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The Role of Energy Affordability in the Relationship between Poor Housing and Health Status

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Abstract: Housing quality is a well-established determinant for health and its relevance has been increasing in the context of sustainable development. Prior research has emphasized the importance of adequate housing for the health and comfort of householders. However, this link is still poorly characterized and understood regarding the vulnerable segments of the population. In this study, a mediation analysis is proposed to test and identify the role of energy affordability in the relationship between poor housing and health status. It resorts to microdata from the European Union—Statistics on Income and Living Conditions (EU-SILC) database, focusing on the analysis of Portugal as the case study. Research findings confirm the role of energy affordability as a mediator. The research findings supported the energy efficiency as a direct pathway with protective and preventive effect for poor health, followed by energy affordability as a mediated or indirect pathway. A complementary approach that addresses energy efficiency and energy poverty should be pursued to maximize health risk reduction.

Keywords: energy poverty; cold homes; perceived health status; energy efficiency; decomposition analysis; microdata; Portugal

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1. Introduction

A study by Velux (2018) concerning the impact of buildings on European citizen's health has emphasized that currently at least one in six Europeans lives in buildings with at least one of the following poor housing conditions: (1) dampness, (2) not enough daylight (too dark) or (3) thermal discomfort [1]. Simultaneously, energy poverty though widespread across Europe, presents an uneven distribution, with higher incidence in Southern and Eastern European countries [2]. In the former countries, energy affordability concerns or the ability to afford adequate energy services, such as lighting, seem to have a pronounced expression as a measure of energy poverty (e.g., [3]). Thus, despite the increasing publications demonstrating the relevance and multidimensional nature of this topic (see [4,5]), further policy integration efforts require the consideration of energy poverty links to other policy areas (see [6]). Recent studies, such as Magalhães et al. (2016) and Simões et al. (2016) provided empirical evidence of cold homes and fuel poverty regarding space heating and cooling in Portugal [7,8]. However, few studies have been conducted to assess how poor housing relates to contextual factors such as householder's age, income and health (e.g., [9]). A study by Horta et al. (2019) emphasized the high vulnerability of energy poor households in Portugal to indoor cold (in winter) and heat (in summer), and the relevance of considering 'socioeconomic context and the low quality of the housing stock' in its assessment [10]. The authors mention that the perception of thermal (dis)comfort and its acceptance by households may affect the recognition of the problem and its impacts on health and wellbeing, but to date, no assessment of these variables has been made.

The main objective of this study is to address this gap, i.e., to determine the role of energy efficiency and the energy affordability regarding the improvement of perceived health status. The aim was to show policy makers the main pathways to address the impacts of inefficient (poor) housing upon health. Moreover, the definitions adopted for the lack of energy efficiency and the energy affordability are aligned with those used to identify energy poverty, namely the 'struggle to heat or cool home' or the struggle to 'pay the energy bill on time', respectively (see [11]). Therefore, the assessment of the relationships between health status (dependent variable) and poor housing conditions, namely thermal discomfort (proxy for energy inefficiency) or ability to afford/pay to keep warm (proxy for energy affordability), as main independent variables, resorted to a mediation analysis.

To the best of our knowledge, no such study has been performed for Portugal. Additionally, the current study also aims to extend prior research, by zooming in on vulnerable segments of the population, such as the elderly. It aims to address this gap by applying a newly developed mediation analysis that extends traditional mediation analysis by considering binary outcome and binary mediators. This novel approach takes into consideration interactions between thermal discomfort and affordability to test and identify the role of energy affordability in the relationship between poor housing (indoor temperature perception) and health status for the case of Portugal. This statistical approach is known as 'four-way decomposition' analysis [12], and to our knowledge, it has not yet been applied in the context of poor housing and health. It will enable us to study indoor temperature perception (thermal discomfort) and affordability (ability to keep warm), their interconnection and subsequent link with health status. Taking into consideration and extending prior research, this study seeks to answer the following research questions:

- What is the relationship between thermal discomfort and poor health status, according to socioeconomic background (e.g., age or income), using affordability as mediator?
- What is the portion of the overall effect that is allocated to each component of the 'four-way decomposition' analysis?

This study addresses the case of Portugal using data from the European Union—Statistics on Income, Social Inclusion and Living Conditions (EU-SILC) microdata database (see [13]). The database can be provided to recognize scientific research centers and university institutions, for scientific purposes, upon a strict access and usage protocol. The present study resorts to 2012 ad hoc module [14] devoted to housing conditions. After this brief introduction to the subject, this paper continues by presenting a brief literature review (Section 2), after which the dataset and sampling approach (Section 3), and the theoretical framework for the modelling approach are described (Section 4). In the results (Section 5), the findings obtained are presented and discussed. The paper then concludes in Section 6 by presenting possible implications for the development of policies to tackle energy inefficiency and unhealthy housing quality.

2. Literature Review

In this section, a review of the relationships between poor housing and health is presented, followed by an overview of the proposed mediation modelling approach.

There seems to be compelling evidence of the association between poor housing and householder's health status. A wide range of adverse health effects has been reported and could configure a 'poor health status', from cardiorespiratory to mental health conditions. For instance, while studying the influence of the economic crisis in energy and environmental quality of low-income households in Greece, Santamouris et al. (2014) found a strong association between these parameters. The results showed that indoor temperatures were below minimum levels and that a high share of the households were not using heating at all [15]. In very low-income households, a high share of the population was diagnosed with poor mental health, namely depression issues. An increased risk of poor mental health was also evidenced in the UK by Pevalin et al. (2017), for people living in social housing with poor housing conditions and for extended periods of time [16]. Furthermore, a recent study at the EU level [17] has found that people who are exposed to poor housing conditions have a higher probability of reporting poor health (by 70% in contrast to non-exposed). Based on the analysis of the correlation between health and poor housing, exposure to damp or cold homes reported the highest correlation to poor health (1.7 times higher than non-exposed).

A comparison between two social housing neighborhoods in Porto, Portugal, was conducted by Ramos et al. (2018). This study looked to understand the impact of indoor humidity and temperature conditions on quality of life, resorting to a Short Form Health survey (SF36) [9]. The results showed that the rehabilitated neighborhood had increased satisfaction of householders along with improved indoor hygrothermal conditions. As a matter of fact, a review undertaken by Fisk et al. (2020) emphasized that the improvement indoor temperatures and the presence of damp and mold promote a shift in householder's perception concerning thermal comfort and health status. Obtained results point towards an improvement in these aspects after energy efficiency retrofits [18]. These examples also reenforce why World Health Organization (WHO) considers the improvement in the exposure to low and high indoor temperatures as one of the major areas to reduce health risks from poor housing quality [19].

Additionally, few studies have resorted to mediation analysis to test the role of a third variable concerning the relationship between poor housing and health (e.g., [20,21]).

Recent studies have explored the effect of neighborhood on the health of building occupants. Chan and Liu (2018) found that, in Hong Kong, occupant's health is significantly affected by neighborhood qualities (building density and height, cleanliness and greenspace). A statistically significant correlation between neighborhood qualities and health was mediated by indoor environment, namely visual and acoustic comfort and indoor air quality) [22]. Rodrigues et al. (2021) found that the impact of neighborhood socioeconomic disparity in self-rated health is mediated by violence in poor or disadvantaged neighborhoods in Brazil [23]. Regarding poor housing, Heyman et al. (2005) investigated if energy efficiency was a mediator between socio-economic status and the risk of poor health in the UK. His findings supported that objective energy efficiency indicators, such as energy efficiency ratings, made an important contribution to the relationship between lower socioeconomic status and poorer health [20]. More recently, Boomsma et al. (2017) established an indirect effect of poor housing (damp, cold and mold) on health through energy affordability in the UK. The authors claim that houses experiencing cold, damp and mold issues reported more difficulty in paying energy bills and that this concern affect in turn their mental health and wellbeing [21].

The relationship between the thermal comfort, low energy consumption and aging population is still largely missing, in an increasingly aging population and climate change context [24].

In contrast to the abovementioned context, studies from the health sector have often resorted to mediation analysis to assess the impacts on health from different environmental exposures. For instance, Discacciati et al. (2019) and Lee et al. (2018) used the four-way decomposition approach to study the role of birth outcomes (e.g., birth length) in explaining the impact of the exposure to manganese on child neurodevelopment [25,26]. Higher pollutant concentrations were associated with lower cognitive score, and this effect was mediated through child length. Mediation and interaction was found between birth length being associated with the other two variables (manganese exposure and cognitive score). Though recently developed, the four-way mediation approach has been increasingly used given its advantage to simultaneously allow to estimate beyond the mediation and to focus also the interaction effects (see [25–28]).

Overall, despite this increasing evidence, research linking poor housing to socioeconomic background and health impacts is still largely underdeveloped. Additionally, the resource to newly developed approaches could provide additional insight regarding these associations on whether part of the effect of poor housing on health results from the influence of affordability. The next section presents the database, and the chosen modelling approach are presented.

3. Materials and Methods

A detailed description of the data and modelling approach is presented in this section.

3.1. Dataset and Variables: Data Sources and Survey Description

The European Union—Statistics on Income, Social Inclusion and Living Conditions (EU-SILC) is considered a reference database at the EU level, covering variables from different topics at the household and householder levels, namely income, poverty, social exclusion, housing, labor, education and health [29]. The present work resorted to a specific dataset or ad hoc module that provides the most recent data on poor housing conditions, namely regarding the indoor temperature perception for cold and heat. This is a variable of interest in the study of the relationship between poor housing and health status that is not provided on a regular basis.

EU-SILC provides annual statistics of two main types: cross-sectional, i.e., specific to a given time or time period, and longitudinal, i.e., measures 'individual-level changes' over a maximum of a four-year period [13]. Though the ad hoc modules are also developed on a yearly basis, they feature different yet relevant topics regarding social cohesion and inclusion. Among those subjects of interest is the 2012 module on housing conditions, featuring additional aspects of building characteristics, such as space in the dwelling, heating facilities and accessibility to basic services.

In Portugal, the initial sample size for 2012 cross-sectional ad hoc module edition included a total of n = 6257 houses and n = 13,584 householders. A sequence of filters was applied to the initial sample size, in order to obtain the final sample (n = 6031 houses and householders) for the modelling approach, as illustrated in Figure 1.

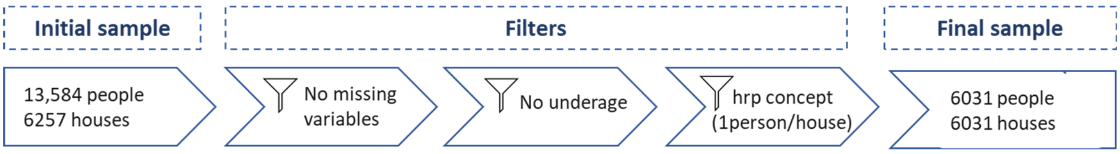

Figure 1. Filters from initial to final sample.

The filters correspond to the exclusion criteria through which the final sample was obtained. They consist of three simple steps: the first filter excludes missing information from variables of interest at the house or householder levels (e.g., house type or education); the second filter excludes data from multiple household members below the minimum age for interviews. Additionally, because answers at house level are given by a single respondent, the third filter applies household representative person (hrp) concept to match house and householder file, reducing the sample to one person per house (1 person/house). The hrp concept is commonly used by national and Eurostat level databases [30,31]. Furthermore, the use of a single respondent potentially avoids subjective bias [32]. This set of filters has accounted for a drop of 7553 people and 228 houses from the initial sample.

3.2. Dataset and Variables: Dependent and Independent Variables and Summary Statistics

Information regarding building characteristics or poor housing conditions socioeconomic variables, as described in Table 1.

Table 1. Variables or socioeconomic and housing conditions.

Variables	**General Health**	**House Type**	**Tenure status**	**Damp & Rot**	**Lack of Daylight**	**Ability to Keep Warm ***	**Heating Facilities**	**Warm during Winter ****	**Cool during Summer**	**Surface Area**	**Urbanization Level**	**Gender**	**Age**	**Birthplace**	**Marital Status**	**Education Level**	**Household Size**	**Economic Status**	**Income Quintile**	**Chronic Conditions**
Type																				
Dependent	√																			
Independent		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Data collection																				
Permanent	√	√	√	√	√	√					√	√	√	√	√	√	√	√	√	√
Occasional							√	√	√	√										

* Proxy for energy affordability; ** Proxy for energy efficiency
√ (shaded) poor housing conditions √ socioeconomic conditions

Information regarding building characteristics or poor housing conditions (e.g., damp and rot; house type or heating facilities) are collected at the house level. Meanwhile, most socioeconomic variables are collected at the householder level (e.g., gender, education level, economic status or general health). Among these variables is, for example, the ability to keep the household warm, which is more related to the energy affordability issue, since it is derived from the EU SILC question "Can your household afford to keep its home adequately warm?". Therefore, it may be considered as a proxy for energy affordability, representing householders' energy service concerns, namely for heating needs (see [21]). Therefore, henceforth 'ability to keep warm' will be designated as 'energy affordability'. Other variables are collected for a given year and for a particular subject, namely regarding living condition topic, known as the ad hoc modules.

Among the complementary 'ad hoc' living condition variables (e.g., 'surface area'; 'warm during winter'; 'cool during summer' and 'heating facilities'), for this analysis 'warm during winter' and 'cool during summer' are taken as the perception of indoor temperature during winter and summertime. Moreover, these variables may be considered as proxies for energy efficiency; henceforth, 'warm during winter' is re-named 'thermal comfort', and likewise, 'not warm during winter' becomes known as 'thermal discomfort'.

The key concern behind the 'thermal discomfort' variable is whether the house is sufficiently insulated and equipped with energy efficient appliances against cold [14]. Therefore, though not explicitly, this question provides us with information regarding specific poor housing conditions that complement other more explicit variables for poor housing conditions, such as the presence of 'damp and rot'. It is expected that the perceived thermal discomfort derived from the lack of wall insulation/heating inefficiency and damp walls could adversely affect health status, particularly for vulnerable segments of the population. These (poor) housing quality variables have been used consistently in the study of the relationship between energy and thermal comfort in Portugal (e.g., [10]). They have been further considered by Simões et al. (2016) as key defining features that need to be addressed regarding energy poverty, along with other socioeconomic variables such as income [8]. Furthermore, according to Carmichael et al. (2020), besides low efficiency rating associated with the lack of wall insulation, two other pathways are known to influence cold exposure; they are the heating facilities and excessive damp that reduces thermal insulation [33]. For the current study, we argue that the focal poor housing condition is thermal (dis)comfort, which could be considered a proxy for energy efficiency or lack of it. Other poor housing conditions, such as 'damp and rot' and the type of 'heating facilities' are included in the model as additional independent variables (covariates).

Among socioeconomic variables is the dependent variable that captures the self-perceived health status, i.e., how a person perceives their general health. It results from a broader question ("How is your health in general?"), and as such, it is expected to depict different health dimensions ('physical, social, emotional as well as biomedical signs and symptoms') [13,34]. It is measured as an ordinal variable, ranging in scale from 1 to 5, where 1 corresponds to very good health and the other extreme 5 corresponds to very bad health. In between the upper and the lower ends of the scale are the intermediate values (2 to 4), denoting a good, fair or bad health status. Similarly, to prior works (see [35–37]), this variable has been dichotomized between good and bad health status, taking the value of 0 if the person is in good health (encompassing fair, good and very good categories) or 1 if the person is in poor health (encompassing bad and very bad categories). This transformation of the dependent variable helps to better accommodate high degree of distribution skewedness [36]. Moreover, besides being a common practice, this conversion into a binary variable enables the application of the four-way decomposition analysis, suitable for binary, continuous or count variables (see [32]).

According to [38], one of the main advantages of using the EU-SILC database is that in a single database, several covariates or independent variables that can influence health status are available. Therefore, although poor housing conditions are the main explanatory variables, in this study, other typical socioeconomic variables are controlled for. For instance, low-income households are known to account for a substantial share of cold homes in several countries (e.g., [7,39,40]). The equivalized disposable income is used by Eurostat as a poverty indicator [41]; based on this concept, income quintile groups are computed to better identify different income groups. The data for total equivalized disposable income for each person are ordered, and based on cut-off points, it is possible to split the sample into five groups equally represented by 20% of individuals, from the lowest income (1st quintile) to the highest income (5th quintile) [42].

The present study takes special interest in the analysis of the elderly population, with age variable ranging from 17 onwards to over 65 years of age. In many countries, there is an increasing trend in terms of aging population and growing incidence of non-communicable or chronic diseases, namely heart disease, stroke, cancer, diabetes and chronic respiratory diseases [43,44]. In this sense, in contrast to previous studies, the presence of chronic disease is considered among independent or explanatory variables to account for person-specific unobserved factors related to health. This variable is binary and assumes the value of 1 for the existence of chronic disease or 2 otherwise. It looks to answer the following question "Do you have any longstanding illness or health problem?", accounting for a health condition that is permanent and may require a long-term supervision, observation or care [13]. Householder education level and occupation are also taken into consideration. Given that it has been acknowledged that senior citizens, often retired, tend to spend greater amounts of time indoors [45]. Controlling for overall socioeconomic variables could contribute to avoid bias due to unobserved heterogeneity, according to [25]. A full listing of available variables and detailed description is provided at Eurostat's metadata [46]. A summary of sample statistics is available, in Table 2.

Most people in the sample seem to live in detached houses (40.82%) in comparison to building flats. This higher share of houses is plausible given that rural areas are emphasized at the urbanization level, when compared to urban and peri-urban areas. Rural areas are characterized by sparsely populated areas in contrast to urban densely populated areas. As expected, there seems to be a much higher incidence of homeowners versus tenants. Regarding poor housing conditions, although the majority of houses are not affected by the damp walls, lack of daylight or the ability to keep the household warm (all above 70%), the share of houses that do suffer from these issues is still high (with the exception of lack of daylight, all variables are above 20%). Additionally, non-fixed heating systems seem to prevail against fixed heating systems. Meanwhile, the share of houses without any heating is high (17.87%) and well above the share of central heating systems. Given this background, the perception of thermal comfort during the winter is slightly above the discomfort felt during the wintertime (54.04% vs. 45.96%). Thermal discomfort during wintertime is more relevant than thermal discomfort during the summertime. Almost twice the share of people feel more comfortable during the summer than otherwise (66.14% vs. 33.86%).

Table 2. Summary statistics.

	Independent Variables	Categories	Percentage (%)/Mean
Poor housing conditions	House type	Detached house *	40.82
		Semi-detached or terraced house	23.41
		Flat in a building ≤ 10 dwellings	22.17
		Flat in a building ≥ 10 dwellings	13.60
	Tenure status	Owner *	50.90
		Owner (mortgage)	24.76
		Tenant (market rate)	9.90
		Tenant (reduced rate)	7.11
		Free accommodation	7.33
	Damp and rot [1]	Yes *	22.09
		No	77.91
	Too dark	Yes *	10.94
		No	89.06
	Energy affordability	Yes *	71.85
		No	28.15
	Heating facilities	Central heating *	9.75
		Other fixed heating	33.99
		Non-fixed heating	38.39
		No heating at all	17.87
	Thermal comfort	Yes	54.04
		No *	45.96
	Cool during summer	Yes	66.14
		No *	33.86
	Surface area (m^2)	continuous	102.85 [2]
	Urbanization level	Urban *	34.29
		Peri-urban	28.24
		Rural	37.47
Socioeconomic background	Gender	Male *	45.60
		Female	54.40
	Age	(17–35) *	9.35
		(36/44)	14.94
		(45/54)	19.33
		(55/64)	18.47
		(≥ 65)	37.90
	Birthplace	Local *	94.35
		Other (EU)	1.26
		Other (Non-EU)	4.39
	Marital status	Never married *	13.43
		Married	62.44
		Widowed	15.90
		Divorced	8.22
	Education level	Primary education *	49.25
		Secondary education	24.85
		Tertiary education	11.29
		No formal education	14.61
	Household size (equivalized nº of household members)	continuous	5.29 [2]

Table 2. *Cont.*

Independent Variables	Categories	Percentage (%)/Mean
Economic status	Working full-time *	32.58
	Working part-time	2.04
	Unemployed	9.02
	Students	1.72
	In retirement	39.26
	Permanently disabled	1.77
	Fulfilling domestic tasks and care responsibilities	7.03
Income quintile [3]	1 (poorest) *	13.73
	2	27.05
	3	27.32
	4	14.42
	5 (richest)	17.48
Chronic disease	Yes *	45.25
	No	54.75

* Reference category for Section 4. [1] includes also leaking roof, damp walls/floors/foundation or rot in window frames or floor. [2] Mean. [3] contribution percentages for each quintile to overall equivalized disposable income.

Regarding the householder profile, the sample is composed by a higher share of women (54.40%), over 30% from older age ranges (≥65 years of age) and that was mostly born locally. To a large extent people have a lower education level (49.25% of the sample has primary education as highest education level attained) and are currently retired (39.26%). As previously mentioned, income is represented here according to income quintiles. Income quintiles enable us to study income inequality through group comparison, i.e., those in high income with middle income and low income. While the 1st income quintile, the bottom 20% with very low income, accounts for 13.73% of total disposable income, the 2nd quintile is the next lowest and accounts for a greater amount of disposable income (27.05%). However, the 3rd quintile, medium low, accounts for the greatest share of disposable income (27.32%). The 4th and 5th quintiles account for a greater amount of income in comparison to the 1st quintile but below the values reported for the 2nd and 3rd income quintiles. Concerning health background, over 50% of householders do not present any chronic illness. The first step for the modelling approach is undertaken in the next section, with the model specification.

3.3. Model Specification

In the 'counterfactual approach', a novel mediation analysis is proposed to understand what the role of the energy affordability in the relationship between poor housing conditions (thermal discomfort) and health status is. With this purpose in mind, a newly statistical model design, the four-way decomposition approach, developed by [25,47] was followed.

A mediation analysis implies that an exposure affects an outcome. This approach has been largely applied in medical and epidemiological field to study environmental exposures (e.g., [25]). Poor housing is often associated with environmental exposures such as damp or cold. In this case, poor housing conditions become the exposures in the mediation analysis, i.e., the exposure to poor housing conditions causes poor health. However, in the context of mediation analysis, the effect or impact of poor housing on health might follow different paths, implying an additional variable between the exposure and the outcome—a mediator. In Figure 2, consider the poor housing condition, with exposure to the cold (thermal discomfort) directly affecting health status (1); an alternative or indirect pathway (2) is if the thermal discomfort, as a proxy for lack of efficiency, affects a third variable, which could be energy affordability, and this variable affects the outcome, becoming the mediator between the exposure (thermal discomfort) and the outcome (health status). This assumption seems plausible since thermal discomfort from inefficient cold homes could lead to an increase in the use of energy and could compromise energy affordability by increasing households' energy expenditure for heating purposes.

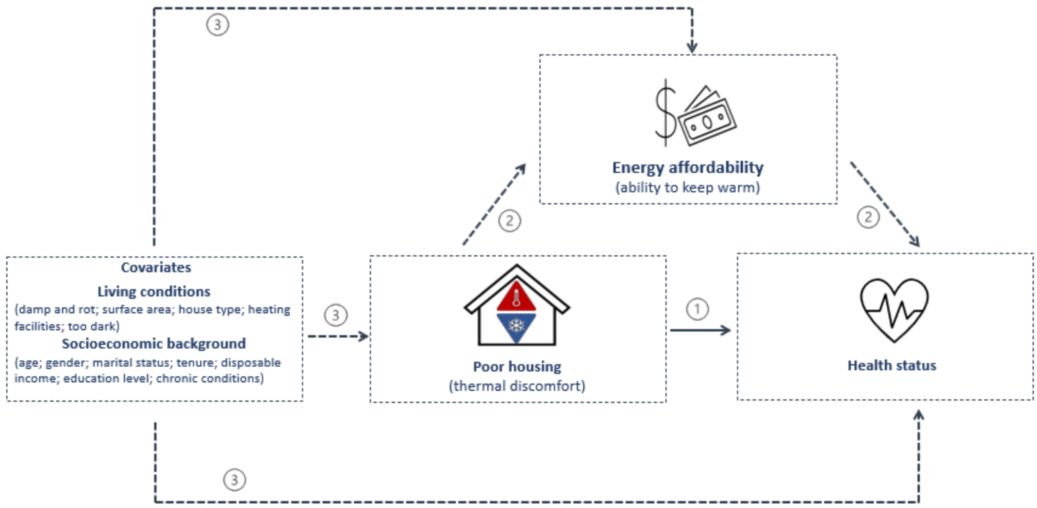

Figure 2. Mediation-directed acyclic graph with socioeconomic and living conditions covariates.

Pathways (1) and (2) in Figure 2 configure the 'conventional' mediation analysis, the more recent approach; the four-way decomposition approach enables us to consider covariates, such as the socioeconomic background variables; in this case, the example of age, is represented as pathway 3. Moreover, it is necessary to control these covariates, as they can affect both mediators and outcome, since for instance, the elderly may have different thermal comfort and health requirements. Additionally, the interaction between exposure and mediator is also taken into consideration, which is plausible given that cold homes could be considered houses that are difficult to heat, affecting the energy affordability (ability to keep warm). Similarly, the inability to keep warm could also influence thermal comfort perception, since energy affordability issues could lead householders to endure thermal discomfort to reduce their energy expenditures and to prevent the adoption of energy efficiency alternatives. Overall, there are four main variables of interest in this mediation analysis: the outcome variable (Y); the exposure (A), which can also be seen as a treatment variable and is hypothesized to have direct and indirect causal effects on the outcome; the mediator (M), which is hypothesized to be causally affected by the exposure/treatment (A) and that alternatively directly affects the outcome variable (Y); and the covariates (C) [48].

Poor housing conditions, such as the exposure to thermal discomfort could be addressed through energy efficiency measures, as their use could promote the transition from thermal discomfort towards thermal comfort. In this sense, the presence or absence of housing energy efficiency could be considered a 'treatment' for the exposure to poor housing conditions. Departing from this principle, we extend the VanderWeele's four-way decomposition method [47] to better understand the relationship between poor housing conditions (a proxy for the absence of energy efficiency), expressed as 'thermal discomfort' perception, versus 'thermal comfort' perception (a proxy for the presence of energy efficiency) and health status. Moreover, the interpretation of obtained results takes this approach into consideration.

Mediation analysis enables us to partition the total effect of thermal discomfort on health status into a direct effect (pathway 1) and an indirect effect (pathway 2) (see [37]). Resorting to the four-way decomposition, these effects can be further decomposed under a counterfactual approach. Vanderweele (2016) claims that total effect can provide additional information regarding the portion of the effect that (a) is only due to mediation; (b) that is only due to interaction; (c) that is due to both mediation and interaction; and (d) that is due neither to mediation nor to interaction [12,47]. A detailed definition of these effects is given in Table 3.

Table 3. Definition and interpretation of decomposition effects (adapted from [25,37]).

Decomposition Effect	Counterfactual Definition	Interpretation		Contextual Definition
Total Effect (TE)	$Y_a - Y_{a^*}$	Total effect of exposure A (changing from a^* to a) on the outcome Y	Overall effect	What is the risk of poor health among those transitioning from thermal discomfort to thermal comfort?
Controlled Direct Effect (CDE)	$(Y_{am} - Y_{a^*m^*})$	Effect of exposure A (changing from a^* to a) on the outcome Y, intervening to fix the mediator M to m	Due neither to mediation nor interaction	What is the risk of poor health among those transitioning from thermal discomfort to thermal comfort, if everyone is able to keep warm (has the same level of energy affordability)?
Reference Interaction (INT_{ref})	$(Y_{am} - Y_{am^*} - Y_{a^*m} + Y_{a^*m^*})$ (M_a)	An additive interaction that operates only if the mediator is present ($M_{a^*} \neq 0$) when exposure is a	Due to interaction only	What is the risk of poor health among those with thermal discomfort and affordability issues (inability to keep warm), if thermal discomfort does not have an effect on the energy affordability?
Mediated Interaction (INT_{med})	$(Y_{am} - Y_{am^*} - Y_{a^*m} + Y_{a^*m^*})$ $(M_a - M_{a^*})$	An additive interaction that operates only if the exposure A (changing from a^* to a) has an effect on the mediator M ($M_a - M_{a^*} \neq 0$)	Due to mediation and interaction	What is the combined risk of poor health among those with thermal discomfort and affordability issues (inability to keep warm), if thermal discomfort has an effect on the energy affordability?
Pure Indirect Effect (PIE)	$(Y_{a^*m} - Y_{a^*m^*})(M_a - M_{a^*})$	Effect of the mediator (changing from m^*to m) on the outcome Y when exposure A is a, multiplied by the effect of exposure A (changing from a^* to a) on the mediator M	Due to mediation only	What is the risk of poor health among those transitioning from thermal discomfort to thermal comfort and no affordability issues, if thermal discomfort has an effect on the energy affordability?

Y is the outcome (poor health); M is the mediator the ability to pay; A is the exposure thermal discomfort; (a*) is the reference level of exposure (thermal discomfort); (a) is the level of thermal comfort, the level of actual exposure and (m) is being able to keep warm/affordability or the level of the mediator at which the four-way decomposition is computed.

Table 3 denotes 'chain of risk' similarly to [27]. The four-way decomposition can be explained by Equation (1) [12,26,49].

$$TE = CDE + INT_{ref} + INT_{med} + PIE \quad (1)$$

where TE denotes the total effect, decomposed into its four components: CDE (controlled direct effect), representing the effect neither due to mediation nor to interaction; (INT_{ref}), known as the reference interaction and representing the effect only due to interaction; and (INT_{med}), or mediated interaction, which is the effect due to mediation and interaction; and finally, PIE (pure indirect effect), due to mediation alone. It should be noted that, controlling for covariates, such as age, gender, income and education level, or the damp and rot, ensures that the assumptions of no unmeasured confound between exposure and outcome, between mediator and outcome, and between exposure and mediator are ensured. Additionally, the mediator–outcome confounders should not be affected by the exposure. Therefore, and similarly to prior studies, the results were interpreted under the assumption that covariates (potential confounders) were controlled for and that the exposure does not affect any of the mediator–outcome covariates.

The counterfactual approach is also based on outcome and mediator models, upon which the decomposition into its four components takes place. The regression model for the outcome (health status) is a function of the exposure (thermal discomfort), the mediator and their interaction. The regression for the mediator (energy affordability) is a function of the exposure. Both models are controlled for covariates (living conditions and socioeconomic background variables). Based on [26,47], the mediator and outcome model, allowing for exposure–mediator interaction, can be expressed by Equations (2) and (3):

$$\text{Outcome Model} : \text{logit}\ \{\text{P} = 1\,|\text{a}\,,\text{m},\text{c}\} = \theta_0 + \theta_1\text{a} + \theta_2\text{m} + \theta_3\text{am} + \theta_4^{'}\text{c} \quad (2)$$

$$Mediator\ Model : logit\{M = 1|a, c\} = \beta_0 + \beta_1 a + \beta_2^{'} c \quad (3)$$

where θ_1 to θ_p and β_1 to β_p are the model's coefficients, a is the exposure (thermal discomfort in Figure 2), M and m are the mediator (energy affordability), and c is a set of covariates (socioeconomic and other living conditions in Figure 2). The mediation was run with the reference level of exposure (a*) set at presence of poor housing (thermal discomfort), the mediator was set at the m level, and affordability or ability to keep warm level and the covariates were set at average levels. Mediation analysis is further decomposed into its four components automatically by resorting to the 'med4way' command in STATA software, recently developed by [25,26].

4. Results

In this section, the results from the statistical modelling are presented and discussed, namely regarding the energy efficiency (CDE) and the energy affordability (PIE) pathways.

A detailed summary of the components of the four-way decomposition is provided in Table 4. It shows the reduced output, which provides estimates of the total effect (TE) of thermal discomfort on health. It also shows the attributable proportion (PA), which results from the contribution of the different components to the total effect (TE). PA is an estimate of which share of the total effect of thermal discomfort on health is due to the direct effect, to the mediation effect or to the interaction effect.

There seems to be a negative association between the presence of poor housing conditions and poor health, for both samples, with high significance level. This means the overall effect of transitioning from thermal discomfort (reference level) to thermal comfort implies a reduction in the health risk (of poor health status). This reduction is more accentuated for the elderly ($\beta = -0.332$, SE = 0.076; $p \leq 0.001$) than for the overall sample ($\beta = -0.282$, SE = 0.058; $p \leq 0.001$). Figure 3 proposes a path diagram, where the black full lines illustrate the contribution of each decomposition effect and the grey dotted line illustrates its absence, with the respective coefficients and significance levels.

Table 4. Model coefficients for 'counterfactual' approach.

Overall Sample Decomposition Effects	β Coefficients (Std. Err.)	*p*-Value	PA (%)	Elderly Sample Decomposition Effects	β Coefficients (Std. Err.)	*p*-Value	PA (%)
Total effect (TE)	−0.282 (0.058)	≤0.001	100	Total effect (TE)	−0.332 (0.076)	≤0.001	100
Controlled direct effect (CDE)	−0.180 (0.069)	≤0.008	64	Controlled direct effect (CDE)	−0.236 (0.087)	≤0.008	71
Reference interaction (INT_{ref})	0.047 (0.105)	≤0.801	−17	Reference interaction (INT_{ref})	0.071 (0.130)	≤0.587	−21
Mediated interaction (INT_{med})	−0.031 (0.027)	≤0.802	11	Mediated interaction (INT_{med})	−0.048 (0.089)	≤0.590	14
Pure indirect effect (PIE)	−0.118 (0.030)	≤0.001	42	Pure indirect effect (PIE)	−0.119 (0.085)	≤0.008	36

Proportion attributable (PA) (%)

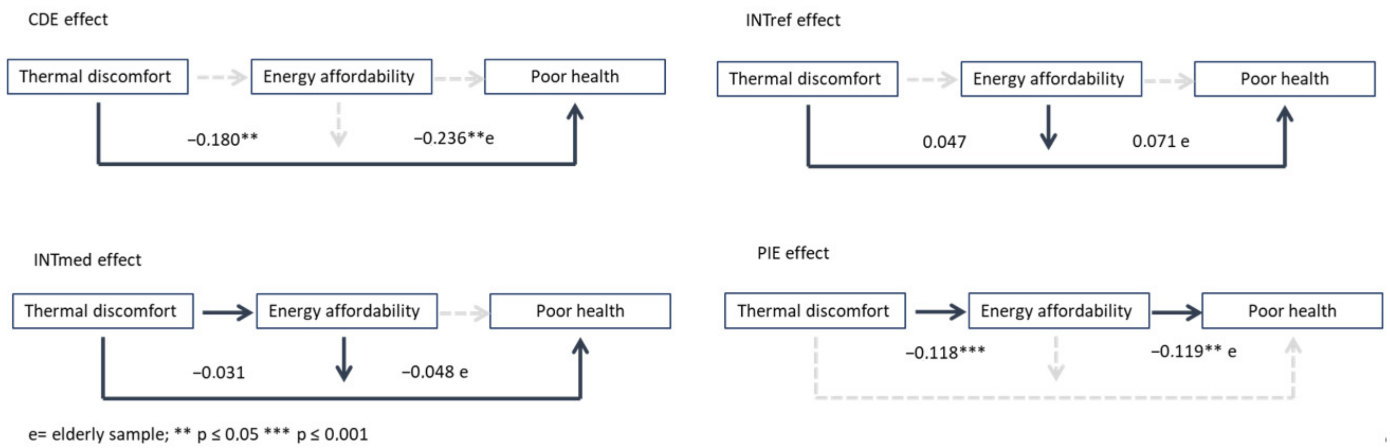

Figure 3. Path diagram for decomposition effects (adapted from [50]).

As illustrated in Figure 3, the only statistically significant paths are the direct and indirect pathways, through the contribution of CDE effect and PIE effect, respectively. Similarly to the overall decomposition effect (TE effect), in Table 4, the coefficients for CDE and PIE effects are smaller for overall population (CDE β = −0.180 SE = 0.069; $p \leq 0.008$; PIE β = −0.118, SE = 0.030; $p \leq 0.001$ than for elderly population segment (CDE β = −0.236, SE = 0.087; $p \leq 0.008$; PIE β = −0.119, SE = 0.085; $p \leq 0.008$).

Furthermore, the relevance of the role of exposure (thermal discomfort) and mediator (energy affordability) that underly the abovementioned decomposition effect is better understood in the results from the outcome and mediator models (see Table S1 in the Supplementary Materials). The obtained coefficient for thermal discomfort in the mediator model with positive and highly significant coefficients implies that exposure to thermal discomfort increase the likelihood of poor health for both general population (coeff. = 1.465 (0.070), $p \leq 0.001$) and the elderly (coeff. = 1.600 (0.111), $p \leq 0.001$).

Meanwhile, energy affordability also presents a highly significant but negative coefficient in the outcome model for both general and elderly population segments (coeff. = −0.430 (0.107), $p \leq 0.001$ versus coeff. = −0.377 (0.142), $p \leq 0.008$). The negative coefficient implies that people with the ability to pay for keeping the house warm show a lower likelihood of poor health status. The interaction between thermal discomfort and energy affordability was non-significant, similarly to decomposition effects in Table 4.

The most significant results from decomposition approach (CDE and PIE effects) are further explored in the next section.

5. Discussion

The obtained results seem plausible, given that on one hand, other studies have suggested that the elderly tend to spend more time indoors [45]; therefore, they might be more exposed to indoor environment. On the other hand, the elderly population often tends to suffer from chronic conditions [51,52], which could make them more susceptible to small variations in indoor temperature and thermal comfort or discomfort. Therefore, it seems possible that given the different characteristics of the sampled population, it could be affected differently by the same poor housing condition. The obtained results reinforce the relevance of adequate housing for this segment of the population and the need to understand what this means for this segment of the population.

The controlled direct effect (CDE) also shows a negative effect. This implies that, had we intervened, excluding energy affordability issues, the harmful effect of thermal discomfort on health status would be reduced by 64% in the overall sample and 71% in the elderly sample. Taking into consideration that the CDE effect is reflective of the improvement of thermal discomfort that results neither from mediation nor from interaction, this implies that the adoption of energy efficiency alternatives seems to significantly reduce health risks from poor housing, particularly among vulnerable population segments. The health risk reduction associated with the CDE effect seems plausible, given the energy inefficient nature of the building stock in Portugal (see [7]). Additionally, recent empirical studies have pointed out that households in different geographic locations of the country could be considered cold homes (see [53,54]) and, therefore, could possibly foster thermal discomfort perception. Therefore, it is expected that a large share of households might benefit from the thermal comfort resulting from the adoption of energy efficiency measures, as proposed by CDE effect. Besides reinforcing the notion of cold homes and the extensive need for renovations to fulfill thermal comfort and safety requirements (e.g., [7,54]), the CDE further suggests that energy-efficient alternatives that can be used for climate change adaptation may also present benefits in terms of health.

The decomposition results also show that the only other significant pathway towards the improvement of indoor temperature perception is the indirect pathway. According to the pure indirect effect (PIE), tackling issues related to affordability or the inability to keep the house warm could also contribute to further reduce the risks of thermal discomfort on health by 42% in the overall sample and by 36% for the elderly sample. Moreover, this result is relevant for policymakers since the inability to keep warm or affordability issues might be viewed in this context as a proxy for energy poverty. This result also emphasizes the relevance of socioeconomic context, along with living conditions. The obtained results are in accordance with prior studies that have emphasized that Portugal is amongst the European countries that are affected by this issue (see [10,55]). Other effects, namely for interactions (INT_{ref}) and (INT_{med}), were non-significant.

Overall, obtained results have shown that the relationship between poor housing conditions, namely thermal discomfort, and health status seem to be partly mediated by the ability to keep the household warm. This risk seems to be greatly reduced, for the overall population and its vulnerable segments (the elderly), using housing energy efficiency alternatives. The relevance of housing energy efficiency beyond energy and emission reduction in the climate change mitigation context has been established. The decrease in the CDE and PIE coefficients showed if upon action to improve thermal discomfort, either in a direct or indirect manner, a reduction in the health risk posed by poor housing exposure could be possible. Measures focusing exclusively on energy affordability issues (PIE effect) might not be enough, given that the greatest impact in reducing health risk from thermal discomfort is reached directly through the adoption of energy efficiency measures (CDE effect). More importantly, obtained results seem to emphasize that the maximization of the potential health benefits is better realized by eradication of thermal discomfort promoted by energy efficiency, followed by alleviation of thermal discomfort where the affordability issues (i.e., inability to keep warm) is also tackled. Furthermore, obtained results seem to convey that a complementary approach that promotes the adoption of energy efficiency alternatives while taking into consideration the energy poverty/socioeconomic background should be undertaken. These results are aligned with Declós and Vidal (2021) findings that reinforce that efficiency and affordability housing initiatives should strive both for climate and housing cost neutrality [56]. In this setting, the development of urban living laboratory (ULL) to study urban interventions in the context of sustainability, as suggested by [57], could be of interest.

It should also be noted that, a sensitivity analysis, based on resetting the mediator level, was performed to test robustness of obtained results. Though differences were found in the coefficients of CDE, no differences in terms of sign of the coefficient and significance level were found in the total effect (TE) nor at the mediator level (PIE), reinforcing obtained results. A similar result was obtained by [49]. Therefore, answering the proposed research question the energy affordability seems to be a valid mediator between poor housing and health status. However, the causality assessment based on mediation analysis should be cautious since misclassification of health status due to self-diagnosis might also be reasonable and should not be disregarded. Discacciati et al. (2019) has warned about this potential source of bias [25]. Additionally, due to the aggregate nature of the data available on the database the use of localized climate data was compromised, as well as the ability to establish more detailed links to energy and building characteristics, since information regarding construction age, building materials, possible energy efficiency interventions was lacking. It should also be noted that, the restrictions of the current database, regarding the availability of a proxy for energy affordability during summertime, limits the study of the mediation effect to the wintertime. Still, the relevance of summertime period and the exposure to heatwaves is becoming an increasingly recognized subject for indoor thermal comfort research (see [58,59]).

6. Conclusions

A mediation analysis was made to better understand whether the relationship between thermal discomfort and health status is further explained through an underlying association with energy affordability. Based on data from Eurostat's European Union -Statistics on Income, Social Inclusion and Living Conditions (EU-SILC) database, the relationship between thermal discomfort and health status was assessed, to test the role of the energy affordability as a potential mediator. This analysis contributes for policy makers not only to identify the impact of thermal discomfort on health but also, most importantly, to acknowledge the main pathways to address negative impacts. For that purpose, VanderWeele's four-way decomposition approach was adapted and extended to the energy efficiency field. The findings show that suggest that the ability to keep warm is a valid mediator for the association between poor housing and health. The mediator or PIE effect accounted for 36% reduction of health risk for the elderly and 42% for overall population.

The greatest risk reductions for incurring in poor health are reached directly via energy efficiency. The results show a 71% health risk reduction for the elderly and 64% for overall population by promoting the transition from thermal discomfort to thermal comfort. These results have relevant policy implications, namely that, in order to achieve health benefits, the development of energy efficiency policies need to be complemented with socioeconomic background information, namely energy poverty status. Therefore, policies need to be targeted towards people who cannot afford them without assistance.

This work emphasized the need to further develop quantitative indicators (for energy and health fields) and their integration into existing databases and related cost–benefit analysis. For instance, the lack of information regarding energy affordability for summertime hinders the possibility to properly understand the impact of thermal discomfort from heat on health, which is imperative in the context of climate change and increasing exposure to extreme events such as heatwaves. Additionally, relevant variables for this study such as thermal discomfort are only available when ad hoc modules for living conditions take place. This fact prevents continuous monitoring of energy-related issues, such as energy efficiency, energy poverty and climate change, ultimately preventing policy makers to access best available information for decision making process. Besides self-reported health status, the use of different health metrics regarding mental health, chronic conditions and wellbeing is required for future research. Collaboration with local health services is crucial to develop databases that contemplate objective medically assisted health indicators, use of healthcare services and medication. Collaboration with local municipalities is also critical to identify and monitor poor housing conditions (e.g., inadequate indoor temperature and dampness) as well as an opportunity to gather information regarding energy poverty status at community level. We further argue that there is a pressing need to incorporate health in energy and climate change policies for housing, under the penalty of the potential benefits from the improvement of thermal discomfort passing unnoticed at policy level, potentially increasing instead of decreasing the risk for health.

Ensuring that measures that promote building renovation and renewable energy in buildings do not become an additional cost burden and a health hazard for vulnerable population segments could, upon further research, contribute towards promoting and accelerating a just energy transition.

A holistic approach is essential to promote Sustainable Development Goals (SDG). That requires the development of policies that encompass living conditions, energy efficiency, health and an aging population. The inclusion of health impacts into prominent policies such as energy and urban planning is recommended.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su142114435/s1, Table S1: Outcome and the mediator model coefficients.

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