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Review

A Review of the Relation between Household Indoor Temperature and Health Outcomes

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Abstract: This paper provides a review of research that addresses the relationship between indoor temperatures and health outcomes, taking into consideration studies that focus heat or cold exposure within the household context. It aims to extend previous research by considering both indoor temperatures from existing housing, and empirical studies that focus on energy efficiency measures and subsequent health impacts. To achieve this aim, a literature review was undertaken, combining engineering and health databases. The review established that, overall, inadequate indoor temperatures are associated with poor health status, whereas energy efficiency measures have been associated to improved indoor temperatures and occupant's health namely regarding cardiovascular, respiratory and mental health disorders. These health conditions are among the most prevalent non-communicable diseases (NCD). The review also highlighted the need for more empirical studies with an extended timeframe to deal with climate change challenges. It underlined the potential advantages of the convergence between health and energy efficiency studies, for better modelling and planning.

Keywords: indoor environment; indoor temperature; health; buildings; elderly; fuel poverty

1. Introduction

Health has been increasingly recognised as one of the areas that could be most adversely affected by climate change. It is currently estimated that the impacts of human activity could lead to a loss or reversal of health benefits conquered over the last five decades [1]. As many if not most of the world's households do not have fully functional HVAC systems, the changes in outdoor temperatures are expected to influence also the indoor temperatures. Among the most susceptible to these variations in temperature are the elderly. It has been noted that this segment of the population tends to spend a greater amount of time indoors [2], which emphasises the relevance of studying the health outcomes in the context of the urban built environment and more specifically within the household.

In Europe, concerns regarding the potential health impact of heatwaves date back to the 2003 heatwave with a reported excess of 30,000 deaths [3] and have drawn attention to the expected increase in extreme events, which leveraged studies on the potential adverse effects on health. When addressing mortality and morbidity associated to environmental factors triggered by climate change, Liu et al. [4] have noted the relevance of indirect health impacts, related to respiratory and cardiovascular causes, in contrast to direct health impacts, related to hypothermia or hyperthermia [4].

A recent review of temperature-related mortality and morbidity effects, performed by Bunker et al. [5] reported that a likely rise in ambient temperature, induced by climate change, would result in an increased risk of cardiovascular, cerebrovascular and respiratory outcomes among the ageing population [5].

The upsurge of heatwaves, however, does not mean that winter mortality should be neglected and neither health impacts linked to non-extreme ambient temperature [6]. In fact, a cross-country comparison to quantify mortality has attributed the greatest death burden to outdoor cold, mostly associated with moderate rather than extreme temperature events [7].

Therefore, although studies have reinforced the existing association between temperature and health outcomes, the previously mentioned background points towards the pertinence of considering the association between indoor temperature and health outcomes within the building context.

The built environment (with a focus on housing conditions) has been considered a key area of concern in establishing indicators to assess the population's health for different stakeholders in Europe [8]. Furthermore, too high or too low indoor temperatures in the households have been recently considered by Howden-Chapman, Roebbel, and Chisholm [9] as two key focal areas for establishing healthy housing guidelines (HHGL). In addition, based on World Health Organisation (WHO) guidance on housing, energy and thermal comfort, Ormandy and Ezratty [10] have concluded that health protection from high or low indoor temperatures should be taken into consideration for the development of policies in an energy context, such as energy efficiency, fuel poverty and climate change. Recently, Graff and Carley [11] have also emphasised the need for authorities to recognise and deal with the prevalence of energy insecurity at the household level. The inability of households to keep comfortable indoor temperatures might result in adverse health outcomes, particularly for vulnerable groups, such as children and the elderly population [11].

Although a few review studies already addressed the interlinkage between health, energy efficiency and outdoor temperature, the relation between energy efficiency, indoor environment (i.e., temperature), and health outcomes still require further research. Therefore, we conducted a review to answer the two research questions focused on these interlinkages:

- How do indoor temperatures affect health outcomes?
- How does housing energy efficiency improve health outcomes?

Taking into consideration this background, the present work aims to critically review literature which addresses the link between indoor temperatures and health. The contribution is twofold: (1) To address the association between indoor temperature and health-related outcomes; (2) to ascertain how indoor temperature improvements resulting from household energy efficiency measures impacts health.

The remainder of this paper is organised in the following sections: Section 2 provides a review of the links between indoor temperature and health outcomes in health and energy efficiency studies.; Section 3 outlines the main research methodological steps of the current study A critical analysis based on key indicators and dimensions is described in subsequent Section 4. Main conclusions and further research needs are presented in Section 5.

2. On the Relevance of Indoor Temperature and Housing Energy Efficiency for Health Outcomes

2.1. Relevance of Indoor Temperature for Health Outcomes

Focus on epidemiological studies has gained relevance in the context of climate change, given that temperature-related events have also been considered, as one of the main reasons of future concern by the Intergovernmental Panel on Climate Change (IPCC) [12].

In this section, the importance of indoor temperature for health outcomes is briefly contextualised. Several aspects of diversified background have been emphasised as being influencing factors in the association between indoor temperature and a given health outcome.

In the case of heat, the human response to temperature exposure is influenced by external and internal factors. External factors are related to environmental aspects, such as air temperature and humidity level, while internal factors are more linked to physiological and behavioural aspects, such as gender, ageing, adaptation, fitness, hydration and chronic diseases—diabetes; hypertension and obesity, among others [13].

Heat and cold exposure, have both been known to increase the risk for adverse health effects in elderly particularly those suffering from cardiorespiratory conditions, such as chronic obstructive pulmonary disease (COPD) [14]. Medical conditions such as cardiovascular (e.g., heart attack and stroke), respiratory diseases (e.g., COPD and asthma) and diabetes are a few examples of long-term chronic disabilities that have been categorised as non-communicable diseases (NCDs).

According to the World Health Organisation [15], NCD's have accounted for 70% of premature deaths for age ranges between 30 and 69 years old, at a worldwide level. In view of their increasing relevance in developed and developing countries, they have been considered a priority field of action, influenced by environmental and behavioural risk factors with interlinks to housing and urban expansion. Among driving forces for NCD are aspects related to sedimentary lifestyles, such as tobacco use, unhealthy diet and lack of physical activity [15,16].

These driving forces may adversely influence relevant biomarkers for cardiovascular conditions among for elderly, such as raised blood pressure. However, the relevance of other influencing factors, such as the built environment, has been increasingly recognised in terms of physiological responses to temperature [17–20].

2.2. Relevance of Housing Energy Efficiency for Health Outcomes

Recently, higher excess winter mortality has been associated to temperate regions with fewer energy-efficient houses, such as the Mediterranean countries, emphasising the links to housing, indoor temperatures and socioeconomic background [21,22]. According to Miguel-bellod, et. al, high rates of excess winter mortality in Southern European countries are determined, to a great extent, by the high incidence of poverty rates, energy inefficient building stocks and high energy prices [23].

These aspects give a glimpse of the complexity and multiple causalities that can be associated with the assessment of health outcomes in the context of variable temperatures, in keeping with the multifaceted concept of healthy housing. The World Health Organisation has established that healthy housing is associated not only to physical but also to mental and social wellbeing [24].

In this context, emerging research has looked to identify the explanatory pathways that connect the urban housing environment features to health outcomes. The need to simultaneously reduce energy consumption while ensuring comfortable and healthy indoors has led to consider a new integrated goal (wellbeing), resulting from the convergence of strictu-sensu health and of thermal comfort [25].

Associated to the evaluation of housing energy efficiency programs, Willand et al. [26] have identified benefits in health outcomes as being related to three main explanatory factors: indoor warmth; affordability of fuel; and, psycho-social focal areas. These explanatory factors illustrate the different theoretical ways, or pathways, in which energy efficiency could potentially impact health.

The improvement of indoor temperatures, stipulated within the warmth pathway, also contemplated effects from warmth on mortality and morbidity (respiratory, cardiovascular and general health outcomes). Meanwhile, mental health symptoms, as well as energy consumption, have been comprised within the affordability pathway. Whereas the perception of the householder regarding its home has been focused on the psychosocial pathway.

More recently, Armstrong et al. [27] have developed an empirical study, also considering the main pathways. The author's aim was to determine which sets of energy efficiency measures affect energy and health outcomes, i.e., how changes in housing energy efficiency measures impact different categories of health outcomes. This study found that an upscale of energy efficiency measures by the building stock is required, in order to reach health full potential benefits and climate change reaching climate change mitigation targets. The building envelope (walls, roofs, floors and windows) insulating properties; ventilation control, energy efficiency of the heating, lighting and other appliances, as well as energy sources have been considered the main four energy efficiency categories. While the main health outcomes have been associated with cardiorespiratory conditions, winter mortality and morbidity, thermal comfort, psychosocial wellbeing and nutrition outcomes. Additionally, to be associated to different efficiency pathways, these outcomes have also been classified according to their time horizon, as short term /immediate or long-term impacts (timeframe greater than 10 years) [27].

Figure 1 represents an approach which emphasises the need not only to assess health outcomes associated to already established energy efficiency pathways, as proposed by Willand et al. [26] but also to study this association throughout time, as suggested by Armstrong et al. [27]. Such a complementary approach would enable to further understand interactions between pathways through time while accounting for short term and long-term impacts for all health stages, being compliant with "healthy household" definition.

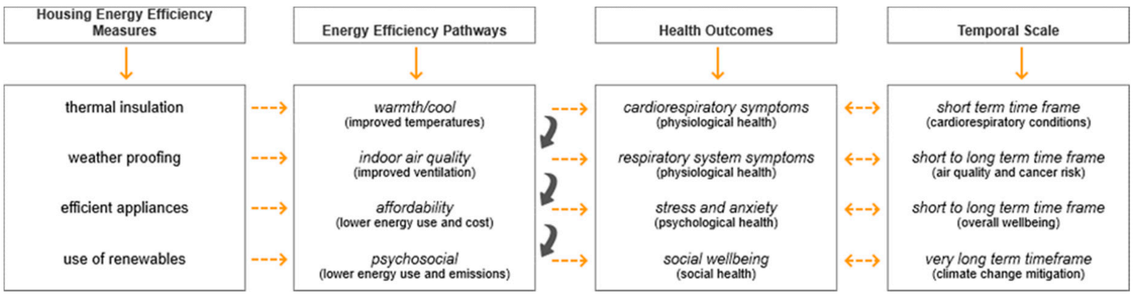

Figure 1. Housing energy efficiency pathways and related health outcomes (based on References [26,27]).

This may imply that for instance, the improvement of the building envelope may be linked to the improvement of indoor temperatures through housing energy features, as illustrated in Figure 1. The interaction between pathways is represented by the grey arrows: it shows that theoretically, a warmer household could positively influence affordability and psychosocial pathways. Based on the hypothesis posited by Willand [26] and Armstrong [27], improvements at building envelope level should lead to improvements in indoor temperature that may contribute to reducing energy consumption and related costs, *ergo* promoting energy affordability, particularly for low income households.

A recent review by Kolokotsa and Santamouris [28] has considered improvements to the building envelope as one of most cost-effective and efficient technologies to deal with indoor environmental quality and energy consumption issues, for low income households in Europe.

Improvements to indoor temperature may also affect the psychosocial pathway, by improving householder perception of his home, reinforcing social interaction with family and friends, based on the increasing use of his house. For instance, Poortinga et al. [29] have reported evidence that improvements to indoor temperatures were associated with increased use of more rooms in the house, enabling frequent visits from relatives and friends.

If achieved through efficiency, this could be possible by simultaneously requiring less energy use, expenditures and emissions, contributing to improving health outcomes at different time frames. For instance, better cardiorespiratory conditions on a short time frame, as well as less stress, anxiety and overall social health in the longer term. Benefits from improved air quality may imply an almost immediate reduction in air pollutants, but with long term implications (≥10 years), in terms of cancer risk [27].

3. Method

The steps that have led to the identification of key indicators and dimensions to be considered in the research are illustrated in Figure 2. This figure includes two lines for the literature review (1 and 2) and another two for critical analysis and results (3 and 4). Level 1 shows the three databases used in the research, level 2 shows the keywords considered in the search, which have contributed to establishing the criteria for the analysis, defined in level 3, as key indicators and key dimensions.

Key indicators are defined as general topic areas that are common to studies identified in previous steps (1 and 2), such as geographic location, focal area and health benefits. Key dimensions more specific, such as temperature exposure; health outcome, energy efficiency measures etc. These key features are at the basis of the critical analysis, identified in Figure 2 as level 4.

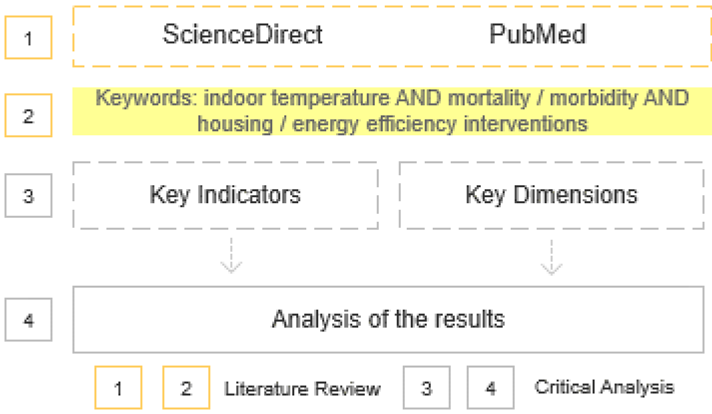

Figure 2. Search and review outline.

The present review has looked to promote a search that encompasses both engineering and health databases. In addition to keywords in Figure 2, the following exclusion criteria from the critical analysis was applied in order to select studies from different databases:

1. Studies for which full paper is not available on the database;
2. Studies addressing health outcomes not related to human and other health outcomes (e.g., vector-borne diseases);
3. Studies that are duplicated;
4. Studies that are not written in the English language;
5. Studies that are not empirical;
6. Studies that do not monitor indoor the temperature in loco, with the exception of studies that use empirical indoor temperatures from national surveys;
7. Studies that do not assess concurrently indoor temperatures and health outcomes;
8. Studies for which the focal point is to assess indoor air quality-related health outcomes;
9. Time restrictions are not applied.

Primary literature research aimed to identify peer-reviewed papers (n = 292), according to the selected keywords. The aforementioned exclusion criteria were then applied, and an approach based on Willand et al. [26] was subsequently used. This approach consisted of screening the references or the 'cited-by sections' of the documents found on primary research which enabled to locate new 'low-profile' studies that were added to the original selection. From this process resulted the final set of selected studies (n = 15).

The scarcity of energy efficiency studies comparatively to the topic of indoor temperature and human health should be seen under the light of the exclusion criteria undertaken and justifies the pertinence of this study. This is not an uncommon problem, for example, Mauree et al. faced also a similar issue of shortage of studies when reviewing the future implications of climate change on urban design and thermal comfort [18]. Although relevant from an energy and thermal comfort perspective, a more detailed approach to studies that monitor indoor temperature and energy consumption, but disregard its health implications, goes beyond the scope of this review, since the association to a health outcome would be lacking.

The use of such systematised guidelines for conducting the current report synthesis has been considered helpful to deal with validity concerns. Validity concerns have been gaining increasing importance associated with the growth of systematic reviews in the literature [30]. Following the study from Zhou et al. [31], the main threats to validity were considered and mitigation actions included to minimise their effect, which is reflected in the specified research exclusion criteria.

Literature from trustworthy intergovernmental Organisations, such as the World Health Organisation (WHO), have also been considered, within this context.

Prior reviews have highlighted relevant issues on the intersection between energy and health. For instance, Ormandy and Ezratty have emphasised that while thermal comfort and household energy efficiency are directed towards protecting the health householders, particularly the vulnerable ones, many challenges lie ahead in integrating strategies for key concerns such as energy efficiency, fuel poverty and climate change [10]. More recently, reviews by Kolokotsa and Santamouris have emphasised several energy efficiency alternatives to address the energy and indoor environmental issues for low-income households in Europe [28].

Meanwhile, Willand et al. have emphasised the complexity of energy efficiency interventions, and that the interactions between energy efficiency measures, householders and health-related outcomes is still misunderstood [32]. Liddell and Morris further claim that health impact assessment needs to be extended to incorporate mental besides physical wellbeing [33].

In this sense, Ortiz et al. have highlighted the concept of wellbeing should be interpreted as the overlap of health and comfort, which is linked to both environmental and behavioural aspects [25]. Hoof et al. considers that financial constraints may lead older people subject to inadequate indoor temperatures with adverse health outcomes, go currently undetected [34]. The evidence of the impacts of cold indoor temperature thresholds on human health has been recently reviewed by Jevons et al. that showed that despite scarce available evidence, minimum indoor temperature threshold should be at least 18 °C for the whole population [35].

Compared to existing reviews, namely References [24,26,36], the current study extends prior research by considering both indoor temperatures from existing housing, and studies that focus on energy efficiency measures and subsequent health impacts. By integrating these elements we intend to demonstrate the beneficial association between energy efficiency measures and health conditions. This should contribute to show the relevance of following a multi-disciplinary research agenda with approaches that tie health and engineering to support policymaking.

For this study, the housing and energy efficiency pathways of Figure 3 were then taken into consideration to establish the links between indoor temperature and health outcomes illustrated Figure 3, which served as the basis for the subsequent critical analysis.

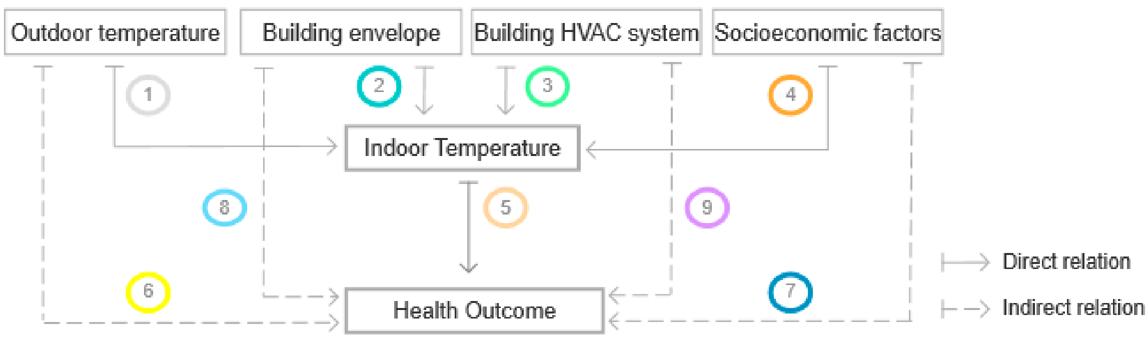

Figure 3. Links between indoor temperatures and health outcomes.

Indoor temperature is considered to be influenced by environmental, technological and socio-economic aspects (direct relation: links 1 to 4) which then impacts health directly (link 5) or indirectly (links 6 to 9). The main focus of the literature is on empirical studies that monitor the indoor temperature and its direct relation to health outcomes. However, four indirect links have also been identified (links 6 to 9).

For content analysis, particular focus was given to non- communicable diseases (NCD) health outcomes, namely from the cardiorespiratory system, given their relevance under the Sustainable

Development Goals (SDG's) scope ([37,38]) and the increasingly focused contribution of energy efficiency measures to improve these health outcomes ([27,29]).

4. Results and Critical Analysis

The literature review allowed us to identify relevant links that were used to draw a distinction of studies based on the type of relationship between indoor temperature and health outcomes.

4.1. Analysis of Direct and Indirect Links between Indoor Temperature and Health Outcomes

Table 1 presents the studies addressing each one of the links described in Figure 3 and summarises the identified energy efficiency-indoor temperature-health outcomes.

Table 1. Distribution of studies on indoor temperature by link to health outcomes.

Links		Studies on Indoor Temperature
1	outdoor- indoor temperature	[27,29,39–50]
2	building envelope- indoor temperature	[27,29,40,44,46–48]
3	HVAC system- indoor temperature	[22,27,29,44,46,48]
4	socioeconomic factor- indoor temperature	[27,29,39–50]
5	indoor temperature- health outcome	[27,29,39,40,47–50]
6	outdoor temperature- health outcome	[27]
7	building envelope- health outcome	[22,27,45,46]
8	HVAC system- health outcome	[22,27,45,46]
9	socioeconomic factor- health outcome	-
Cause-Effect assessed		
[22]	energy efficiency upgrade—low indoor temperature—emergency hospital admissions cardiovascular and respiratory conditions and injuries	
[27]	energy efficiency upgrade—low indoor temperature—cardiovascular and respiratory health related conditions	
	outdoor temperature—cardiovascular and respiratory-related mortality and morbidity	
[29]	high indoor temperature—emergency hospital admissions cardiovascular and respiratory conditions; psychosocial impacts	
[39]	low indoor temperature—emergency care for cardiovascular and respiratory conditions	
[40]	low indoor temperature—cardiovascular and mental health related biomarkers	
[41]	low indoor temperature—cardiovascular and mental health related biomarkers	
[42]	low indoor temperature—cardiovascular and mental health related biomarkers	
[43]	low indoor temperature—cardiovascular related biomarkers	
[44]	high indoor temperature—heat-related health symptoms	
[45]	low indoor temperature—long term health disabilities	
[46]	energy efficiency upgrades—low indoor temperature cardiovascular and respiratory-related mortality	
[47]	energy efficiency upgrade—low indoor temperature general health; respiratory-related conditions and general practitioner's hospital admissions	
[48]	energy efficiency upgrade—low indoor temperature—respiratory related conditions, general health status hospital admissions	
[49]	low indoor temperature—cardiovascular related biomarkers	
[50]	low indoor temperature—cardiovascular related biomarkers	

The most prevalent steps that establish the direct relation between indoor temperature and health outcomes are links 1 to 5. This means that most studies take into consideration the influence and interconnection with outdoor temperatures or climate (link 1). The higher relevance assigned to socioeconomic factors-indoor temperature and indoor temperature-health outcome (links 4 and 5) compared to other direct relations, namely building envelope-indoor temperature and HVAC system-indoor temperature (links 2 and 3) is clear.

The influence of outdoor temperatures on the indoor environment has been assessed in studies such as Uejio et al. [39] and Osman et al. [40]. Several studies such as [41–44] have stressed that indoor temperatures were more significantly related to a given health indicator than the outdoor temperature.

Amongst the reviewed studies, only one study [27] measured the association between temperature and health outcome indirectly based on outdoor temperature (link 6), without directly monitoring indoor temperature. However, changes in indoor temperature and health outcomes from energy efficiency studies have also been considered when resorting to existing empirical datasets. Energy Follow Up Survey or the English Housing Survey are examples of databases that integrate indoor temperature and energy efficiency used by studies associated to different links (e.g., References [27,45,46] from the outdoor temperature-health outcome; building envelope-health outcome and HVAC system-health outcome—links 6, 7 and 8). The studies in References [46] and [47] are connected on the other hand, as they are based on the same empirical fieldwork data. As for, Rodgers et al. [22] their study adopts a retrospective approach to investigate if empirical improvements to housing standards could lead to better health in householders.

Conversely, as expected given the empirical nature of the studies, most of the cause-effect relationships assessed are based on link 5 (indoor temperature-health outcome association). Within this scope, fewer studies have considered building envelope aspects (link 2), though when considered, this link is often associated with energy efficiency upgrades. From these, only one study [44] has accounted for the existence of air conditioning (link 3). Though currently not considered a widespread feature, some studies forecast the increase of its relevance in the context of climate change [51]. A large majority of studies in HVAC system-indoor temperature (link 3) (e.g., References [22,27,29,46,48]), is therefore associated with heating in contrast to cooling systems. Many studies address both building envelope/HVAC system-indoor temperature (link 2 and link 3) because studies often consider simultaneously multiple energy efficiency improvements, such as thermal insulation and upgrades to heating systems. Although the focal point of the present work is indoor temperature, building HVAC systems (link 3) also contemplates ventilation issues. It should be mentioned that of the abovementioned studies, only Armstrong et al. [27] take into consideration how insulation improvements may change ventilation and indoor air quality along with changes in winter indoor temperatures.

The number of studies in socioeconomic factor-indoor temperature (link 4) is indicative that socioeconomic influence seems to be more accounted for than building envelope aspects (link 2). The difference between these two links could be attributed to the fact that studies with health as a focal area tend to account for sociodemographic while largely disregarding building envelope aspects. Whereas studies focusing on energy efficiency take into consideration building variables from the upgrades or alterations to building envelopes, such as wall insulation or double glazing. This issue is consistent with existing literature, which has emphasised the relevance of household characteristics for health outcomes and energy efficiency contexts and how it has often been overlooked and considered a drawback from a health perspective ([34–36]).

Nevertheless, a significant amount of studies from link 2 are also featured in link 4, being associated to social housing or the lower income segment of the population, where the probability of occurrence of worst housing quality is higher [22,29,47,48]. Yet, the highlight goes to one study [29] that assessed relevant issues for both energy and health, such as fuel poverty status, financial difficulties and stress, food security, social interaction, thermal satisfaction and self-reported housing conditions.

These results show the segmentation between these focal study areas and denote the need to consider both socioeconomic and building aspects, in order to promote a better understanding of the association between indoor temperatures and health outcomes to contribute towards identifying potential energy efficiency measures to improve the characterisation of indoor temperature-health outcome (link 5), building envelope–indoor temperature (link 2) and socioeconomic–indoor temperature (link 4). The consideration of both latter links and fields of knowledge is desirable and could contribute to shifting health sector's perception regarding the need for energy efficiency measures for healthcare reasons. In this sense, Jonathan Wilson et al. [52] claims that a shift towards a more opened and receptive attitude from health sector would require more empirical evidence.

This insight is also in keeping with a key challenge pointed out by Haines et al. [53], which consists on the need for the public health sector to establish partnerships with other relevant areas (e.g., city planners) and various stakeholders (research institutions, governmental and non-governmental bodies, public and private), in order to provide decision makers with well-grounded research evidence.

Meanwhile, studies that circumvent in loco monitoring of indoor temperatures have been categorised in HVC system–health outcomes and socioeconomic–health outcomes (links 7 and 8), as favouring less direct relationships to health outcomes.

No identified studies featured the interconnection between building HVAC system and health outcomes (link 9). The low number and/or absence of studies from HVAC system-indoor temperature (links 3) and HVAC system-health outcome (link 9) might be related to the fact that in Europe, in contrast to the United States, there is not a widespread adoption of air conditioning in the residential building stock [51].

However, a recent review by Willand et al. has also cautioned that the householder's response may also undermine the outcome of residential energy efficiency interventions, among which limited technical knowledge to deal with energy efficiency measures is highlighted [32]. The relevance of the impact of technical aspects such as filtration on residential energy use has been further explored by Alavy et al. [54]. While the integration of human dynamics in the control of HVAC systems has been studied by Jung and Jazizadeh [55].

Yet the use of air conditioning is also closely linked to socioeconomic status, namely to household income. The Howden-Chapman [56] study on energy poverty and health emphasised the increased vulnerability of low-income households with elderly. This segment of the population spends a high share of their income on energy. They are also more likely to be hospitalised for respiratory and cardiovascular conditions [56]. Furthermore, Xu and Chen concluded that low income households have fewer energy efficiency appliances and less access to energy efficiency programs and require tailored policy measures to make energy more affordable and accessible [57].

The strong association between income and household energy may also play a relevant role in a household's adaptation to climate change and the choice between air conditioning and thermal insulation choices. De Cian et al. [58] found that the future adoption of thermal insulation might be more difficult given that the adoption of air conditioning is promoted by income, urbanisation and demographic trends.

These studies anticipate the relevance of the interconnection between socioeconomic variables (link 4) to building envelope/HVAC system/indoor temperature and health (links 2, 3 and 9) with climate change. They also reinforce the need for conceptual frameworks to consider a time scale in the assessment of the relationship between household energy efficiency, indoor temperature, and health outcomes.

4.2. Analysis of the Relevance of Climate Change Timeframe for Health and Energy Efficiency

Moreover, though cardiovascular and respiratory health outcomes seem to prevail in the cause-effect column, different conditions and biomarkers are specific to each study. A more detailed perspective of these aspects is provided below.

The assessment of cause-effect relations on Table 1 has enabled us to emphasise the high number of studies that focus health outcomes from exposure to low indoor temperatures (12 out of 15 studies) in contrast to Uejio et al. [39] and Loenhout et al. [44] that feature outcomes related to exposure to high indoor temperatures (2 out of 15 studies). Only one study reviewed (Armstrong et al. [27]) considers both cold indoor and overheating exposures. The geographical distribution of these studies and indoor temperature, focus on overheating (in orange) versus cold indoors (in blue) or both (in yellow), is illustrated in Figure 4.

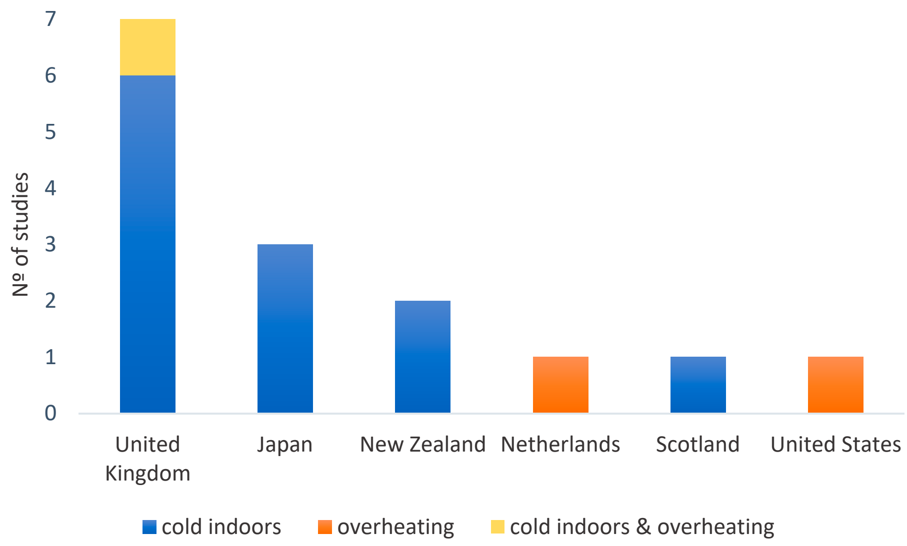

Figure 4. Geographic distribution and indoor temperature focus of the studies reviewed.

Armstrong et al. [27] present a longer timeframe than all others, contemplating winter and summer seasons, that is aligned with the nature of the health indicators used. This timeframe (of 10 years) is consistent with climate change concerns, and this is the only study that has looked to assess the perception of householders regarding home energy efficiency and climate change.

In addition, it is noticeable that studies focused mainly on developed countries. Noteworthy is the considerable amount of research developed in the United Kingdom (UK), which might result from the available national datasets with empirical indoor temperature measurements, as emphasised by Huebner et al. [45].

Even within developed countries, results show that there is a considerable lack of empirical research in countries that have been greatly affected by cold homes and excess winter mortality such as Portugal, Malta, Spain or Greece. A recent body of research has emphasised that these countries are at the top rate of excess winter mortality out of a total of 30 European countries [59]. These and other mild climate counties have been targeted as experiencing unacceptably low indoor temperatures [60,61].

Another observation is the scarcity of studies featuring indoor temperature monitoring during summertime, as emphasised in Figure 4. This field of research has been considered scarce, despite the growing interest and concern within academic and local communities, as well as overall society. This argument has been supported by recent studies developed within either the health or more energy efficiency and indoor temperature oriented scopes [27,29,39].

Departing from previously identified cause-effects in Table 1, it is also possible to establish that a greater number of studies features morbidity outcomes comparatively to mortality. Figure 5 illustrates the relation between the number of studies by health outcomes and study timeframe (in years). It is possible to see that there is a large diversity in study period considered for morbidity outcomes, that constitute 87% the of total number of studies. Yet, mortality outcomes (13% of total studies) are only associated with studies with longer timeframes (≥5 years). Once more, this result is in accordance with prior studies [27,46].

Given that longer timeframes in the research of indoor temperatures are also compatible with climate change research, results might suggest that mortality and morbidity outcomes could be considered in the context of climate change pathway if studies consider very long-term implications. However, in the current review, only one study, Armstrong et al. [27], has a time frame beyond 10 years.

From a householder perspective, health has been considered a more relevant issue for the implementation of energy efficiency measures than climate change [27]. Despite this, there is not much research to understand the impacts on health on longer timeframes, compatible with climate change issues, as illustrated by Figure 5. Therefore, it is possible to imply that currently, householders might be misinformed and unaware of the real impact of the exposure to inadequate indoor temperatures on health and the relevance of energy efficiency in the context of climate change.

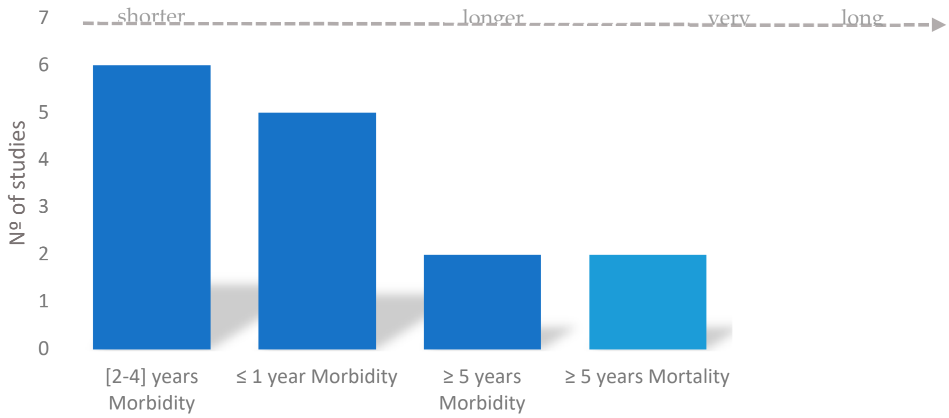

Figure 5. Mortality and morbidity health outcomes by study timeframe.

Consequently, there is an opportunity to leverage on the interest of people for health and promote studies with longer timeframes, that may lead to a better understanding of the impact of heatwaves on indoor temperature and health outcomes. Studies with very long timeframes would also contribute to understanding which energy efficiency measures could help improve health outcomes while mitigating climate change.

This result is aligned with Rodgers et al. findings, that emphasised that some of the co-benefits of energy efficiency may not be immediately perceived and that currently there is a scarcity of existing research in these terms, of the lack of long-term period studies [22].

Armstrong et al. also claim that small sample sizes of empirical indoor temperature monitoring and lack of pre and post-intervention monitoring, make it difficult to determine accurately the impact of energy efficiency on indoor temperature and upon health outcomes [27]. This may have implications in appropriately conveying health co-benefits from energy efficiency to decision and policymakers or even local communities. The consideration of longer timeframes could be crucial to address these issues and provide the scientific community with a more accurate and reliable empirical database to study the impacts of climate change.

Thus, very long-term studies could contribute to increased public awareness about climate change and its impacts and inform, based on empirical data, policymakers towards best available energy efficient solutions to mitigate them.

These results are in line with Willand et al. that have emphasised the need to integrate health goals into low carbon energy transition as a crucial aspect to develop an effective strategy for the housing sector [62].

4.3. Analysis of Health Outcomes by Study

Four main categories of health indicators have been identified as being related to mental health disorders, cardiovascular or respiratory conditions, or other health outcomes. A more detailed listing of health indicators, specific for each study, is provided in Table 2.

Table 2. Summary of health indicators by study.

Health Indicators	Mentioned	Direct Assessment (Measured)
Mental health disorders	[42]	[22,29,39,45]
Altered mental health status	-	[39]
Depression	[42]	-
Long term mental disability (LTD)	-	[45]
Common mental health disorders	-	[22,29]
Cardiovascular	[27,42,43,48,50]	[22,29,39,45,46]
Cardiac condition	-	[39]
Cardiac arrest	-	[39]
Cardiovascular condition	-	[22,29,39,46]
Myocardial infarction	[41,43]	-
Coronary heart disease	[27,42,43]	-
Heart attacks	[43,50,51]	-
Stroke/Cerebrovascular disease	[27,43,48,50]	-
Long term heart disability (LTD)	-	[45]
Respiratory	[44,46,47,50]	[22,29,39,40,45–49]
Difficulty breathing	[39]	[39,45]
Asthma	[46,47]	[22,39]
Respiratory conditions	-	[22,29,39,45–49]
Pneumonia	[39]	[39]
Insufficient cardiac blood flow	-	[39]
Lung disease	-	[39]
Emphysema/Chronic Obstructive Pulmonary Disease (COPD)	-	[22,39,40,48]
Lung function	-	[49]
long term breathing disability (LTD)	-	[45]
Other health indicators	[27,39,41–44,48]	[22,27,29,40–45,47–50]
Hypertension	[39,42–44]	-
Diabetes	[39,41–43]	-
Unconscious	[39]	-

Table 2. *Cont.*

Health Indicators	Mentioned	Direct Assessment (Measured)
Epileptic status	[39]	
Annoyance	-	[44]
Thirst	-	[44]
Sleep disturbance	-	[44]
Excessive sweating	-	[44]
Dehydration	[44]	-
Hyperthermia	[44]	-
Malaise	[44]	-
Hyponatremia	[44]	-
Renal colic and renal failure	[44]	-
Dry mouth	[44]	-
Impaired endurance	[44]	-
Fatigue	[44]	-
Sleep onset latency (SOL)	-	[41]
All-cause mortality	[27,44,47]	-
Excess winter mortality	-	[27]
Nocturia	-	[43]
Reduced quality of life	[43]	[29]
Falls and fractures/injuries	[43]	[22]
Blood pressure	-	[50,52,63]
Mean arterial pressure	-	[50]
Handgrip	-	[50]
Blood low-density lipoprotein level	-	[50]
Vitamin D level	-	[50]
Blood insulin-like growth factor	-	[50]
Blood haemoglobin level	-	[50]
White Blood cell count	-	[50]
Increased Blood viscosity	[52]	-
Platelet count (PTL)	-	[44]
General health status	-	[40,51,52]
Long term vision disability (LTD)	-	[46]
Long term hearing disability (LTD)	-	[46]
Long term mobility disability (LTD)	-	[46]
Long term learning disability (LTD)	-	[46]

The relationship between the identified health outcomes, energy efficiency pathways (from Figure 1) and indoor temperature is summarised by the Sankey diagram in Figure 6.

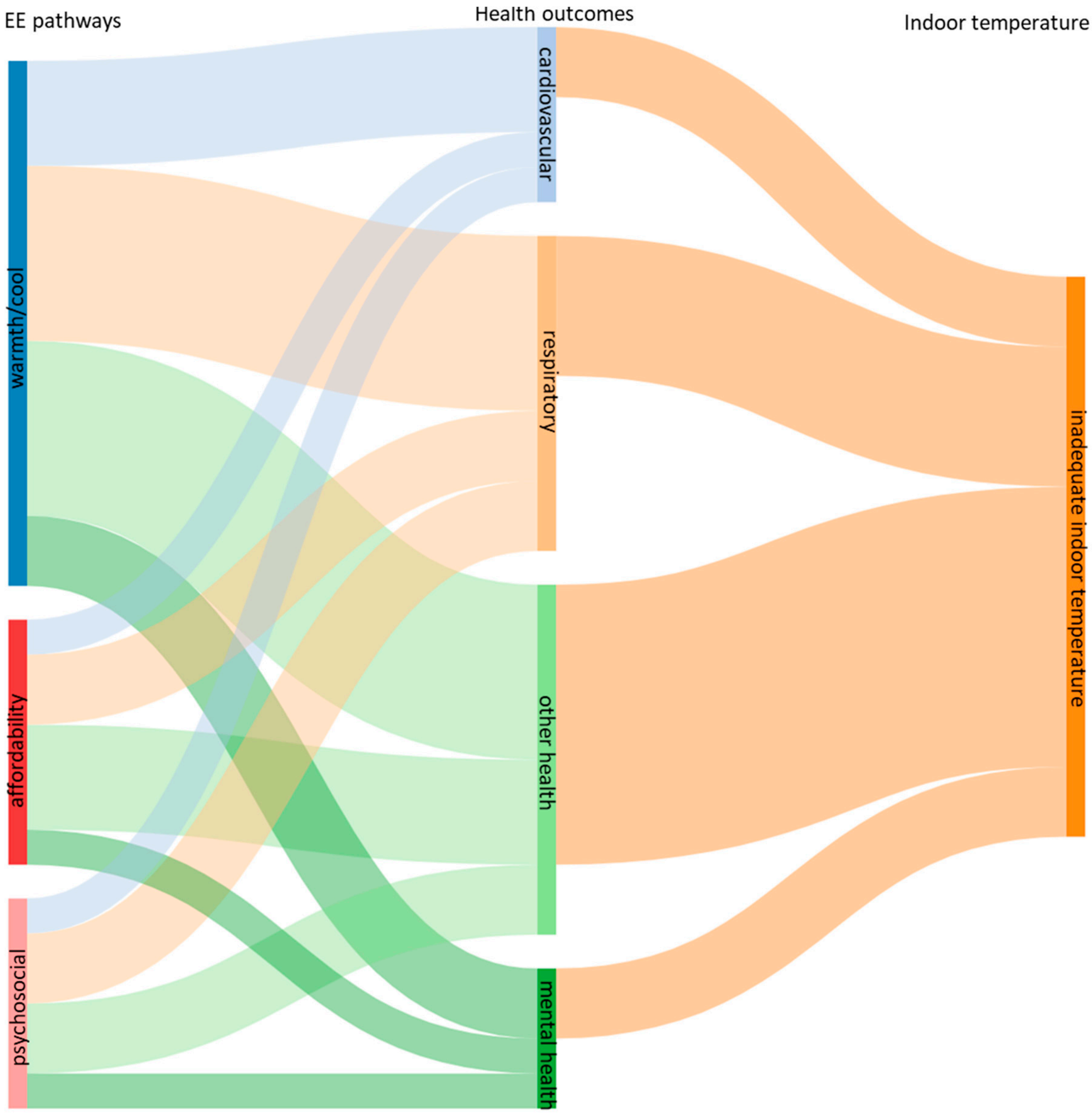

Figure 6. Sankey diagram between energy efficiency pathways, health outcomes and indoor temperature (elaboration using SankeyMATIC [64]).

The Sankey diagram represents fluxes between nodes. These fluxes show the transition from one node to another, here displaying possible energy efficiency pathways, health outcomes and indoor temperature identified in the reviewed studies. It is possible to see the extreme nodes (EE pathways and indoor temperature) are intermediated by a set of common health outcome nodes. The fluxes in a Sankey diagram are representative of the relevance of each health outcome as well as of the associated energy efficiency pathway. This relevance is estimated by the number of studies addressing each of the nodes. For instance, amongst the health outcomes, the least focused category is that of mental health disorders, with a thinner flux. However, its increasing relevance is recognised, as it is mentioned in studies that address diverse health outcomes, such as nocturia health indicator directly assessed by Saeki et al. [42] or sleep onset latency (SOL) or difficulty in falling asleep assessed by Saeki et al. [41].

In contrast to mental health outcomes, respiratory and cardiovascular conditions were the second and third most assessed health indicators, with wider fluxes compared to mental health.

Within cardiovascular and respiratory nodes relevant chronic conditions have been reported. According to the WHO [15], the top positions of deadliest NCD at the worldwide level are occupied by cardiovascular disorders (e.g., heart attack and stroke) in the first place followed by cancer in second place and respiratory conditions (e.g., asthma and COPD) and diabetes in the third and fourth places. These four major NCD disease groups have currently affected approximately 17.9 million and 3.9 million people annually, with cardiovascular and respiratory conditions, respectfully [15].

Yet the node for "other health" indicators category seems to be most representative, from indoor temperature to health outcome and from health outcomes to efficiency pathways, as illustrated in Figure 6. This result is indicative of both the diversity and complexity of direct assessment of health impacts. A few examples of the complex interconnection between different health outcome nodes are given below and are detailed in Table 2.

Most of the indicators categorised as "other health indicators" seem to be interconnected to other categories, namely for cardiovascular health conditions. For example, hypertension, mean arterial or blood pressure, and platelet count have been either mentioned or used as different health biomarkers in studies that aim to associate low indoor temperatures to health biomarkers for cardiovascular conditions (e.g., References [41,43,49,50]). Whereas respiratory cases have been in terms of relevance the second most assessed health condition with the least amount links to "other health indicator" categories. Its relevance comes from being directly assessed in empirical studies (e.g., References [33,45,51]).

Since exposure to inadequate indoor temperatures (too cold or too hot) may imply adverse health impacts, some studies have suggested that through the improvement of indoor temperatures, health gains for householders could be achieved (e.g., References [41–43]). Therefore in Figure 6, health outcomes departing from inadequate indoor temperature are related to warmth/cool EE pathway. However, the fluxes are not directly connected, given that the studies tend to focus on each of the extreme nodes. This lack of connection between studies reinforces, once more, the need for a more holistic approach to address the relationship between energy efficiency-health-indoor temperature that better supports policy-making for efficient and healthy households.

The improvement of indoor temperatures on existing building stock is often, as previously shown in References [22,27,46–48], linked to building envelope aspects (link 2 and link 3), associated to the adoption of energy efficiency measures.

4.4. Analysis of Housing Energy Efficiency and Health

In this section, the relationship between indoor temperature and health outcomes linked to the building envelope is assessed.

A total of 6 out of the 15 studies in Table 2 are household energy efficiency related. A more detailed examination of energy efficiency measures adopted or mentioned is provided in Table 3.

Based on Table 3, it is possible to establish that thermal insulation measures were featured in all studied energy efficiency interventions, with wall insulation being the most adopted one. Improvements in household appliances namely heating systems and to windows and doors were also widely implemented. Other energy efficiency measures are residual comparatively to the previous categories for the studies considered in this review.

Wall insulation and heating systems contributed to increase the indoor temperature but not always to decrease relative humidity (RH), as shown in Table 3.

Table 3. Summary of energy efficiency measures and their effects by study.

EE Measures	Studies	Observation Summary
Insulation wall floor ceilling/roof loft	[22,27,29,48] [46–48] [46,47] [22,27,48]	[22] 65.8% of installed wall insulation met housing quality standard; changes in indoor temperature not specified; [21] 31.8% of installed loft insulation met housing quality standard, changes in indoor temperature not specified [27] loft insulation associated to lower increases in temperature than increases associated to cavity and wall insulation; overall modest change in standard indoor temperature, averaging *0.09 °C [29] external wall insulation was the EE alternative that most contributed to increase indoor temperature (1.12 °C, 95% CI); overall indoor temperature increased on average by *0.84 °C; did not change indoor RH levels (−0.60% RH, 95% CI) [46]; [47] insulation retrofits increased on average bedroom temperatures by 0.5 °C, reduced time exposed to temperatures below 10 °C by 1.7 h per day and decreased relative humidity by 2.3% [a] [48] no adoption of EE alternatives implied lower baseline rating [b] than EE adoption (4.8 vs. 5.6); fewer hours of baseline hours of warmth above 21 °C in living rooms (48 h vs. 69 h) *
Windows & doors	[22,27,29,47]	[22] 52.4% of new windows and doors met housing quality standard; changes in indoor temperature not specified [27] double glazing was adopted and not associated with appreciable energy savings; overall modest change in standard indoor temperature, averaging *0.09 °C [29] new windows and doors did not increase indoor air temperatures significantly on average by −0.02 °C, 95% CI); new windows and doors increased indoor relative humidity (RH) on average by (5.15% RH, 95% CI) [47] EE adoption included draught stopping around windows and doors; changes in indoor temperature not specified by this measure
Appliances heating systems	[22,29,46,48]	[22] 77.4% of new heating systems met housing quality standard; changes in indoor temperature not specified [29] new boiler or heating system did not increase indoor air temperatures significantly on average by (−0.19 °C, 95% CI); did not change indoor RH levels (−1.59% RH, 95% CI) [46] heating retrofits with baseline underfloor and ceiling insulation recorded an increased average living room temperature by1.1°C [a] [48] EE adoption implied improvements in EE rating and fuel costs
Others fuel switching kitchens bathrooms electrical systems [c] garden paths	 [29] [22] [22] [22] [22]	[29] gas network connection significantly increased indoor temperature on average by (0.69 °C, 95% CI); increased indoor RH levels by (3.86% RH, 95% CI) [22] 81.1% of kitchen improvements met housing quality standard [22] 81.9% of bathroom improvements met housing quality standards [22] 91.6% of electric system adoption met housing quality standard [22] 30.2% of garden path improvements met standard housing quality

* average value for all interventions; [a] empirical data from large scale intervention Warm Up New Zealand: Heat Smart (WUNZ: HS); [b] National Home Energy Rating (NHER); [c] electrical system upgrades include adding power sockets, and extractor fans in kitchens and bathrooms; RH- Relative Humidity; CI- Confidence Interval; EE- Energy Efficiency.

Although each energy efficiency alternatives contributed differently for the increase in indoor temperatures, overall increases—for all intervention (e.g., References [27,29])—have been small, on average below 1 °C. However, even this slight increase has contributed in certain studies, such as for Poortinga et al. [29], to reduce the number of hours exposed to very low indoor temperatures (<18 °C or <16 °C). Osman et al. [52] also claim the adoption of EE alternatives has contributed to have fewer hours with unwanted temperatures (<21 °C) in the living room of chronically ill patients. It is also noteworthy that the largest improvements in indoor temperatures have been reached in critical living spaces in the household, such as the living room and the bedroom, where people spend their daytime and night time.

Besides the indoor environment, adopted measures have contributed to improving housing quality and efficiency standards [22,48], namely by reducing energy costs and increasing affordability. Furthermore, combinations of multiple energy efficiency alternatives, such as cavity wall and loft insulation with condensing boiler for the heating system, have reached considerable reductions (11.2%) in gas demand [27]. Taking into consideration information from Tables 2 and 3, regarding health indicators, it is also possible to say that to a large extent, a large share of studies featuring energy efficiency measures tend to focus on NCD health outcomes, compared to studies without energy efficiency measures.

Table 4 displays the most adopted energy efficiency measures vs. the most assessed health outcomes and impact on indoor temperature. The impact scale definition was inspired by Rodgers et al. [22] and adapted for this case. The impact level represents, for each energy efficiency alternative undertaken, if its adoption contributed to improve or worsen a given health outcome. It can range from low to high impact level, with low level (–) being indicative of an undesirable change like an increase in hospital admissions. Conversely, a high impact level (++) is associated with a desirable change in the health outcome, such as a decrease in hospital admissions or medical appointment. Both these conditions are associated with a level of significance, to the *p*-value for each study. No change (nil impact level) in the health outcome implies no association with a specific EE alternative with non-significant p-value. Most health outcomes reported in Table 4 have been assessed individually for each EE alternative, with emphasis for insulation and heating systems. However, some results have been reported aggregately, either as a combination of all health outcomes (e.g., Reference [27]) or as resulting from all intervention (e.g., References [29,48]).

It should also be noted that some of these studies have resorted to proxies in order to establish health status. For instance, Rodgers et al. [22] and Armstrong et al. [27] have resorted to hospital health statistics to assess the impact on health services such as emergency hospital admissions for COPD, asthma and mental disorders as a proxy for health outcomes. Besides hospital admissions Viggers et al. [47], also considers self-reported health status and days off school and work, as well as visits to a general practitioner's office.

From all studies reviewed, only one reported a negative association while the other eleven associations reported improvements in health, though with different levels of impact. Yet, the results also show that a significant number of conducted studies where the association between health indicators, energy efficiency and indoor temperatures was inconclusive. This is particularly highlighted for mental health and for cardiovascular health indicators, given the lower number of studies comparatively to respiratory conditions, as illustrated in Table 4.

Among energy efficiency alternatives, insulation measures have contributed most for the improvement of respiratory and cardiovascular conditions, followed by alterations to windows and doors.

This beneficial association between energy efficiency measures and identified NCD's could denote an effective course of action or opportunity to tackle some of the challenges in the health sector. A more detailed account of key findings for each study is provided in Table 5.

Table 4. Changes in health outcomes in studies with energy efficiency measures.

EE Alternatives / References	Cardiovascular: Insulation	Cardiovascular: Windows & Doors	Cardiovascular: Heating Systems	Respiratory: Insulation	Respiratory: windows & Doors	Respiratory: Heating Systems	Mental Health: Insulation	Mental Health: windows & Doors	Mental Health: Heating Systems	All Health *: Insulation	All Health *: Windows & Doors	All Health *: Heating Systems	Indoor Temperature
[22]	++ a 0 b	0	0	+ a 0 b	++	0		0 d		+ a 0 b	++	0	↑
[27]											+ d		↑
[29]		–			0 d			0 d					↑
[46]	++ c		0	+ c		0							↑
[47]				++ c						++ c			↑
[48]				++ d		++ d							↑

Impact level:

--	-	0	+	++
low	medium low	nill	medium high	high

worsen ←-----------→ improvement

* All health = combined health outcomes; EE alternatives: insulation: [a] wall insulation; [b] loft insulation; [c] floor and ceiling insulation; [d] all intervention (combined EE alternatives).

Table 5. Summary of key findings for EE alternatives upon health outcomes.

Studies	Summary of Key Findings
	Cardiovascular Condition—Older residents:
[22]	- wall insulation was significantly associated with 27% less emergency admissions for cardiovascular conditions - no changes associated (p-value > 0.01) to upgrades for windows and doors, new kitchens and bathrooms, loft insulation, electric system upgrades or heating upgrades
[29]	- for people aged ≥ 60, all intervention measures were significantly associated ($p < 0.009$) to an increase in emergency admissions for cardiovascular conditions - for people aged ≥ 60 and for all intervention measures no changes associated (p-value > 0.10) in emergency admissions for cardiorespiratory and respiratory conditions

Table 5. *Cont.*

Studies	Summary of Key Findings
	Respiratory Condition—Older residents:
[22]	- upgrades to windows and doors were significantly associated to 39% less emergency hospital admissions for respiratory conditions - wall insulation associated with 24%, electrical system upgrades associated to 57% and garden path improvements to 38% fewer emergency hospital admissions for respiratory conditions - no changes associated (p value > 0.01) in emergency admissions for upgrading kitchens and bathrooms, loft insulation or heating
	Injuries (falls and burns)—Older residents:
[22]	- upgrades to windows and doors were significantly associated to 39% less emergency hospital admissions for respiratory conditions - wall insulation associated with 24%, electrical system upgrades associated to 57% and garden path improvements to 38% fewer emergency hospital admissions for respiratory conditions - no changes associated (p value > 0.01) in emergency admissions for upgrading kitchens and bathrooms, loft insulation or heating
	All health outcomes—All ages:
[22]	- for people of all ages, households with electrical system upgrades had 34%; upgrade to windows and doors had 22%; wall insulation associated with 20% and garden path with 19% less combined emergency admissions than the reference group - no changes associated (p value > 0.01) in emergency admissions from heating upgrades, new kitchen and bathrooms or loft insulation
[27]	- the gains in winter temperatures by 0.09 °C are associated with an estimated annual reduction of ≈280 cold-related deaths in England
	Respiratory Condition—All ages:
[22]	- for all ages, prescribed medication for respiratory conditions, such as asthma or COPD have reduced 8% for households with upgrades for windows and doors; electrical system upgrades were associated with 9% fewer general practice attendance
	Cardiovascular and respiratory Condition—All ages:
[46]	- for all ages and all intervention, no changes (p-value > 0.10) in emergency admissions for cardiovascular, cardiorespiratory and respiratory conditions
[46]	- the insulation group relative to the control group, interpretable as a 32.7% reduction in mortality risk during the period studied - no additional health benefit from heating system (not significant, $p = 0.122$)
[47]	- insulated homes were significantly associated with less fair or poor self-rated health, self-reports of wheezing, fewer days off of school and work and visits to a general health practitioner
	Mental health—All ages:
[22]	- no changes associated (p value > 0.01) for any cointervention for prescribed mental health medications
[29]	- no change in self-reported mental health from energy efficiency improvements
	Wellbeing, thermal satisfaction and social interaction:
[29]	- participants who received intervention reported significant association ($p < 0.004$) for improved subjective wellbeing; significant associations were also registered for higher thermal satisfaction ($p < 0.003$) and increased social interaction ($p < 0.012$)

There are also reports of other health outcomes, though less assessed and mentioned than NCD's. This is the case of injuries and falls, that have had significant improvements, translated into less emergency hospital admissions for elderly householders that received upgrade to windows and doors [22]. These results seem to indicate that more vulnerable groups have greater sensitivity to indoor temperatures and that even small readjustments could lead to significant changes regarding temperature-related diseases. This is true particularly for the elderly population, that tends to spend more time indoors. Other previous reviews have also highlighted the potential health benefits associated with even small increases in temperatures [26]. Less objective outcomes such as "wellbeing" and "improved social interaction" have also been associated with improved indoor temperature from energy efficiency measures and might contribute indirectly towards better psychological health [29].

5. Conclusions

This paper has described the main key findings of studies that address the relation between indoor temperature and health outcomes.

It was found that inadequate temperatures (too low or too high) are associated with poor health status, whereas energy efficiency measures have been associated to improved health biomarkers for several health outcomes, namely cardiovascular, respiratory and mental health disorders. The analysis also highlighted that these health conditions are considered among the most prevalent non-communicable diseases (NCD), further emphasising the relevance of adopting housing energy efficiency measures for improving the occupant's health.

Thermal insulation, heating systems and improvements to windows and doors were widely implemented energy efficiency measures and have contributed to small increases in temperatures leading to fewer hours of exposure to low indoor temperatures. Among energy efficiency alternatives, insulation measures have contributed most for the improvement of respiratory and cardiovascular conditions, followed by alterations to windows and doors.

On the methodological front in assessing the problem, the reviewed studies demonstrate there is the need for an integrated approach, that conciliates medical and energy efficiency knowledge. This could promote a better understanding of areas such as mental health and wellbeing, as well as fostering additional evidence-based research geared towards anticipating impacts of climate change.

Further research should be developed to better understand available energy efficiency alternatives, to avoid the environmental and economic burden of improving indoor temperatures, particularly for low income households. Additionally, a longer timeframe should be considered in empirical research, to better attend to these concerns in a climate change context as this time frame seems to play a major role in the assessment of health impacts and its relation to energy use and efficiency, indoor temperatures and climate change. However, this is far from being fully explored in the literature as most studies seem to focus on immediate to short term health impacts and do not effectively address the challenges that changes on the climatic conditions will pose to health.

Joint research of health and energy fields would contribute also to improve the quality of data on housing and health. A recent assessment of available household data databases performed by Alkire and Samman highlighted that high quality and timely surveys, combining household surveys and lighter interim surveys, could provide in-depth information about core indicators regarding socioeconomic conditions such as poverty and deprivation in the household contexts [63]. A multidisciplinary approach could also be a step forward to improve the issue raised by Wilson et al. [52] of translating energy efficiency improvements into benefits for healthcare utilisation.

Thus, a shift towards a more interdisciplinary approach is suggested as future research considerations for policymaking, ultimately contributing to the development of tailored solutions, from promoting the convergence between housing energy efficiency and potential health outcomes, into the local and national planning process.

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List of Acronyms

EE	energy efficiency
HVAC	heating, ventilation and air-conditioning systems
HHGL	healthy housing guidelines
NCD	non-communicable diseases
WHO	World Health Organisation
COPD	chronic obstructive pulmonary disease

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