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Energy use and energy saving in buildings and asthma, allergy and sick building syndrome (SBS): a literature review

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Preface

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Abstract

Energy use in buildings is an important contribution to global CO_2 emissions and contributes to global warming. In recent years, there has been concern about creating energy efficiency buildings, green buildings and healthy buildings but this development needs guidance by multidisciplinary scientists and experts. Since energy saving can influence the indoor environment in different ways, epidemiological research is needed in different climate zones to evaluate the health consequences of making the buildings more energy efficient. Epidemiological studies and modelling studies are available on health effects and indoor effects of energy conversation, improved thermal insulation, increased air tightness and creating green buildings. The health-related literature on this issue was reviewed, by searching scientific articles in the medical Database PubMed and in the general database Web of Science as well as Nature database. In this literature review, 53 relevant peer reviewed articles on health effects of energy use and energy saving were found. Most of the studies had investigated residential buildings. One main conclusion from the review is that combined energy efficiency improvements in buildings can be associated with improvement of general health, such as less asthma, allergies, sick building syndrome (SBS) symptoms, respiratory symptoms, and reduced cold-related and heat-related mortality. Moreover, combined energy efficiency improvements can improve indoor air quality, increase productivity and satisfaction and reduce work leave and school absence. Effective heating of buildings can reduce respiratory symptoms and reduce work leave and school absence. However, some potential health problems can occur if increased energy efficiency will reduce ventilation flow. Energy saving by increasing air tightness or reducing ventilation is associated with impaired indoor air quality and negative health effects. In contrast, improved ventilation may reduce SBS, respiratory symptoms and increase indoor air quality. Installation of mechanical ventilation can solve the negative effects of making the building construction in dwellings more air tight. In future research, more studies are needed on health impacts of single energy efficiency improvement methods. Existing studies have mostly used a combination of improvement methods. In addition, modelling software programs should more often be used, since they can take into account effects of different energy efficiency improvement methods on indoor air quality in different types of buildings and in different climates.

Table of contents

1 Introduction

1.1 Background

In western modern society, people spend more than 90% of the time in indoor environments and most of the time is spent in the home environment. Energy is needed to heat or cool buildings and energy use in buildings is an important issue in the modern society. The climate change issue, linked to increased CO_2 emissions from coal, oil or gas combustion, has increased the demand to save energy in buildings in different parts of the world. Because of this demand, different strategies have been applied to increase energy efficiency in buildings and to create a sustainable development of the built environment which combine a healthy and energy efficient indoor environment. However, this is a complex issue, and there is a need to involve scientists from many different disciplines as well as stake holders, government officers and other decision makers.

In recent years, there has been more and more a focus on low energy buildings, zero energy buildings, green buildings and healthy buildings etc. In USA, they have created Leadership in Energy and Environmental Design (LEED) credits to assess green buildings for many years [1-5]. In UK, they have created the UK Government's Standard Assessment Procedure (SAP) to assess energy efficiency buildings for many years as well [6-8]. However, it seems difficult to develop commonly accepted energy efficiency rating systems for buildings that can be used in different countries.

When building engineers meet a demand on energy saving, retrofit or renovation, most of them will search the most cost-efficient way to achieve better energy efficiency, and will mainly focus on checking thermal comfort for their methods linked to energy efficiency improvements. However, the payback time for huge energy saving retrofits (huge investments) of buildings could be several years and this could limit the will to invest money in measures increasing the energy efficiency in buildings. In this case, the potential long-term health benefits of energy saving works need to be pointed out to the building owners.

A number of scientific articles have been written on different aspects of energy use in buildings, mainly from technical perspectives. This literature review has focused on health aspects of energy use, energy saving and energy efficiency in buildings.

1.2 Aims

In this literature review, the associations between energy system, indoor environment and health have been reviewed, including peer reviewed scientific articles on health aspects of energy use in buildings. The main aim is to summarize the current knowledge on how energy saving measures and energy use influence our health and the indoor environment. The second aim is to gather knowledge on types of energy saving or energy use that should be promoted from a health perspective. A third aim is to give some evidence-based advice on how future studies on the associations between energy use in buildings and health should be designed.

2 Methods

Scientific articles published in peer reviewed journals were extracted from three major databases containing medical scientific publications: The medical database PubMed, and the Web of Science Core Collection, and Nature database. All publication years were included. Scientific articles were searched by combining search terms on health effects with technical search terms linked to energy use. Search terms on health effects included medical search terms such as: asthma, respiratory, lung function, rhinitis, eczema, dermatitis, sick building syndrome (SBS), cardiovascular disease and total mortality. Technical search terms linked to energy use included energy use, energy consumption, energy efficiency, energy saving, low energy building, green building etc.To select relevant articles, the energy search terms were sometimes combined with building related search terms such as: building, built environment, home, dwelling, indoor etc.

In total, 53 relevant peer reviewed articles were identified, including 9 review articles, 9 modelling-study articles and 35 field-study articles in results section. These articles have been included in the reference list of the master thesis and were categorized in Excel table where energy-related building technologies were arranged in the rows and different health effects were arranged in the columns as a help to organize the structure of results. Each paragraph in the result part of this thesis includes one type of energy-related building technology. In the beginning of the results part, one paragraph on previous review articles and another paragraph on modelling studies have been included. The remaining 35 field studies have been organized into different paragraphs. In each paragraph, field studies with only environmental measurements (no heath data) are presented first followed by health-related field studies.

3 Results

3.1 Review articles

3.1.1 Heat and indoor pollutant exposure

One review article included studies on associations between indoor overheated temperatures and mortality, focusing on the need for prescribing indoor heat thresholds values. Overheating may occur in buildings with inadequate ventilation or air conditioning, top floors of buildings, south-facing flats, and in urban dwellings [9]. They reported that overheated bedroom temperatures may cause poor sleep and that absence of night-time relief from heat may cause heat-related mortality.

Another review study focused on studies on associations between asthma control and environmental factors, including energy efficiency buildings, indoor allergen exposure, environmental tobacco exposure, airborne pollutants [10]. They concluded that environmental tobacco smoke exposure (ETS) could increase asthma symptoms. Overweight could enhance the effects of air pollution exposure on asthma. They mentioned that improved air tightness in homes could increase indoor pollutant levels which could increase asthmatic symptoms or asthma attacks.

3.1.2 Combined energy efficiency improvements

One review article included 28 peer reviewed studies on associations between home energy efficiency interventions and householder health. The studies were classified according to type of intervention, draught proofing, insulation, more efficient heating system, and use of renewable energy [11]. They concluded that there was some evidence for negative health effects of energy efficiency improvement linked to inadequate ventilation but this risk was relatively small. They found that draught proofing (causing inadequate ventilation) might cause more respiratory symptoms. In contrast, increased insulation could result in fewer respiratory and cardiovascular symptoms. In addition, they reported that a more efficient heating system (linked to fuel poverty) could reduce stress and anxiety and that use of renewable energy had a positive impact on satisfied housing and social health.

Another review article included studies on associations between the building environment, energy and health. This review focused on building energy efficiency in homes in high-income and low-income countries, and greenhouse gas reductions and clean energy technology [12]. They concluded that in high-income countries, e.g. United Kingdom, energy inefficiency and fuel poverty of space heating in homes can increase the risk of cold-related mortality in winter from cardiovascular disease. Moreover, they concluded that by replacing biomass fuels with cooking and heating by electricity in low-income countries, indoor air pollution in homes would be reduced and health and wellbeing would be improved.

3.1.3 Green buildings (combined energy efficiency)

One review article focused on associations between green building design strategies and health risks linked to exposure to extreme heat. The study assessed 81 Leadership in Energy and Environmental Design (LEED) credits or adaptation strategies in green building design and selected 12 out of 81 credits referring to the extreme heat conditions. The 12 LEED credits included 8 credits classified into sustainable sites, 3 credits into energy and atmosphere and one credit into indoor environmental quality. Building characteristic included heat island effect roofs, optimized energy performance, on-site renewable energy, enhanced performance commissioning, thermal comfort design [1]. They reported that the 12 LEED credits (strategies) could reduce the health risks linked to extreme heat exposure, reduce heat stress and heat-related morbidity and mortality.

Another review article included studies on associations between green buildings, environmental quality and human health. The review defined buildings with LEED rating system as green buildings [2]. They concluded that green buildings could reduce sick building syndrome (SBS) symptoms, respiratory symptoms among children, physical and mental health. They also concluded that green buildings could improve work productivity and reduce work absenteeism due to asthma and allergic infections. Moreover, green building could lower employee turnover rate and reduce the time of hiring staffs. Furthermore, they concluded that green hospital buildings could improve quality of care and record keeping and reduce bloodstream infections and reduce patient mortality.

In another review article, nine foundational elements of healthy buildings were identified, based on previous Rating Systems (RS) of green buildings. The nine foundational elements of healthy buildings included indoor air quality, ventilation, thermal health, water quality, as well as dampness and mold, dust and pests, noise, light and views, safety and security [13]. They concluded that poorly ventilated indoor spaces might cause asthma, respiratory symptoms and sick building syndrome (SBS) symptoms. Moreover, they concluded that inadequate heat, humidity, and low ventilation flow in the office spaces might increase self-reported itchy or watery eyes, headaches, throat irritation and respiratory diseases, as well as increased heart rate, bad mood, SBS symptoms and fatigue. Furthermore, they concluded that moisture-induced mold exposure might cause asthma, allergic symptoms, respiratory symptoms and decreased productivity.

3.1.4 Improved and reduced ventilation

A review article from Denmark included studies on health and comfort in relation to type of ventilation system, focusing on comparing personalized ventilation system with mixing ventilation system (total volume air distribution). The study included personalized ventilation cases from homes, offices, hospitals and vehicle compartments [14]. They concluded that installation of a personalized ventilation system with a passive chilled beam might save up to 80% of the total ventilation air demand compared to a mixing ventilation system when the room background temperature is maintained at around 27-28°C. Moreover, they concluded that personalized ventilation might decrease sick building syndrome (SBS) symptoms, improve perceived indoor air quality, thermal comfort and work performance as compared to mixing ventilation.

Another review article included studies on associations between reduced ventilation rate and indoor air quality as well as risk of asthma [15]. They found that indoor air exchange rates could be reduced by nearly 90% when reduced ventilation flow was combined with increased air tightness and limited air infiltration rates in homes. The reduced ventilation flow could create warmer and more humid indoor conditions which could increase house dust mite allergens and consequently increase risks of asthmatic symptoms. Moreover, they reported that installation of a mechanical ventilation system with heat recovery could improve indoor air quality and improve lung function as compared to natural ventilation and mechanical exhaust/supply ventilation.

3.2 Modelling articles

3.2.1 Outdoor air pollution control

In an exposure modelling study from United States, the public health benefits of improved insulation in existing housing were estimated. They focused on estimating the number of single-family homes that needed improved insulation across US. Moreover, they modelled energy saving and reduced emissions, aiming to calculate the effects on health outcomes. The health estimation was based on data from previous studies, including exposure-response functions for mortality or morbidity [16]. They reported that improved thermal insulation in 46 million US homes could reduce 8×10^{14} British Thermal Units per year, thereby reducing 3 100 tons of $PM_{2.5}$ (particulate matter with diameter $\leq 2.5\mu m$), 100 000 tons of NO_x, and 190 000 tons of SO_2 per year (emission reductions linked to the reduced energy use in buildings). Furthermore, they estimated that improved insulation in single-family homes across US (linked to reduced emission) could avoid 240 deaths, 6 500 asthma cases, and 110 000 restricted activity days per year.

In another exposure modelling study from United States, potential health benefits of LEED-certified green buildings were examined. The study focused on an estimation of the total energy savings and pollutant emissions reductions in LEED-certified green buildings in United States, China, India, Brazil, Germany, and Turkey. They modelled health benefits linked to the reduced energy use in the green buildings. Energy data from the Green Building Information Gateway (GBIG) were applied to estimate energy savings in each country each year. The health estimation was based on the data from previous studies, including exposure-response functions for mortality or morbidity [3]. They reported that LEED-certified buildings in those six countries reduced total energy use by 96.48 billion KWh, of which electricity was 55.56 billion KWh, natural gas 30.50 billion KWh, fuel oil 2.99 billion KWh, other combustion fuels 7.43 billion KWh from 2000 to 2016. This energy saving can reduce 33 megatons of CO_2, 51 kilotons SO_2, 38 kilotons of NO_x, and 10 kilotons of $PM_{2.5}$ entering into the atmosphere. Moreover, they estimated that LEED-certified green buildings in United States could reduce 172-405 premature mortalities, 171 hospital admissions, 11 000 asthma exacerbations, 54 000 respiratory symptoms, 21 000 missed work days and 16 000 missed school days from 2000 to 2016.

In one exposure modelling study from United Kingdom, public health benefits of reducing household energy use were estimated for UK and India. The study modelled a UK household energy efficiency program and a cookstove program for India. Energy data from WHO's Comparative Risk Assessment exercise were applied to baseline and future estimations for both programs. The health estimation was based on data from previous studies, including exposure-response functions for mortality or morbidity. The energy efficiency intervention scenarios for UK program included fabric insulation, improved air tightness and ventilation, fuel switching, reduced indoor temperature and combined measures. The energy efficiency intervention for India program shifted traditional stoves to clean fuels or advanced biomass stoves [17]. They reported that the combined energy efficiency measures in the UK program would reduce 850 disability-adjusted life-years (DALYs) and reduce 0.6 megatons of carbon dioxide (CO_2), per million population per year. Moreover, they concluded that the cookstove program in India would reduce around 240 000 respiratory symptoms in children as well as decreased at least 1.8 million premature adult mortalities from ischemic heart and chronic obstructive pulmonary disease (COPD) from 2010 to 2020, which is equal to reduce 12 500 disability-adjusted life-years (DALYs) and reduce 0.1-0.2 megatons of carbon dioxide (CO_2), per million population per year.

3.2.2 Indoor air pollution and temperature control

In an exposure modelling study from China, indoor $PM_{2.5}$ concentrations linked to different ventilation intervention scenarios were estimated for an apartment in Beijing. The study designed 14 intervention scenarios, including one type of ventilations (natural or mechanical) combined with one type of air tightness levels (level 3,5,7) and one type of $PM_{2.5}$ filtration efficiencies of mechanical ventilation system (50%, 70%， 90%， 99%). Basis scenario represented current scenario. They used a series of formulas to calculate indoor $PM_{2.5}$ concentrations and annual economic benefits for those intervention scenarios [18]. They reported that annual averages of indoor $PM_{2.5}$ concentration reduction in intervention scenarios ranged from 5.52 to 25.24 $\mu g/m^3$. The estimated mortality reduction percent of intervention scenarios ranged from -2.65 to 4.23% comparing to the basis scenario. Moreover, they concluded that high air tightness level in building envelope (≥ Chinese National Standard Level 7) combined with high filtration efficiencies of mechanical ventilation (≥90%) should be applied in Beijing to reduce indoor $PM_{2.5}$ concentrations, due to the high outdoor air pollution.

In one exposure modelling study from United Kingdom, health effects of indoor particles in England and Wales were evaluated. The study focused on an estimation of health improvements related to the estimated 3 $\mu g/m^3$ reduction in average indoor $PM_{2.5}$ from outdoor sources when making the building construction tighter in connection with increased home energy efficiency. The health estimation was based on data from previous studies, including exposure-response functions for mortality or morbidity. Home energy efficiency measures in this study included improved building fabric and ventilation, as well as fuel switching and occupant behavior changes [19]. It was concluded that home energy efficiency measures reducing indoor $PM_{2.5}$ exposure from outdoor sources would reduce 260 000 mortalities and morbidities cases from asthma, 53 000 coronary heart disease cases and 3 000 lung cancer cases in UK.

In another exposure modelling study from United Kingdom, the effects of home energy efficiency interventions and winter fuel payments on winter-related and cold-related morbidity and mortality were assessed. They used previous homes energy efficiency database and temperature data as well as previous mortality and hospital admissions data from UK and used a IOMLIFET life table model to estimate the health effects. Energy efficiency interventions in the model included double glazing, insulation of loft, solid and cavity wall as well as boiler replacement and gas central heating [20]. They reported that installation of fabric energy efficiency retrofit in homes could reduce gas energy use by 790 KWh /year or 3.9% of the total gas demand in UK housing stock in 2006. The corresponding improvement of heating energy efficiency retrofit was 1 950 KWh /year or 10.4%. They estimated that 300 cold-related mortalities per year could be avoided by energy efficiency improvements in UK between 2002 and 2007, linked to the estimated increase of indoor winter temperatures (0.1°C arise) from energy efficiency improvements. Moreover, they reported that winter fuel payments in UK can reduce winter- or cold-mortality.

In another exposure modelling study from United Kingdom, potential public health effects of home energy efficiency retrofits were assessed. The study focused on modelling the effects on cardio respiratory diseases, lung cancer, asthma and mental disorders due to reduction of indoor air pollutants. Building environment and energy data were from the English housing survey 2009 (baseline) and the CONTAM simulation program (future estimation). They used IOMLIFET life table model to estimate the health effect. Energy efficiency retrofit scenarios included fabric and ventilation retrofits for homes without a risk of poor ventilation (scenario 1), and fabric and ventilation retrofits for homes at risk of poor ventilations (scenario 2 and 3) [21]. They concluded that home energy efficiency retrofits with good ventilation can reduce indoor air pollutant concentration ($PM_{2.5}$ 53%, radon 11%, secondhand tobacco smoke 13%, mold 23%) and increase indoor winter temperatures (0.3°C), thereby reducing net mortality and morbidity of 2 241 disability-adjusted life-years (QALYs) per 10 000 persons over 50 years.

3.2.3 Indoor radon levels control

In an exposure modelling study from United Kingdom, the effects of reduced home ventilation rates on mortality from radon related lung cancer in the whole country was estimated. Four modelling scenarios were evaluated, including air tightness (scenario 1), air tightness with purpose-provided ventilation (scenario 2), scenario 2 but with mechanical ventilation with heat recovery (called scenario 3) and 10% failures of scenario 3 (called scenario 4). For each scenario, they used the CONTAM simulation program to model the distribution of indoor radon levels. Finally, they used IOMLIFET life table model to estimate the effect of changed radon levels on lung cancer death [22]. Their model implied a significant increase in radon concentrations when ventilation rates were below 0.3 air changes per hour.They found that mean radon concentrations at baseline, scenario 1, scenario 2, scenario 3 and scenario 4 were 21.2 Bq/m^3, 33.2 Bq/m^3, 25.5 Bq/m^3, 19.6 Bq/m^3 and 21.8 Bq/m^3 respectively. Energy savings in heating demand for ventilation in scenario 1, scenario 2, scenario 3 and scenario 4 were 34%, 19%, 28% and 28% respectively. They concluded that energy savings linked to reduced ventilation rates in airtight homes could increase indoor radon level and increase the risk of lung cancer. However, they concluded that installation of a mechanical ventilation system with heat recovery linkd to improved ventilation rates would decrease indoor radon levels in the most airtight dwellings.

Another early exposure modelling study from United Kingdom estimated increased radon related cancer risks of home energy saving by reducing ventilation, including draught proofing and double glazing. They calculated health costs linked to the increase of outdoor pollutant emission from electricity production (0.01-0.1 pence per KWh) based on a health cost formula reported in another exposure study. Then they calculated health cost linked to the increase of radon due to reduced ventilation linked to energy saving measures in homes in United Kingdom, based on the same formula [23]. They reported that energy saving by draught proofing or double glazing in an average home in United Kingdom was 1 200 KWh /year. Moreover, they concluded that this energy saving would increase the indoor radon level in homes by 30%. The final conclusion was that the societal cost of the impaired health linked to the increase of radon in homes with energy saving measures in United Kingdom was at least 10-100 times more than the estimated impaired health linked to the increase of outdoor pollutant emission from electricity production and supply. Thus, they warned that energy saving in homes could cause societal costs linked to an increase of impaired health.

3.3 Field studies

3.3.1 Combined energy efficiency renovations and retrofits

In an exposure field study from Bulgaria, indoor radon-safety in relation to energy efficient reconstructions was assessed by indoor measurements using special plastic disks. The polycarbonate material of the discs could measure mean concentrations of radon daughters by alpha track technology. This before-after study investigated the same building twice, before and after reconstruction. A total of 20 rooms in 16 buildings were investigated. No control group was included. Energy efficient reconstructions included replacement of old windows with new energy-efficient tight windows. After the reconstructions, the mean indoor radon increase was 193 Bq m^{-3} (range: 33-656 Bq m^{-3}) and for rooms with no significant change 45 Bq m^{-3} (range: 11-192 Bq m^{-3}) [24]. They concluded that indoor radon concentration significantly increased in 35% of rooms and none of the rooms had a decrease of indoor radon concentration after the reconstruction.

In one exposure field study from homes in Germany, effects of improved thermal insulation and installation of central heating systems on house dust mite allergen concentrations (Der f 1), mold spores and air exchange rate were studied. This before-after study examined bedrooms in 98 apartments in Lenzkirch (former East-Germany). No control group was included. The energy efficiency improvements included installation of insulated windows and central heating systems [25]. The measured air exchange rate was reduced from mean 0.73 air exchanges per hour (ACH) to 0.52 ACH after the intervention. Moreover, they found that installation of insulated windows and central heating systems increased the Der f 1 concentrations in the carpet dust and mattress dust and moreover increased the concentration of the allergenic mold *Aspergillus fumigatus* in carpet dust from the bedrooms. The authors concluded that the observed negative effects on the indoor environment could be due to reduced ventilation.

In an exposure field study from Switzerland, the effects of low energy measures on indoor house dust mite allergen concentration in dust were studied. The low energy building group included 556 children and adults living in 277 apartments. The control buildings group without any low energy measures included 730 children and adults living in 314 apartments. The low energy buildings had enhanced thermal insulation of walls and windows, a mechanical ventilation system with heat recovery in all rooms and passive solar heating design [26]. They found that mean energy index was 129 KWh/m^2 in low energy buildings and 200 KWh/m^2 in control buildings. The median mattress dust concentration of the major house dust mite allergen Der f 1 was 67 ng/g dust in low energy buildings and 954 ng/g of dust in control buildings. The authors concluded that house dust mite growth and house dust mite allergen can be reduced in low heating energy building construction. The mechanical ventilation in the low-energy apartments could reduce indoor relative air humidity and improve life for mite-allergic patients.

In one exposure field study from United States, the effect of green housing on measured indoor air quality (IAQ) was investigated. The before-after study included 64 children with doctor diagnosed asthma living in 28 green-renovated homes and 14 homes without any renovation (controls) in Ohio, US. The green renovation included energy efficient windows and doors, lighting and bulbs, thermal insulation of the house and installation of central heating/cooling systems with thermostats [27]. Indoor air samples were collected from children's bedrooms. They found that there were no significant differences in indoor concentrations of $PM_{2.5}$, black carbon, sulfur, ultrafine particles, total VOCs, and formaldehyde when comparing green-renovated homes with non-green control homes. However, they found that indoor black carbon levels decreased and indoor formaldehyde increased immediately after renovation in the green-renovated homes, possibly due to reduced opening of windows.

In a field study from Germany, the impacts of the home environment on health complaints were evaluated. The study investigated 165 cases of health problems occurring after home energy saving measures. No control group was included. Energy saving measures included installation of new windows, thermal insulation and installation of new central heating systems [28]. They measured indoor mold in 52 of the homes and found mainly *Penicillium, Aspergillus and Alternaria* species. They concluded that the health problems were associated with installation of new tight windows and doors. The occupants contributed to the indoor problems by not airing their homes enough because they wanted to save heating costs.

In one field study from United Kingdom, short term health effects of an energy efficiency intervention in south Devon, UK were investigated. The study included 119 council owned houses with 481 residents. A total of 50 houses got an early intervention (intervention group) and another 69 houses with a later intervention (after the study was finalized) served as control group. The intervention included installation of a central heating system, a mechanical ventilation system, as well as rewiring, insulation and re-roofing the buildings [29]. The study found that the energy efficiency intervention reduced non-asthma-related chest problems, and reduced an asthma symptom score among adults, as compared to the control houses. Moreover, there was limited evidence that the intervention could protect against development of asthmatic as well as non-asthmatic respiratory disease.

In another field study from United Kingdom, the impacts of home energy efficiency investments on residential mental and physical health and psychosocial outcomes were examined. The study included 364 adults in intervention group with energy efficiency investments and another 418 adults in the control group (no energy efficiency investments). The study was performed in low-come communities in Wales, UK. Energy efficiency measures included improved external wall insulation, installation of a central heating system (boilers and radiators), and access to a gas network [30]. The study found that the home energy efficiency investments were not associated with improved short-term self-reported health. However, the intervention increased residential wellbeing and psychosocial-related health. Moreover, they reported that better housing conditions seem to improve health in the longer term.

In a field study from United Kingdom, potential health effects of home energy efficiency improvement were investigated for elderly COPD patients. The energy efficiency data in this study was based on National Home Energy Rating. The follow-up study included 45 patients with energy efficiency intervention and another 133 patients with no intervention (control group), living in Aberdeen, UK. Energy efficiency intervention included improved central heating systems, enhanced insulation of the loft, under-floor and cavity wall, and benefit reassessment [31]. They reported that annual heating costs were reduced by 65.3 pounds and home energy efficiency rating score improved by 10%. Moreover, they found that the intervention could improve respiratory health status. However, they reported that lowering number of hours with a warm indoor environment resulted in poorer respiratory health status.

In one field study from Finland and Lithuania, effects of energy efficiency retrofits on indoor air quality in homes were evaluated. The before-after study included 45 multi-family buildings with 240 apartments in Finland and 20 multi-family buildings with 96 apartments in Lithuania. A total of 37 multi-family buildings in Finland and 15 multi-family buildings in Lithuania were apartments with energy efficiency retrofits. The retrofits included improvements of energy sources, improve thermal insulation of the building envelope, increased air tightness, and improvements of the heating and ventilation systems [32]. The study found that the mean annual heating energy use was reduced by 24.1% in Finland and by 49.3% in Lithuania. The retrofits in the Finnish buildings increased indoor air concentrations of benzene, toluene, ethyl benzene and xylenes but reduced indoor concentrations of airborne mold and bacteria. The retrofits in the Lithuanian buildings increased indoor radon concentrations. Moreover, installation of mechanical ventilation reduced formaldehyde concentrations in Finnish buildings. In addition, the study could demonstrate that the energy efficiency retrofits reduced upper respiratory symptoms and reduced days of missing work or missing school due to respiratory infections.

In another field study from Finland and Lithuania, the effects of energy efficiency retrofits on health and occupant satisfaction with indoor environment quality (IEQ) in multi-family buildings were examined. This before-after study included an intervention in 39 Finnish and 15 Lithuanian multi-family buildings. On average, there were five apartments per building and one adult per apartment. Moreover, the study included 7 Finnish and 5 Lithuanian non-retrofitted buildings (controls). Energy retrofits in building in Finland included replacement of the windows and installation of heat recovery in the existing exhaust ventilation system. Energy retrofits in Lithuania included improved thermal insulation of the walls and roofs, replacement of the windows and glazing the balconies [33]. The study demonstrated that energy efficiency retrofits in multi-family buildings increased occupant satisfaction with indoor temperature, reduced noise nuisance, reduced upper respiratory symptoms and reduced absence from school or from work due to respiratory infections.

In a field study from United States, change of health status of the occupants living in buildings getting modern energy efficiency retrofits was investigated. The before-after study included 248 households with 248 adults and 75 children in Boston, Chicago, and New York. No control group was included. The energy efficiency retrofits included improvements of thermal insulation, heating equipment, windows and doors, and installation of bathroom fans and leak repair [34]. The study found that energy retrofits may have a positive impact on resident health when the energy saving work is conducted by trained professionals. The improvements included significant improvements in general health, reduced asthma medication use and less sinusitis. Moreover, residents felt healthier in those buildings where they were satisfied with the energy efficiency retrofits.

In another field study from United States, resident health and building performance outcomes after green efficiency renovation were investigated. This before-after study included 31 low-income homes with 50 adults and 29 children in Minnesota. There was no control group. Green efficiency renovation included improved windows, installation of a geothermal heating/cooling system and ventilation systems, thermal insulation of exterior walls and roof, as well as control of moisture, mold, pests, and radon, and use of sustainable materials [35]. The energy consumption was reduced by 45% during the year after renovation. The authors concluded that the green renovation of low-income housing can have a significantly positive effect on health. Among adults, the retrofitting improved overall health, reduced asthma and reduced non-asthmatic respiratory problems. Among children, the retrofitting improved the overall health, especially non-asthmatic respiratory problems.

In one field study from United States, the effects of home energy efficiency retrofits on indoor climate, health and comfort of the residents were examined. This before-after study included 57 low-income older adults living in 53 units of an apartment complex in Phoenix, US. No control group was included. The energy efficiency renovation included improved roof insulation and sealing, installations of new heating/cooling units and thermostats and improved building envelope insulation to reduce air infiltration [36]. The study found that the energy efficiency retrofits reduced energy use by 19% on average. Moreover, they concluded that the renovation improved general health, emotional distress, and improved sleep among the older adults.

In another field study from United States, the benefits of green efficiency renovation on self-reported health were assessed. The study focused on elderly living in a low-income public housing apartment building with 101 units in Mankato, Minnesota. Two study groups with green efficiency renovation were obtained from a previous survey and in the present interview. Two control groups without any green efficiency renovation were from the previous survey only (controls). The intervention group included 40 persons and the control group included another 40 persons. The elderly intervention group included 22 persons, and the elderly control group included another 572 persons. Green efficiency renovation included improvements of building envelope, air sealing, thermal insulation and exterior cladding, replacements of heating, electrical, ventilation systems and windows, retrofits of fixtures, appliances, low-emitting building materials, avoiding asbestos, mold abatement and an indoor no-smoking policy [37]. The study found that the green efficiency renovation improved mental and general physical health, and could prevent accidents from falls and reduce exposure to environmental tobacco smoke.

In a field study from United Kingdom, long-term health impacts of energy efficiency investments were investigated. The study was a 10-year follow-up including 136 300 homes in Wales. A total of 4 968 homes were energy efficiency intervention homes (with 25 908 inhabitants). Another 12 350 homes were social housing control homes (with 48 261 inhabitants). A third group consisted of another 118 982 control homes in poverty areas (with 524 596 inhabitants). The intervention measures included external wall insulation, solar hot water, change of fuel type and installation of air source heat pumps [38]. The study found that energy efficiency intervention was associated with a significant increase in emergency cardiovascular admissions among elderly (aged over 60 years). However, they pointed out that this negative health effect could be due to lack of control for confounding linked to aging.

3.3.2 Energy efficiency rating buildings (combined energy efficiency)

A field study from United Kingdom measured fungal allergens by monoclonal antibodies, and viable allergenic mold in energy efficient homes. The study included 41 energy efficient homes with 93 residents. No control group was included. Energy efficiency ratings, the presence of condensation, moisture within the building fabric, property type and energy efficiency level were assessed in the study. Energy efficiency ratings of this study were calculated basing on UK Government's Standard Assessment Procedure (SAP), ranging from 0 to 120. Energy efficiency ratings (SAP) of the houses were 66 on average (range: 50-81) [6]. It was concluded that increased energy efficiency might reduce the risk of allergenic fungal contamination in homes, and thus can reduce the risk of mold-related respiratory illnesses. However, they pointed out that energy efficiency improvements causing increased air tightness in homes must be combined with increased airing (window opening).

In another field study from United Kingdom, associations between energy efficient homes and doctor diagnosed asthma were studied. The follow-up study included 944 adult participants (mean age of 59) living in 706 energy efficient homes. No control group was included. Energy efficiency ratings included type of heating system and glazing, insulation levels, and the time when there were any energy efficient improvements. Energy efficiency ratings were calculated basing on UK Government's Standard Assessment Procedure (SAP), ranging from 0 to 120. Mean energy efficiency rating of those buildings was 65.7 and ranged from 24 to 88 [7]. The study found that increased energy efficiency might increase the risk of doctor diagnosed asthma. They suggested that the negative impact of increased home energy efficiency could be due to inadequate heating, inadequate ventilation, and increased concentrations of indoor pollutants.

3.3.3 Green and healthy rating buildings (combined energy efficiency)

In another field study from United States, the health impact of LEED-certificated green office buildings were assessed by a web-based survey. This before-after study included 56 employees working in platinum LEED rating buildings and another 207 employees working in gold LEED rating in Lansing, Michigan. All of them had moved from conventional offices to green office buildings. LEED-certificated green buildings included credits for indoor air quality, temperature, humidity, as well as ventilation, lighting, acoustics, ergonomic design and safety [4]. The authors concluded that improved indoor environment quality (IEQ) in green building could reduce absenteeism due to asthma, respiratory allergies, depression and stress, and improve work productivity.

In a field study from a university campus in Canada, health effects of a range of indoor ergonomic issues in green buildings were investigated. The study included 319 occupants (249 females), in green classrooms. The two green classrooms were in buildings getting Leadership in Energy and Environmental Design (LEED) credits. Moreover, there was a conventional classroom with no LEED credits. The LEED rating system included strategies for energy efficiency, sustainable materials, natural light and air ventilation [5]. The study found that in the green classrooms it was usually better health, performance, and satisfaction. However, green classrooms did not always own the highest LEED ratings for environment, health and productivity.

3.3.4 Energy use (without energy efficiency renovations or ratings)

In a field study from Sweden, home environment risk factors for asthma, allergy and eczema among adults in Stockholm were studied. The risk factors included building characteristics, home environment and energy use for heating. The questionnaire study included 472 multi-family buildings (10 506 dwellings with 7 554 adult participants). The technical investigation included measurement of energy use for heating, and data on type of ventilation system [39]. Those living in buildings with supply/exhaust air ventilation systems had more doctor diagnosed allergy, as compared to those in buildings with exhaust air ventilation only (no supply air). Subjects living in buildings using more energy for heating had less pollen allergy. Those living in larger buildings had more often eczema and those living in buildings using more energy for heating had less often eczema.

In another field study from homes in Sweden, health effects of ventilation rate and insulation level of the buildings were investigated among adults. The study measured indoor environment and ventilation and calculated the degree of thermal insulation in 605 single-family homes with 1 160 adults. The mean values of air exchange rate and U-value in those buildings were 0.36 ACH (0.07-1.14 ACH), 0.491 W/m^2K (0.2-1.43W/m^2K) respectively [40]. The study found that most of the homes did not meet the minimum value for air exchange rate (0.5 ACH) in the existing ventilation standard in Sweden. Moreover, the study found that at higher air exchange rate, asthma symptoms were less common. However, they found no significant associations between the insulation level of the buildings (U-value) and wheeze, asthma symptoms, respiratory infections or rhinitis.

In the same field study from Sweden, associations between sick building syndrome (SBS) symptoms and ventilation rate and insulation level of the buildings were investigated (605 single-family homes with 1 160 adults). The mean values of air exchange rate, U value in those buildings were 0.36 ACH (0.07-1.14 ACH), 0.491 W/m^2K (0.2-1.43 W/m^2K) respectively [41]. They found no significant association between the air exchange rate in the homes and SBS symptoms. However, they found that a low U-value (high insulation level) was associated with a lower prevalence of SBS symptoms. This result supported the view that those living in an energy efficient building can have less SBS symptom.

In one field study from Sweden, the health impact of energy use, heating and ventilation, energy conservation, and reconstruction in older multi-family houses was investigated. The questionnaire study included 231 multi-family buildings (with 4 815 dwellings) and 3 241 adults in Stockholm. Energy conservation measures included improved heating and ventilation, window sealing or replacement, roof insulation and façade insulation [42]. Ocular and nasal symptoms were less common in buildings with a mechanical ventilation system as comparing to buildings with only natural ventilation. However, throat irritation and tiredness were slightly more common in buildings with mechanical exhaust ventilation, while cough and headache were more common in buildings with supply/exhaust ventilation. Furthermore, they reported that heating by electric radiators, heating by wood burning and use of heat pumps were associated with an increase of symptoms. Moreover, major reconstruction of the interior of the building increased the prevalence of symptoms. In buildings with more than one sealing measure, there was an increase of ocular, nasal symptoms, headache and tiredness. The authors concluded that energy saving could decrease and increase different types of symptoms. However, multiple sealing and insulation of older multi-family building could cause sick building syndrome (SBS).

In a field study from United Kingdom, risk factors for cold-related mortality in elderly were assessed, focusing on home energy use and fuel poverty. The study included 1 402 men aged 74-95 years. No control group was included. The questionnaire investigation asked about types of home insulation and heating system [43]. The study did not find any clear association between type of heating system and cold housing. However, lack of thermal insulation in the wall cavity or solid walls could increase cold-related mortality.

3.3.5 Lower indoor temperature

In a cold exposure field study from United Kingdom, the impacts of winter fuel payment on indoor temperature and cold-related mortality were estimated. The before-after study included 5 902 subjects from a sample of 12 210 adults (aged 50-90 years). No control group was included. They compared fuel expenditure of households with elderly. A winter fuel payment intervention was offered to the oldest members (>60 years), aiming to increase domestic heating in the coldest months to counteract fuel poverty, increase indoor temperature and thereby decrease excess winter mortality. [44]. They found that low indoor temperature increased systolic and diastolic blood pressure and increased fibrinogen levels. However, they found no evidence that winter fuel payment leaded to warmer homes, improved health or lower cold-related mortality.

In another field study from a university campus in Norway, health effects of indoor daytime and nighttime temperature were investigated. The study included 96 university workers in two buildings with SBS-symptoms and another 76 workers in two control buildings with no recent health complaint. All buildings had mechanical supply and exhaust ventilation system and local electric heating system except one problem building which had water-borne central heating with local radiators [45]. The mean night air temperature was 20.9 °C and mean day air temperature was 22.2 °C for all four buildings. They found that general symptoms were more common in the problematic buildings as compared to the control buildings. Moreover, they found that a lower mean night air temperature, and a lower air temperature at 6:00 o'clock in the morning decrease tear film stability, especially for workers exposed to mean day air temperature≥22.1°C. They concluded that saving energy by lowering the nigh-time temperature could cause some health problems during the day.

3.3.6 Energy efficiency heating

In a field study from United Kingdom, health effects of efficiency intervention in homes were evaluated. The before-after study included 72 children with previous doctor diagnosed asthma living in 59 damp homes getting energy efficiency intervention in Cornwall, UK. No control group was included. The energy efficiency intervention included installation of central heating and measures to reduce dampness and indoor mold growth [46]. They reported that energy efficiency ratings improved from 4.4 to 6.5 out of 10. The standard for a new-build house is 8. They reported that the energy efficiency intervention decreased all types of respiratory symptoms, especially nocturnal cough. Moreover, missed school days due to asthma were reduced.

Another field study from New Zealand aimed to improve children health and home energy efficiency by installing more effective heating. This community-based study investigated 409 children with doctor diagnosed asthma from five communities. They lived in homes with plug-in electric heaters or gas heaters. The intervention included installing of more effective heating and thermal insulation [47]. They found that energy use was reduced by 19% when comparing insulated houses with uninsulated houses. They concluded that installing more effective heating in insulated home could reduce children self-reported poor health, asthma symptoms and sleep disturbances due to wheeze and dry cough. Moreover, missed school days could be reduced.

3.3.7 Fuel poverty behaviors

In an exposure field study from United Kingdom, effects of fuel poverty on occupants' risk perception and ventilation and mold contamination in social housing were investigated. The questionnaire study included 671 participants (mean age 60 years). A total of 87.8% of the households were built with insulated loft (depth >250mm), 83.7% with insulated cavity wall, and 99.8% had double glazed windows. No control group was included. Energy efficiency ratings were calculated based on the UK Government's Standard Assessment Procedure (SAP), ranging from 0 to 120. Energy efficiency ratings (SAP) of those houses were 65.7 on average (range: 22-88) [8]. They reported that fuel poverty behaviors, which were found in one third of the households, were associated with increased exposures to dampness and mold, even though there were increased risk perception and use of mechanical ventilation in the homes.

In a field study from Spain, mortality in relation to home fuel poverty in Barcelona was assessed. The study included 2 552 deaths, of which 1 397 were in homes with an energy efficiency intervention and another 1 155 deaths were in homes without intervention (control group). The study focused on the associations between cold outdoor temperature in winter and mortality, especially among elderly. The intervention included home energy efficiency façade retrofitting (EEFR) (insulation retrofits) [48]. The study concluded that retrofitting with energy efficient façade had reduced cold-related mortality in women, but increased cold-related total mortality in men. Among men aged 75 or more, the façade retrofitting increased cold-related deaths from respiratory system diseases. They explained that the negative impact linked to façade insulation may cause by more smokers among men than women. In contrast, among women, façade retrofitting reduced extreme cold-deaths from cancer, the circulatory system and the respiratory system, especially in women with no education and in those aged 75 or older. They explained that women with no education and aged 75 or older may have more fuel poverty behaviors.

3.3.8 Improved ventilation

In an exposure study from Austria, indoor air quality in homes with different types of ventilation was investigated. The study included 123 modern homes, of which 62 homes had mechanical ventilation with heat recovery systems (test group) and 61 had no mechanical ventilation system (control group) [49]. The measured indoor air quality in homes with mechanical ventilation was better than in homes without mechanical ventilation, including nearly all investigated components such as TVOC (median 1st measurement 300 vs 560 $\mu g/m^3$; 2nd measurement: 120 vs. 230 $\mu g/m^3$), aldehydes (median 1st measurement: 32 vs. 53 $\mu g/m^3$; 2nd measurement: 18 vs. 33 $\mu g/m^3$), CO_2 (median 1st measurement: 1 360 vs 1 830 ppm; 2nd measurement: 1 280 vs. 1740 ppm), radon (annual averages 17 vs. 31 Bq/m^3), and mold spores (10% vs. 20% higher indoor concentrations than outdoors).

In a field study from Austria, health and wellbeing impacts of home ventilation methods were studied in energy efficient buildings. The study included 123 modern homes with 575 participants (409 adults and 166 children). Test group with mechanical ventilation included 299 participants. The control group without mechanical ventilation included 276 participants [51]. They reported that participants living in the homes with mechanical ventilation were more satisfied with their health, indoor air quality and environment. The only exception was that dry eye symptoms were more common in home with mechanical ventilation.

In a field study from Denmark, the impacts of three types of mechanical ventilation rates in an office (36 m^2, 108 m^3) on perceived indoor air quality, sick building syndrome (SBS) symptoms and work productivity were studied. The study included 30 health females, exposed to an outdoor airflow rate of 3, 10 or 30 L/s per person respectively, corresponding to an air change rate of 0.6, 2 or 6 h^{-1} in this office space. [50]. The authors concluded that increasing mechanical ventilation rate in a normal office, where subjects can maintain thermally neutral, could increase perceived indoor air quality and productivity, and reduce the intensity of SBS symptoms. Moreover, they reported that ventilation rates well above the minimum threshold value prescribed in existing standards and guidelines had benefits for human health, comfort and productivity. Furthermore, the overall work productivity could increase with 1.7% for every 2-fold increase of the ventilation rate.

In a field study from United States, the effects of home ventilation rates on respiratory health were investigated. They study included 302 participants (≥8 years old) living in 216 non-smoking, low-income single-family or urban homes. Each home had a multi-point depressurization blower test on an exterior door to estimate the annual average air exchange rate. The annual average air exchange rate was 0.49 ACH in all homes and was defined into four levels, of which low level was 0.1-0.42

ACH, moderate 0.43-0.52 ACH, high 0.53-0.77 ACH, and very high 0.79-2.17 ACH [52]. The study found that high home ventilation rates can increase chronic cough, asthma and asthma-like symptoms, probably caused by infiltration of outdoor air pollutants.

3.3.9 Reduced ventilation

In a field study from Sweden, health effects of home energy saving by reducing 20% ventilation flow during the heating season were investigated. The study had a cross-over design. The study included 44 adults living in a multi-family building with the same type of exhaust ventilation system. During the first heating season, group A with 18 adults got a reduced ventilation flow (0.4-0.5 ACH), while group B with 26 adults got constant ventilation flow (0.5-0.8 ACH). During the second heating season, group A had constant ventilation flow, while group B had reduced ventilation flow [53]. They found that that energy use for running the electric fans in the ventilation system was reduced by 17% and energy loss in the ventilation system was reduced by 13% after a 20% reduction of the mechanical ventilation flow during the heating season. The study found that the energy saving by reduced ventilation flow had no effects on SBS symptoms but increased the perception of impaired air quality. The authors concluded that reducing the ventilation flow to a level just below the existing Swedish ventilation standard (0.5 ACH) could reduce perceived air quality.

4 Discussions

4.1 Methodological aspects of the review

Methodologic aspects of a literature review article are important issues. This literature review has a number of strengths. Since this review focused on health aspects of energy use and energy saving in buildings, peer reviewed articles from three major medical databases (PubMed, Web of Science and Nature database) were extracted. This means that most of the health-relevant peer reviewed articles I found should have been linked to the topic. Moreover, for each field study included in the review, the sample size of the study, the country of the study, number of buildings and number of participants were noted in the review. Information on types of energy efficiency intervention methods were extracted and the study design of the investigation was noted, if there was any control group with no intervention or just a before-after study in the same buildings. In addition, the types of the intervention and information on types of energy use and energy saving for each study were tracked. In field studies with exposure measurements, information on indoor concentrations and changes of concentrations of major pollutants were collected. In studies with unexpected results or negative impacts of energy use and energy saving, explanations of the results reported by the authors were included. Weak points of the studies were noted as well. One major weak point of many of the intervention studies is that there was no information in the article on how much energy that had been saved (lack of measurements of energy use in the buildings). However, the energy interventions were mostly well described and energy efficiency ratings by government's credits system, energy experts, or residents in the buildings were included.

Nine previous literature reviews on energy saving and green buildings were found. Most previous review articles only presented previous studies briefly in a summary table. In this literature review, details on methodology and main results have been shown for each study in the result section one by one rather than a summary table. By this approach, readers could get a better insight of specific energy saving methods or energy use and how the influenced indoor exposure and different aspects of health.

Nine articles were modelling studies. They modelled the changes of indoor exposure after the intervention, followed by an estimation of health effects due to the calculated changes of the indoor exposure. Data used in the modelling included indoor environmental or household energy data, including indoor pollutants concentrations, temperature, energy efficiency, or energy saving data from previous studies. Indoor environmental or energy data in the modelling studies were from government database, hospital database, or energy modelling software. The methods for health estimations in the modelling studies included exposure-response estimation, life table estimation, and risk calculation. I had no practical possibility to judge if the assumptions used in the modelling were reasonable, since there were no raw data available and moreover I have no experience to perform this type of modelling. This is a potential problem when evaluating modelling studies in this field.

4.2 Types of energy saving measures used in the published articles

This literature review found that energy saving by improving fabric insulation; increasing air tightness; reducing the ventilation flow; installation of a central heating system; fuel switching; installation of mechanical ventilation with a heat recovery system were the more common energy saving methods. Energy saving by lowering the indoor temperature, installation of thermostats, installation of photovoltaic, solar hot water, passive solar design, installation of heat pumps, and accessing to gas network were less common. No study on the health impacts of a mechanical cooling system was found. This could be because most of published studies were from European countries.

4.3 Indoor environment improvements by energy saving or in green buildings

Some studies reported improved indoor quality after energy efficiency improvements, especially for air pollutants from outdoor sources. Firstly, combined energy efficiency improvements may reduce the exposure of $PM_{2.5}$ [3, 16, 18, 21, 22], CO_2 [3, 17, 49], NO_x and SO_2 [3, 16], major mite allergen Der f 1 [26], fungal and bacterial [32], black carbon [27], total volatile organic compounds (TVOC), aldehydes [49] and secondhand tobacco smoke [21], and increase indoor winter temperatures [20, 21]. Secondly, combined energy efficiency renovation may reduce radon and mold concentrations [21, 49]. Thirdly, mechanical ventilation may reduce formaldehyde concentration [32].

4.4 Indoor environment impairment by energy saving or in green buildings

Some studies reported impaired indoor quality after energy efficiency improvements. Firstly, combined energy efficiency renovation may increase radon concentration [24, 32], formaldehyde concentration [27], and the indoor concentrations of benzene, toluene, ethyl benzene and xylenes [32]. Secondly, reduced ventilation may increase radon concentration [23] and major house dust mite allergen Der f 1 concentration in dust [25]. Improved ventilation with low infiltration from outdoor pollutants may increase radon concentration [22]. Thirdly, fuel poverty may increase indoor mold concentration [8].

4.5 Studies reporting beneficial health effects of energy saving measures

A total of 53 relevant peer-reviewed articles were included in this literature review. The studies were on the health impacts of energy use and energy saving, including direct and indirect impacts. Most of the studies found that energy efficiency improvements had positive impacts on health. This is in agreement with a previous review article [11].

In this paragraph, beneficial health effects reported by at least two studies are summarized. Firstly, combined energy efficiency improvements can be associated with improvement of general health [5, 21, 34-36], and related to less common health problems such as asthma [3, 29, 34, 35], respiratory symptoms [2, 6, 13, 29, 31, 33, 35, 44, 46], mortality [1, 2, 13, 21]. Moreover, combined energy efficiency improvements can improve indoor air quality [6, 21], productivity [2, 4, 5] and satisfaction [5, 11, 33, 34] and reduce work leave and school absence [2-4, 33, 44], as well as mental health and physical health [2, 37]. Furthermore, effective heating were associated with improved health [12, 47], reduced respiratory symptoms [17, 46] and less work leave and school absence [46, 47]. Besides, improved ventilation may reduce SBS and improve productivity [14, 50], and increase indoor air quality [14, 21, 49, 50].

Furthermore, some minor positive health effects of energy saving were found (only reported in one study). Thermal insulation improvement may reduce SBS-type symptoms [41], respiratory and cardiovascular symptoms [11], cold housing [43] and decrease mortality and asthma [16]. Furthermore, lower mean night air temperature (an energy saving measure used in some countries) and lower air temperature in early morning may decrease tear film stability [45].

4.6 Studies reporting negative health effects of energy saving measures

Energy saving by increasing air tightness or reducing ventilation flow can be associated with impaired indoor air quality [10, 15, 18, 53]. Moreover, energy saving by increasing air tightness and reducing ventilation flow can have negative health effects [11, 13, 23, 28, 41, 42]. The solution to this problem is to combine energy saving measures causing increased air tightness with installation of a mechanical ventilation system [15, 21, 26, 32, 49-51]. Installation of mechanical ventilation may solve the negative effects of increased air tight in dwelling, but there is a potential negative health effect of increasing the ventilation flow if there are significant levels of outdoor air pollution [18, 52].

4.7 Implications of the studies

There are important implications from the existing studies. According to the results reported above, energy efficiency improvements combined with installation of a mechanical ventilation system should be promoted. This approach could reduce levels of indoor air pollutants and potential health risk of air tight dwellings. Moreover, since most intervention studies had used a combination of energy saving measures, it is important to further evaluate the efficiency of different types of interventions to increase the energy efficiency in different types of building and in different climate zones.

5 Conclusions

Increased energy efficiency and use of green building technology in buildings can influence exposure to air pollution in indoor environments and can influence health. Most studies found that energy efficiency improvements are associated with improvements of general health, and can reduce asthma, respiratory symptoms, and total mortality. Moreover, energy efficiency improvements can improve indoor air quality, productivity and satisfaction and reduce work leave and school absence, as well as mental health and physical health. Since most of the interventions in the studies have used a combination of technical improvements, it is difficult to separate the effects of different technical solutions to increase energy efficiency in buildings. Another limitation in existing studies is that most of them are performed in residential buildings. Some health risks linked to energy efficiency renovations exists. More effective heating can improve health, reduced respiratory symptoms and less work leave and school absence. However, energy saving by increasing air tightness or reducing ventilation in buildings was found to be associated with impaired indoor air quality and more negative health effects. In contrast, improved ventilation may reduce SBS and improve productivity, and increase indoor air quality. One special concern has been about the increase of indoor radon, which can cause lung cancer, in buildings with increased air tightness. Installation of mechanical ventilation can solve many of the negative affect linked to airtight dwellings. However, increased ventilation flow can increase the indoor exposure to outdoor air pollutant in areas with high levels of outdoor air pollution. In future studies, more focus should be on evaluating health impacts of single energy efficiency improvement methods. Furthermore, more measurements of actual energy use before and after the interventions are needed to evaluate how much the energy efficiency has been increased. In addition, modelling software programs should more often be used, since they can take into account effects of different energy efficiency improvement methods on indoor air quality in different types of buildings and in different climates.

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