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Residential Energy Efficiency Retrofits: Potential Unintended Consequences

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Abstract: Improving the energy efficiency of the residential building stock has increasingly been promoted by policy makers as a means of reducing energy demand in the residential sector. We review the literature on some non-energy impacts of energy efficiency retrofitting measures aimed at increasing the air tightness and thermal insulation of residential properties. Specifically, we review the impact of retrofitting measures on indoor pollutants, mould growth, attenuation of radio signal and overheating. We show that without the provision of adequate ventilation, increased air tightness can result in higher levels of indoor pollutants and mould growth. Similarly, we show that in certain circumstances thermal insulation has the potential to result in increased signal attenuation and overheating. We detail the policy implications of these findings and outline policy actions that have been implemented in case study countries where these consequences are an issue.

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1. Introduction

As policy makers become more aware of issues relating to climate change, a stated aim of the European Commission is to reduce total energy consumption and carbon emissions across the European Union. The 2012 Energy Efficiency Directive (European Commission, 2012) and the 2006 Energy End-Use Efficiency and Energy Services Directive (European Commission, 2006) established a set of binding measures to help the EU target a 20% reduction in energy use by 2020. Under these directives, each Member State is required to outline a National Energy Efficiency Action Plan to reduce emissions across all sectors. For many Member States this has involved improving the energy efficiency of the residential building stock in order to reduce demand for energy.

Energy efficiency retrofitting provides many intended benefits. Firstly, energy efficiency retrofitting can reduce household energy demand, which not only has positive environmental impacts but also reduces energy costs for households. Secondly, increasing the level of comfort and warmth experienced in a home has many health benefits for the occupiers. Furthermore, it may also increase the value of the home for prospective buyers or rental tenants. Many unintended benefits can also arise from energy efficiency retrofitting. For example, increased insulation can reduce noise pollution for occupants, and similarly the provision of employment to contractors can be economically beneficial.

In addition to these benefits, retrofitting can also result in some unintended consequences that policy makers may not have previously considered. This paper examines some of these consequences which may be of concern to policy-makers and home owners alike. Drawing upon Shrubsole et al. (2014), we similarly define unintended consequences as outcomes which arise unintentionally as a result of implementation of energy efficiency retrofitting measures. Shrubsole et al. (2014) also distinguish between two types of unintended consequences; those which confer an unexpected negative or beneficial effect in addition to the desired effect of the policy, and those which undermine the original intent of the policy. This paper predominantly focuses on the former. As such, we see that while the retrofitting measures outlined in this paper fulfil their original objective of increasing the energy efficiency of the dwelling, there are additional unintended outcomes which must also be considered.

This paper investigates unintended consequences arising from retrofitting measures which increase the air tightness and level of insulation in homes. In particular we examine how increased air tightness of a home might result in higher levels of indoor pollutants and changed rates of mould growth, while increased thermal insulation might in certain circumstances result in increased signal attenuation and overheating. We find that while the welfare effects of some of these unintended consequences are relatively ambiguous (e.g, mould growth rates), there could be potential negative welfare effects with regards to increased levels of indoor pollutants, attenuation of radio signals and overheating. We highlight the importance of considering both the health and economic impacts of these unintended consequences when designing efficient public policy with regard to retrofitting measures. We then provide a case study where each consequence has been engaged with from a policy perspective. Investigating these consequences provides an opportunity to identify international practices, anticipate future issues and consider efficient and proactive policies.

The paper is structured as follows. Sections 2 and 3 consider the unintended consequences arising from measures which increase the air tightness of a dwelling, while Sections 4 and 5 consider the unintended consequences arising from measures which increase the thermal insulation of a dwelling. Each section considers the policy implications of these unintended consequences and provides a case study of how policy makers have dealt with these issues in countries where they are of particular relevance. Section 6 then concludes.

2. Indoor Pollutants

The vast majority of human time is spent in an indoor environment. Figures from the US suggest that over 87% of time is spent within a closed environment (Klepeis et al., 2001), while in the UK it is estimated that over 95% of time is spent indoors with 66% of time spent in the home (Schweizer et al., 2007). Given the length of time spent in indoor environments, it is therefore important to identify retrofit measures which have the potential to impact indoor air quality, and thus alter exposure to indoor pollutants. Retrofit measures which potentially impact indoor air quality are those which increase the air tightness of a building. Increased air tightness improves the energy efficiency of a building by reducing thermal loss, and is implemented through such retrofitting measures as wall insulation, double glazing and draught-proofing.

Increasing the air tightness of a building can, however, also lead to the accumulation of indoor pollutants. Examples of these indoor pollutants include volatile organic compounds, carbon dioxide, carbon monoxide, particulate matter and radon. The accumulation of these indoor pollutants can be overcome through the installation of adequate ventilation such as trickle vents, extraction fans and mechanical ventilation with heat recovery. Extraction fans can be relatively effective for the removal of carbon dioxide and particulate matter, particularly those emitted during cooking, and trickle vents and open flues prove effective for the removal of carbon monoxide, which can spread from faulty oil or gas boilers. However, the use of intermittent ventilation is less effective for indoor pollutants such as radon, which have a continuous source. Below we consider in depth the effect of increased indoor radon levels as an unintended consequence of retrofitting.

2.1. Indoor Radon Sources

Radon is a naturally occurring inert gas formed by the radioactive decay of uranium in the earth's crust. As a gas, radon moves freely through the soil where it is then diluted to harmless concentrations in the atmosphere. However, radon becomes problematic when it accumulates to high levels of concentration in indoor environments. Radon primarily enters a building by seeping through the ground floor. In particular, its transportation is facilitated by structural defects such as cracks in solid floors and walls below construction level, gaps in suspended concrete and timber floors and around service pipes, through crawl spaces, cavities in walls, construction joints and small cracks or pores in hollow-block walls (Appleton, 2007). Other sources of indoor radon also include building materials and the radon concentrations of groundwater used for domestic drinking water.

2.2. Impact of Retrofitting on Radon Levels

Indoor radon concentration levels are also affected by the air exchange of a building. As such, buildings which are better ventilated have lower levels of indoor radon concentration. This means that retrofitting measures which increase the air tightness of a building have the potential to increase the level of indoor radon concentration. Observations that this could be a negative consequence of retrofitting first gained prominence in the literature during the early 1980s. Fleischer et al. (1982) completed a survey on conventional and energy efficient homes in northeastern New York State and found that air tight homes had up to three times the levels of radon as conventional homes. Similarly Burkart (1986) found that energy efficient homes in the Swiss Alps had lower air exchange rates due to weather-stripping and caulking of windows, doors and blinds, which increased levels of indoor radon by a factor of 1.5. Elevated indoor radon levels in energy efficient homes have since been found in a variety of other international contexts (Gunby et al., 1993; Yarmoshenko et al., 2014; Pressyanov et al., 2015).

2.3. Health Effects

Classified as a Group 1 carcinogen (IARC, 1988), radon exposure is the second most prominent cause of lung cancer in most countries, after smoking (WHO, 2009). The WHO recommends a national reference level of 100 Bq/m^3, although suggests that if this cannot be reached due to country specific conditions that the reference level should not exceed 300 Bq/m^3 (WHO, 2009). A national reference level is the maximum accepted radon concentration level in a residential building, above which remedial action is strongly recommended. Using a pooled analysis from 13 European case-control studies, Darby et al. (2005) estimated the dose-response relation to be linear, with the risk of lung cancer increasing by 16% for every 100 becquerels per cubic metre (Bq/m^3) increase in radon. In addition, they found no evidence of a threshold value, with the dose-response relation holding for individuals in homes which measured indoor radon values less than 200 Bq/m^3 (the national reference level advocated by many countries). Radon interacts synergistically with cigarette smoke which means that the risk of developing radon-induced lung cancer is far greater for cigarette smokers than non-smokers, for any given level of radon concentration. At a radon concentration of 200 Bq/m^3 this translates to risk of 1 in 30 for active smokers and 1 in 700 for lifelong non-smokers (RPII and NCRI, 2005).

Given that retrofitting can result in increased indoor radon levels it is important to quantify the effect that this might have on public health. Milner et al. (2014) modelled indoor radon levels in England using data from the English Housing Survey 2009 (which covers 22.3 million dwellings) and estimated that present day levels of radon and the associated risk in lung cancer mortality, accounted for 1000 deaths per year in England (slightly lower than other published estimates). They then modelled the associated increase in radon-induced lung cancer, according to four possible retrofitting scenarios. The first scenario increased air tightness in line with current regulations, the second scenario included purpose provided ventilation (trickle vents and extraction fans), the third included mechanical ventilation with heat recovery, and finally, the fourth scenario assumed that 10% of the mechanical ventilation with heat recovery failed. The first scenario estimated a 56.6% increase in indoor radon levels from the present day mean of 21.2 Bq/m^3 to 33.2 Bq/m^3, resulting in an additional 278 deaths per year in England. The second scenario reduced these increased radon levels to 25.5 Bq/m^3 but did not restore them to present day levels of 21.2 Bq/m^3, leading to 100 additional deaths per year. Scenario three mitigated the increased radon, reducing the mean to 19.6 Bq/m^3, while scenario four resulting in only a slight increase in the mean radon level to 21.8 Bq/m^3. These findings highlight the need to consider adequate ventilation measures in order to avoid an increase in radon-induced lung cancer deaths.

2.4. Policy Implications

It is important going forward that there is an increased awareness of the impact that retrofitting measures can have on indoor radon levels, specifically those which increase the air tightness of a building. Given the findings discussed in Section 2.3, Milner et al. (2014) argue that safer retrofitting strategies should be emphasised, such as those which decrease the conductivity of building materials (i.e. through insulation) or through de-carbonisation of the energy supply, rather than those which solely rely on increasing the air tightness of a dwelling. Other alternatives to consider include promoting policies which decrease the prevalence of smoking, as this is the population group most likely to be affected by increased indoor radon levels.

Indoor radon levels should be tested after retrofitting has taken place, to ensure that post-retrofit indoor radon levels remain below the national reference level. In cases where post-retrofitting levels of indoor radon exceed the national reference level, steps to mitigate radon levels should be taken. This will primarily involve the installation of a radon sump, which lowers sub-floor air pressure relative to indoor air pressure. If radon levels are found to be high, the sump can be activated by installing an extraction fan via an external vent pipe to actively purge the radon before it can infiltrate the property.

2.5. Case Study: Ireland

Ireland has the eighth highest indoor radon concentration (WHO, 2009) within the OECD countries, with radon exposure currently estimated to cause up to 250 cases of lung cancer in Ireland every year (EPA, 2016). Currently, Ireland's national reference level is 200 Bq/m^3. Although the average indoor radon level in Ireland is estimated to be 89 Bq/m^3, well below the national reference level of 200 Bq/m^3, levels of up to 550 times this value have also been measured.

Given that Ireland has relatively high levels of indoor radon it is important to ensure that retrofitting measures which increase the air tightness of a building, do not also increase indoor radon levels above the national reference level. However, to date very few studies have examined the impact of retrofitting on indoor radon levels in Irish homes. An internal report from the Environmental Protection Agency (Long and Smyth, 2015) has given preliminary findings that when a number of retro-fitting measures are installed, including measures which potentially decrease the ventilation of a dwelling (such as replacing or draft-proofing windows and doors), radon levels may potentially increase by up to 50%. However, due to data limitations, these findings are based on the relatively small sample size of 32 homes. Although the wide range of pre-retrofit indoor radon values (measurements ranged from 9-123 Bq/m^3) make it difficult to compare pre- and post-retrofit levels in a meaningful way, post-retrofit indoor radon levels remained below the national reference level in all cases. It is also important to note that retrofitting measures which did not decrease the air tightness of homes (e.g. attic and cavity wall insulation) and which were installed alongside additional background ventilation, were found to have no impact on average indoor radon levels. Future studies might therefore provide greater clarity within an Irish context.

Ireland defines High Radon Areas as areas in which a predicted 10 per cent or more of homes exceed the national reference level. Technical Guidance Document C of the 1997 Building Regulations requires all new build homes to be fitted with a standby radon sump which can be activated if radon concentrations become too high. In addition, homes built in High Radon Areas are required to install a radon barrier. High levels of indoor radon following energy efficiency retrofitting measures can therefore be remediated in homes built after the introduction of the 1997 Building Regulations, through activation of the radon sump. However, for homes built before the introduction of the 1997 Building Regulations, options for dealing with increased indoor radon levels are relatively limited. In order to reduce indoor radon levels, additional radon remediation techniques may therefore have to be considered. This could involve sealing floors and walls, increasing indoor and under-floor ventilation, positive pressurisation and/or the installation of radon sumps (RPII, 2004).

The installation of radon sumps are generally considered the most effective method of radon remediation, with the Environmental Protection Agency (EPA) estimating the average cost of a radon sump to be €850[1]. At present, there are no grants available to assist with the cost of radon remediation, although home owners can qualify for tax credits of 13.5% of the cost of works under the Home Renovation Incentive Scheme. This means that the true cost of engaging in energy efficiency retrofitting measures which increase indoor radon levels above the national reference level, could potentially be higher for home owners who live in homes built prior to 1997 (in particular those in High Radon Areas). It is important to therefore consider that this may have the potential to act as a possible disincentive for home owners considering engaging in energy efficiency retrofitting. However, one must also acknowledge that the need for additional radon remediation works will only arise if adequate ventilation has not been implemented throughout the retrofitting process and post-retrofit indoor radon levels exceed the national reference level.

3. Mould Growth

As outlined by Dales et al. (2008), mould growth primarily arises due to leaks in building fabric, unattended plumbing leaks, household mould (for example from kitchen sources) and condensation. Retrofitting measures which alter the condensation levels of a building therefore have the potential to change the rate of mould growth. Condensation levels are primarily affected by retrofitting measures which alter indoor humidity and surface temperatures. Below we first consider retrofitting measures which potentially increase the rate of mould growth before then considering those which potentially decrease the rate of mould growth.

3.1. Impact of retrofitting on Mould Growth

3.1.1. Increased Mould

Higher levels of condensation can be caused by two different types of retrofitting measures; those which increase the air tightness of the building and those which directly impact the temperature differential between internal and external surfaces. While mould growth is largely dependent on the behaviour of occupants, the likelihood of mould formation is increased by retrofitting measures which increase the air tightness of a building. These retrofitting measures will result in higher levels of humidity if adequate ventilation mechanisms are not put in place to remove the moisture content of the air. These higher humidity levels might in turn lead to increased condensation and faster rates of mould growth (Willand et al., 2015).

Retrofitting measures such as increased insulation which change the temperature differential between different surfaces can also increase the likelihood of condensation occurring. This particularly occurs when warm, humid internal air comes into contact with a cold surface. Below we consider two types of condensation which can arise from internal insulation; interstitial insulation and thermal bridging condensation. Interstitial condensation occurs *within* external walls, floors and roofs when warm, moist air passes through from the inside of the building and condenses at colder parts within it. Two structures of the building are particularly vulnerable to this type of condensation. These are internally insulated walls with a damaged or deficient vapour barrier, and attics. This is due

[1]For more information please see `http://www.epa.ie/radon/getinformed/faq/`

to the fact that attic insulation creates colder attic spaces which have higher levels of humidity and thus a higher probability of mould growth, if not properly ventilated (Hagentoft, 2011). In addition, any gaps in the floor of the attic which allow warm moist air to pass through from the house below, will allow faster rates of condensation due to the cooler temperature of the attic space. Lastly, condensation can also arise due to incorrectly installed internal insulation which allows thermal bridging (i.e. a break in the thermal barrier) to occur (Totten et al., 2008).

3.1.2. Decreased Mould

As noted by Willand et al. (2015), conflicting evidence exists regarding the impact of retrofitting on mould growth. As described above, the primary channel through which retrofitting measures alter the rate of mould growth is through changed levels of condensation. Yet thermal insulation can also reduce condensation levels through the following two mechanisms. Firstly, increased thermal insulation of a dwelling raises indoor temperatures which lowers average relative humidity levels and and thus the potential for condensation and mould growth (Willand et al., 2015). Secondly, thermal insulation such as double-glazed windows can reduce the likelihood of surface condensation occurring due to minimisation of the temperature differential (Heseltine and Rosen, 2009).

A large body of literature exists outlining the reduction of mould growth in homes following the introduction of retrofitting measures. For example, upon examining social housing in the UK, Sharpe et al. (2015) found that a one unit increase in the energy efficiency of a building, as measured using the UK Government's Standard Assessment Procedure, led to a 4-5% reduction in the risk of visible mould growth and a mouldy/musty odour. Likewise, a randomised study on low income communities in New Zealand found that houses where retrofitting insulation measures had been installed reported having significantly less mould than those which had not (Howden-Chapman et al., 2007). The Sustainable Energy Authority of Ireland has also found that households availing of the Warmer Homes Scheme reported that the prevalence of damp, mould growth or condensation fell from 68% to 22% (SEAI and CPA, 2009).

3.2. Health Effects

Identifying the extent to which retrofitting measures impact potential mould growth has important implications for the health of individuals. The link between respiratory health conditions and mould has been observed extensively in the epidemiological literature. In particular, mould has been associated with asthma development, asthma exacerbation, dyspnea, wheeze, cough, respiratory infections, bronchitis, allergic rhinitis, eczema, and upper respiratory tract symptoms, with children being particularly susceptible to developing these conditions (Mendell et al., 2011). The impact of housing conditions on the rate of mould growth, and how this in turn affects respiratory health outcomes has also been extensively explored (Platt et al., 1989; Peat et al., 1998; Crook and Burton, 2010; Sharpe et al., 2015). Given the substantial health effects associated with mould growth it is therefore important to identify which retrofitting measures have the potential to alter the rate of mould growth and, in particular, whether they result in increased or decreased levels of mould.

3.3. Policy Implications

As discussed in section 3.1.1 increased mould growth following retrofitting measures is attributable to either a lack of adequate ventilation or incorrectly installed insulation which allows condensation to occur. This highlights the importance of installing appropriate ventilation systems and ensuring good attention to detail when installing internal insulation.

3.4. Case Study: Sweden

Mould growth has been shown to be an issue in Swedish dwellings, with various studies in the country examining the extent of mould growth and/or the effects of mould growth on health outcomes of occupants. For example Hagentoft (2011) investigates the determinants of mould growth, finding that up to 60-80% of single-family houses in a Swedish region had significant mould growth. Similarly, a study by Hägerhed-Engman et al. (2009) examining the effects mouldy odours have on the risk for allergic symptoms in children found a mouldy odour along the skirting board of 47% of homes and in at least one room in 39% of homes.

Efforts have been made to ensure adequate ventilation in buildings through appropriate building standards and ensuring compliance with these standards. Building standards in Sweden are set by the Swedish National Board of Housing, Building and Planning, known as BOVERKET. BOVERKET administer a system of mandatory inspections of buildings to ensure that the indoor climate is suitable and that ventilation systems are functioning. This is known as the Obligatory Ventilation Control and is performed on new builds and when new ventilation is installed for single and two-dwelling houses. Multi-dwelling buildings must be assessed every three or six years, depending on the type of ventilation used[2]. Any issues identified with the ventilation system are the responsibility of and must be rectified by the home owner.

While the implementation of such standards and testing are in place to protect the health of occupants, the current regulatory system in Sweden does not provide for testing following retrofits. For example, wall insulation could be installed in a manner that disrupts the ventilation system of a home, but if this occurs in a single- or two-dwelling building, Obligated Ventilation Control testing is not required. Similar to the installation of radon sumps discussed in section 2.5, while mandated testing of the ventilation system could ensure air quality and prevent mould growth, this may act as a disincentive to retrofitting as the cost of engaging in a retrofit would increase as a result.

4. Radio Signal Attenuation

Radio waves consist of electromagnetic radiation in the frequency range of 3kHz-300GHz. Radio waves are used by such devices as televisions, mobile phones, wireless networking and AM/FM radios. However, there is an emergent literature which suggests that certain retrofitting measures have the potential to impact on radio frequency signal propagation. The attenuation of radio signals is primarily affected by the use of metallic materials which reduce thermal loss from buildings. In particular, metallic materials have a greater impact on the higher radio signal frequencies used by mobile phone networks rather than the lower radio signal frequencies used by FM radio or television networks.

4.1. Impact of Retrofitting on Signal Attenuation

Walls and windows are the two features of a building most likely to use metallic materials to reduce thermal loss from a building. Walls are sometimes insulated with polyurethane plates covered in aluminium foil which drastically increase the attenuation of radio signals. Although walls play an important role in the attenuation of radio signal into a building, we do not consider them to be of particular concern with regard to the unintended consequences of retrofitting. This is due to two reasons. First, there exist a wide variety of alternative measures of insulating walls which do not involve the use of metallic materials. Second, due to their thickness, walls have never been the primary mode through which a radio signal penetrates into a building. Instead, radio signal enters the building through the lowest point of attenuation, which has traditionally been the windows of a building (Rodriguez et al., 2014). As such, we discuss the impact of energy efficient windows on signal attenuation in greater detail.

Energy efficient windows are given extra thermal insulation through the application of a thin layer of metallic oxide on one side of the glass (Kiani et al., 2007). While transparent at the visible end of the electromagnetic spectrum, the metallic coating reduces both infrared and ultraviolet radiation. This prevents heat escaping from the building during the winter, thus reducing thermal loss during cold weather and preventing heat entering during the summer, in turn reducing the cost of cooling the dwelling. However, this metallic coating may substantially increase the attenuation of radio signals. Asp et al. (2014) found that for the frequency bands used by most mobile commercial networks (900MHz, 2100MHz), the average attenuation loss in modern buildings was around 19-23dB, whereas the average attenuation for older buildings was around 6-9dB. This means that the use of modern construction materials leads to a substantial average increase of attenuation by 13-14dB (in other words the signal attenuates to one twentieth of its original strength). Rodriguez et al. (2014) show similar findings, with the increased attenuation almost exclusively due to the use of metal-shielded materials aimed at increasing the energy efficiency of the building. In order to overcome this attenuation problem, Kiani et al. (2011) have suggested designing a specific pattern to be etched into the coatings of the energy-saving glass which simulta-

[2]For more information please see `http://www.boverket.se/en/start-in-english/building-regulations/national-regulations/obligatory-ventilation-control/?tab=elaboration`

neously improves the transmission of useful signals while preserving the infrared attenuation as much as possible.

4.2. Policy Implications

If government policy advocates increased energy efficiency of buildings, while technological advancements result in increased reliance on wireless technology, the quality of service from communications networks may suffer in the future, potentially resulting in negative economic and social consequences. For example, as more and more households shift away from landlines to mobile telecommunication technology, it is crucial that the ability to make emergency calls from within energy efficient buildings is guaranteed. Considering these consequences can ensure that resources used to invest in communications technology are not negated by those used to incentivise retrofitting measures and that public policy is aligned and operating in an efficient manner.

4.3. Case Study: Finland

The problem of increased attenuation of radio signals in energy efficient buildings has already been recognised by policy-makers as a potential issue in Finland, which can be attributed to two main reasons. Firstly, due to its cold climate, the majority of energy efficiency retrofit measures in Finland focus on reducing thermal loss and, as such, the employment of metallic materials is high. Secondly, Finland has had a pioneering position in the development of mobile network communications, which means that there are lower numbers of households with a fixed landline compared to international norms.

This has led to the establishment of working group by the Finnish Ministry of Transport and Communications in order to further examine the issue[3]. Their recommendations include establishing official RF values for the most common building materials. RF values are numerical values which indicate the average attenuation characteristics of a material at frequencies currently used for mobile telecommunications. The working group recommends requiring new buildings and renovation projects to use materials which comply with these norms.

[3] `http://urn.fi/URN:ISBN:978-952-243-366-4`

5. Overheating

Overheating is another unintended consequence of energy efficiency retrofitting (Davies and Oreszczyn, 2012) which is likely to become an increasingly pertinent issue as climate change contributes to higher summer temperatures and as increased urbanisation leads to urban heat island effects (Shrubsole et al., 2014). Yet as identified by Dengel and Swainson (2012), a universally accepted definition of over-heating does not yet exist. Existing definitions include the Passivhaus standard which advocates a *threshold* temperature value of 25°C, with overheating occurring when this temperature is exceeded for more than 10% of total occupied hours, and the *adaptive approach* which instead suggests that the indoor temperature should be reflective of the external temperature at that time Sameni et al. (2015).

5.1. Impact of retrofitting on overheating

Energy efficient homes which have increased air tightness and insulation and which make use of passive solar gains through both solar orientation and the employment of large areas of glazing have already experienced incidences of overheating. Morgan et al. (2015) recorded temperatures in 26 newly built low-energy and Passivhomes in Scotland over a two-year period, with results showing that overheating was prevalent in both the main living areas and bedrooms. Likewise, Sameni et al. (2015) found that social housing flats built to the Passivhaus standard in Coventry (UK) were at a significant risk of summer overheating, with over two-thirds of the flats exceeding the Passivehaus temperature threshold.

Although these studies predominantly relate to new builds, the problems of over-heating can still occur with the introduction of retrofitting measures. While the solar orientation of the property is unlikely to be altered, retrofitting measures which increase the levels of insulation and air tightness in a building may lead to over-heating. In particular, both Mavrogianni et al. (2012) and M. Porritt et al. (2013) find that although external insulation decreases the likelihood of overheating occurring, internal insulation tends to increase this likelihood of overheating. As seen in Section 2 and Section 3, increased air tightness can also contribute to overheating if adequate ventilation measures are not put in place to remove excess heat that has built up inside the dwelling.

5.2. Health Effects

A wide variety of health effects exist with respect to indoor overheating, with the severity of these health effects substantially greater for vulnerable groups such as the elderly, young children, those who are obese, the chronically ill or those on medication. As identified by Dengel and Swainson (2012), the health effects of overheating can range from mild, for example dehydration, prickly heat, heat cramps, heat oedema, heat syncope, heat rash, and reduced productivity and mental concentration, to more severe effects such as heat exhaustion and heat stroke. In addition, high indoor night-time temperatures can lead to increased difficulty in falling asleep, interruptions to sleep and changes in sleeping patterns, all of which have knock-on negative mental and physical health effects.

5.3. Policy Implications

Internal overheating primarily occurs due to lack of adequate ventilation in a building. A lack of adequate ventilation can be an unintended consequence of retrofitting measures which aim to reduce thermal loss, by increasing the air tightness of a building. As we have seen previously, in order to overcome this problem, mechanical ventilation with heat recovery (MVHR) systems are often employed. This ensures that thermal loss is minimised while simultaneously keeps the rate of air exchange at an appropriate level. However as identified by Toledo et al. (2016), the predominant aim of MVHR systems is to provide fresh air rather than prevent summer overheating. This means that additional ventilation measures which allow for summer cooling (e.g. air conditioning units) must be considered, in particular in warmer climates. However, this in turn can have the unintended consequence of undermining the increased energy efficiency of the retrofitted building. If the goal of policy is to increase energy efficiency, then the use of increased mechanical ventilation is not an ideal response to the problem of overheating.

A wide range of actions can be taken to prevent indoor overheating occurring in retrofitted homes. These include changes to occupant behaviour (for example encouraging the use of shading on windows to reduce heat gain, and the opening of windows to ensure adequate ventilation) and the prioritisation of certain retrofitting measures (for example external wall insulation rather than internal wall insulation, which tends to exacerbate indoor overheating problems (Mavrogianni et al., 2012; M. Porritt et al., 2013)). While changes to occupant behaviour can be encouraged through education and awareness campaigns, care must be taken to prevent over-reliance on window-opening as a policy measure to overcome the problem of overheating. In areas with high levels of air pollution this could lead to increased exposure to outdoor pollutants with the associated negative impacts on respiratory health. Likewise, opening windows in areas with high levels of noise pollution will lead to negative health effects such as increased hypertension and sleep disturbance (Babisch et al., 2008). Lastly, leaving windows open during the day may not be a feasible option if occupants live in areas where there are security concerns.

5.4. Case Study: United Kingdom

The United Kingdom Department for Communities and Local Government (DfCLG) has identified overheating as an issue in residential buildings, estimating that 2,000 deaths are brought about due to overheating each year, a figure which could rise to 5,000 by the year 2080 due to climate change (DfCLG, 2012). Building standards provide a standard definition of overheating in the UK, defining overheating as occurring if living area temperatures exceed 28°C or bedroom temperatures exceed 26°C for 1% or more of occupied hours (CIBSE, 2012). After recognising the problem, a 2012 study of overheating identified building types and areas at risk of overheating and made a suite of recommendations for policy, including the use of solar reflective external building materials, external shutters and shading, passive stack ventilation and circulation fans (DfCLG, 2012). While these advised measures provide useful methods to mitigate overheating, they have not, at the time of writing, been mandated by policy in construction or renovation works.

6. Conclusion

This paper examines residential energy efficiency retrofitting as a policy action in helping to meet EU 2020 energy targets. In particular, we examine unintended consequences associated with energy efficiency retrofitting. These unintended consequences are often left out of public discourse regarding the costs and benefits associated with engaging in wide scale retrofitting. We find, however, that many of these unintended consequences have health and economic implications and thus require due consideration. Specifically, this research highlights how increased air tightness can lead to higher levels of indoor radon concentrations and, in some cases, increased mould growth. Secondly, we highlight how thermal insulation can lead to telecommunications signal attenuation and overheating.

Using case studies of countries where policy makers have reacted to these consequences, our findings lead to several policy implications. With regard to increased indoor radon concentrations we emphasise the importance of testing post-retrofitted homes to ensure that national reference levels are not exceeded. Radon remediation measures (e.g. the installation of radon sumps) are highlighted as mechanisms for dealing with increased levels of indoor radon in retrofitted homes. We consider how this additional cost of radon remediation could act as a potential disincentive for home owners considering engaging in retrofitting measures. Similarly we see that the attenuation of radio signal is an important issue for ensuring that future communication in homes is not hindered by thermal insulation and energy efficient windows. The design and implementation of standard characteristics of materials to avoid attenuation could help prevent this becoming an issue in retrofitted homes. Lastly, we emphasise the importance of considering the potential for overheating when designing standards for retrofitting.

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