Census, 2021[27]	The proportion of households in the area that contain one or more dependent children, defined as a person aged 0 to 15 years or a person aged 16 to 18 years who is in full-time education and lives in a family with their parent, parents, grandparent or grandparents.
Ethnic minority individuals (%)	Continuous	Census Output Area	UK Census, 2021[27]	The proportion of individuals in the area who are of an ethnic minority group, defined as any ethnic group apart from White British.
Single-person households (%)	Continuous	Census Output Area	UK Census, 2021[27]	The proportion of households in the area that contain one person living alone.
LSOA IMD rank	Continuous	Lower-Layer Super	Energy Saving	The LSOA's rank (out of all LSOAs in England) based on the

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Variable name	Variable type	Geography	Source and year of data collection	Description
		Output Area	Trust, 2019[32]	2019 Index of Multiple Deprivation (IMD) score in England.
Lone-parent households (%)	Continuous	Census Output Area	UK Census, 2021[27]	The proportion of households in the area that contain one parent with a dependent child (described above), living in a household with no other people.
Median age of individuals (Years)	Continuous	Census Output Area	ONS, 2020[24]	The median age in years of all individuals living in the area.
MSOA Income (£00's)	Continuous	Middle-Layer Super Output Area	Energy Saving Trust, 2018[32]	The median income (£ per annum) of households in the MSOA the property is located within. Figures represent net annual income, after housing costs. Based on ONS estimates.
Individuals in poor health (%)	Continuous	Census Output Area	UK Census, 2021[27]	The proportion of individuals in the area self-reporting as having bad or very bad general health.
Individuals seeking employment (%)	Continuous	Census Output Area	UK Census, 2021[27]	The proportion of individuals in the area of working age (16 to 64 years) who were economically active and unemployed, including people who were looking for work and could start within two weeks, or waiting to start a job that had been offered and accepted, excluding full-time students.
Underoccupied households (%)	Continuous	Census Output Area	UK Census, 2021[27]	The proportion of households in the area whose property has more bedrooms than required for the

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Variable name	Variable type	Geography	Source and year of data collection	Description
				occupants. The following should have their own bedroom: adult couple, any remaining adult (aged 21 years or over), two males/females (aged 10 to 20 years), one male/female (aged 10 to 20 years) and one male/female (aged 9 years or under) if there is an odd number of males/females aged 10 to 20 years, one male/female aged 10 to 20 years if there are no males/females aged 0 to 9 years to pair with him/her, two children (aged 9 years or under) regardless of sex, any remaining child (aged 9 years or under).
Unemployed individuals (%)	Continuous	Census Output Area	UK Census, 2021[27]	The proportion of individuals in the area of working age (16 to 64 years) who were either economically active and unemployed, or economically inactive due to long term sickness and disability, looking after home and family, or another reason given, excluding full-time students and retired individuals.
SAP Band rating	Categorical	Household	Energy Saving Trust, 2021[32]	The energy efficiency (SAP) band of the property.
Property age	Categorical	Household	Energy Saving Trust, 2021[32]	The time period the property was built.

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Variable name	Variable type	Geography	Source and year of data collection	Description
House type	Categorical	Household	Energy Saving Trust, 2021[32]	The type of property.
Tenure	Categorical	Household	Energy Saving Trust, 2021[32]	The type of housing tenure.
Estimated floor area (m^2)	Continuous	Household	Energy Saving Trust, 2021[32]	An estimate of the property's total floor area (m2).
Wall type	Categorical	Household	Energy Saving Trust, 2021[32]	The property's wall construction type.
Loft insulation	Categorical	Household	Energy Saving Trust, 2021[32]	Indicates whether the property has a loft and if so, what its insulation thickness is.
Wall insulation	Categorical	Household	Energy Saving Trust, 2021[32]	Indicates whether the property's walls are insulated.
Glazing type	Categorical	Household	Energy Saving Trust, 2021[32]	Indicates the main type of glazing on the property's windows.
Main fuel type	Categorical	Household	Energy Saving Trust, 2021[32]	The primary fuel type used to heat the property.

Associations between each independent variable and fuel poverty status were examined using univariate logistic regression models. Variables showing a significant association with fuel poverty, determined if $p<0.05$, were eligible to be included in a multivariate logistic regression model.

A multivariate logistic regression model was built to identify significant predictors of fuel poverty among Bradford households, using fuel poverty status as the dependent

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variable, and purposefully selected predictors of fuel poverty as independent variables. Model assumptions were tested and the model adjusted accordingly. All variables were entered into the final model simultaneously. Any independent variable in the final logistic regression model with $p<0.05$ was considered a statistically significant predictor of fuel poverty when all other factors were held constant.

Aim 2: to evaluate if households possessing significant predictors of fuel poverty were equitably referred to a local fuel poverty service

Data was provided by the lead WHHP service provider, Groundwork[29]. Demographic and housing characteristic data of each household is collected by Groundwork employees when conducting home visits to referred households. Data used in the analysis was collected between January 2018 to April 2023 and consisted of 1,588 **entries that included a household postcode within Bradford District and were therefore eligible to be utilised in the analysis**. Although this is a subset of all WHHP referrals in Bradford **as Groundwork work in partnership with multiple organisations who also provide the WHHP service,** the dataset is considered broadly representative of all households referred into the service **as Groundwork is the lead service provider and responsible for the majority of referrals**.

Variables **representative of those** found to be significant predictors of fuel poverty in Bradford, as determined by the final multivariate logistic regression model in Aim 1, were used in the WHHP analysis at household level (Table 3). All variables were contained in the dataset apart from SAP Band rating, individuals in poor health, and underoccupied households. As only the postcode of households referred to WHHP were included in the dataset, estimated SAP Band ratings were calculated by using

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the mean SAP Band rating for the household's postcode, derived from household level SAP Band ratings as of 31 May 2023[33]. Data for individuals in poor health and underoccupied households could not be accurately sourced so were not included in the analysis.

Table 3 - Variables used in the analysis of the WHHP data and the percentage of households in the total dataset (n=1,588) with a completed entry for the variable, January 2018 to April 2023.

Variable name	**Variable type**	**Percentage of households with a completed entry**
Annual household income (£s)	Continuous	6.4%
Employment status of household reference person	Categorical	59.3%
Receiving benefits	Categorical	*
Lone-parent household	Categorical	59.3%
Single-person household	Categorical	59.3%
Age of household reference person (Years)	Continuous	55.7%
Ethnicity of household reference person	Categorical	47.5%
Count of long-term health conditions of household reference person	Categorical	*
Mean SAP Band rating of postcode	Categorical	99.7%
Tenure status	Categorical	62.5%
Property type	Categorical	63.2%
Property build year	Categorical	41.6%
Number of bedrooms per household member	Categorical	35.1%

** The percentage of households with a completed entry is unknown due to the way in which the response, or unanswered question, was coded in the dataset provided.*

For each predictor of fuel poverty determined by the univariate and multivariate regression models, WHHP service reach was deemed equitable if there was a **statistically** significant difference in the predictor values of the WHHP households compared to all Bradford households in the same direction as the relationship of the predictor with fuel poverty, ie. the predictor characteristic was overrepresented among WHHP households compared to the Bradford average. If the direction of the

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relationship between fuel poverty and the predictor characteristic was opposite in the univariate and multivariate logistic regression models, the direction of the relationship in the univariate model would be used to determine equity as the **statistical tests used (described below) did not adjust for confounders, consistent with the univariate model**.

Bradford data was gained from the Home Analytics dataset used in Aim 1 (n=226,696 properties). For continuous variables, Mann-Whitney U tests were performed as all variables did not follow a normal distribution, with the null hypothesis being that there is no difference between the medians or mean ranks[34]. For categorical variables, a chi-square test of homogeneity was performed as all variables met the assumption that at least 80% of the expected frequencies were 5 or greater and all the expected frequencies have a value of at least 1. The null hypothesis was that the WHHP households had the same proportions of fuel poverty characteristics as all Bradford households. Null hypotheses were rejected if $p<0.05$.

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Results

Aim 1: to determine significant local-level predictors of fuel poverty

The univariate logistic regression (Table 4) showed that all independent variables were statistically significantly associated with fuel poverty, so could be included in the multivariate logistic regression model.

After rigorous assumption checking for the multivariate logistic regression model (see Supplementary material Section 1), the final model contained 226,489 data points and 13 variables. **The following variables were removed from the final model due to high collinearity with other variables: estimated floor area, wall**

type, loft and wall insulation, glazing type, main fuel type, LSOA IMD rank, households with dependent children, and unemployed individuals. All independent variables in the final model had a squared scaled general variance inflation factor (GVIF) value <4. The final model had good predictive power as demonstrated by the McFadden's R^2 statistic being 0.69 **and an area under the ROC curve value of 0.98** (see Supplementary material Section 2). The model (Table 4), showed that all predictor variables of fuel poverty remained significant after adjusting for the other independent variables in the model, apart from the 1983-1995 category in the property build year variable (p=0.22).

Continuous independent variables which increased the likelihood of households in Bradford being fuel poor after controlling for other independent variables in the model (Table 4) included living in an MSOA with lower average household income (OR=0.930, 95%CI=0.929–0.931), living in a census output area with a higher proportion of ethnic minority individuals (OR=1.026, 95%CI=1.024-1.027), individuals in poor health (OR=1.044, 95%CI=1.034-1.053), underoccupied households (OR=1.013, 95%CI=1.011-1.015), and a lower median age of individuals (OR=0.984, 95%CI=0.979-0.988). Households living in COAs with a smaller proportion of individuals seeking employment (OR=0.955, 95%CI=0.947-0.962) and lone-parent households (OR=0.959, 95%CI=0.954-0.963) were more likely to be fuel poor when all other variables were held constant. Households living in COAs with a lower proportion of single-person households (OR=0.991, 95%CI=0.989-0.994) or a higher proportion of benefits claimants (OR=1.008, 95%CI=1.004-1.012) were significantly more likely to be fuel poor, however the 95% CIs of these variables were close to 1.

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A lower SAP Band and older property age (except properties built <=13 years before the reference group, post-1996) significantly increased the likelihood of a household in Bradford being fuel poor (Table 4). The estimates of the SAP Bands were large, for example SAP Band F-G households were 383.58 times (95%CI=310.12-474.44) more likely to be fuel poor than SAP Band A-B households. The magnitude of the estimate and width of the confidence intervals may be influenced by the relatively small proportion of households in the reference group, SAP Band A-B (5% of all Bradford households), with only 0.3% of Bradford's fuel poor households having a SAP Band of A-B (see Supplementary material Section 3), reducing stability of the estimates.

Detached homes (the reference group) were most likely to be fuel poor out of all property types, followed by end- and mid-terraced houses (OR=0.62, 95%CI=0.56-0.68 and OR=0.58, 95%CI=0.53-0.63 respectively). Owner occupied houses (the reference group) were most likely to be fuel poor, followed by privately rented homes (OR=0.72, 95%CI=0.68-0.75).

Table 4 - Results of the univariate (unadjusted) and multivariate (adjusted) logistic regression model with fuel poverty as the dependent variable, presented to 3 decimal places for continuous variables (due to narrow confidence intervals) and 2 decimal places for categoric variables.

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Variable	Group	Unadjusted odds ratio (95% confidence interval)	p-value from univariate model	Adjusted odds ratio (95% confidence interval)	p-value from multivariate model
MSOA average income (£00's)	-	0.950 (0.949, 0.950)	<0.001	0.930 (0.929, 0.931)	<0.001
Individuals claiming benefits (%)	-	1.041 (1.04, 1.042)	<0.001	1.008 (1.004, 1.012)	<0.001
Individuals seeking employment (%)	-	1.248 (1.244, 1.252)	<0.001	0.955 (0.947, 0.962)	<0.001
Lone-parent households (%)	-	1.018 (1.017, 1.020)	<0.001	0.959 (0.954, 0.963)	<0.001
Single-person households (%)		0.973 (0.973, 0.974)	<0.001	0.991 (0.989, 0.994)	<0.001
Median age of individuals (Years)	-	0.829 (0.827, 0.831)	<0.001	0.984 (0.979, 0.988)	<0.001
Ethnic minority individuals (%)	-	1.057 (1.057, 1.058)	<0.001	1.026 (1.024, 1.027)	<0.001
Individuals in poor health (%)	-	1.071 (1.068, 1.074)	<0.001	1.044 (1.034, 1.053)	<0.001
Underoccupied households (%)	-	0.955 (0.954, 0.956)	<0.001	1.013 (1.011, 1.015)	<0.001
SAP Band	A-B (reference)	-	-	-	-
	C	1.59 (1.32, 1.9)	<0.001	1.52 (1.23, 1.88)	<0.001
	D	14.32 (12.08, 16.97)	<0.001	29.5 (24.18, 35.98)	<0.001

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Variable	Group	Unadjusted odds ratio (95% confidence interval)	p-value from univariate model	Adjusted odds ratio (95% confidence interval)	p-value from multivariate model
	E	56.59 (47.75, 67.05)	<0.001	180.06 (147.2, 220.25)	<0.001
	F-G	63.07 (53.06, 74.97)	<0.001	383.58 (310.12, 474.44)	<0.001
Property build year	Post-1996 (reference)	-	-	-	-
	1900-1929	13.03 (12.23, 13.88)	<0.001	2.54 (2.26, 2.84)	<0.001
	1930-1949	3.67 (3.43, 3.92)	<0.001	1.41 (1.26, 1.59)	<0.001
	1950-1966	2.39 (2.23, 2.55)	<0.001	1.87 (1.66, 2.11)	<0.001
	1967-1982	1.96 (1.83, 2.11)	<0.001	1.3 (1.16, 1.47)	<0.001
	1983-1995	1.14 (1.04, 1.25)	<0.05	1.09 (0.95, 1.26)	0.22
	Pre-1900	13.47 (12.65, 14.33)	<0.001	3.28 (2.93, 3.68)	<0.001
Property type	Detached house (reference)	-	-	-	-
	Block of flats	4.34 (4.09, 4.6)	<0.001	0.24 (0.21, 0.28)	<0.001
	End-terraced house	2.8 (2.65, 2.95)	<0.001	0.62 (0.56, 0.68)	<0.001
	Flat in mixed use building	3.2 (3.01, 3.41)	<0.001	0.19 (0.17, 0.22)	<0.001
	Large block of flats	1.89 (1.76, 2.02)	<0.001	0.14 (0.12, 0.16)	<0.001

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Variable	Group	Unadjusted odds ratio (95% confidence interval)	p-value from univariate model	Adjusted odds ratio (95% confidence interval)	p-value from multivariate model
	Mid-terraced house	6.31 (6.04, 6.6)	<0.001	0.58 (0.53, 0.63)	<0.001
	Semi-detached house	1.45 (1.38, 1.51)	<0.001	0.51 (0.47, 0.55)	<0.001
	Small block of flats/dwelling converted in to flats	1.09 (1.02, 1.16)	<0.05	0.24 (0.21, 0.27)	<0.001
Tenure	Owner occupied (reference)	-	-	-	-
	Housing Association	0.43 (0.41, 0.44)	<0.001	0.42 (0.39, 0.45)	<0.001
	Local Authority	0.3 (0.2, 0.44)	<0.001	0.47 (0.27, 0.82)	<0.05
	Privately Rented	1.62 (1.58, 1.66)	<0.001	0.72 (0.68, 0.75)	<0.001

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Aim 2: to evaluate if households possessing significant predictors of fuel poverty were equitably referred to a local fuel poverty service

Tables 5 and 6 present comparisons, including significance testing, of demographics and household characteristics of the WHHP households compared to all Bradford households. An overview of the tables is provided below.

The pattern of referrals for income and employment variables was as expected, with WHHP households having significantly lower median household income, and a significantly higher proportion of household reference persons (HRPs) seeking employment and receiving benefits compared to the Bradford average.

For occupant demographic variables, a significantly higher proportion of WHHP households were lone-parent households than the Bradford average which was the expected direction according to the regression results. However, for single-person households and median age of HRPs the pattern of referrals was in the opposite direction to expected, with a significantly higher proportion of single-person households and older HRPs among the WHHP households compared to the Bradford average. There was no significant difference between the proportion of ethnic minority households among WHHP households and the Bradford average, in contrast to the regression results which showed that ethnic minority households are significantly more likely to be fuel poor.

The pattern of referrals for housing characteristic variables was as expected, with a significantly higher proportion of WHHP households living in a postcode with lower energy efficiency properties (mean SAP Band of D or below), a significantly higher proportion living in older properties (built before 1967), and a significantly lower proportion of WHHP households being homeowners and living in detached properties compared to the Bradford average.

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Table 5 - Results of Mann-Whitney U test for continuous variables deemed significant predictors of fuel poverty in Bradford, comparing households in the Warm Homes Healthy People Programme (WHHP) with all households in Bradford. The final column indicates if the difference in values between the WHHP respondents and total Bradford population is in the same direction as expected from the regression results (Table 4).

Variable	WHHP respondents (n)	WWHP median	Bradford median	U-Statistic	p-value	Estimate (95% confidence intervals)	Expected direction based on regression results
Annual household income (£s)	101	14,000.00	36,600.00	1,639,571	<0.001	-21,400.00 (-22,700.00, -20,000.00)	Yes
Age (Years) – 17+ only	885	47.00	46.00	193,941,521	<0.001	3.00 (1.00, 4.00)	No

Table 6 – Results of chi-square test of homogeneity for categorical variables deemed significant predictors of fuel poverty in Bradford, comparing households in the Warm Homes Healthy People Programme (WHHP) with all households in Bradford. The final column indicates if the difference in values between the WHHP respondents and total Bradford population is in the same direction as expected from the regression results (Table 4).

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Variable	WHHP respondents (n)	WHHP proportion (%) and 95% CIs	Bradford households (n)	Bradford proportion (%) and 95% CIs	Chi-square test statistic	P-value	Expected direction based on regression results
Proportion of benefits claimants	1,588	44.33 (41.89, 46.77)	226,696	17.39 (17.23, 17.55)	795.21	<0.001	Yes
Proportion seeking employment	941	21.04 (18.44, 23.64)	226,696	3.62 (3.54, 3.70)	802.41	<0.001	Yes
Proportion of lone-parent households	942	21.23 (18.62, 23.84)	226,696	8.99 (8.87, 9.11)	169.38	<0.001	Yes
Proportion of single-person households	942	36.09 (33.02, 39.16)	226,696	30.78 (30.59, 30.97)	12.17	<0.05	No
Proportion of people from an ethnic minority	755	41.72 (38.20, 45.24)	226,696	43.28 (43.08, 43.48)	0.69	0.41	No
Proportion of households in SAP Band's D, E, F or G	1,588	79.79 (77.81, 81.77)	226,696	71.37 (71.18, 71.56)	54.11	<0.001	Yes
Proportion of home owners	992	35.28 (32.31, 38.25)	226,696	64.32 (64.12, 64.52)	361.17	<0.001	Yes
Proportion of people living in	1,004	4.18 (2.94, 5.42)	226,696	12.99 (12.85, 13.13)	67.97	<0.001	Yes

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Variable	WHHP respondents (n)	WHHP proportion (%) and 95% CIs	Bradford households (n)	Bradford proportion (%) and 95% CIs	Chi-square test statistic	P-value	Expected direction based on regression results
detached properties							
Proportion of people living in properties built before 1967	661	75.04 (71.74, 78.34)	226,696	66.50 (66.31, 66.69)	21.18	<0.001	Yes

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Discussion

The results of the multivariate logistic regression model showed that after holding all other variables constant, households in Bradford were significantly more likely to be fuel poor if they lived in an area with lower average household income, a lower average age of individuals, and a higher proportion of ethnic minority individuals, individuals in poor health, and benefits claimants. A higher proportion of individuals seeking employment, lone-parent households, and single-person households in the area significantly reduced the likelihood of being fuel poor. In terms of housing characteristics, older properties, detached homes, owner-occupied homes, and underoccupied households were most likely to be living in fuel poverty. **Households living in properties with a lower SAP Band rating were also significantly more likely to be fuel poor, with large odds ratios, indicating SAP Band could be a strong predictor and efficient criterion for identifying fuel poor households,**

but the estimates for this variable may be unstable due to relatively low frequencies of fuel poor households in the reference category (SAP Band A-B). Although significantly associated with fuel poverty as shown by the respective univariate regression models, LSOA IMD rank, proportion of households with dependent children, and additional property characteristics related to energy efficiency (household floor area, fuel type, glazing type, loft insulation, wall type, and wall insulation) were removed from the final multivariate regression model due to high collinearity with other variables. **This local information enables local fuel poverty interventions to target those most at risk of fuel poverty in Bradford, rather than relying on national estimates which has been the focus of most previous research in the UK[8,10,15,18,19,35].**

These findings largely agree with previous research on national risk markers of fuel poverty[15,18,19], with predictors in Bradford covering all three main categories of household income and employment, occupant demographics, and housing characteristics, however the direction of the relationship of some variables with fuel poverty in the final multivariate model (namely lone-parent households, property type, and tenure) was found to be inverse to that of some national research[18], **discussed below.**

Households in areas with a higher proportion of lone-parent households were less likely to be fuel poor in Bradford **after controlling for other predictors**, whereas national research suggests that they are more likely to be fuel poor than other households compositions[18,35], **consistent with the univariate regression findings.** Households living in detached homes were most likely to be fuel poor in Bradford **after controlling for other predictors**, whereas national research indicates they are least likely to be fuel poor[18], **consistent with the univariate regression findings.**

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Homeowners were most likely to be fuel poor in Bradford **after controlling for other predictors**, whereas national research suggests privately rented households are most likely to be fuel poor[5,18,35], **consistent with the univariate regression findings. Possible explanations for these differences include** using different **definitions** of fuel poverty, or adjusting for confounders in the final multivariate regression model in the study which **had not been** adjusted for in previous national research. These differences reaffirm the complexity of the relationship between fuel poverty and household characteristics, and the challenge of measuring fuel poverty.

Previous evaluations of schemes similar to WHHP were largely process evaluations which did not consider equity or provide in-depth service-user demographics[36], highlighting the value of this study to fill a research gap. Most predictors of fuel poverty in Bradford were significantly overrepresented among WHHP households compared to the Bradford average, suggesting the targeting and reach of the WHHP service was equitable for the majority of predictors of fuel poverty. This is a positive finding and contrasts with other evaluations of fuel poverty schemes that highlight poor targeting of fuel poor households[12,13,22]. This novel insight shows the potential benefit of local interventions such as WHHP who **possess in-depth knowledge** about the local demographic and housing context of areas **and have developed meaningful partnerships with well-established local organisations, increasing the likelihood of successfully targeting and engaging with households most vulnerable to fuel poverty.** This is particularly important to mitigate the impacts of the ongoing cost-of-living crisis[17,23] and documented failures in the UK's wider social security system[37].

However, some variables showed no significant overrepresentation or were underrepresented in WHHP households, namely ethnicity, multi-person households,

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and younger household-reference persons, even though they have been identified as national predictors of fuel poverty [8,19] and were important local predictors in this study. This indicates that service reach may not be completely equitable, and there is a need for these disparities to be explored further.

Limitations and further research

As a number of variables were estimated using small-area geography averages due to lack of household-level data, particularly demographic characteristics, future research studies should collect appropriate household-level data for all fuel poverty-related variables to improve internal validity of the study findings and remove possibility of ecological fallacy. **The majority of variables in the regression model to determine predictors of fuel poverty utilised 2021 data, whereas the data from WHHP households was collected over 5 years (2018 to 2023), a likely period of change in some household characteristics such as income and employment status due to impacts of the COVID-19 pandemic and cost-of-living crisis. Future studies should aim to collect household data over a shorter time period to ensure all variables represent a specific time point.**

Some WHHP variables had over 50% of entries missing (Table 3), reducing the power of the study. There was also an issue with determining data completeness for two variables (long-term conditions and benefits) due to the question format, meaning it was unknown whether a blank response meant the respondent did not answer the question or did not have any long-term conditions/receive any benefits. This resulted in the total proportion of long-

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term conditions and benefits claimants in the WHHP population likely being underreported.

Due to risks of non-response bias, selection bias, and poor questionnaire validity in the current dataset which must be reviewed and minimised, further research should explore the inequities highlighted in more detail and determine possible explanations via interviews and focus groups with representative populations, in addition to obtaining and analysing data from the other providers in the WHHP partnership **beyond the lead provider, Groundwork**. This will allow future interventions to be developed to ensure that the WHHP service successfully engages with all households most likely to be living in fuel poverty.

Conclusions

Significant predictors of fuel poverty for households in one local area in England (Bradford) were similar to previously researched national predictors of fuel poverty, covering all three main categories of household income and employment, occupant demographics, and housing characteristics. However, identified differences between the direction of the relationship of some national and local predictors of fuel poverty reaffirm the complex relationship between fuel poverty and multiple household characteristics, and highlight the usefulness and need for research on local predictors of fuel poverty.

The WHHP service equitably reaches fuel poor households in Bradford across the majority of predictors of fuel poverty. However, ethnic minority groups, younger people, and households containing more than one individual are seemingly underrepresented in the service. This knowledge is vital to appropriately target

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resources during the ongoing cost-of-living crisis and cuts to local budgets, and has filled a research gap around assessing the equity of a local fuel poverty intervention.

This approach should be reproduced among other local authorities across England to ensure fuel poverty services effectively target local households most at risk of fuel poverty rather than relying on national averages.

Acknowledgments

Ethical approval

Ethical approval was not required as this secondary research study used anonymised datasets containing no identifiable information, in accordance with the [redacted] Ethics Committee policies. The datasets were used in accordance with a data sharing agreement agreed prior to the project. The raw datasets are compliant to GDPR regulations.

Competing interests

This research was carried out as part of Public Health Registrar Training, supported by Health Education England and whilst on placement with [redacted], supervised by [redacted] academics. [redacted] works with the [redacted].

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[redacted] [grant reference [redacted]]. [redacted] post is funded by a [redacted] [grant reference [redacted]].

References

1. Li K, Lloyd B, Liang X-J, et al. Energy poor or fuel poor: What are the differences? *Energy Policy* 2014; 68: 476–481.
2. Boardman B. *Fuel Poverty: From Cold Homes to Affordable Warmth*. London: Belhaven Press, 1991.
3. de Vries R, Blane D. Fuel poverty and the health of older people: the role of local climate. *Journal of Public Health* 2013; 35: 361–366.
4. Institute of Health Equity. Fuel Poverty, Cold Homes and Health Inequalities in the UK, https://www.instituteofhealthequity.org/resources-reports/fuel-poverty-cold-homes-and-health-inequalities-in-the-uk (2022, accessed 3 July 2023).
5. Institute of Health Equity. The Health Impacts of Cold Homes and Fuel Poverty, https://www.instituteofhealthequity.org/resources-reports/the-health-impacts-of-cold-homes-and-fuel-poverty (2011, accessed 3 July 2023).
6. National Institute of Health and Care Excellence (NICE). Excess winter deaths and illness and the health risks associated with cold homes, https://www.nice.org.uk/guidance/ng6/chapter/what-is-this-guideline-about (2015, accessed 3 July 2023).
7. Hills J. Getting the Measure of Fuel Poverty: Final Report of the Fuel Poverty Review. GOV.UK, https://www.gov.uk/government/publications/final-report-of-the-fuel-poverty-review (2012, accessed 3 July 2023).

For Peer Review

8. Middlemiss L. Who is vulnerable to energy poverty in the Global North, and what is their experience? *WIREs Energy and Environment* 2022; 11: e455.
9. NHS Confederation. Could the energy crisis cause a public health emergency?, https://www.nhsconfed.org/long-reads/could-energy-crisis-cause-public-health-emergency (2022, accessed 13 October 2023).
10. Robinson C, Lindley S, Bouzarovski S. The Spatially Varying Components of Vulnerability to Energy Poverty. *Annals of the American Association of Geographers* 2019; 109: 1188–1207.
11. Mould R, Baker KJ. Uncovering hidden geographies and socio-economic influences on fuel poverty using household fuel spend data: A meso-scale study in Scotland. *Indoor and Built Environment* 2017; 26: 914–936.
12. März S. Assessing the fuel poverty vulnerability of urban neighbourhoods using a spatial multi-criteria decision analysis for the German city of Oberhausen. *Renewable and Sustainable Energy Reviews* 2018; 82: 1701–1711.
13. Walker R, Liddell C, McKenzie P, et al. Fuel poverty in Northern Ireland: Humanizing the plight of vulnerable households. *Energy Research & Social Science* 2014; 4: 89–99.
14. Gouveia JP, Seixas J, Long G. Mining households' energy data to disclose fuel poverty: Lessons for Southern Europe. *Journal of Cleaner Production* 2018; 178: 534–550.
15. Robinson C, Bouzarovski S, Lindley S. 'Getting the measure of fuel poverty': The geography of fuel poverty indicators in England. *Energy Research & Social Science* 2018; 36: 79–93.

For Peer Review

16. Imbert I, Nogues P, Sevenet M. Same but different: On the applicability of fuel poverty indicators across countries—Insights from France. *Energy Research & Social Science* 2016; 15: 75–85.
17. University of York. Cost of living crisis: fuel poverty, https://www.york.ac.uk/business-society/research/spsw/cost-living-crisis-fuel-poverty/ (2023, accessed 1 August 2023).
18. Department for Business, Energy & Industrial Strategy (BEIS). Annual fuel poverty statistics report: 2022 (2020 data), https://www.gov.uk/government/statistics/annual-fuel-poverty-statistics-report-2022 (2022, accessed 4 July 2023).
19. Department for Business, Energy & Industrial Strategy (BEIS). Modelling the likelihood of being fuel poor, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/266469/likelihood_of_being_fuel_poor.pdf (2013, accessed 4 July 2023).
20. Kearns A, Whitley E, Curl A. Occupant behaviour as a fourth driver of fuel poverty (aka warmth & energy deprivation). *Energy Policy* 2019; 129: 1143–1155.
21. House of Commons Library. Fuel poverty in the UK, https://commonslibrary.parliament.uk/research-briefings/cbp-8730/ (2023, accessed 5 July 2023).
22. Boardman B. *Fixing Fuel Poverty: Challenges and Solutions*. London: Earthscan, 2010.
23. Broadbent P, Thomson R, Kopasker D, et al. The public health implications of the cost-of-living crisis: outlining mechanisms and modelling consequences. *Lancet Reg Health Eur* 2023; 27: 100585.

For Peer Review

24. Office for National Statistics. Population and household estimates, England and Wales, https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/bulletins/populationandhouseholdestimatesenglandandwales/census2021unroundeddata (2022, accessed 3 July 2023).
25. Department for Energy Security and Net Zero and Department for Business, Energy & Industrial Strategy. Fuel poverty statistics. GOV.UK, https://www.gov.uk/government/collections/fuel-poverty-statistics (2023, accessed 4 July 2023).
26. Ministry of Housing, Communities and Local Government. English indices of deprivation 2019. GOV.UK, https://www.gov.uk/government/statistics/english-indices-of-deprivation-2019 (2019, accessed 4 July 2023).
27. Office for National Statistics. Topic Summaries - 2021 Census, https://www.nomisweb.co.uk/sources/census_2021_ts (2023, accessed 4 July 2023).
28. Office for National Statistics. Households by housing tenure and combined economic activity status of household members: Table D, https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/employmentandemployeetypes/datasets/workingandworklesshouseholdstabledhouseholdsbyhousingtenureandcombinedeconomicactivitystatusofhouseholdmembers (2023, accessed 8 August 2023).
29. Groundwork. Groundwork Homepage, https://www.groundwork.org.uk/ (2023, accessed 5 July 2023).
30. Dubois U. From targeting to implementation: The role of identification of fuel poor households. *Energy Policy* 2012; 49: 107–115.

For Peer Review

31. Department for Business, Energy & Industrial Strategy (BEIS). Sustainable warmth: protecting vulnerable households in England. GOV.UK, https://www.gov.uk/government/publications/sustainable-warmth-protecting-vulnerable-households-in-england (2021, accessed 3 July 2023).
32. Energy Saving Trust. Home Analytics, https://energysavingtrust.org.uk/service/home-analytics/ (2022, accessed 3 July 2023).
33. Department for Levelling Up, Housing & Communities. Energy Performance of Buildings Data England and Wales, https://epc.opendatacommunities.org/login (2023, accessed 31 July 2023).
34. Bland M. *An Introduction to Medical Statistics*. 4th ed. Oxford: Oxford University Press, 2015.
35. Keung A, Bradshaw J. Who are the fuel poor? University of York, https://www.york.ac.uk/media/business-society/research/Who_are_the_fuel_poor_revised_v2.pdf (2023, accessed 11 March 2023).
36. **Public Health England. Warm home fund helped vulnerable residents, https://www.gov.uk/government/news/warm-home-fund-helped-vulnerable-residents (2013, accessed 30 August 2023).**
37. Changing Realities. 'Terrified for this winter': Why the cost-of-living crisis is far from over for families on a low income. Changing Realities, https://changingrealities.org/ (2023, accessed 3 November 2023).

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Supplementary Material for Predictors of fuel poverty and the equity of local fuel poverty support: secondary analysis of data from Bradford, England

1. Assumption checking for the multivariate logistic regression model

1.1. Assumption checking – sufficiently large sample size

It was estimated that 19.7% of households are fuel poor in the dataset, and there would be a maximum of 22 independent variables. Therefore, the minimum sample size required would be 10*22/0.197 = 1,117 households. As there are over 200,000 households in the dataset this assumption was met.

1.2. Assumption checking - multicollinearity

It was decided to exclude energy efficiency variables that will influence a property's SAP rating (estimated floor area, wall type, loft and wall insulation, glazing type, and main fuel type) from the final model as there was likely to be collinearity and duplication of information, confirmed by appropriate chi-square and Kruskal-Wallis tests (Tables S.1 and S.2) which showed a statistically significant ($p<0.001$) association for all variables and SAP rating. The energy efficiency variables, rather than the SAP Band rating variable, were chosen to be excluded as they had mainly been estimated in the dataset, so have greater risk of being incorrect, and there is no up-to-date record of these property characteristics for all households in Bradford so it would be impractical to target fuel poverty intervention to households with these characteristics. Whereas, the household's SAP rating, which has been produced for each household, is a freely available and more comprehensive predictor of energy

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efficiency, making it a more practical metric to use to identify households most likely to be living in fuel poverty in Bradford.

Table S.1 - Chi-square test of independence to check for collinearity between SAP rating bands and categoric energy efficiency variables.

Variable	**Chi-square test statistic**	**P-value**	**Degrees of freedom**
Main fuel type	25,727.77	<0.001	20
Glazing type	6,544.82	<0.001	4
Loft insulation estimate	69,046.71	<0.001	12
Wall construction	21,901.31	<0.001	12
Wall insulation estimate	70,382.70	<0.001	4

Table S.2 - Kruskal-Wallis test to check for collinearity between SAP rating bands and floor area estimate (a continuous variable).

Variable	**Kruskal-Wallis test statistic**	**P-value**	**Degrees of freedom**
Floor area estimate	23,892.42	<0.001	4

A correlation matrix heatmap (Figure S.1) was produced for all independent continuous variables. It showed that the correlation coefficient between LSOA IMD rank and MSOA income was above 0.8, a strong positive relationship, and therefore one of these variables should be removed from the final model. LSOA IMD rank had the higher squared scaled GVIF values (Table S.3) of the initial model (2.31 vs 2.15), it was determined that this was most appropriate to exclude from future iterations of the model as it was demonstrating stronger colinear relationships with other variables in the model.

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GVIF values (Table S.3) were then reproduced using the amended model (excluding LSOA IMD rank), and the households with dependent children variable showed the highest squared scaled GVIF value (11.16), so was removed from the model. This process was repeated again, with the unemployed individuals variable having the next highest GVIF value (5.57). Once these three variables were removed from the model, no variables had a squared scaled GIVF value >4 so could remain in the analysis as the assumption that there was little multicollinearity between independent variables was satisfied.

Figure S.1 - Correlation matrix plot between all continuous independent variables.

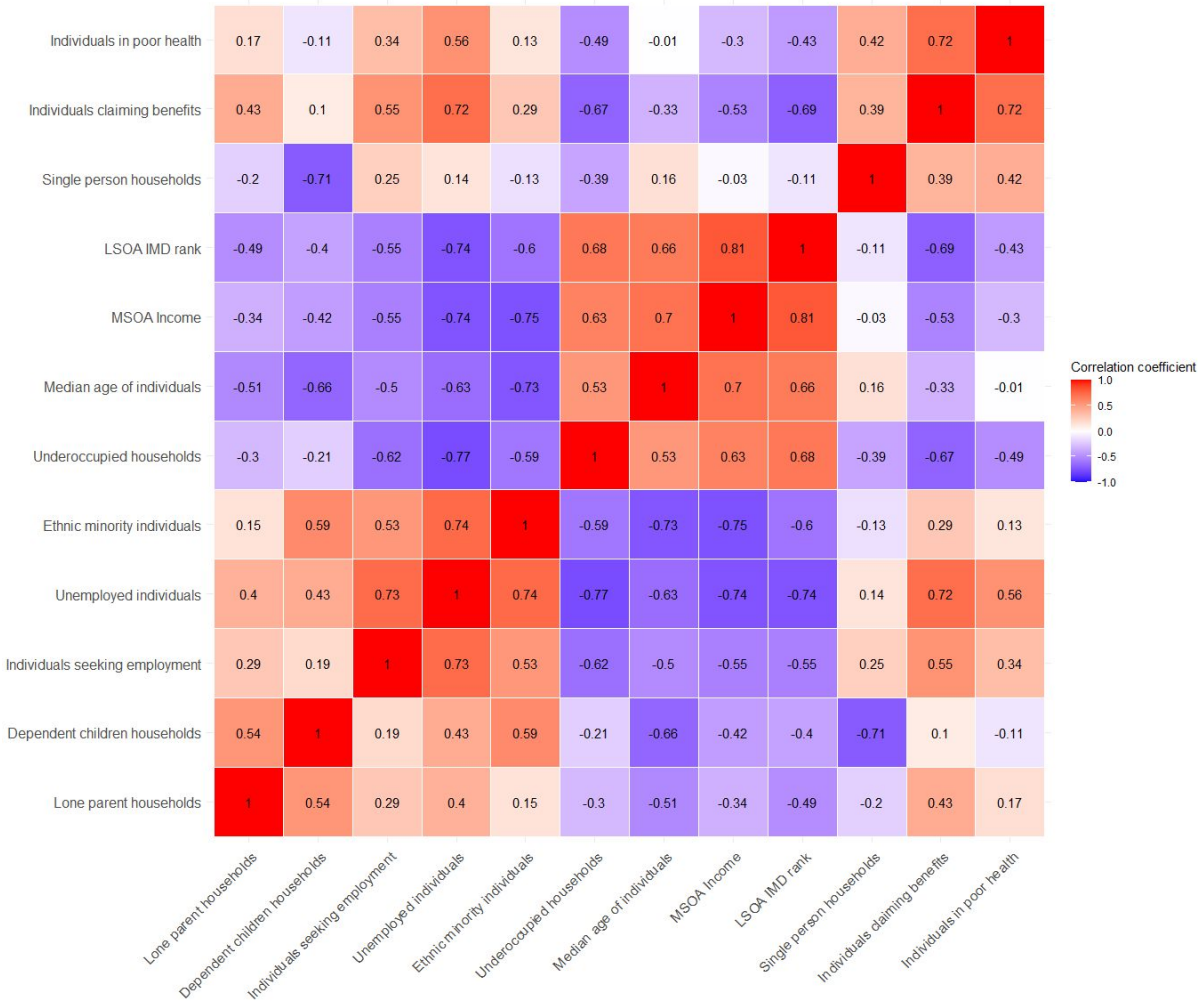

Table S.3 - Squared scaled generalised variance inflation factor (GVIF) values after systematically removing variables with the highest values (>4) and repeating the modelling process. The variables removed in each model can be identified as they have a blank GVIF value (represented by '-').

Variable	Squared scaled GVIF (model 1)	Squared scaled GVIF (model 2)	Squared scaled GVIF (model 3)	Squared scaled GVIF (model 4)
Property type	1.21	1.21	1.21	1.21
Tenure	1.16	1.16	1.15	1.15
Property age	1.17	1.17	1.17	1.17
SAP rating band	1.14	1.14	1.14	1.14
LSOA IMD rank	2.31	-	-	-
MSOA Income (£00's)	2.15	2.02	2.00	1.99
Median age of individuals (Years)	3.51	3.47	3.33	3.21
Individuals claiming benefits (%)	3.64	3.37	3.28	2.98
Lone-parent households (%)	2.49	2.48	2.06	2.05
Dependent children households (%)	11.17	11.16	-	-
Single-person households (%)	8.18	8.17	2.89	2.86
Underoccupied households (%)	2.94	2.89	2.81	2.73
Unemployed individuals (%)	5.79	5.81	5.57	-
Individuals seeking employment (%)	1.91	1.91	1.86	1.61
Ethnic minority individuals (%)	4.86	4.87	4.29	3.40
Individuals in poor health (%)	2.67	2.67	2.58	2.15

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1.2.1.1. Assumption checking – influential outliers

Using the model with all independent variables deemed to be multicollinear removed, there were 15,094 data points considered influential in the dataset as their Cook's distance value was greater than 4/n (Figure S.2). 207 data points were deemed to be a possible extreme outlier as their absolute standardised residual value was >3 (Figure S.3). All 207 possible extreme outliers were also deemed to be influential, so were removed from the dataset in the final model.

Figure S.2 - Cook's distance plot showing the influence of each data point in the dataset with the threshold line in red where data points above this line are deemed to be potentially influential.

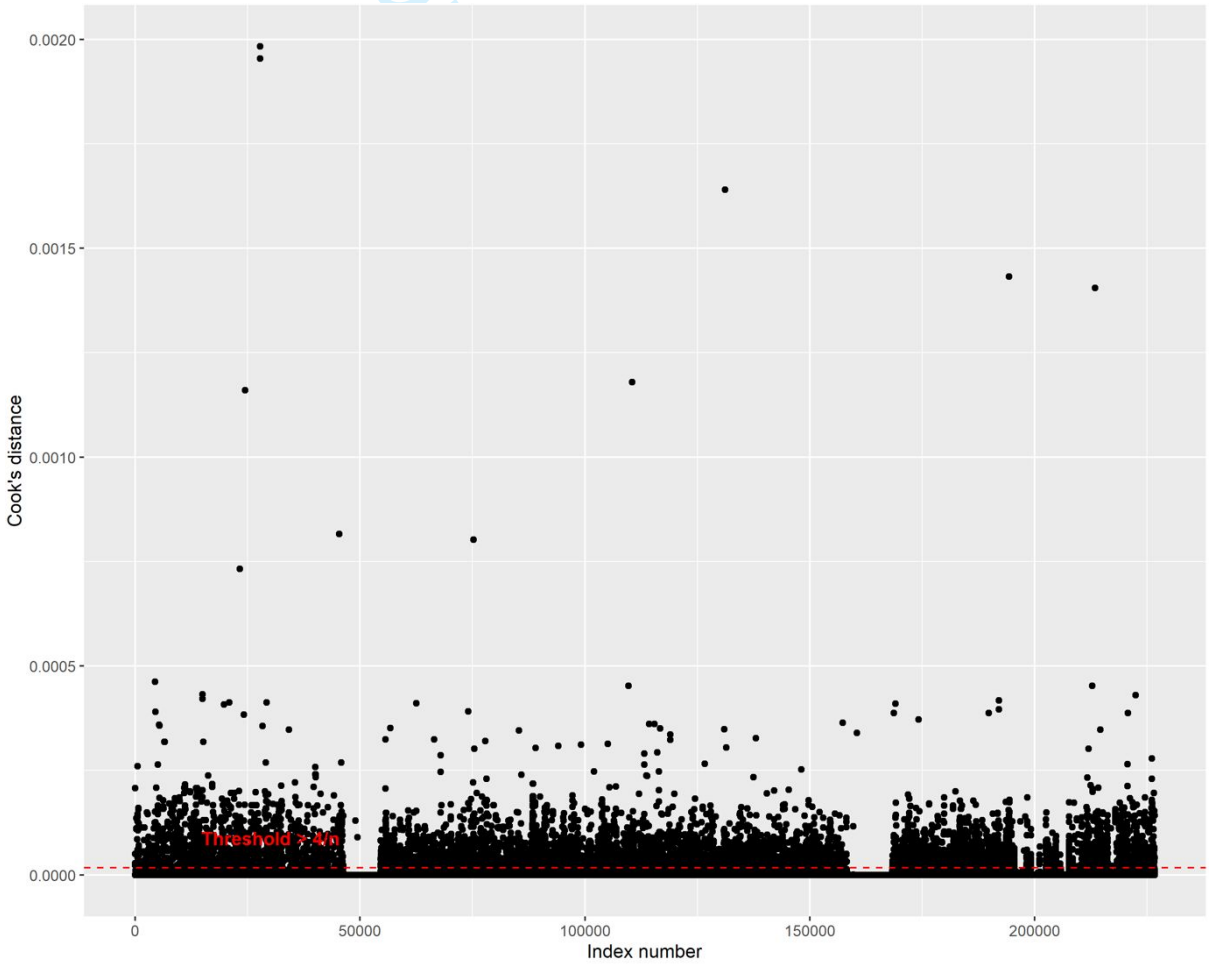
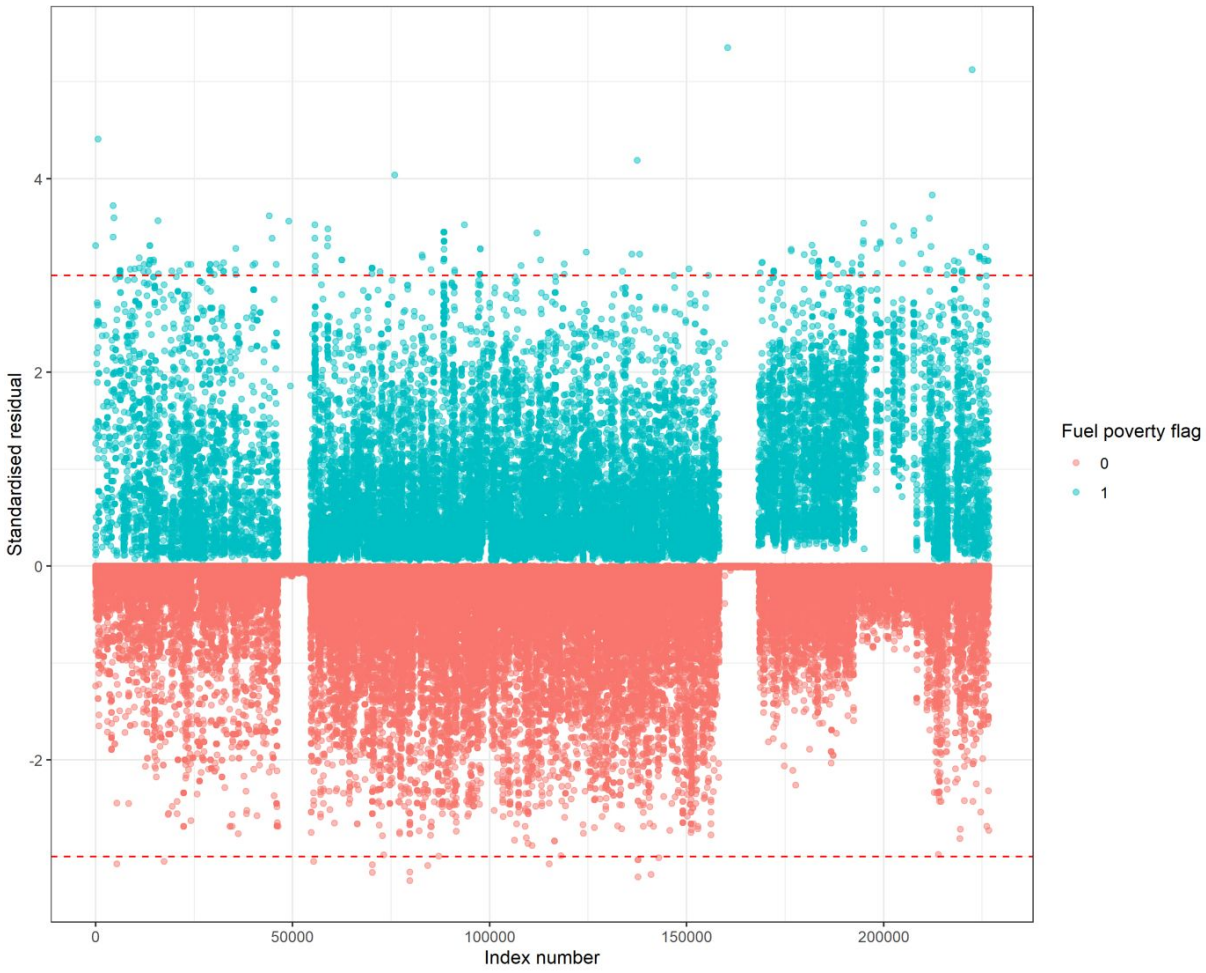


Figure S.3 - Standardised residual plot showing potential extreme outliers outside the threshold lines (in red) split by fuel poverty status (0 = not fuel poor, 1 = fuel poor).



1.2.1.2. Assumption checking - Linear relationship between continuous independent variables and the logit of the dependent variable

Using the model with all independent variables deemed to be multicollinear and data points deemed to be influential outliers removed, scatterplots were produced for all remaining continuous independent variables (Figure S.4). The scatterplots show that only the median age of individuals and MSOA average income variables demonstrates linearity with the logit of the dependent variable, the others show different relationships so violate this assumption. However, it is possible that the

large number of data points in the final model (n = 226,489) are influencing the non-linear relationships observed. The non-linear variables were transformed (via the cubed root transformation) to see if this improved the linear relationship with the logit of the dependent variable, however this had minimal impact (Figure S.5).

Figure S.4 - Scatterplots showing the relationship between continuous independent variables included in the final model and the log-odds (logit) of the dependent variable (fuel poverty).

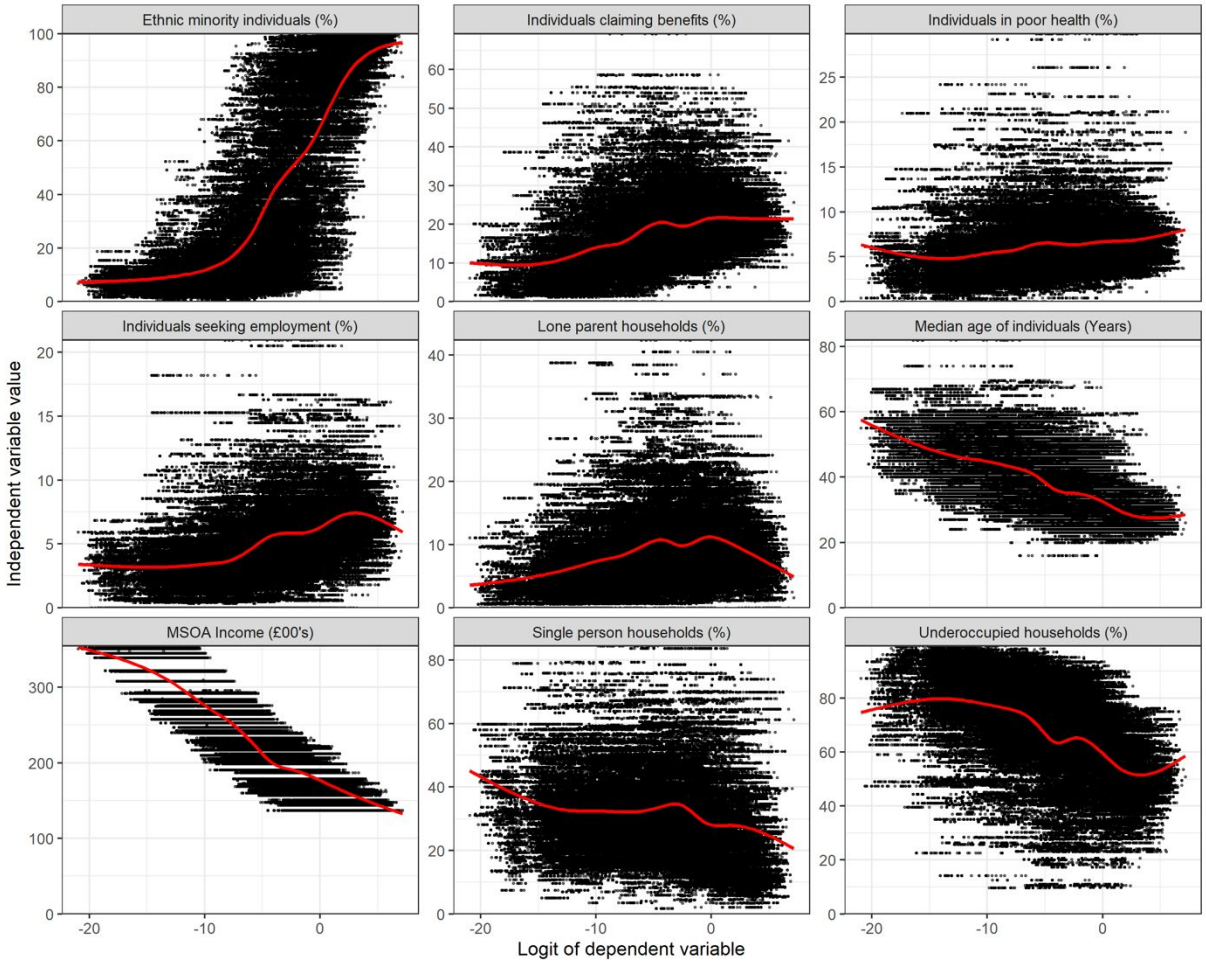
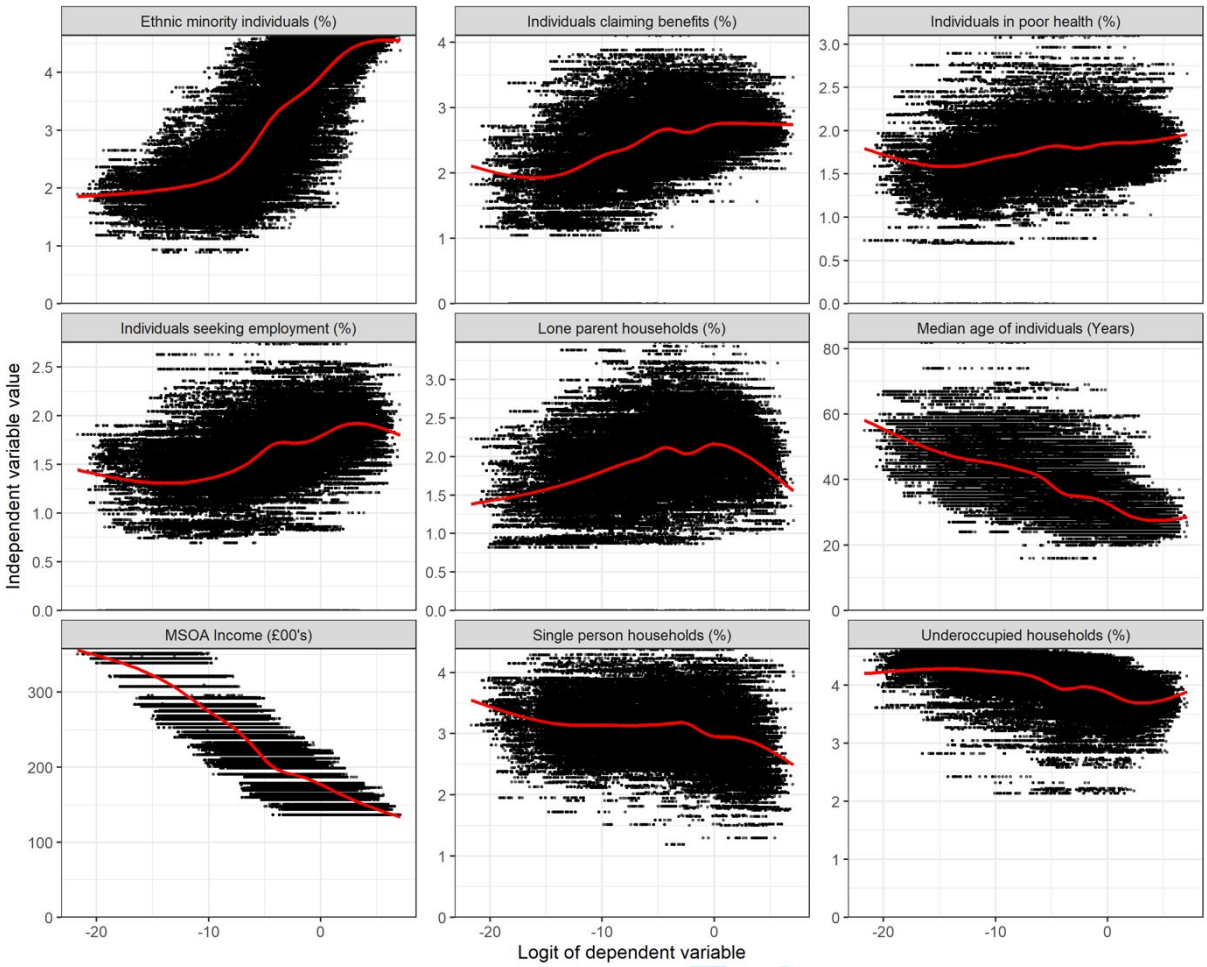


Figure S.5 - Scatterplots showing the relationship between cubed root transformed continuous independent variables (all apart from MSOA income and median age) and the log-odds (logit) of the dependent variable (fuel poverty).



2. Multivariate logistic regression model selection and goodness of fit

2.1. Model selection

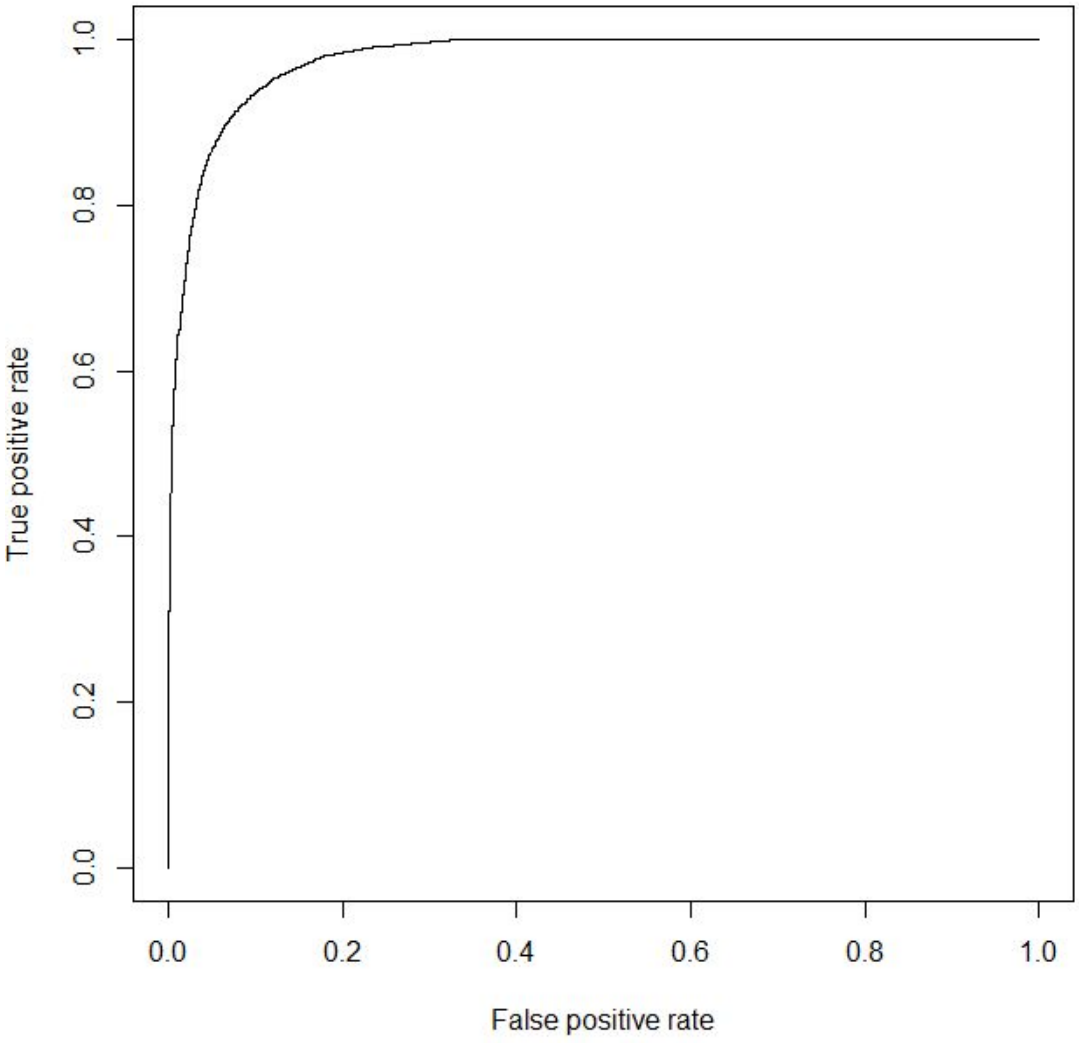
The AIC and BIC values of the transformed (cubed-root) vs non-transformed model were assessed to determine which should be used as the final model. The transformed model has a slightly worse fit (AIC = 69,330.93, BIC = 69,640.84) compared to the untransformed model (AIC = 68,959.43, BIC = 69,269.35), and as transforming the non-linear independent variables did not significantly improve their

linearity with the logit of the dependent variable (Figure S.5), it was decided to use untransformed variables in the final model.

2.2. Multivariate logistic regression goodness-of-fit

The final model had good predictive power as demonstrated by the McFadden's R^2 statistic being 0.69, using the rule of thumb that a value over 0.4 indicates a good model fit. The ROC curve (Figure S.6) also demonstrates that the model performs well, with an area under the curve value of 0.98 (with values close to 1 indicating the model has strong predictive ability).

Figure S.6 - Receiver operating characteristic (ROC) curve of the final logistic regression model.



3. Descriptive statistics of variables used in the univariate and multivariate regression models

Table S.4 - Descriptive statistics of continuous variables by estimated fuel poverty status.

Indicator	Fuel Poverty Category	Median	Mean	Standard Deviation (SD)	Minimum	Maximum	25th quartile	75th quartile	Interquartile range (IQR)
Individuals claiming benefits (%)	Not Fuel Poor	14.38	16.72	10.76	0.00	69.28	8.86	22.84	13.98
	Fuel Poor	20.33	21.36	7.12	0.00	69.28	16.58	25.00	8.42
Dependent children households (%)	Not Fuel Poor	29.13	30.79	12.75	0.83	89.83	22.33	38.15	15.82
	Fuel Poor	47.86	45.51	15.15	3.77	89.83	34.78	56.90	22.11
Ethnic minority individuals (%)	Not Fuel Poor	15.93	28.47	27.42	0.70	100.00	8.03	41.74	33.71
	Fuel Poor	87.50	79.33	23.09	1.63	100.00	74.24	96.10	21.86
Household floor area (m2)	Not Fuel Poor	74.00	84.41	40.53	20.00	954.00	59.00	93.20	34.20
	Fuel Poor	110.00	124.33	60.79	20.00	1,202.00	84.00	151.10	67.10
Single-person households (%)	Not Fuel Poor	30.51	32.80	14.13	1.69	84.43	22.48	40.00	17.52
	Fuel Poor	23.53	27.63	16.56	1.69	83.65	15.85	35.71	19.86
LSOA IMD rank	Not Fuel Poor	9,628.00	11,966.53	9,450.18	75.00	32,445.00	3,305.00	19,334.00	16,029.00
	Fuel Poor	2,328.00	3,425.15	2,966.32	75.00	30,606.00	1,465.00	5,489.00	4,024.00
Lone-parent households (%)	Not Fuel Poor	7.41	8.73	6.36	0.00	42.42	4.03	11.76	7.73
	Fuel Poor	8.72	9.45	5.39	0.00	42.42	5.71	12.82	7.11

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Indicator	Fuel Poverty Category	Median	Mean	Standard Deviation (SD)	Minimum	Maximum	25th quartile	75th quartile	Interquartile range (IQR)
Median age of individuals (Years)	Not Fuel Poor	40.00	40.72	9.58	16.00	82.00	33.00	47.50	14.50
	Fuel Poor	29.00	29.81	5.52	16.00	59.50	26.00	32.00	6.00
MSOA Income (£)	Not Fuel Poor	23,900.00	24,000.15	5,500.39	13,700.00	35,200.00	20,100.00	28,100.00	8,000.00
	Fuel Poor	162.00	163.44	18.95	137.00	352.00	148.00	173.00	25.00
Individuals in poor health (%)	Not Fuel Poor	5.20	5.92	3.54	0.00	29.85	3.63	7.22	3.59
	Fuel Poor	6.35	6.86	3.14	0.43	29.85	4.93	8.01	3.08
Individuals seeking employment (%)	Not Fuel Poor	4.02	4.54	3.08	0.00	20.97	2.47	6.07	3.60
	Fuel Poor	6.67	6.90	2.80	0.00	20.97	5.07	8.33	3.27
Underoccupied households (%)	Not Fuel Poor	74.49	71.16	18.34	9.76	99.26	60.26	85.81	25.55
	Fuel Poor	53.85	55.12	14.19	9.84	94.67	45.80	65.07	19.27
Unemployed individuals (%)	Not Fuel Poor	21.18	25.02	14.39	1.82	80.56	13.64	34.38	20.74
	Fuel Poor	44.17	42.93	9.78	6.98	80.56	38.08	49.31	11.23

Table S.5 - Categorical variables counts and percentages by estimated fuel poverty status.

Indicator	Group	Not fuel poor count (n)	Fuel poor count (n)	Not fuel poor percentage (%)	Fuel poor percentage (%)
SAP Band	A-B	11,003	136	6.05	0.30
	C	45,445	891	24.98	1.99

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Indicator	Group	Not fuel poor count (n)	Fuel poor count (n)	Not fuel poor percentage (%)	Fuel poor percentage (%)
	D	85,285	15,091	46.88	33.72
	E	33,678	23,555	18.51	52.63
	F-G	6,525	5,087	3.59	11.37
Property build year	Pre-1900	28,633	18,236	15.74	40.74
	1900-1929	21,083	12,995	11.59	29.03
	1930-1949	28,163	4,882	15.48	10.91
	1950-1966	33,039	3,728	18.16	8.33
	1967-1982	32,073	2,980	17.63	6.66
	1983-1995	14,863	800	8.17	1.79
	Post-1996	24,082	1,139	13.24	2.54
Fuel type	Biomass/Solid	3,093	1,247	1.70	2.79
	Electricity	16,540	3,127	9.09	6.99
	LPG	352	49	0.19	0.11
	Mains Gas	160,869	39,951	88.42	89.26
	No fuel	325	367	0.18	0.82
	Oil	757	19	0.42	0.04
Glazing type	Double/Triple	174,663	42,349	96.00	94.61
	Single/Partial	7,273	2,411	4.00	5.39
Loft insulation	0-50mm	39,463	23,621	21.69	52.77
	51-150mm	37,917	2,817	20.84	6.29
	150mm+	78,152	16,370	42.96	36.57
	No Loft	26,404	1,952	14.51	4.36
Wall type	Cavity Construction	122,893	22,431	67.55	50.11
	Solid Brick or Stone	50,068	21,009	27.52	46.94
	System Built	6,542	1,039	3.60	2.32
	Timber Frame	2,433	281	1.34	0.63
Wall insulation	Insulated	109,319	10,304	60.09	23.02
	Uninsulated	72,617	34,456	39.91	76.98
Property type	Block of flats	7,693	3,150	4.23	7.04
	Detached house	26,905	2,539	14.79	5.67
	End-terraced house	16,179	4,268	8.89	9.54
	Flat in mixed use building	7,390	2,235	4.06	4.99
	Large block of flats	8,522	1,519	4.68	3.39
	Mid-terraced house	34,424	20,500	18.92	45.80
	Semi-detached house	66,645	9,095	36.63	20.32
	Small block of flats/dwelling	14,178	1,454	7.79	3.25

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Indicator	Group	Not fuel poor count (n)	Fuel poor count (n)	Not fuel poor percentage (%)	Fuel poor percentage (%)
	converted in to flats				
Tenure	Housing Association	27,019	2,727	14.85	6.09
	Local Authority	382	27	0.21	0.06
	Owner Occupied	117,894	27,926	64.80	62.39
	Privately Rented	36,641	14,080	20.14	31.46

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