Combining self-reported and sensor data to explore the relationship between fuel poverty and health well-being in UK social housing

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Abstract

Tenants of social housing are more vulnerable to fuel poverty since social housing generally support older and lower-income households. Linking novel real time sensor data with a comprehensive individual baseline survey, this study estimates the socio-economic and behavioural determinants of fuel poverty and its effect on the physical and mental health of social housing tenants in the south-west of the UK. Structural equation modelling is applied to show that socio-economic characteristics such as age, household size, and house size are important determinants of fuel poverty. Fuel poverty is also related to poorer mobility and it has a significant negative effect on mental health. Our results suggest that special attention should be paid to tenants with disabilities and chronic diseases since they are more vulnerable to fuel poverty and health issues. Understanding the determinants of fuel poverty will help inform future polices to maximise the co-benefits of energy efficiency improvements (i.e. identifying and supporting fuel poor households) and carbon reduction efforts in the housing sector.

Key words: Fuel poverty, Sensor data, Social housing, Health-related quality of life, Structural equation modelling

Highlights:

- Fuel poverty has negative health impacts among social housing tenants.
- Real-time sensor data and survey data are collected.
- Fuel poverty relates to socio-economic and housing characteristics.
- Fuel poverty also relates to poor mobility.
- Tenants with disabilities and chronic diseases are more vulnerable to fuel poverty.

1 Introduction

The linkages between human health and well-being to poor living and housing conditions has a long history as a driver of public health policy and action (Sharpe et al., 2018). Fuel poverty, the inability to keep the home adequately warm due to the unaffordability of energy and poor energy efficiency of buildings (including poor insulation and heat loss) (Antanasiu et al., 2014), is a growing problem in European countries. Current estimates indicate that fuel poverty affects approximately 2.53 million UK households (DBEIS, 2019) and up to 34% of homes in some European countries, thus representing a considerable burden to society (Liddell and Morris, 2010). This is a complex social issue and recent research has begun to focus on national policy changes to allow greater flexibility for local authorities to target and support fuel poor households (Sharpe et al., 2020) and the impact of fuel poverty on physical and mental health (Sharpe et al., 2018).

Cold homes have been found to impact negatively on general self-rated health well-being (Lacroix and Chaton, 2015; Zhang et al., 2019), physical health (Hills, 2012; Liddell and Morris, 2010) and mental health (Sharpe et al., 2018; Liddell and Guiney, 2015). In addition, increased winter mortality and respiratory problems have been associated with households who are unable to afford to heat adequately their homes (Hills, 2012; Howden-Chapman et al., 2012; Liddell and Morris, 2010).

In the UK, the definition of fuel poverty has changed from the inclusion of households who spend more than 10% of their disposable income on energy (Boardman, 1991), to the Low Income High Cost (LIHC) criteria which refers to households with less than 60% of the UK's median income and high energy needs, i.e. more than 10% of their income on energy (Hills, 2011). As an expenditures-based approach, a clear disadvantage of the LIHC approach refers to the actual expenditure of households on energy, rather than the necessary cost required to ensure an adequate thermal temperature for households. As a result, expenditure-based approaches may underestimate fuel poverty (Atsalis et al., 2016; Azpitarte et al., 2015; Legendre and Ricci, 2015). Whilst previous research has tried to overcome this issue by focusing on required, rather than actual, fuel spending in order to take under-consumption into account, this approach requires a large quantity of household information that is usually not available (Dubois, 2012; Fahmy et al., 2011).

An alternative approach is to define fuel poverty according to the household indoor temperature during the winter. A recent report on fuel poverty defined the UK's adequate standard of warmth as 21ºC for the main living area and 18 ºC for other occupied rooms (DBEIS, 2019). Although an objective measure such as temperature provides clarity, previous studies using this approach have had to rely on self-reported indoor temperature (Atsalis et al., 2016; Legendre and Ricci, 2015). Self-reported temperature may lead to biased indoor temperatures, with levels of thermal discomfort in homes being under declared (Healy and Clinch, 2002; Thomson et al., 2017). The widespread of real-time indoor environmental sensors over the last decade has offered opportunities to collect real-time sensor temperature data in the home. However, installing sensors in home environments or gaining access to routine household temperature data on a large scale remains a challenge. As such, to date there are only a few large-scale home temperature monitoring studies using real time sensor data.

Oreszczyn (2006) investigated the determinants of room temperature during winter in 1604 low income households in five cities of the UK. They found that indoor temperatures depend on property's age, construction and thermal efficiency and the household size and the age of household reference person. The Carbon Reduction in Buildings (CaRB) project (Huebner et al., 2013; Kelly et al., 2013) monitored daily heating period and thermostat settings across a representative sample of 248 English houses. Another research project investigated the number of days for which indoor temperatures meet the UK's standard of warmth (18°C) and assessed the determinants of winter indoor temperature using sensor data and survey data of 635 households in England (Huebner et al. 2018; Huebner et al., 2019). Housing characteristics, household type, and geographic location were found in this study to be important determinants of indoor temperature and that households with occupants aged over 64 years or having a long-term disability were more likely to meet the 18°C condition than those without disability and those in younger age groups (Huebner et al. 2018).

In the UK, social housing associations are responsible for the provision of affordable housing to low income populations (Sharpe et al., 2015a). Whilst social housing properties are generally well maintained and have higher energy efficiency levels in countries such as the UK (Home, 2006), social housing tenants are more vulnerable to fuel poverty than homeowners as they are on average an older and lower-income population (Anderson et al., 2012). For example, Anderson et al. (2012) found that a large percentage of low-income households in their sample had to reduce their energy consumption in the previous winter (63%) and approximately half of the participants (47%) had experienced cold homes. In addition, improvements to the indoor thermal performance did not eliminate the risk of living in a cold home. Recent studies found that tenants of private and social housing are more vulnerable to fuel poverty (Bramley et al., 2017) and fuel poverty combined with housing faults causes negative effect on health well-being among social housing tenants (Boomsma et al., 2017).

This study extends the current literature on fuel poverty by (i) providing a comparison of self-reported measures of fuel poverty and revealed fuel poverty using sensor data; and (ii) examining the impact of fuel poverty on both mental and physical health well-being of social housing tenants. The paper is structured as follows. Section 2 reviews the literature on measuring fuel poverty. Section 3 presents the methodology, including the measurement of fuel poverty and health well-being and the survey. Section 4 presents the results of statistical analysis. Section 5 discusses our results and summarizes the paper.

2 Methods

2.1 Data collection

A face-to-face survey was administered by trained enumerators and researchers in Cornwall, UK, over the period September 2017 to June 2018. Using a closed-question approach the questionnaire included questions on socio-demographics, fuel poverty and health, indoor and outdoor activities, and the home environment (Moses, 2019). The contact list was provided by Coastline Housing, a not-for-profit housing association in south-west England, and 1707 invitations were sent by letters. In total, 329 households were surveyed. The overall survey lasted for approximately 45 minutes. The survey data were merged with Coastline Housing's asset management and stock condition data including building type, energy performance rating, and number of rooms in each residence.

Among the surveyed participants, 280 allowed sensors to be installed in their home to collect real-time data on their indoor environment before 01/12/2017. Figure A1 in the Appendix presents a picture of the model of the sensor. The sensors were inconspicuous and installed by professionals to avoid installation mistakes. In this study, we take the average overnight (from 7pm to 7am) temperature during winter (from 01/12/2017-28/02/2018).

2.2 Measurement of fuel poverty

Measuring self-reported fuel poverty applying the capabilities approach

Following the EU statistics on income and living conditions (EU-SILC) survey and previous studies (Bouzarovski and Tirado Herrero, 2017; EESC, 2013; Sharp et al., 2015a), three criteria should be used to identify if a household is in fuel poverty including: i) being able to keep the house warm; ii) being able to afford energy needed; iii) being able to prevent the home from housing faults which are mainly damp and rot, poor insulation and ventilation in the UK (Sharp et al., 2015a, Boomsma et al., 2017). Thus, the self-reported fuel poverty (denoted as E1) is measured using the following three questions in the survey:

ep1: Do you think your home is adequately heated? (Yes/No)
ep2: Do you avoid turning on the heating because of the cost? (Yes/No)
ep3: Do you avoid ventilating your home to save heat / energy? (Yes/No)

Measuring revealed fuel poverty using the sensor data

Although the 18°C warmth standard is commonly applied (DBEIS, 2019), recent research argues that a minimum warmth standard is less important for healthy adults (Wookey et al., 2014). Therefore, this study uses two different warmth standards to define revealed fuel poverty. First, we define revealed fuel poverty (denoted as E3) applying a fixed 18 °C warmth standard to identify the household who are living in fuel poverty using data from the temperature sensors. The coldness level variable "*Cold_temp_fix*" is defined as the difference between the overnight bedroom temperatures and the chosen warmth standard (18 °C) and it equals to zero if the temperature is higher than the warmth standard, i.e. the participant is not fuel poor. Second, we define a second revealed fuel poverty variable (denoted as E4) applying a more flexible warmth standard for participants deemed to be healthy adults. As per Wookey et al. (2014), the coldness level variable "*Cold_temp_flex*" is defined using 18 °C as the warmth standard for vulnerable people and 17 °C for healthy adults (See Table 2).

Combining self-reported and observed data

Our fourth measure, a hybrid fuel poverty measure (denoted as E2), is a composite indicator of fuel poverty using both self-reported and observed information, i.e. the coldness level "*Cold_temp_fix*" is added as the fourth item to measure the hybrid fuel poverty. Previous studies has established composite measures combining self-reported information on energy expenditures measures, affordability of appropriate heating and indoor temperature (e.g.

Charlier and Legendre, 2019, Churchill et al., 2020). No previous study, to the knowledge of the authors, has established a fuel poverty measure combining self-reported fuel poverty with indoor temperatures observed by sensors.

2.3 Measurement of physical and mental health

The SF-12™ version 2 functional health and well-being survey (SF-12V2) was employed to evaluate participant's physical and mental health. The SF-12V2 is a multipurpose clinical scales assess general health-related quality of life. It is a validated and reliable survey with numbers of applications (Ware et al., 1996; Kung et al., 2018). It measures eight health domains, which are weighted and summed to provide two scores; Mental Component Summary (MCS) score and Physical Component Summary (PCS) score. These range from 0 to 100 and are measures of physical and mental health functioning and overall health-related quality of life in a population (Mchorney et al., 1993). In this study, the MCS and PCS score is computed using the software "Health Outcomes Scoring software 5.1" following the SF12v2's manual (Maruish, 2012).

2.4 Econometric specification

Structural Equation Modelling (SEM) was employed to measure fuel poverty among the participants and estimate the effects of fuel poverty on mental and physical health well-being. In Model M1, self-reported fuel poverty E1, a latent variable is measured by using the 3-item fuel poverty scales ("ep1-ep3") following Sharpe et al., 2015a. In Model M2, the hybrid fuel poverty E2 is measure using the 3-item fuel poverty scale and an additional item "*Cold_temp _fix*" which is the observed coldness. Figure 1 presents the structure of the structural equation models using E2.

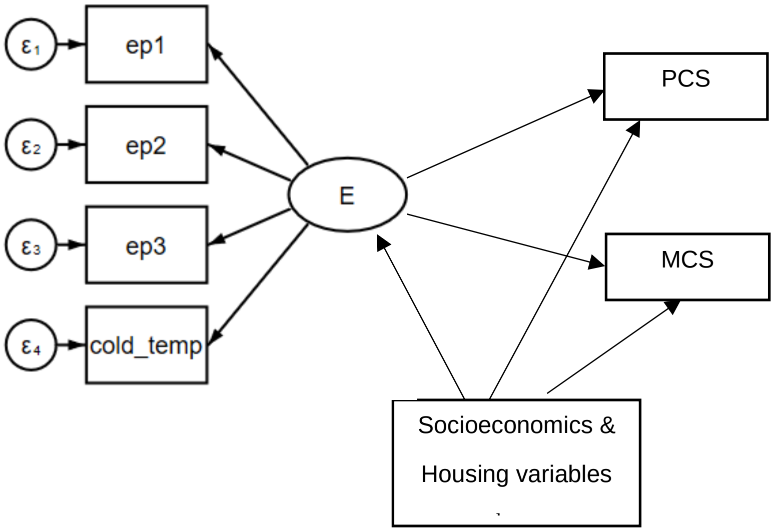

Figure 1 Model M2: Structural equation model for effects of self-reported fuel poverty on health and well-being. E represents the latent fuel poverty.

The measurement equation for measuring the latent fuel poverty is defined as following:

$$\mathrm{I}_i = constant_i + \alpha_i * E + \varepsilon_i \qquad (1)$$

where I_i is a vector of measured indicators of fuel poverty which includes 3 items in M1 and 4 items in M2. The latent variable E denotes the latent fuel poverty with the associated vector of parameters α_i. The error term ε_i is independently and identically distributed with a zero mean and a variance of ve_i. To estimate the effect of E on health and wellbeing, Equation 1 and Equation 2 are estimated jointly in M1 and M2, as shown in Figure 1.

Using the following structural equation, we estimate the determinants of self-reported fuel poverty as:

$$E = \mu_0 + \mu * X + \varepsilon_e \qquad (2)$$

where E depends on a vector of socioeconomic and housing variables X with the associated vector of parameters μ. The error term ε_e is independently and identically distributed with a zero mean and a variance of $v\varepsilon_e$. Revealed fuel poverty E3 and E4 are directly included in

Model M3 and M4 since they are observable. As a result, the Eq. 1 is not included in Models M3 and M4.

Structural latent variable equations on physical and mental health:

$$MCS = r_0 + \theta * E + r * X + \varepsilon_m \quad (3)$$

$$PCS = r_0 + \theta * E + r * X + \varepsilon_p \quad (4)$$

The two health scores, MCS and PCS, depend on the underlined fuel poverty E with the associated parameter θ and a vector of socio-economic and housing variables X with the associated vector of parameters r. The error term ε_m and ε_p is independently and identically distributed with a zero mean and a variance of $v\varepsilon_m$ and $v\varepsilon_p$.

Finally, we estimate the determinants of revealed fuel poverty E3 and E4 using a Tobit model in which the dependent variable is the coldness level "*Cold_temp _fix*" and "*Cold_temp_flex*". One issue with using the warm standard as a cut-off point to define the coldness level is that it is not possible to observe the residents who still feel cold even if the temperature is higher than the selected warmth standard. Applying a Tobit model, the dependent variable becomes an uncensored latent variable, where instead of using zero as observed coldness level if the temperature is higher than the selected warmth standard, we specify a latent depend variable.

3 Results

3.1 Descriptive statistics

Comparing the distribution of our sample to the England Housing Survey (EHS) 2017-18 data on social housing tenants, our sample has a similar distribution in terms of age (54.7 years), marital status (41.1% are single) and household with children (37.5%) and unemployed tenants (4.3%). The percentage of women and retired people in our sample is higher than the national average.

Table 1. Sample representativeness

Variable	Observation	Survey sample	National average [a]
Gender (=1 if participant is female)	280	69.20%	59%
Age (year)	280	54.7	53
Retired	280	35%	28%
Single	280	41.1%	41%
Household with children	280	37.5%	33%
Unemployed	280	4.3%	5%

a: Source: English Housing Survey (EHS) Social rented sector, 2017-18

Table 2 presents the descriptive statistics for the variables used in our estimation. 35% of the participants are retired. The average household size is 2.1 person. With regard to health status which are related with fuel poverty (Hills, 2011), the survey data indicates that 26% of our participants are disabled or with long-term illness and 10% of them have Chronic Obstructive Pulmonary Disease (COPD). Participating in physical activity is an important determinant of health (Meyer et al., 2014). In terms of participant's indoor/outdoor activities, on average participants take more than a 10 mins walk 3.9 days a week and have 2.6 days with at least 30 mins of physical activity[1]. Occupant behaviours, such as time spent at home, are significantly linked with fuel poverty (Kearns et al., 2019). On a typical weekday, our participants spend 8 hours sitting on average. Our participants spend on average 20 hours a day at home during the week or weekend.

Table 2. Descriptive statistics of survey data, housing data, and sensor data

Variable	Description	Mean	Std. Dev.	Min	Max
Disable	Dummy. =1 if participant has a long-term illness or disability.	26%			
Householdsize	Number of members in the household.	2.1	1.3	1	7

[1] The UK's National Health Service recommends a 10-minute daily walk and 30 minutes minimum for each physical activity.
https://www.nhsinform.scot/healthy-living/keeping-active/getting-started/types-of-exercise
https://www.nhsinform.scot/healthy-living/keeping-active/activities/walking

Children	Dummy. =1 if household has children under 16 year old.	21%			
Asthma	Dummy. =1 if participant has Asthma.	24%			
COPD	Dummy. =1 if participant has COPD.	10%			
Walking	Number of days with at least 10 mins of walking during the last 7 days.	3.9	2.9	0	7
PhysicalActivity	Number of days with at least 30 mins of physical activities during the last 7 days. (including professional activities)	2.6	2.85	0	7
Hourwk	The time a participant spends at home during a week.	19.9	3.6	2	24
Hourwknd	The time a participant spends at home during a weekend.	20.2	3.5	1	24
SittingHour	The time a participant spends sitting on a week day including at work and driving during the last 7 days.	8.0	4.6	0	23
Flat	Dummy. =1 if is flat. =0 if is house/semi-detached house.	25%			
Nbroom	Number of room (living room, separated kitchen, dining room, bedroom, utility room, bathroom)	4.9	0.98	3	8
Gas Heating	The participant has a gas boiler.	89%			
Energy Performance Certificates(EPC) rating				D	B
EPC_B	Dummy. =1 if EPC=B.	7%			
EPC_C	Dummy. =1 if EPC=C.	80%			
EPC_D	Dummy. =1 if EPC=D.	13%			
Bed_temp	The average overnight (7pm-7am) temperature of participant's main bedroom from 01/12/2017 to 28/02/2018.	17.3	2.9	12.1	25.3
Cold_temp_fix	Room coldness level is defined applying the 18 °C warmth standard. When Bed_temp is under the warmth standard, it's the distance from the standard. Cold_temp _fix=0 if Bed_temp is higher than the warmth standard, i.e., it not cold.				
Cold_temp_flex	Room coldness level is defined applying a 17 °C warmth standard for healthy adults and a 18 °C warmth standard for vulnerable groups (Age>65 or Disable=1 or COPD=1 or Asthma=1)				
Cold_temp _fixsq	Cold_temp _fixsq = Cold_temp_fix * Cold_temp_fix				
Cold_temp2_flexsq	Cold_temp_flexsq= Cold_temp_flex * Cold_temp_flex				

The house Energy Performance Certificate (EPC) rating (from A to G) was also collected. In our data, the minimum rating is D and the maximum rating is B. In the social housing sector in England, 2.2% of dwellings were given an A/B, 50% of dwellings were given a C, and 41.3% of dwellings were given a D in 2017 (MHCLG, 2018). Our participants' homes are more energy efficient compared to the national statistics and at least one grade higher than the UK's minimum standard for renting which is E (DBEIS, 2018). The average main bedroom overnight temperature is 17.2 °C and 45.4% of the participants' main bedroom overnight temperature is lower than 18 °C. The distribution of the main bedroom overnight temperature is presented in Figure 2.

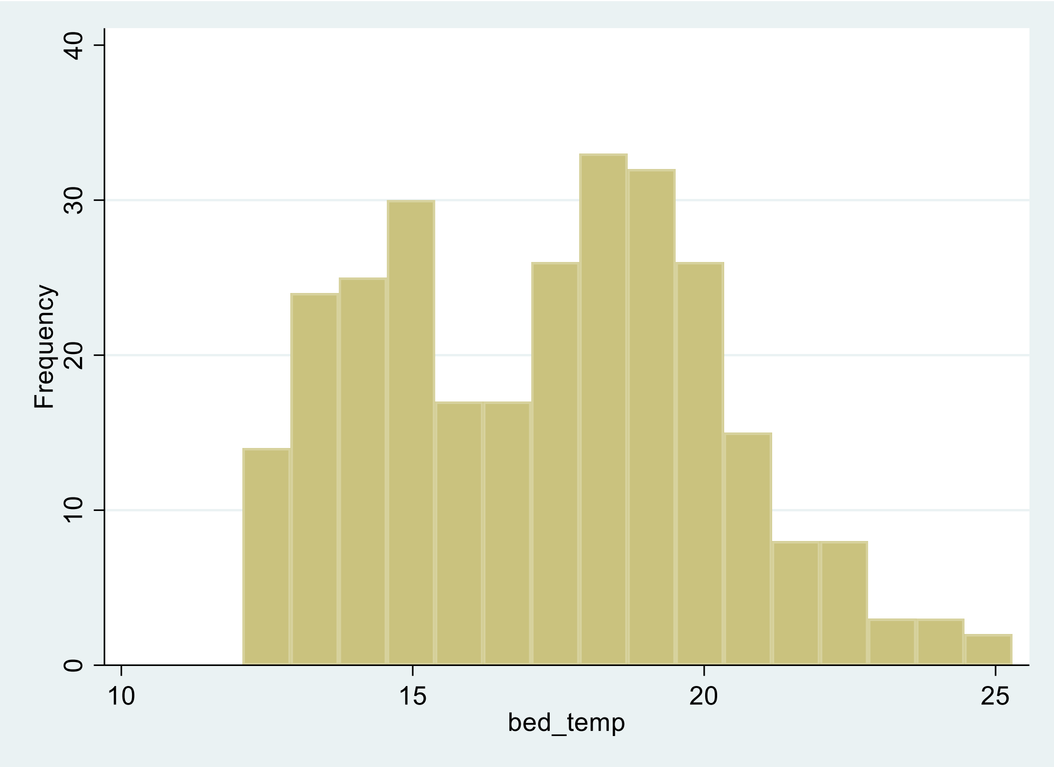

Figure 2. Distribution of the average overnight temperature of participant's main bedroom

In terms of participant physical and mental health (Table 3), mean reported MCS score and PCS score are 48.7 and 40.5. Compared to previous surveys in the UK, the GoWell survey in Glasgow finds a mean of 49.2 for MCS and 42.2 for PCS (Egan et al., 2016). The Welsh health survey reports a mean of 48.58 for MCS and 48.59 for PCS (Wales Health Survey, 2015). Our PCS is lower compare to both surveys. However, research has indicated that social housing tenants have more physical health problems (MHCLG, 2019) than other housing tenure groups.

Table 3. Health measures within SF-12V2

Variable	Obs	Mean	Std. Dev.
Physical functioning scale	280	51.3	40.4

Role physical scale	280	58.0	36.7
Bodily pain scale	280	58.0	37.6
General health scale	280	40.6	31.7
Vitality scale	280	43.4	31.1
Social functioning scale	280	66.0	36.6
Role emotional scale	280	73.4	32.5
Mental health scale	280	64.6	28.7
PCS	280	40.5	13.7
MCS	280	48.3	13.7

3.2 The determinants of fuel poverty

Table 5 presents the estimated the determinants of fuel poverty (complete table of results see Table A1 in Appendix). The results indicate that older participants (*Age*), households with more members (*Household size*) and households living in flats (*Flat*) are less likely to report fuel poverty or living in a cold home. The houses with the lowest energy performance rating in our sample, are not significantly colder than other houses (*EPC_D*). In other words, higher energy efficiency houses are not associated with the home's warmth level. In the case of E2, the *EPC_D* is significant which implies that participants are more likely to live in fuel poverty considering both the self-reported information and observed coldness level.

Applying the fixed 18 °C warmth standard (E3), participants with disability and long-term illness (*Disable*) are more likely to live in fuel poverty compare to others. However, if the flexible warmth standard (E4) is applied, we found no association between fuel poverty and disability and long-term illness, i.e. the result is the same as the results of self-reported fuel poverty (E1) or E2. It implies a flexible warmth standard fits better the householders' needs for indoor warmth.

Some determinants of self-reported fuel poverty are different compared to those for revealed fuel poverty. For example, the main bedroom temperature is lower in houses with more rooms and the occupants are more likely to be revealed as fuel poor according to both criteria. Living in a house with more rooms has no significant effect on self-reported fuel poverty. Participants with COPD are more likely to report being fuel poor even though their home is not significantly colder than other homes. Fuel poverty is also related to time spent at home, with households who spend more time at home during the week having colder homes (*Hourswk*). However, although participants who spend more time at home during the weekend are also more likely to live in colder homes as measured by the sensor data, they are less likely to report fuel poverty (*Hourswknd*).

Table 5. The determinants of fuel poverty

Model	OLS	M1	M2	M3	M4
Dependent variable	Bedroom temperature	E1	E2	E3	E4
Age	0.055***	-0.006***	-0.007***	-0.053***	-0.047**
	(0.000)	(0.008)	(0.003)	(0.004)	(0.010)
Gender	-0.372	0.022	0.025	0.230	0.259
	(0.315)	(0.662)	(0.621)	(0.577)	(0.536)
Retired	0.069	-0.107	-0.126	-0.548	-0.005
	(0.908)	(0.307)	(0.167)	(0.428)	(0.994)
Household Size	0.730***	-0.041	-0.057**	-0.744***	-0.766***
	(0.001)	(0.147)	(0.031)	(0.000)	(0.000)
Number of rooms	-0.452*	-0.027	-0.015	0.586**	0.649***
	(0.071)	(0.313)	(0.585)	(0.014)	(0.008)
Flat	1.050**	-0.108**	-0.120**	-0.801*	-0.701
	(0.020)	(0.048)	(0.022)	(0.097)	(0.150)
Gas Heating	-0.783	0.041	0.050	0.825	0.759
	(0.167)	(0.583)	(0.469)	(0.205)	(0.248)
EPC_D	-0.180	0.114	0.125*	0.476	0.481
	(0.728)	(0.166)	(0.082)	(0.406)	(0.411)
COPD	0.164	0.220***	0.198**	-0.054	0.016
	(0.771)	(0.004)	(0.010)	(0.934)	(0.980)
Disable	0.672	0.013	-0.029	-0.951*	-0.228
	(0.170)	(0.897)	(0.721)	(0.089)	(0.687)
Hourwk	0.093*	0.015**	0.014**	-0.054	-0.048
	(0.064)	(0.041)	(0.047)	(0.385)	(0.450)
Hourwknd	-0.091*	0.006	0.009	0.130**	0.123*
	(0.084)	(0.364)	(0.196)	(0.039)	(0.054)
N	280	280	280	280	280

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

3.3 The impact of fuel poverty on health

Table 6 presents the results of the Eq. 3 which estimates the association between fuel poverty and mental health, estimated using the MCS score. Poor health conditions such as disability and long-term sickness and having COPD, are associated with poor mental health. Participants' mental health also differs according to their daily indoor/outdoor physical activities, with better mental health associated with increased number of days with at least 10 mins of walking.

With regard to the fuel poverty variables, self-reported fuel poverty is found to be the strongest predictor of mental health and well-being. In Model M1 and M2, the stated fuel poverty E1 and hybrid fuel poverty E2 has a significant negative effect on mental health. In Model 3 and Model 4, the coefficients of the coldness level variables (*Cold_temp_fix* and *Cold_temp_flex*) are both significantly negative which implies living in a cold bedroom has a negative effect on mental health. In model M4, using a more flexible way to define fuel poverty, we found that the effect of cold bedroom temperature on mental health well-being is negative and convex since the coefficient of "*Cold_temp_flexsq*" is positive. The flexible warmth standard is found to better explain participants' mental health and well-being with the variable "*Cold_temp_flex*" found to be more significant than "*Cold_temp_fix*".

Table 6. Results of the Eq. 3: the determinants of mental health (MCS)

Model	M1	M2	M3	M4
Fuel poverty measure	E1	E2	E3	E4
	Coef.	Coef.	Coef.	Coef.
Age	0.136	0.124	0.247***	0.252***
	(0.187)	(0.204)	(0.002)	(0.002)
Gender	-0.052	-0.051	-0.069	-0.069
	(0.364)	(0.368)	(0.192)	(0.192)
Retired	-0.024	-0.035	-0.029	-0.031
	(0.807)	(0.720)	(0.747)	(0.733)
COPD	-0.021	-0.033	-0.110**	-0.108**
	(0.771)	(0.600)	(0.040)	(0.046)
Disable	-0.237***	-0.256***	-0.321***	-0.319***
	(0.005)	(0.000)	(0.000)	(0.000)
Physical Activity	0.026	0.025	0.014	0.010
	(0.660)	(0.668)	(0.817)	(0.875)
Walking	0.123**	0.119**	0.123**	0.122**
	(0.043)	(0.049)	(0.049)	(0.049)
Stated fuel poverty	-0.379***	-0.390***		
	(0.000)	(0.000)		
Cold_temp_fix			-0.314*	
			(0.092)	
Cold_temp_fixsq			0.223	
			(0.233)	
Cold_temp_flex				-0.398**
				(0.020)
Cold_temp_flexsq				0.334*

				(0.052)
N	280	280	280	280

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
p-values in parentheses

Table 7 presents the results of the Eq. 4 which aims to estimate the association between fuel poverty and physical health. A higher score on the PCS is associated with the increase of a number of days with physical activities (*PhysicalActivity*) and at least 10 mins of walking (*Walking*). No fuel poverty measure was found to have a significant impact on physical health .

Table 7. Results of the Eq.4: the determinants of physical health (PCS)

	M1	M2	M3	M4
Fuel poverty measure	E1	E2	E3	E4
Age	-0.269^{***}	-0.261^{***}	-0.219^{***}	-0.228^{***}
	(0.003)	(0.003)	(0.008)	(0.005)
Gender	0.045	0.043	0.035	0.035
	(0.413)	(0.433)	(0.518)	(0.517)
Retired	-0.010	0.001	0.022	0.026
	(0.903)	(0.989)	(0.781)	(0.743)
PhysicalActivity	0.156^{**}	0.159^{***}	0.162^{***}	0.167^{***}
	(0.011)	(0.008)	(0.007)	(0.006)
Walking	0.236^{***}	0.238^{***}	0.245^{***}	0.245^{***}
	(0.000)	(0.000)	(0.000)	(0.000)
Fuel poverty (E)	-0.168	-0.110		
	(0.340)	(0.359)		
Cold_temp_fix			0.211	
			(0.267)	
Cold_temp_fixsq			-0.136	
			(0.475)	
Cold_temp_flex				0.269
				(0.126)
Cold_temp_flexsq				-0.237
				(0.177)
N	280	280	280	280

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
p-values in parentheses

4 Discussion

Bringing together self-reported and revealed measures based on indoor sensors offers interesting insights into fuel poverty. A range of socioeconomic characteristics (e.g. age, household size, chronic disease, poor mobility and house size) have been shown to influence indoor temperatures and risk of fuel poverty. One question is whether a new multidimensional measure of fuel poverty (E2) or a flexible one (E4) can better define fuel poverty. The utilisation of home monitoring and recognising the drivers for fuel poverty could help improve fuel poverty policy and practice at the national level. This is important because it helps shape the way we support fuel poor households that do not technically meet the low income criteria (Sharpe et al., 2020).

Synthesis with existing literature

Consistent with prior research, this paper found that living in fuel poverty and/or a cold home has a negative impact on participant mental health (Dear and McMichael, 2011; Gilbertson et al., 2012; Hernández et al., 2016) and mental health (Howden-Chapman et al., 2007; Liddell and Morris, 2010; Liddell and Guiney, 2015). However, we did not find a significant relationship between physical health well-being and fuel poverty. This is in contrast to previous research (Hills, 2012; Howden-Chapman et al., 2012; Liddell and Morris, 2010) that highlights the increased risk of cold related morbidity and mortality. These previous studies which either focused on the risk of having diseases and other low-probability health problems, or applied general health self-rating as the health measure. The current study employs clinical health scales focus on household's general health-related quality of life evaluation applying clinical health scales (SF12V2). Another previous study using area level health and energy efficiency data found reported mixed findings depending on the household energy efficiency measures employed, such as improved heating, insulation and glazing (Sharpe et al., 2019). Our findings are also likely to be influenced by the higher proportion of participants with a disability and/or long term condition, which is typical of social housing occupancy demographics (Bramley et al., 2017).

Alternatively, these findings may also be a result of different indoor home behaviours, including for examples, people's ability or awareness to access help, knowledge and their personal heating behaviours (Tod et al., 2012), as well as multiple social, cultural and economic factors (Sharpe et al., 2018).

The importance of these wider behavioural and social factors may explain why household energy efficiency improvements alone may not eliminate the risk of cold in the lowest income households (Anderson et al., 2012), alleviate someone's poor physical (e.g. cardio-respiratory diseases) and mental health (Sharpe et al., 2019, Sharpe et al., 2020) nor account for risk perception and choices when heating the home (Critchley et al., 2007). Rising living costs and energy prices mean that households may continue to ration heating regardless of the energy efficiency of the home (Howden-Chapman et al., 2012; Lomax and Wedderburn, 2009). Furthermore, the impact of cold and poorly designed energy efficiency measures to help support fuel poor households can impact air quality (Howieson, 2014), which further increases the risk of poorer physical and psycho-social health outcomes (Grey et al., 2017). This may explain why we found no statistical association between physical health and fuel poverty.

Whereas someone's mental health maybe be susceptible and variable to the impacts of fuel poverty, wider lifestyle factors influencing health and well-being and changes in energy efficiency, particularly when measured by self-reported outcome tools (Sharpe et al., 2020). The impact of fuel poverty on health and well-being maybe further modified by the characteristics of a property. We found that those living in flats experienced less fuel poverty. However, flats require greater ventilation to maintain adequate indoor air quality and can suffer from problems with condensation and mould contamination (Sharpe et al., 2015a). This complex interaction between resident behaviours, the indoor environment and health can modify physical and mental well-being outcomes (Oreszczyn, et al., 2006).

Measuring the extent of fuel poverty may also influence our findings. The expenditure-based approach does not take into account the thermal temperature of a property and may underestimate the presence of fuel poverty (Azpitarte et al., 2015; Lengendre and Ricci, 2015). Self-reported measures can be biased, and participants can under declare problems with fuel poverty (Healy and Clinch, 2002; Thomson et al., 2017), which may result from stigma resulting from fuel poverty (Sharpe et al., 2020). Alternatively, health status may be a result of differences between subjective and objective measures of indoor warmth. To account for variance caused by definitions of fuel poverty, this paper tried to account for this by allowing a more flexible definition of cold homes as an indication of fuel poverty. Compared to using the UK's warmth standard, the flexible warmth standard was found to better explain mental health. This means that healthy adults may still feel comfortable even if the temperature is a bit lower than the actual warmth standard. In addition, participants with chronic diseases like COPD stated they live in fuel poverty even if their main bedroom is not colder than other participants. This further highlights the complexity in understanding the drivers and health impacts of living in fuel poverty, and in turn how these should inform future policy and practice (Sharpe et al., 2020).

From a public health perspective, the results here highlight the importance of maintaining adequate indoor home temperatures (Sharpe et al., 2019; Sharpe et al., 2015b). Consistent with Sharpe et al., (2020) and Bramley et al., (2017), those living in more energy efficient homes remained in fuel poverty. This provides further evidence of the need for more 'whole house' fuel poverty interventions that address resident behaviours (e.g. training) and the whole property (i.e. in and outdoors) to ensure that it is affordable to both heat and ventilate (Sharpe et al., 2018). When targeting fuel poor households, it is also important to consider the impact of poor mobility and reduced activity levels because these vulnerable populations were found to spend more time indoors. This is supported by those households regularly walking experiencing improved mental health outcomes. This poses a number of policy implications that support more holistic public health measures for vulnerable households living in fuel poverty.

Strengths and limitations

Our study contributes to the growing literature on the effect of fuel poverty on physical and mental health and need for more holistic public health focused fuel poverty policies and interventions. Proposing alternative ways of measuring fuel poverty combining self-reported fuel poverty measures and revealed fuel poverty measures will help policy makers to identify and support the most vulnerable populations, and consequently reduce the burden of cold related morbidity and mortality. For example, this has the potential to support more flexible fuel poverty interventions to enable local authorities to better target and support fuel poor households that are not in receipt of benefits but remain vulnerable to cold and fuel poverty. Based on an established health and housing project with large scale indoor monitoring, new evidence is given on the interaction between a range of socio-economic factors and housing characteristics influences the risk of fuel poverty in social housing. Living in fuel poverty and/or a cold home increased the risk of poorer mental well-being outcomes. However, the lack of consistency associated with cold homes and physical health well-being may be a result of a complex interaction between resident behaviours, socio-economic status, and the built environment. Additionally, the temporal scale of the sensor data (one year) and prior improvements to make homes more affordable to heat (i.e. these social housing properties had a higher proportion of energy efficient homes) or other cheaper alternatives to maintain adequate warmth (i.e. thick clothes and blankets) may further influence our findings.

This study has several limitations. First, our study is limited to social housing tenants and may not be generalizable to the wider population, particularly home owners and those in private rental accommodation. For future studies, large-scale data across all housing sectors needs to be collected to generalise our finding to the whole population. The effect of fuel poverty on physical health may be a long term effect and the participant and housing characteristics of those participating in the study. Also, the temporal nature of fuel poverty in the households investigated remains unknown. However, overall the ability to compare both subjective and objective measures of fuel poverty via survey responses and indoor temperature sensors, and accounting for the potential impact of healthier adults adds strength to the study.

5 Conclusion

This study further supports the need for future fuel poverty policies to consider more flexible temperature based approaches to identifying and defining fuel poverty and the adoption of more whole house approaches that addresses improvements to the building, environment and communities. These public health measures should also take a more holistic approach and incorporate physical activity interventions to help support fuel poor households to be more active and overcome mobility issues. The combination of these public health measures could result in more sustainable health and well-being outcomes.

Further use of sensor technology to inform health interventions is also merited – as they will allow for the better targeting of interventions across a range of public health issues. There is scope for further investigation of the use of such sensors in targeting physical activity, indoor air quality and other issues that may affect health.

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7 Appendix

Figure A1 The sensor used to measure the indoor temperature: QC0160 ultra-RF, manufactured by Invisible System Limited (7.5min data profile, accurate to ± 0.5°C).

Table A1: Full results table of M1 M2 M3 M4

	M1		M2		M3		M4	
	Coef.	p-value	Coef.	p-value	Coef.	p-value	Coef.	p-value
PCS								
E	-0.168	0.340	-0.110	0.328				
Age	-0.269***	0.003	-0.261***	0.002	-0.219***	0.007	-0.228***	0.005
Woman	0.045	0.413	0.043	0.432	0.035	0.518	0.035	0.517
Retired	-0.010	0.903	0.001	0.989	0.022	0.781	0.026	0.743
PhysicalActivity	0.156**	0.011	0.159***	0.008	0.162***	0.006	0.167***	0.006
Walking	0.236***	0.000	0.238***	0.000	0.245***	0.000	0.245***	0.000
Cold_temp_fix					0.211	0.266		
Cold_temp_fixsq					-0.136	0.475		
Cold_temp_flex							0.269	0.126
Cold_temp_flexsq							-0.237	0.177
MCS								
E	-0.379***	0.007	-0.390***	0.000				
Age	0.136	0.190	0.124	0.202	0.247***	0.002	0.252***	0.002
Woman	-0.052	0.365	-0.051	0.367	-0.069	0.192	-0.069	0.192
Retired	-0.024	0.807	-0.035	0.720	-0.029	0.747	-0.031	0.733
Copd	-0.021	0.771	-0.033	0.600	-0.110**	0.040	-0.108**	0.046
Disable	-0.237***	0.006	-0.256***	0.000	-0.321***	0.000	-0.319***	0.000
PhysicalActivity	0.026	0.660	0.025	0.668	0.014	0.817	0.010	0.875
Walking	0.123**	0.044	0.119*	0.049	0.123**	0.048	0.122*	0.050
Cold_temp_fix					-0.314*	0.094		
Cold_temp_fixsq					0.223	0.233		
Cold_temp_flex							-0.398**	0.021
Cold_temp_flexsq							0.334*	0.053
E								
Age	-0.374***	0.008	-0.417***	0.005				
Woman	0.040	0.662	0.044	0.618				
Retired	-0.196	0.307	-0.229	0.144				
Householdsize	-0.202	0.147	-0.275**	0.023				
Nbroom	-0.100	0.313	-0.055	0.584				
Flat	-0.180**	0.048	-0.198**	0.020				
Heatgas	0.049	0.583	0.059	0.458				
Epc_d	0.145	0.166	0.158*	0.062				

Copd	0.258***	0.004	0.231**	0.014				
Disable	0.021	0.897	-0.048	0.717				
HoursWeek	0.206**	0.041	0.192**	0.044				
HoursWkEnd	0.089	0.364	0.122	0.186				
ep1								
E	0.581	0.000	0.586	0.000				
ep2								
E	0.255***	0.010	0.245***	0.006				
ep3								
E	0.335***	0.001	0.327***	0.000				
Cold_temp_fix								
E			0.196**	0.030				
/								
var(e.ep1)	0.663***	0.000	0.657***	0.000				
var(e.ep2)	0.935***	0.000	0.940***	0.000				
var(e.ep3)	0.888***	0.000	0.893***	0.000				
var(e.pcs)	0.756***	0.000	0.773***	0.000	0.779***	0.000	0.780***	0.000
var(e.mcs)	0.651***	0.000	0.644***	0.000	0.758***	0.000	0.755***	0.000
var(e.E)	0.633*	0.090	0.621**	0.015				
var(e.cold_temp_fix)			0.961***	0.000				
cov(e.pcs,e.mcs)	-0.256***	0.001	-0.238***	0.001	-0.199***	0.002	-0.198***	0.003
Comparative fit index	0.819		0.767		0.757		0.757	
RMSEA	0.057		0.058		0.274		0.275	
SRMR	0.040		0.044		0.042		0.042	
Number of participants	280		280		280		280	