Wellbeing, Space and Society 3 (2022) 100070

Contents lists available at ScienceDirect

Wellbeing, Space and Society

journal homepage: www.sciencedirect.com/journal/wellbeing-space-and-society

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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A B S T R A C T

Linking novel real-time sensor data with comprehensive individual baseline survey data, this study estimates the effect of fuel poverty on the physical and mental health of social housing tenants in the southwest of the UK. Structural equation modeling is applied to show that fuel poverty has a significant negative effect on mental health. Other socio-economic characteristics (such as age, household size) and house characteristics (e.g., energy-efficient rating, house type) are associated with fuel poverty. Fuel poverty is also related to poorer mobility. 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.

1. Introduction

The linkage 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). Since fuel poverty is a complex social issue, recent research has begun to focus on the impact of fuel poverty on physical and mental health (Sharpe et al., 2018) and national policy changes to allow greater flexibility for local authorities to target and support fuel poor households (Sharpe et al., 2020).

Cold homes have been linked to poor health outcomes by many studies, such as self-rated health well-being (Zhang et al., 2019; Lacroix and Chaton, 2015), physical health (Hills, 2012; Liddell and Morris, 2010) and mental health (Sharpe et al., 2018; Liddell and Guiney, 2015; Marmot and Bell, 2012). In addition, households who cannot afford adequate heating have higher winter mortality and risk of having respiratory diseases (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 whose required energy expenditure (based on maintaining a decent heating regime) exceeds 10% of their disposable income (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 to meet their basic needs (Hills, 2011). More recently, by its access to large amounts of household information, a more detailed Low Income Low Energy Efficiency (LILEE) indicator to define fuel poverty (DBEIS, 2021a) has been developed for England. The LILEE indicator defines a fuel poor household as households living in a property with an energy efficiency rating of band D (MHCLG, 2018) or below and who are left with a residual income below the official poverty line after they purchase the required amount of energy. A clear disadvantage of expenditures-based approaches is that they examine households' actual spending on energy, rather than the necessary energy to ensure an adequate thermal temperature according to households' needs. In the case of the LILEE indicator, household energy efficiency improvements (above D) alone may not eliminate the risk of cold in the lowest income households (Anderson et al., 2012) since households may continue to ration heating regardless of the energy efficiency of the home due to households being unwilling or unable to divert limited disposable income to cover energy bills (Howden-Chapman et al., 2012; Lomax and Wedderburn, 2009). As a result, the above approaches may underestimate fuel poverty (Atsalis et al., 2016; Legendre and Ricci, 2015). Although previous research has tried to overcome this issue by focusing on required, rather than actual fuel spending to take potential household under-consumption into account, applying these approaches requires a

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https://doi.org/10.1016/j.wss.2021.100070
Received 21 June 2021; Received in revised form 4 November 2021; Accepted 16 December 2021
Available online 23 December 2021

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. Currently, the UK's adequate standard of warmth is 21 °C for the main living area and 18 °C 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 temperatures (Atsalis et al., 2016; Legendre and Ricci, 2015). Self-reported temperatures may lead to biased indoor temperatures, with levels of thermal discomfort in homes being under-declared (Healy and Clinch, 2002; Thomson et al., 2017). Over the last decade, the widespread of real-time indoor environmental sensors 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.

Some studies have investigated the health impact on fuel poverty using simple telemetry on a small scale (Pollard et al., 2019). Oreszczyn et al. (2006) investigated room temperature during winter in 1604 low-income households in five cities of the UK using sensor data. They found that the indoor temperature is associated with the property's age, construction and thermal efficiency, and social demographics such as the age and family size of the 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 assessed the number of days for which indoor temperatures above the UK's standard of warmth (18 °C) and investigated the possible factors that relate to 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 associated with indoor temperature, and households with occupants aged over 64 years or having a long-term disability were more likely to meet the 18 °C-warmth standard than those without disability and those in younger age groups (Huebner et al., 2018).

In the UK, social housing associations and local authorities are responsible for the provision of affordable housing to low-income populations (Sharpe et al., 2015a; OECD, 2020). The social housing sector accounted for 17% of homes in the UK, compared with 20% for the private rented sector (ONS, 2019). Whilst social housing properties are generally well maintained and have higher energy efficiency levels in countries such as the UK (DEBIS, 2021b), social housing tenants are more vulnerable to fuel poverty than homeowners as they are on average an older and lower-income population. Overall, 23.2% of fuel poor households are social housing tenants (DEBIS, 2021b). In addition, improvements to the indoor thermal performance did not eliminate the risk of living in a cold home (Anderson et al., 2012). Recent studies found that households in the private rented and social housing sector are more vulnerable to fuel poverty (Bramley et al., 2017), and fuel poverty combined with housing faults harms health well-being among social housing tenants (Boomsma et al., 2017).

In brief, the actual expenditure-based fuel poverty measures require a large amount of household information and therefore consensual fuel poverty measures are still widely applied by studies, such as the fuel poverty measures of the EU SILC Survey (e.g., Bosch et al., 2019). As discussed above, observing the exact winter indoor temperature using indoor sensors provides an opportunity for housing landlords to recognize the signs and risks of fuel poverty earlier and help mitigate its impacts on the property and resident health. However, very few studies have observed actual indoor temperature using home monitoring devices (Oreszczyn; 2006; Huebner et al., 2013; Kelly et al., 2013, 2018; Huebner et al., 2019). In this study, we expand on existing knowledge by comparing and combining self-reported and revealed fuel poverty to provide more insights into the potential causes of fuel poverty.

In this context, this study extends the current literature on fuel poverty by providing a comparison of self-reported measures of fuel poverty and revealing fuel poverty using sensor data, and 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 presents the methodology, including the measurement of fuel poverty and health well-being and the survey. Section 3 presents the results of statistical analysis. Section 4 discusses our results, and Section 5 presents conclusions and some policy implications.

2. Methods

2.1. Study population

Building on prior health and housing research (Sharpe et al., 2015a, 2015b), the Smartline project focused on a social housing population residing in Cornwall, South West of England. Cornwall is a rural county with dispersed settlement patterns, a high number of properties off the gas, and high levels of deprivation (Cornwall Council, 2015) and has many coastal communities (Whitty, 2021). The area is largely influenced by a maritime climate which is dominated by mild temperatures, strong wind speeds, and wet winters (Kosanic et al., 2014). The combination of these factors along with resident and building characteristics contributes to higher rates of fuel poverty than the national average (PHE, 2019). This has been previously observed in those residing in social housing who have experienced high levels of fuel poverty (Boomsma et al., 2017). Factors contributing to the increased risk of fuel poverty in Cornwall are also observed nationally, particularly in coastal communities (Whitty, 2021). The target population resided in properties owned and managed by a medium-sized Social Housing Association, Coastline Housing, a not-for-profit organization responsible for the provision of affordable housing (Sharpe et al., 2015b).

2.2. 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 et al., 2019). The contact list was provided by Coastline Housing, a not-for-profit housing association in southwest England. In total, 1707 invitations were sent by letters, and finally, 329 households were surveyed. The overall survey lasted for approximately 45 min. The survey data were merged with Coastline Housing's asset management and stock condition data, including building type, energy performance rating, and the number of rooms in each residence.

Among the surveyed participants, 280 households allowed sensors to be installed in their homes 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. Participants' daytime activities vary tremendously, and there are many more unknown private activities associated with daytime temperature. For example, a participant's average daytime temperature is low, which may be due to no one at home or regularly opening the windows during the day. The main bedroom's overnight temperature is more comparable since people spend most of their time sleeping and resting at night in their main bedroom. Thus, we take the average overnight temperature (from 7 pm to 7 am) during winter (from 01/12/2017–28/02/2018).

This project was approved by the University of Exeter Research Ethics Committee and conformed to the principles embodied in the Declaration of Helsinki. All participants needed to consent to participate in the survey and to have sensors installed to join the project.

2.3. Measurement of fuel poverty

2.3.1. 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)

2.3.2. 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 a revealed fuel poverty measure (denoted as E3) applying a fixed 18 °C warmth standard to identify the households 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), which equals 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).

2.3.3. 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 have established composite fuel poverty measures combining self-reported information on energy expenditures, affordability of appropriate heating, and indoor temperature (e.g., Charlier and Legendre, 2019, Churchill et al., 2020). To our knowledge, no previous study has established a fuel poverty measure combining self-reported fuel poverty with indoor temperatures observed by sensors.

2.4. Measurement of physical and mental health

The SF-12™ version 2 functional health and well-being survey (SF-12V2) was employed to evaluate participants’ physical and mental health. The SF-12V2 is a multipurpose clinical scale that assesses general health-related quality of life. It is a validated and reliable survey, and it has been widely applied in the literature (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 was computed using the “Health Outcomes Scoring software 5.1″ software following the SF12v2’s manual (Maruish, 2012).

2.5. 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 measured using the 3-item fuel poverty scale and an additional item “*Cold_temp _fix*” which is the observed coldness. Fig. 1 presents the structure of the structural equation models using E2.

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

$$I_i = constant_i + \alpha_i * E + \varepsilon_i \tag{1}$$

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 $v\varepsilon_i$. To estimate the effect of E on health and wellbeing, Eqs. (1) and (2) are estimated jointly in M1 and M2, as shown in Fig. 1.

Using the following structural equation, we estimate the associations between respondents’ personal and housing characteristics and their self-reported fuel poverty as:

$$E = \mu_0 + \mu * X + \varepsilon_e \tag{2}$$

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:

$$\boldsymbol{MCS} = \boldsymbol{r}_0 + \boldsymbol{\theta} * \boldsymbol{E} + \boldsymbol{r} * \boldsymbol{X} + \boldsymbol{\varepsilon}_m \tag{3}$$

$$\boldsymbol{PCS} = \boldsymbol{r}_0 + \boldsymbol{\theta} * \boldsymbol{E} + \boldsymbol{r} * \boldsymbol{X} + \boldsymbol{\varepsilon}_p \tag{4}$$

The two health scores, $\boldsymbol{MCS}$ and $\boldsymbol{PCS}$, depend on the underlined fuel poverty $\boldsymbol{E}$ with the associated parameter $\boldsymbol{\theta}$ and a vector of socio-economic and housing variables $\boldsymbol{X}$ with the associated vector of parameters $\boldsymbol{r}$. The error term $\boldsymbol{\varepsilon}_m$ and $\boldsymbol{\varepsilon}_p$ is independently and identically distributed with a zero mean and a variance of $\boldsymbol{v\varepsilon}_m$ and $\boldsymbol{v\varepsilon}_p$.

Finally, we investigated the relationship between respondents’ personal and housing characteristics and the revealed fuel poverty E3 and E4 using a Tobit model in which the dependent variables are two

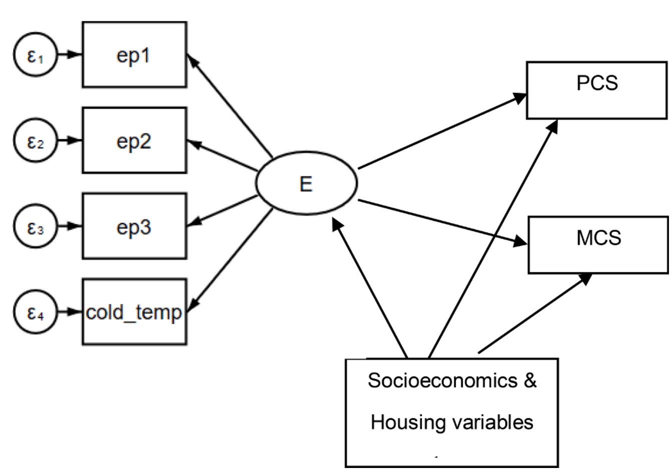

Fig. 1. Model M2: Structural equation model for effects of self-reported fuel poverty on health and well-being. E represents the latent fuel poverty.

variables that describe the coldness level “Cold_temp _fix” and “Cold_-temp_flex”. One issue with the warm standard as a cut-off point to define the coldness level is that it is impossible to observe the residents who still feel cold even if the temperature is higher than the selected warmth standard. By applying a Tobit model, the dependent variable becomes an uncensored latent variable, i.e., instead of using zero as the observed coldness level if the temperature is higher than the selected warmth standard, we specify a latent dependent 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), 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 (see Table 1).

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 people. Regarding the various indicators of health status previously associated with fuel poverty (Hills, 2011) and available in the Smartline National Survey, 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 significantly associated with health status (Meyer et al., 2014). In terms of participants’ indoor/outdoor activities, participants take more than a 10 mins walk 3.9 days a week and have 2.6 days with at least 30 min of physical activity on average. 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 h sitting on average. Our participants spend on average 20 h a day at home during the week or weekend.

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 2017, 2.2% of dwellings were given an A or B, 50% of dwellings were given a C, and 41.3% of dwellings were given a D in the social housing sector in England (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 distribution of the main bedroom overnight temperature is presented in Fig. 2. The average main bedroom overnight temperature is 17.2 °C. 45.4% of the participants’ main bedroom overnight temperature is lower than 18 °C.

In terms of participant physical and mental health (Table 3), the 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 compared to both surveys. However, research has indicated that social housing tenants have more physical health problems (MHCLG, 2019) than other housing tenure groups.

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
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
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				

3.2. Findings on the factors associated with fuel poverty

Table 4 presents the results on the factors related to 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 living in flats (*Flat*) are less likely to report fuel poverty or living in a cold home. The houses with the lowest energy performance

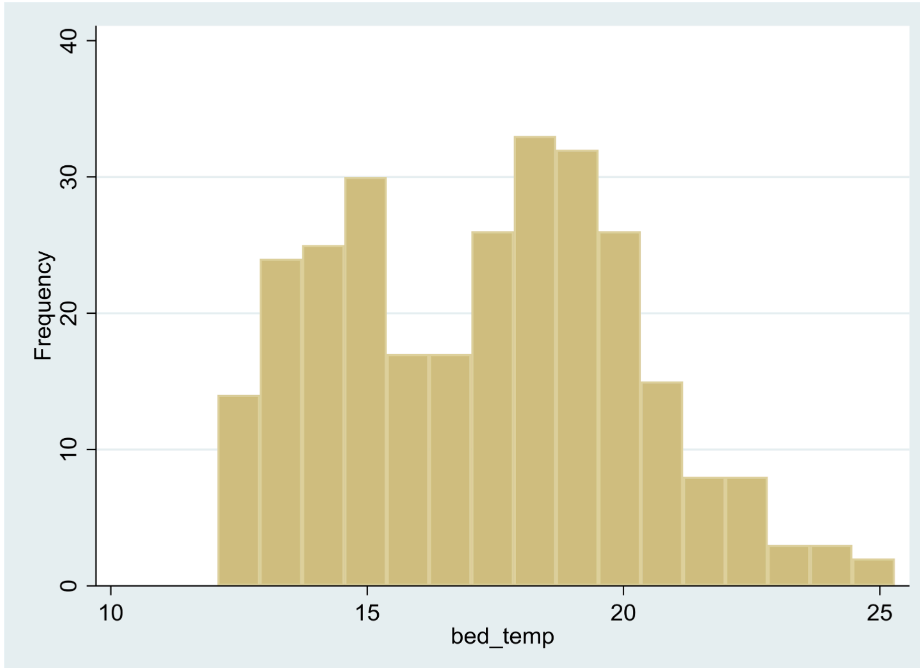

Fig. 2. Distribution of the average overnight temperature of participant's main bedroom.

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

rating (*EPC_D*) in our sample are not significantly colder than other houses. In other words, higher energy efficiency houses are not significantly associated with the home's warmth level. In the case of E2, the "*EPC_D*" is significant that 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 disabilities and long-term illness (*Disable*) are less likely to live in fuel poverty compared to others despite the coefficient being weakly significant (at the 10% level). 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 hybrid poverty (E2). It implies that using a flexible warmth standard better fits the householders' actual needs for indoor warmth.

Some associated factors 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*).

3.3. The impact of fuel poverty on health

Table 5 presents the results of Eq. (3) that estimate the association between fuel poverty and mental health. Poor health conditions, such as disability and long-term sickness (*Disable*), and having COPD (*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 an increased number of days with at least 10 mins of walking (*Walking*). Regarding the fuel poverty variables, self-reported fuel poverty (*Stated fuel poverty*) is found to be the strongest predictor of mental health and well-being. We have found a significant and negative effect on mental health in Model M1 and M2, which estimate stated fuel poverty E1 and hybrid fuel poverty E2. The coefficients of the coldness level variables (*Cold_temp_fix* and *Cold_temp_flex*) are both significantly negative in Model 3 and Model 4. It implies that living in a cold bedroom has a significant 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 be better at explaining participants' mental health and well-being since the variable "*Cold_temp_flex*" is more significant than "*Cold_temp_fix*".

Table 6 presents the results of 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 the number of days with physical activities (*Physical activity*) and at least 10 mins of walking (*Walking*). None of the fuel poverty measures have a significant impact on physical health.

4. Discussion

Bringing together self-reported and revealed measures based on

Table 4
The factors associated with 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

* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$; p-values in parentheses.

Table 5
Results of the Eq. (3): factors associated with 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 6
Results of the Eq. (4) : factors associated with 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.

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 the 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. Our application of home sensor technology and recognizing the drivers for fuel poverty could help improve fuel poverty policy and practice at the national level. Furthermore, it helps shape the way we support fuel poor households that do not technically meet the low-income criteria (Sharpe et al., 2020).

4.1. *Synthesis with existing literature*

Consistent with prior research, this paper found that living in fuel poverty and/or a cold home is negatively associated with participant mental health (Dear and McMichael, 2011; Gilbertson et al., 2012; Hernández et al., 2016; 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 contrasts with previous research (Hills, 2012; Howden-Chapman et al., 2012; Liddell and Morris, 2010) that highlights the increased risk of cold-related morbidity and mortality. There are several explanations for this finding. First, previous studies 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 focused on household's general-health-related quality of life evaluation by applying clinical health scales (SF12V2). A recent study using area-level health and energy efficiency data in England also reported mixed findings depending on the household energy efficiency measures employed, such as improved heating, insulation and glazing, and health outcomes (Sharpe et al., 2019). Second, our findings are also likely to be influenced by the higher proportion of participants with a disability and long-term condition, which is typical of social housing occupancy demographics (Bramley et al., 2017). Third, our findings on the relationship between physical health and fuel poverty may also be a result of different unobserved indoor home behaviours. Such behaviours include, for example, people's ability or awareness to access help, knowledge and their personal heating behaviours (Tod et al., 2012), the building they live in, as well as multiple social, cultural, and economic factors (Sharpe et al., 2018). For example, we found that those living in flats experienced less fuel poverty than those in houses. In contrast, mental well-being may be more susceptible and variable to the impacts of fuel poverty (Sharpe et al., 2020), particularly in the short term.

Measuring the extent of fuel poverty using sensors rather than self-reported data may also influence our findings. The expenditure-based approach does not consider the thermal temperature of the property and may underestimate the presence of fuel poverty (Churchill et al., 2020; Atsalis et al., 2016; 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 address the limits of the current fixed warmth standard (Wookey et al., 2014), this paper also develops a more flexible definition of cold homes as an indication of fuel poverty. Compared to the UK's warmth standard, this study found that using a flexible warmth standard better explains mental health. For example, this study finds that healthy adults may still feel comfortable even if the temperature is a bit lower than the actual warmth standard. On the other hand, participants with chronic diseases like COPD stated that they lived in fuel poverty even if their main bedrooms are not significantly colder than other participants. This result further highlights the complexity in understanding the individual drivers and health impacts of living in fuel poverty and, in turn, how these should inform future policies and practices (Sharpe et al., 2020).

From a public health perspective, the results highlight the importance of maintaining adequate indoor home temperatures (Sharpe et al., 2019, 2015b) and raise the awareness of the negative impact of low indoor temperatures on the mental health of home occupiers (Pollard et al., 2019). Consistent with Sharpe et al. (2020) and Bramley et al. (2017), we found that more energy-efficient homes are not warmer than less energy-efficient ones. This finding provides further evidence of the need for more 'whole house' fuel poverty interventions that address resident behaviors (e.g., training) and the property as a whole (i.e., in and outdoors) to ensure that it is affordable to both heat and ventilate the house (Sharpe et al., 2018). When targeting fuel poor households, it is essential 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 our finding that respondents who reported that they regularly go for a walk experienced better mental health outcomes. Therefore, these results pose a number of policy implications that support more holistic public health measures for vulnerable households living in fuel poverty.

Previous studies detected higher levels of fuel poverty among working-age disabled people using the expenditure-based fuel poverty measures (Gillard et al., 2017; Snell et al., 2015). Using self-reported and sensor data, we found that the overnight main bedroom temperature of participants with long-term illness and disability is not significantly different from other participants during winter among social housing tenants. And also, the likelihoods of reporting fuel poverty are statistically the same between disabled participants and participants who did not report a disability. However, if the 18 °C warmth standard is applied to define a cold home, we have found a weak negative correlation between being disabled and living in a cold home, which is different from the findings of previous studies.

4.2. *Strengths and limitations*

This study contributes to the growing literature on the effect of fuel poverty on physical and mental health and the need for more holistic public health-focused fuel poverty policies and interventions. The paper proposes alternative ways of measuring fuel poverty by combining self-reported and revealed fuel poverty measures that will help policymakers 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 support for 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, we provide new evidence on the interaction between a range of socio-economic factors and housing characteristics that 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 homeowners and those in private rental accommodation. For future studies, large-scale data across all housing sectors needs to be collected to generalize our findings 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. Another limitation of this study is that data on participants' incomes were not collected because it was felt there would be limited variation in this given the study population. Income may be a causal factor underlying both fuel poverty and poor wellbeing. Thus, the correlation between fuel poverty and mental health is not necessarily evidence of direct causation. 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 and policy implications

This study collected self-reported fuel poverty measures by conducting a survey and combined the survey data with indoor temperature data from sensors in the homes of social housing tenants. Our results show a clear association between fuel poverty and mental health well-being. This paper 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 address 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. This paper also demonstrates the potential of using sensor-based data to inform public health research, first by identifying previously 'hidden' homes in fuel poverty and second, by allowing better targeting of home-based interventions across a range of public health issues.

Declaration of Competing Interest

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

Acknowledgments

This study is in the frame of the Smartline project and Smartline extension project (www.smartline.org.uk) which are funded by the England European Regional Development Fund (Grant Nos. 05R16P00305, 05R18P02819) as part of the European Structural and Investment Funds Growth Programme 2014–2020. The Department for Levelling Up, Housing and Communities (and in London the intermediate body Greater London Authority) is the Managing Authority for the European Regional Development Fund. Established by the European Union, the European Regional Development Fund helps local areas stimulate their economic development by investing in projects which will support innovation and businesses, and create jobs and local community regenerations. For more information, visit https://www.gov.uk/european-growth-funding. The Smartline project is also funded by the South West Academic Health Science Network, Cornwall Council and HM Government, and is in a partnership between the University of Exeter, Coastline Housing, Volunteer Cornwall, Cornwall Council and the South West Academic Health Science Network. The authors are grateful to the whole Smartline team who helped with the collection of the survey data and administration of the project, particularly Andrew James Williams for his efforts in managing the survey design process, and to two anonymous reviewers for their valuable comments.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.wss.2021.100070.

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