**Title**

A tale of two cities: comparison of impacts on CO2 emissions, the indoor environment and health of home energy efficiency strategies in London and Milton Keynes

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**Abstract**

Dwellings are a substantial source of global CO2 emissions. The energy used in homes for heating, cooking and running electrical appliances is responsible for a quarter of current total UK emissions and is a key target of government policies for greenhouse gas abatement. Policymakers need to understand the potential impact that such decarbonization policies have on the indoor environment and health for a full assessment of costs and benefits. We investigated these impacts in two contrasting settings of the UK: London, a predominantly older city and Milton Keynes, a growing new town. We employed SCRIBE, a building physics-based health impact model of the UK housing stock linked to the English Housing Survey, to examine changes, 2010-2050, in end-use energy demand, CO2 emissions, winter indoor temperatures, airbornepollutantconcentrations and associated health impacts. For each location we modelled the existing (2010) housing stock and three future scenarios with different levels of energy efficiency interventions combined with either a business-as-usual, or accelerated decarbonization of the electricity grid approach. The potential for CO2 savings was appreciably greater in London than Milton Keynes except when substantial decarbonization of the electricity grid was assumed, largely because of the lower level of current energy efficiency in London and differences in the type and form of the housing stock. The average net impact on health per thousand population was greater in magnitude under all scenarios in London compared to Milton Keynes and more beneficial when it was assumed that purpose-provided ventilation (PPV) would be part of energy efficiency interventions, but more detrimental when interventions were assumed *not* to include PPV. These findings illustrate the importance of considering ventilation measures for health protection and the potential variation in the impact of home energy efficiency strategies, suggesting the need for tailored policy approaches in different locations, rather than adopting a universally rolled out strategy.

1. **Introduction**

Housing is responsible for one quarter of the UK’s total end-user CO2 emissions, half of which comes from space heating (Hamilton et al., 2009; DECC, 2011). Motivated by CO2 emissions reduction targets, fuel poverty, energy security and in response to the EU Energy Performance of Buildings Directive (EPBD), the UK Government is implementing policies designed to make major improvements to the energy performance of the housing stock (DECC, 2009; EU, 2011a). In order to meet the UK’s ambitious target of an 80% reduction in CO2 emissions from 1990 levels by 2050 (DECC, 2012a), a number of programs and policies are being employed that aim to increase dwelling air tightness and increase fabric performance through the provision of insulation, glazing upgrades and improvements in heating systems. The UK Government estimates that fabric efficiency measures including cavity, solid wall and loft insulation could result in energy savings of ~12 TWh by 2020 (DECC, 2014). As existing dwellings are predicted to represent 70-80% of the 2050 building stock (Palmer & Cooper, 2011), much of the energy efficiency gains must be obtained through retrofitting of the existing stock. This requires substantial investment, as nearly all of the UK’s 26.4 million dwellings will require an upgrade in energy performance to meet emission reduction targets (CCC, 2010; EU, 2011b). Interventions applied to reduce ventilation heat loss such as draught stripping and double glazing impact the airtightness of dwellings (Hong et al., 2004). Making dwellings more airtight without additional purpose provided ventilation (PPV) increases the risk of exposure to higher concentrations of indoor sources of pollutants such as PM2.5, mould, environmental tobacco smoke (ETS) and radon, whilst reducing ingress of externally sourced contaminants and increasing indoor winter temperatures (Bone et al., 2010; Milner et al., 2014). However, increasing PPV to improve indoor air quality(IAQ) may result in a reduction in energy efficiency gains through ventilation heat loss (Godish. & Spengler, 2004), which on average in the UK is estimated to account for 12% of a dwellings total energy use (Hamilton et al., 2009). The trade-off between these different policy objectives (energy conservation and ventilation for health) has been previously noted (Crump et al., 2011). With the UK population spending on average around 80% of their time indoors, and around 50% of their time in their homes (Kornartit et al., 2010), building are important modifiers of population health (Thompson et al., 2013). Recent UK based monitoring has shown that homes with higher energy performance levels are associated with a higher risk of diagnosed asthma (Sharpe & Shearer, 2014), suggesting that retrofits as currently implemented can have negative effects on household health. In addition, poorly designed interventions could lead to a range of unintended consequences across multiple domains (Shrubsole et al., 2014). Yet, if measures are properly designed, applied and operated, it is probable that they could have major net benefits for public health (Wilkinson et al., 2009).

National targets for CO2 emissions reduction in the UK, one of the main drivers of changes in energy performance in dwellings (Rosenow, 2012), are set out in the Climate Change Act of 2008 (HM Government, 2008). Individual sectors such as housing, have contributory targets (CCC, 2012). Total emission reductions from the housing stock will occur through energy efficiency interventions and by decarbonizing the dwelling energy supply. The carbon intensity (CI) of the supply grid will influence future CO2 emissions depending on the mix of sources, e.g. coal or gas fired power stations, renewables and nuclear. Scenarios have been described for decarbonizing the grid, in line with emissions reductions targets (CCC 2010). These changes to power generation, in conjunction with policies aimed at transport and industry are also expected to reduce airborne pollution, improving future air quality (Williams, 2007). The coupling of fuel source and power grid decarbonization scenarios with energy efficiency retrofits to the housing stock and the impact on IAQ and health is a relatively new area of research, although they are increasingly recognized as factors in achieving UK wide CO2 reduction targets by Government (DECC, 2013).

In this paper we describe a modelling study to assess changes in energy use, CO2 emissions, winter indoor temperatures, indoor airborne pollutant concentrations and associated impact on health of selected combined home energy efficiency and electricity grid decarbonization scenarios. We apply these scenarios to London and Milton Keynes. London, a major city with an estimated 2010 population of 7.83 million, responsible for 8.4% (44.71Mt) (GLA, 2010) of UK CO2 emissions, and characterized by both new and old buildings and higher density forms; Milton Keynes, 72 km north-west of London, created under the UK’s 2nd New Towns Act 1965, with an estimated 2010 population of 241,500, and responsible for 0.3% (1.76 Mt) of UK CO2 emissions (MKiO, 2014), with predominantly newer and low-density forms. Population figures for 2010 are used to coincide with scenario start dates and inform health calculations.

1. **Methods**

*2.1. Modelled Scenarios: Decarbonization of the Housing Stock and Electrical Grid*

We modelled the current stock (2010) and the impact of three future housing/electricity grid decarbonization scenarios applied to the housing stock in London and Milton Keynes (Table 1).

**Table 1**

Starting from the 2010 stock in both locations, interventions were applied that brought the 2050 stocks to parity in order to quantify the possible health impacts, energy use and CO2 savings. The future contrasting scenarios are:

(i) ‘Energy Efficient (EE)’: This assumes a business-as-usual trajectory with regard to the carbon intensity of the electricity grid to 2050 with a range of housing interventions applied to all properties not currently having them. For housing interventions, data on the existing measures in the current stock (2010) were derived from a variety of empirical sources (EHS, 2012; CSE, 2012; HECA, 2013; HEED, 2014; MKiO, 2014).

(ii) ‘Energy Efficiency Plus (EE+)’: This assumes business-as-usual carbon intensity of the grid, but with additional housing interventions focused on heating and seeks to investigate the impact of a greater focus on technical adaptation of dwellings. These are applied to all properties currently without them and therefore represent the upper bound case.

(iii) ‘Low Carbon Supply (LCS)’: This assumes an aggressive supply decarbonization scenario with housing interventions as in (i) and that space heating in houses will be 100% electrified by 2050.

All scenarios and their individual components start from a base line of 2010 and were specified to coincide with the CO2 reduction target date of 2050.

The grid decarbonization scenario used in (i) and (ii) are equivalent to the ‘resilient’ scenario, whilst (iii) is equivalent to the ‘Low-carbon’ scenario both seen in the UKERC Research Report (UKERC, 2013).

The baseline (2010) figure for carbon intensity (CI) comes from data for centralized electricity generation from the Digest of UK Energy Statistics, DUKES (2011). The emission reductions of the energy supply grid and power sector fuel mix and grid emission figures for carbon intensity (CI) were derived from the UK Energy Research Centre (UKERC) scenarios within the UK Committee on Climate Change 4th Carbon Budget report. (CCC, 2010; UKERC, 2013). These were chosen as they allow for structural uncertainties in future energy supply and represent the upper and lower boundaries of possible grid decarbonization. The year by year CI figures represent national targets with local trends assumed to evolve similarly over time. UKERC scenarios reduce grid emissions through specific investment choices, such that remaining sector reductions (including housing) are to be achieved through technology, efficiency and conservation (UKERC, 2013).

We assumed that installed measures are replaced once their life expectancy is over (e.g. boilers are replaced after 15 years). Due to uncertainties, we made no allowance for possible future improvements in efficiency or new technology.

Although the UK building regulations require that air quality is made no worse following retrofitting, there is no specific guidance regarding ventilation for energy efficiency retrofits. All future scenarios were run specifying the inclusion of purpose-provided ventilation (PPV) (extract fans and trickle vents) to maintain adequate air exchange following airtightening in accordance with current Building Regulation requirements for new builds (HM Government, 2010). Given the potential importance that ventilation has on air quality in the home (Bone et al., 2010), additional simulations without PPV were run so as to examine the importance of ventilation characteristics for impacts on CO2 emissions and health.

*2.2 Modelling the Scenario Impacts: the SCRIBE Model*

Modelling of scenario impacts was carried out using a UK housing stock computer model known as SCRIBE (Strategies for Carbon Reduction In the Built Environment), developed by University College London (UCL) and the London School of Hygiene and Tropical Medicine (LSHTM) (Hamilton et al, 2015). SCRIBE incorporates (i) a building physics module that enables estimation of energy use, indoor environmental conditions (winter temperatures and annual pollutant concentrations) and mean CO2 emissions under a range of housing interventions and projected changes in grid carbon intensities, and (ii) a model of health impacts associated with indoor environmental conditions. Modelled mean CO2 emission reductions are compared to emission levels required to meet targets set in the Climate Change Act 2008, from a base line of 2010, rather than 1990 (HM Government, 2008). The baseline of 2010 is used due to limitations in data availability for some SCRIBE inputs, particularly building/intervention data for Milton Keynes prior to this date. Consequently, CO2 emission reductions targets are adjusted as follows: for 2020-43%, for 2030-57% and for 2050-75%, all relative to 2010 instead of 1990. This adjustment has no impact on the 2050 results. Details of the SCRIBE model and the inputs used in the various components are outlined in Figure1.

**Figure 1**

*2.3. Modelling Indoor Air Quality*

Within the SCRIBE tool outputs are produced using CONTAM, a validated airflow and pollutant transport building physics tool (Emmerich, 2001). Geometries representative of the London and Milton Keynes housing stocks were constructed to assess changes to the indoor environment (air quality, winter temperature and energy use) associated with interventions of dwellings in the 2010 English Housing Survey (EHS, 2012). Ten dwelling geometries are used based on Oikonomou et al. (2012) and Wilkinson et al. (2009), supplemented with typical floor plans and facades available from the literature. The resultant built forms are matched to each EHS entry using criteria of dwelling type and size.Outline plans and model screen shots for all archetypes are shown in the online supplementary file accompanying this study.

For baseline (2010) indoor pollutant concentrations, each geometry in CONTAM is remodelled with four distinct ventilation system options: (i) no trickle vents or extract fans, (ii) trickle vents only, (iii) extract fans only and (iv) trickle vents and extract fans. This gives a total of 40 dwelling form-ventilation archetypes with which to represent the EHS dwelling variants. All ventilation components are assumed to be functioning correctly with no allowance made for mechanical failure or deterioration with time. It is acknowledged that this could lead to slightly lower indoor pollutant concentrations. Each of the 40 archetypes is modelled with eight permeabilities ranging from 3 to 30 m3/h/m2@50Pa present in the English stock (Steven 1998), giving a total of 320 archetypes. Each EHS variant is mapped to one of these models using the predicted permeability value. These are simulated in CONTAM, to obtain concentrations of indoor and outdoor sourced particulate matter ≤2.5μm (PM2.5), radon, environmental tobacco smoke (ETS), and moisture (as a precursor of mould). Under each scenario the adapted EHS variants are mapped to the CONTAM models to reflect the change in permeability following the interventions, thus future changes in indoor pollutant concentrations are estimated. This mapping includes anticipated reductions in external PM2.5 concentrations, specified by year and location. For London, the 2010 annual mean outdoor urban background concentration PM2.5 is taken as 13.0µg.m-3 (Shrubsole et al., 2012). For Milton Keynes, the figure of 10.9 µg.m-3 is based on data from the Defra mapping project (Defra, 2013). For future PM2.5 concentrations, Defra data is available to 2030 in both locations. For 2050, a linear trend is assumed, in order to bring results in line with 2050 predictions from Williams (2007). The SCRIBE model differentiatesPM2.5 from indoor and outdoor sources due to differences in particle nature and potential (but largely unquantified) relative toxicity, which are sufficiently great as to require separate consideration (Rohr and Wyzga, 2012)giving health impact assessments the opportunity to distinguish relative risks to population health.

Radon exposures are informed by the national distribution reported in Gray (2009) and adapted to allow for regional differences in emission rates (HPA, 2011). Due to low levels of radon in London and Milton Keynes - geometric means 16 and 43 Bq/m3 respectively (HP, 2011) - we have not proposed any specific radon remediation measures in our modelling. Smoking levels are informed by NHS, 2011. No account is taken of any future changes in smoking prevalence, or outdoor smoking behaviour that may influence exposure for non-smokers in smoking households. Indoor pollution emission profiles are derived from empirical studies (Table 2). Within the CONTAM modelling each pollutant has a defined source and emission period: indoor PM2.5 is a function of occupancy and cooking; moisture is a function of occupancy and bathroom use; and ETS is a function of occupancy, with weekend and weekday occupancy profiles differing. Readers are directed to the on-line supplementary data accompanying this study for full details.

**Table 2**

*2.4. Modelling Changes in Indoor Air Temperature and Air Quality*

For London, existing energy and ventilation interventions are modelled directly from the English Housing Survey (EHS, 2012), which comprises a representative sample of properties ( 16,150 surveyed dwellings) with weights for each dwelling variant which can be used to represent all households in England. Regional information enables London dwelling variants to be directly selected and used in the modelling. The survey does not have a sufficient or identifiable sample for Milton Keynes.Dwellings were therefore simulated by either using alternative empirical data sets for the variables required for SCRIBE; for example the range of existing interventions and dwelling age and type (CSE, 2012; HECA, 2013; HEED, 2014; MKiO, 2014). For the few remaining variables that were not available: (i) the Standard Assessment Procedure[[1]](#footnote-2) (SAP) rating, (ii) envelope permeability and (iii) ventilation type; the *known* variables were used to calculate estimates for SAP rating and envelope permeability. The probability of occurrence in each of the ~16,000 EHS variants were then used to randomly sample the Milton Keynes housing stock and scaled to the correct number of dwellings.

The stock modelling input variables and their ranges are shown in Table 3.

**Table 3**

The building efficiency module estimates envelope permeability and heat loss resulting from fabric performance, heating system and ventilation characteristics. A conversion process uses EHS variables to infer features, such as dwelling geometry and construction characteristics to predict ventilation and thermal performance (DECC, 2012b). The SAP criteria is then used to predict total ventilation rate, dwelling permeability, and fabric heat loss rate (Hughes et al., 2013). These are combined with the heating system performance to predict a heat transfer characteristic E-value[[2]](#footnote-3) for each dwelling, using a relationship that takes into account the expected behaviour of the occupant (Oreszczyn et al, 2006). Each intervention is associated with changes in the thermal and ventilation characteristics of the EHS variants. The SAP method is used to calculate the new heat transfer characteristic, and the new E-value is predicted such that changes in energy use can be estimated under the variety of future scenarios. These include PPV, designed to comply with Approved Document F1 (HM Government, 2010). One of the key assumptions in the health impact modelling (section 2.5) is that additional PPV will be installed in dwellings alongside the energy efficiency measures. For outdoor conditions influencing indoor values, transient yearly weather files are constructed using Chartered Institution of Building Services Engineers (CIBSE) Test Reference Year (TRY) and Design Summer Year (DSY) data. The TRY is a synthesized typical weather year suitable for analysing the environmental performance of buildings, whereas the DSY is a complete historical year representing a near extreme warm summer (CIBSE, 2010). These files contain hourly outdoor air temperature, air pressure, wind speed, wind direction, and humidity data.

*2.5. Health Impacts*

The health impacts associated with changes to annual indoor air quality and heating season temperatures, were modelled within the SCRIBE tool using life table methods based on the IOMLIFET model (Miller and Hurley, 2003) using all-cause and cause-specific mortality data for England and Wales available from the Office for National Statistics (ONS), with separate life tables for males and females. The key model output was changes in years of life lived with no morbidity estimates. Exposure-response relationships for changes in indoor exposures (i.e. standardized internal temperature (SIT), ETS, PM2.5 derived from indoor and outdoor sources and radon) were derived from published sources shown in Table 4. Where more than one exposure was related to the same outcome, we assumed that the risks are multiplicative in line with the work of Scarborough et al. (2010).

**Table 4**

Health impacts were modelled year by year to 2050. For all modelled outcomes other than those associated with changes in SIT, we specified outcome-specific inception and cessation lag functions to reflect the time delay between changes in exposure and subsequent change in disease status. See Hamilton et al. (2015) for further details.

1. **Results**

*3.1. Energy Use and CO2 Emissions*

Changes in Energy consumption (kWh) and CO2 emissions of the housing stocks relative to the 2010 baseline taking account of the changing carbon intensity (CI) of the electrical grid are shown for each scenario in Table 5. Values are expressed as the percentage increase relative to the base year of 2010, with negative figures therefore indicating reduction in CO2 emissions.

**Table 5**

Greater reductions in energy use are seen in London relative to Milton Keynes under all intervention scenarios, with the highest gains seen in the EE+ scenario where no additional purpose provided ventilation (PPV) was assumed. For both the EE and EE + scenarios, appreciably greater CO2 reductions were seen in London than in Milton Keynes. Aggressive decarbonization of the electric grid, combined with housing measures in the LCS scenario exceeded the targets needed for compliance with the Climate Change Act, 2008 in both locations. The addition of ventilation interventions increased energy use by an average of 8.6% across the scenarios.

*3.2. Temperature and Pollutant Concentrations Changes*

Table 5 shows the changes that occur in mean indoor temperature during the heating season and annual airborne pollutant concentrations following the installation of both energy efficiency and PPV interventions under the three scenarios for 2050.

**Tables 6**

A mould risk of >1 indicates the likely presence of mould in a property, with figures representing the % of properties where the mould risk is >1. A decrease shows a reduction in health risk. However, these changes in mould risk have not been used in the calculation of health impact for this work (though there is some evidence of likely impact, particularly in children). For scenarios with PPV Higher mean indoor temperatures during the heating season are seen in the housing stock following retrofitting, with appreciable reductions in most of the pollutants studied except for radon gas, which shows small reductions in both locations. As a continuous source radon is not appreciably dissipated by intermittent ventilation measures such as extract fans. However, the values seen are typically low for these cities and well below the 200Bq/m3 action level (HPA, 2011). In Milton Keynes, the housing stock is more recent and therefore built to a higher energy efficiency standard and greater airtightness. The housing typology also differs appreciably with over 50% of London’s stock being purpose built flats (requiring simpler measures to obtain gains), while Milton Keynes stock comprises 80% detached, semi-detached and terraced dwellings with general larger building volumes (MKiO, 2014). This is reflected in the greater reduction in indoor sourced pollutants seem in the London stock.

The changes in mean indoor heating season temperatures were only marginally greater without PPV than in the scenarios which included it. The ingress of PM2.5 derived from the outdoor air was reduced by the greater airtightness without PPV, but concentrations of all other pollutants showed increases from the 2010 base line for both locations. London dwellings suffer more, due to greater relative reduction in envelope permeability and therefore air-tightness. The exception is radon because of the greater emission levels seen in Milton Keynes (which are determined by local geology) (HPA, 2011).

*3.3. Health Impacts*

The impact on health measured in terms of the *per capita* total of life years gained (Table 7) is greater in magnitude in London than in Milton Keynes. These impacts translate into increases in average life expectancy at birth of ~3 months (Milton Keynes) and ~4 months (London) with PPV, but *decreases* in life expectancy of ~2 months (Milton Keynes) and ~5 months (London) if PPV is not installed. This reflects the larger changes in the modelled indoor exposures in London, which are due to the greater potential for improving the housing stock primarily due to the greater age range of the London stock (generally older, less energy efficient dwellings). The results reveal that the inclusion of PPV has substantial bearing not only on the magnitude, but also the direction of health impact. Without PPV large increases occur in exposures to pollutants derived from indoor sources (Table 6), which more than offset the benefits of improved indoor heating season temperatures and protection against outdoor air pollution, resulting in substantial negative consequences for health overall in both settings.

**Table 7**

1. **Discussion**

* There are substantial differences in results for the two locations when housing interventions are the sole mechanism for decarbonization, without additional substantial grid decarbonization. London housing can achieve greater reductions in CO2 emissions (and possible average health net benefits) than that of Milton Keynes. This is as a result of various factors; the Milton Keynes housing stock is more recent, built to a higher energy efficiency standard. Type and distribution of housing differs appreciably with over 50% of London’s stock being purpose built flats (requiring simpler measures to obtain gains), while Milton Keynes stock comprises 80% detached, semi-detached and terraced dwellings with generally larger building volumes that result in smaller concentrations of pollutants per unit volume (MKiO, 2014). To achieve similar reductions in CO2 emissions in Milton Keynes would require a greater investment in more technical housing interventions such as mechanical ventilated heat recovery (MVHR) systems. The appropriateness of such interventions would of course require a detailed cost-benefit analysis. However, based on our study, it would appear that potential CO2 reductions and health impacts (whether positive or negative) are stock-specific and policies should be tailored to take this into account rather than be universally rolled out, with both regional and local strategies focusing on the most appropriate sectors in order to achieve CO2 emissions reduction targets.
* In both London and Milton Keynes, changes to the indoor environment following combined energy efficiency and PPV interventions (if perfectly implemented) would lead to lower CO2 emissions, reductions in indoor pollutant concentrations, and increases in indoor winter temperatures yielding average net health benefits. In this respect our results are consistent with those of other published research. (Wilkinson et al., 2009; Crump et al., 2011; Milner et al., 2014). In scenarios where PPV (properly implemented) is used in conjunction with energy efficiency measures, the overall *per capita* health benefits (including all pollutant exposures and temperatures change) are greater in London, with benefits for cardiopulmonary health due to reductions in indoor exposure to both indoor and outdoor-generated PM2.5. There would also be substantial reduction in lung cancer burdens due to the reduced PM2.5 and radon levels with a minimal impact on ventilation heat loss in both locations. Providing PPV has impact on energy use of +8.6% on average between the different scenarios, whilst potentially yielding substantial health gains. However, a distribution of impacts will occur because of different housing geometries and occupant behaviours and for some homes and behaviours indoor exposures would increase and there would be health dis-benefits for some people. Approved Document F1 of the building regulations states that following retrofitting ventilation should not become worse (HM Government, 2010), however on-site monitoring would suggested this is not always the case (Sinnott & Dyer, 2012).
* The UKERC carbon intensity scenarios used here assume the use of electricity as the energy source for space heating in the domestic sector, which is seen as essential under Low-Carbon scenarios for the UK energy system in 2050 because it can be generated from a range of renewable and low-carbon energy sources including nuclear and the use of carbon-capture technologies (UKERC, 2013). By combining housing interventions with decarbonization of the electric grid a substantial contribution to climate goals can be achieved, with targets exceeded in the UKERC Low-Carbon scenario in both locations. However, in both London and Milton Keynes domestic customer fuel consumption is currently 76% gas (DECC, 2014). It is likely that both legislative and incentive means will be needed to promote change from gas to an all-electric grid. If such a change is delayed or does not occur the predicted reductions in CO2 emissions seen in this study will not be achieved. An energy efficient housing stock with (largely decarbonized) electricity as its fuel represents the upper limit of possible CO2 savings.
* Modelling analyses such as this study rely on multiple assumptions and many uncertainties. Its results should therefore be interpreted only as indicative and relative rather than as precise calculations of impact. We have provided an section (6) on ‘uncertainty in the SCRIBE modelling’ in the supplementary data accompanying this publication. uncertainties in the models have also been explored in previous papers by the authors (e.g. Shrubsole et al., 2012; Hamilton et al., 2015). There is currently limited observed data on the impacts of retrofitting strategies on indoor air quality and health to compare against model outputs. Nonetheless, despite these uncertainties, the results provide important indications of likely impacts that can be used to inform policy decisions.

1. **Conclusions**

This study has investigated the comparative impacts of dwelling-related CO2 reduction strategies in London and Milton Keynes using integrated housing intervention and energy supply decarbonization scenarios to calculate possible end user energy demand, pollutant exposures and health impacts. Where CO2 reduction targets are the main policy driver, substantial reductions can be made in London with energy interventions on housing, whereas for Milton Keynes the potential percentage gains are much smaller because of the already more energy efficient housing stock. Potential net benefits or harms for health are also greater in London as measured in terms of *per capita* gains in life expectancy. We highlight the importance of not applying a ‘one size fits all’ energy saving and CO2 emission reduction policy, as local differences in housing and the environment may have important bearing on the impacts that can be achieved. Decarbonization of the grid is essential in achieving CO2 emissions reduction targets, especially in Milton Keynes.

Moreover, when designing for both low energy use and good health, there are important trade-offs between an increase in the airtightness of dwellings and changes in IAQ. If interventions are not correctly applied, there are risks of serious negative health effects. In order to obtain both health gains and promote success in achieving CO2 emission reduction targets in both locations, policymakers need to consider a wider view that includes strategies to extensively decarbonize the electricity grid with a move away from the reliance on residential use of gas.

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1. SAP: The Government’s Standard Assessment Procedure for Energy Rating of Dwellings (BRE, 2012) [↑](#footnote-ref-2)
2. The E-value represents the dwelling heat transfer characteristic, obtained by combining the estimated fabric and ventilation performance with the heating system (after Oreszczyn et al, 2006). [↑](#footnote-ref-3)