Modeled effects of an improved building insulation scenario in Europe on air pollution, health and societal costs

Calculs des effets sur la pollution atmosphérique, la santé et l'économie d'un programme d'amélioration de l'isolation des bâtiments en Europe

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Résumé

Contexte : en Europe, une partie importante de l'énergie produite est utilisée pour le chauffage domestique et pour la climatisation. La qualité de l'isolation des bâtiments a ainsi un impact significatif sur la pollution de l'air.

Objectifs : modéliser et calculer les effets d'une amélioration importante de l'isolation des bâtiments existants en Europe sur les niveaux de pollution de l'air, sur la santé et sur l'économie.

Méthodes : l'énergie utilisée dans deux scénarios différents a été comparée entre 2005 et 2020 : un scénario d'un programme de l'isolation des bâtiments existants en Europe et un scénario de statu quo. Les variations des émissions issues de ces deux scénarios ont été intégrées dans un modèle de la qualité de l'air *(the Comprehensive Air-Quality Model with extensions).* Les variations annuelles moyennes des principaux polluants atmosphériques ont été calculées pour chaque pays. Des données venant de l'Organisation Mondiale de la Santé (OMS) et de l'Union Européenne (UE) sur les populations et sur les impacts des polluants ont été utilisées pour déduire quels sont les effets sur la santé et l'économie. La qualité de l'air intérieur ne faisait pas partie de l'étude.

Résultats : avec le programme de l'isolation des bâtiments existants en Europe, les niveaux moyens annuels de la pollution atmosphérique particulaire fine ($PM_{2,5}$) variaient de -0,008 µg/m^3 (Finlande) à -0,538 µg/m^3 (Belgique). Le nombre moyen d'années de vie gagné par année par 100 000 adultes était de 24,3 (intervalle de confiance 95 % de 0,9 à 54,5). Le nombre total d'années de vie gagnées chaque année variait, selon les pays, entre 31 en Finlande à 22 524 en Allemagne. Le nombre total d'années de vie gagnées était de 78 678 en Europe. Un total de 7 173 cas de bronchite chronique pourrait être évité chaque année. Plusieurs autres effets sur la santé étaient améliorés de façon similaire. Les coûts pour la société s'élevaient à 6,64 milliards d'euros par an.

Conclusions : en plus de la réduction des émissions de carbone, un programme de l'isolation des bâtiments existants en Europe aurait des avantages substantiels sur la santé grâce à l'amélioration de la pollution atmosphérique. Les effets sur la santé et sur l'économie peuvent contrebalancer de façon significative les coûts d'investissement et devraient être pris en compte lors de l'évaluation des stratégies d'atténuation du réchauffement climatique.

Mots-clés

pollution de l'air, isolation des bâtiments, pollution atmosphérique particulaire fine, mortalité, morbidité, externalités.

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Abstract

Background: In Europe a substantial share of the energy supply is used for domestic heating and cooling. The quality of building insulation thus significantly impacts air pollution.

Objectives: To model the effects of an improved building insulation scenario in Europe on air pollution levels and the resulting effects on health and economy.

Methods: Projected energy savings between 2005 and 2020 were calculated for an improved building insulation scenario and a business as usual scenario. The resulting changes in emissions (e.g. from power plants) were used in the Comprehensive Air-Quality Model with extensions. Mean annual changes in the main air pollutants were derived for each country. World Health Organization (WHO) and European Union (EU) data on populations and on impacts of pollutants were used to derive health effects and costs. Effects on indoor air quality were not assessed.

Results: Projected effects on the mean annual change in $PM_{2.5}$ varied from −0.008 µg/m³ (Finland) to −0.538 µg/m³ (Belgium). The mean number of life-years (LY) gained annually per 100000 adults was 24.3 LY (range 0.9 to 54.5). The total number of LY gained annually varied from 31 in Finland to 22524 in Germany, totaling 78678 LY in Europe. A total of 7173 cases of persistent chronic bronchitis could be avoided annually. Several other health outcomes improved similarly. The saved societal costs totaled 6.64 billion € annually.

Conclusions: In addition to carbon emission reductions, an improved building insulation scenario in Europe would have substantial benefits on health through improvements in air pollution. Health effects and societal cost savings may significantly counterbalance investment costs and should be taken into account when evaluating strategies for mitigation of global warming.

Keywords

air pollution, building insulation, fine particulate matter, mortality, morbidity, externalities.

1. Background

Public health benefits and reduced societal expenses have been largely missing features of the energy consumption and greenhouse gas policies, despite the publication of several “costs of air pollution-related ill health” studies (Pervin et al., 2008; Haines and Dora, 2012). For more than three decades such studies have consistently suggested substantially improved public health and saved costs to society from reductions in air pollution (Zmirou et al., 1999) and impacts and costs have been thoroughly reviewed and estimated (Bickel and Friedrich, 2005; Holland et al., 2005; Hurley et al., 2005). More recently, studies have demonstrated the potential co-benefits to health and economy World-wide from actions to mitigate greenhouse gas emissions (Haines et al., 2009). Control of fossil-fuel particulate black carbon was suggested to be an effective means to slow global warming as well as to improve health in 2002 (Jacobson, 2002), an idea pursued in recent publications (Anenberg et al., 2012; Bond et al., 2013) although without calculation of costs.

The share of energy that is used for domestic heating and cooling is substantial. Thus, building insulation may affect air pollution and public health significantly through changed energy demands leading to changes in air pollution. This connection has rarely been investigated in contrast to studies on energy consumption, job creation, and on carbon dioxide (CO_2), which are common. Levy et al. (2003) estimated the effects of insulation retrofits (to IECC 2000 insulation levels) in existing housing in the United States on ambient pollutant emissions, public health, and the corresponding saved societal costs whereas Wilkinson et al. (2009) estimated the effects in the UK of interventions to improve the energy efficiency of heating of the housing stock on indoor environment and subsequent health effects. Both studies demonstrated appreciable potential for improved public health owing to the scenarios they investigated.

We have previously described the projected changes in major air pollutants in 6 zones of Europe resulting from an improved building insulation scenario and given details on the emission estimation, modeling of air pollutants, and test of quality of predictions (Korsholm et al., 2012). Particulate matter reductions was found to vary from 1.2% in north-eastern Europe to 9% in north-western Europe and we hypothesized that in some countries the health effects of these changes would be substantial. Health effects other than those related to improved ambient air may occur as a result from improved building insulation. When building insulation is altered, indoor air quality may be altered too, both due to changed infiltration rates and due to changed behavior of dwellers. It is hard to predict the extent of such changes and the balance between positive changes (e.g. improved thermal comfort, less indoor wood smoke) and the negative ones (e.g. decreased ventilation and increased humidity and risk of mold growth). It is out of scope of this paper to model health effects due to changes in indoor air quality resulting from the insulation scenario although possible effects will be discussed.

Our primary aim was to illustrate the likely extent of improvements to public health through changes in criteria air pollutants at a regional scale from an ambitious building insulation retrofit and new building scenario – extending these from the 6 zones considered in our previous work to all countries in the region considered. A secondary aim was to calculate the range of externalities in terms of economic savings associated with the health effects. We only considered health effects for which there is broad consensus on the impact and the associated costs and did not consider damage to crops or infrastructure from air pollution. Compared with the relatively few previous studies on health effects of changes to building insulation our study differed by covering a larger region and population; by being based on an air-quality model providing details on criteria pollutant concentrations; by applying life-table analyses at the national level; and by including extensive sensitivity analyses assuming different impacts and cost.

2. Methods

The study comprised 25 European Union (EU-25) states: Finland, Sweden, Austria, Belgium, Denmark, Germany, Ireland, France, Luxembourg, Netherlands, United Kingdom, Italy, Spain, Greece, Portugal, Estonia, Latvia, Lithuania, Poland, Romania, Slovakia, Slovenia, Bulgaria, Czech Republic, and Hungary. In these states, an improved insulation scenario was compared with a business-as-usual scenario and the scenario and the methods applied have been described previously (Korsholm et al., 2012). Briefly, the building insulation scenario ran from 2005 to 2020 with an annual retrofit rate of 2% assuming ambitious insulation levels in new and retrofit buildings. Thus decreasing energy expenditure on heating and cooling was compared with a scenario assuming no changes to current insulation and retrofit practices in Europe. The improved insulation scenario considered roof, wall and floor insulation only and did not include windows, ventilation systems, etc. Thermal conductivity values came from Ecofys (ECOFYS, 2007) and were projected to decrease in all regions and by more than 50% in the regions with poorest insulation (Korsholm et al., 2012). All other variables than the retrofit rate and insulation efficiency were kept constant at the 2005 level; e.g. energy source mix for heating and construction rate of new buildings.

2.1. Air pollution data

Mean annual changes for the 15-year period in the main air pollutants particulate matter less than 10 µm (PM_{10}) and less than 2.5 µm ($PM_{2.5}$), sulphur dioxide, nitrogen oxides, carbon monoxide, ozone, and volatile organic compounds were calculated in the Comprehensive Air-Quality Model with extensions (CAMx) by modeling emissions, emission changes in the two scenarios, atmospheric chemistry and meteorology (Korsholm et al., 2012). Meteorological data from 2009 was used as this was found to be closest to the European normal. Model predictions were controlled by use of data from 8 measurements stations, finding correlations between modeled and measured data of 0.67-0.68 for ozone. Ozone was converted from µg/m^3 to ppb by multiplying with 0.5097 assuming an approximative summer temperature of 25°C. In no case did changes in PM_{10} differ from $PM_{2.5}$ as the entire change in PM was contained within the $PM_{2.5}$ fraction of PM_{10} (Korsholm et al., 2012). Concentration changes were averaged over each country and concentration-response functions applied to the total population as if evenly distributed and exposed to air pollutant concentration changes.

2.2. Population data

Population, morbidity, and mortality data were extracted at the national level from the European Detailed Mortality Database. For infant mortality (between 1 and 12 months) the source was the European Health for All Database (WHO Regional Office for Europe, Copenhagen, DK).

Data from the most recent year were preferred as available in April 2012. Data from 2010 were available for 5, from 2009 for 10, from 2008 for 5, and from 2007 and 2005 for one country each.

2.3. Concentration-response functions (CRF)

CRF are relative risks (RR) describing changes in existing risks associated with measured or modeled concentrations of air pollutants in a population. They are not real dose- or exposure-response functions because the concentrations are based on mean outdoor levels not taking peoples exact location into account. CRF used in this study were applied to the population of each country separately and effects summed. The factors were based on CRF from the literature on mortality and selected health endpoints (morbidity) corresponding to the factors endorsed by the European Commission DG Environment Clean Air for Europe Program (CAFE) (Watkiss et al., 2005) and the more recent EU program Health and Environment Integrated Methodology and Toolbox for Scenario Development (HEIMTSA, 2011). The same CRF are used by the European Environment Agency and several of them by the OECD (OECD, 2007) and the US EPA (US-EPA, 2012).

2.4. Mortality

Mortality from all causes among adults aged 30+ years was assumed to change linearly. Based on the RR of 6% (95% CI 2;11%) per 10 μg/m^3 change in mean annual $PM_{2.5}$ observed in the American Cancer Society Study (Pope et al., 2002) the CRF is given by 1.006(−1/10) for a 10 μg/m^3 reduction in $PM_{2.5}$. None of the other pollutants investigated are considered to have separate impacts on long-term mortality (HEIMTSA, 2011).

For mortality in infancy (from age 1 to 12 months) a linear function with a RR of 0.4% (95% CI 0.2; 0.7%) per μg/m^3 change in mean annual PM_{10} was applied as in (Woodruff et al., 1997).

For effects of ozone, the RR published by Jerrett et al. (2009) on respiratory mortality among adults aged 30+ years of 0.4% (95% CI 0.1%;0.67%) per ppb was used. As this factor applies to the annual mean of the daily 1 h maximum that was (71.62/56.68) 1.26 times higher than the annual daily mean, the modeled ozone concentration changes were multiplied by this factor in order to account for the difference.

For calculation of changes in LY the life table method described by Miller and Hurley (2003) was applied using life-tables from the Institute of Occupational Medicine (Miller, 2011). Specifically, an IOMLIFET ALL_CAUSE table was used for each country individually entering country-specific data on demography, all-cause mortality and modeled air pollution changes as described previously. For modeling of effects of changes in ozone the IOMLIFET MULTI_CAUSE table was used, entering mortality from all respiratory causes (ICD J00-J99) only. Because effects have been documented in the summer season only and ozone was modeled for entire calendar years, the CRF was halved in order to yield halved effects.

2.5. Morbidity

Morbidity effects considered in the analysis were chronic bronchitis (ICD J40-42), cardiac (ICD I00-52) and respiratory (ICD J00-99) emergency admissions, restricted activity days (RAD), use of medication for respiratory disease, and lower respiratory symptoms.

Effects on morbidity were taken from the EU program (HEIMTSA, 2011), assuming similar baseline incidences, similar employment rates, and similar linear CRFs in the 25 states assessed as in the European studies that formed the basis of the methodology.

Thus, the CRF for incidence of chronic bronchitis was calculated as a 2.2% increase per μg/m^3 change in mean annual PM_{10}, an annual incidence of 0.39% among adults and that 90% of the population did not have persistent chronic bronchitis. This corresponds to 7.7 (95%: 0.7; 14) new persistent cases annually of chronic bronchitis per μg/m^3 PM_{10} per 100000 adults aged 18+ years.

For emergency cardiac hospital admission rates the CRF was calculated as 0.43 (95% CI: 0.22; 0.65) additional admissions per μg/m^3 increase in PM_{10} per 100000 total population annually. For emergency respiratory hospital admissions rates the CRF was calculated as 0.56 (95% CI: 0.43; 0.62) additional admissions per μg/m^3 increase in PM_{10} per 100000 total population annually.

The CRF for RAD was 9020 (95% CI: 7920; 10130) additional RAD per μg/m^3 increase in $PM_{2.5}$ per 100000 adults aged 18-64 annually.

The CRF for bronchodilator use among children with asthma was 210 (95% CI: −890; 1400) additional days of bronchodilator usage per μg/m^3 increase in PM_{10} per 100000 children aged 5-14, per year. Among adults with asthma the CRF was 930 (95% CI: −930; 2800) additional days of bronchodilator usage per μg/m^3 increase in PM_{10} per 100000 adults aged 20+ years annually.

The CRF for days with lower respiratory symptoms (LRS) among children was 18600 (95% CI: 9310; 27900)

Table I. Valuation (€) of the health effects quantified in the study.
Estimation (€) des effets sur la santé dans l'étude.

	Valuation (median)	Valuation (mean)
Mortality (deaths, VSL)	1018000[b]	2080000[b]
Mortality (life years lost, VOLY)	125000[b]	54000[a]
Infant mortality (deaths, VSL)	1503000[a]	3060000[b]
Chronic bronchitis (cases)		208000[a]
Hospital admissions		2364[a]
Restricted activity days in working age		97[a]
Respiratory medication use all ages		1[a]
Lower respiratory symptoms in people with chronic symptoms (all ages)		42[a]

[a] core analysis. [b] sensitivity analyses.

additional LRS including cough days per µg/m³ increase in PM_{10} per 100000 children aged 5-14 annually. Among adults the corresponding figure was 3 900 (95% CI: 330; 7200) additional LRS including cough days per µg/m³ increase in PM_{10}, per 100000 adults annually.

HEIMTSA operates with additional impacts (e.g. primary care consultations, work loss days, minor restricted activity days) but as these are originally considered (Hurley et al., 2005) as secondary or sensitivity functions we did not include them.

2.6. Valuation

Mortality and morbidity was valued economically at 2005 values. If not stated otherwise this was done in accordance with the methodology of the CAFE program (Hurley et al., 2005) as listed in table 1. For the core analyses the mean VOLY (value of a life-year) from CAFE was applied to LY lost due to chronic exposure among adults, whereas the infant mortality valuation was conducted by use of the median VSL (value of a statistical life) times the mean marginal rate of substitution (of 1.5) as in the CAFE Program (Hurley et al., 2005).

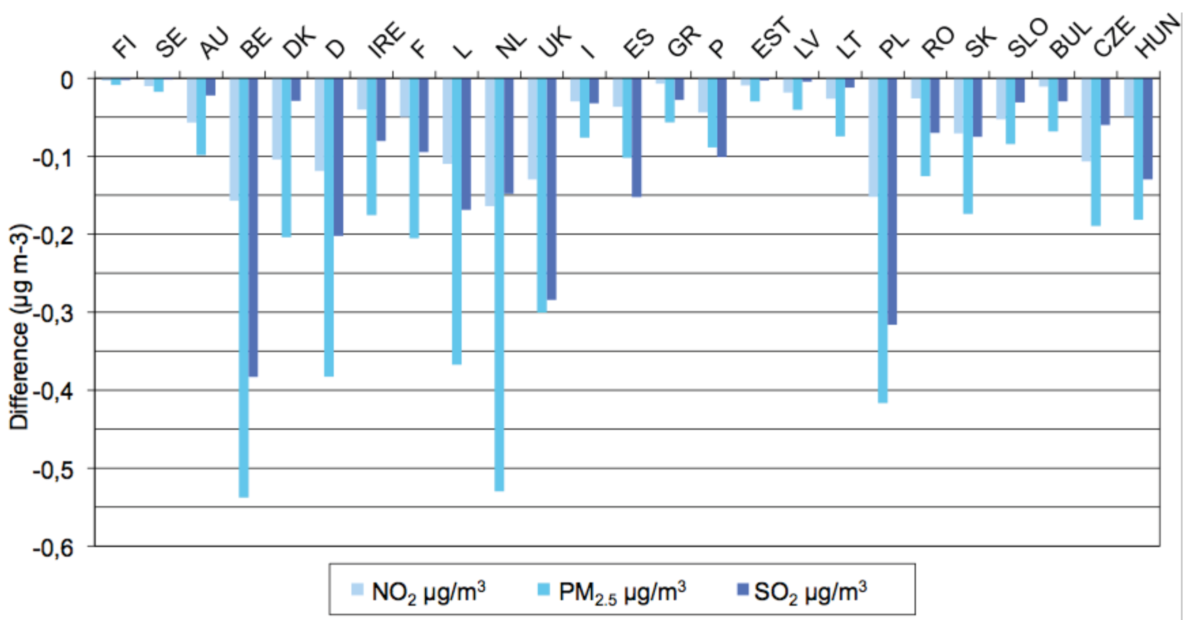

Figure 1. Changes (decreases) in mean air pollutant concentrations from the improved building insulation scenario in the EU-25 states.
Changements dans les niveaux des moyennes annuelles des polluants dans les 25 pays européens avec le programme d'isolation des bâtiments.

2.7. Sensitivity analyses

As suggested in the CAFE program, both the mean and median VSL and the VOLY approaches were used for sensitivity analyses for the sake of transparency. Similarly, mean marginal rates of substitution of 1.0 and 2.0 were applied in sensitivity analyses of the value of saved lives of infants.

For sensitivity analyses on the percent change in all-cause adult mortality the proposed 75% plausibility interval of a CRF between 0.1% and 1.2% per µg/m³ increase in annual $PM_{2.5}$ suggested by the expert elicitation of COMEAP (COMEAP 2009) was used. Also the central estimates on the percent change in all-cause mortality ranging from 0.7 to 1.6 % per µg/

Table II. Annual PM change and gain in life-years (LY) in the EU-25 states due to the insulation scenario.
Les changements du niveau des moyennes annuelles de $PM_{2,5}$ et du nombre d'années de vie gagnées dans les 25 pays européens avec le programme d'isolation des bâtiments.

	PM change	Population	LY	LY/100000 adults	LY at 0.1%/µg*m⁻³	LY at 1.6%/µg*m⁻³
Finland	–0.008	5.34E+06	31	0.9	5	79
Sweden	–0.018	9.38E+06	98	1.6	17	249
Austria	–0.098	8.39E+06	528	9.5	90	1338
Belgium	–0.538	1.05E+07	3712	54.8	630	9363
Denmark	–0.204	5.45E+06	719	20.5	121	1801
Germany	–0.383	8.18E+07	22618	39.9	3850	57277
Ireland	–0.175	4.46E+06	374	14.7	63	941
France	–0.205	6.21E+07	8236	21.1	1397	20811
Luxembourg	–0.367	4.89E+05	94	30.4	16	239
Netherlands	–0.530	1.66E+07	5045	47.2	857	12742
United Kingdom	–0.300	6.18E+07	11752	30.3	1990	29618
Italy	–0.076	5.98E+07	2927	7.0	498	7418
Spain	–0.102	4.56E+07	2771	9.1	470	7006
Greece	–0.057	1.13E+07	395	5.1	67	999
Portugal	–0.089	1.06E+07	629	8.9	107	1593
Estonia	–0.030	1.34E+06	35	4.2	6	89
Latvia	–0.041	2.25E+06	89	6.2	15	226
Lithuania	–0.075	3.34E+06	233	11.2	39	589
Poland	–0.417	3.82E+07	12273	52.1	2083	30986
Romania	–0.126	2.14E+07	2250	16.4	379	5644
Slovakia	–0.174	5.42E+06	670	20.0	113	1686
Slovenia	–0.084	2.04E+06	117	8.6	20	297
Bulgaria	–0.068	7,62E+06	471	9.3	80	1199
Czech Republic	–0.190	1,05E+07	1404	20.4	240	3574
Hungary	–0.182	1.00E+07	1714	26.1	293	4363
All states		4.957E+08	78678	24.25[a]	13446	200126

**PM change in µg/m³. LY gain in years. [a] unweighted mean*

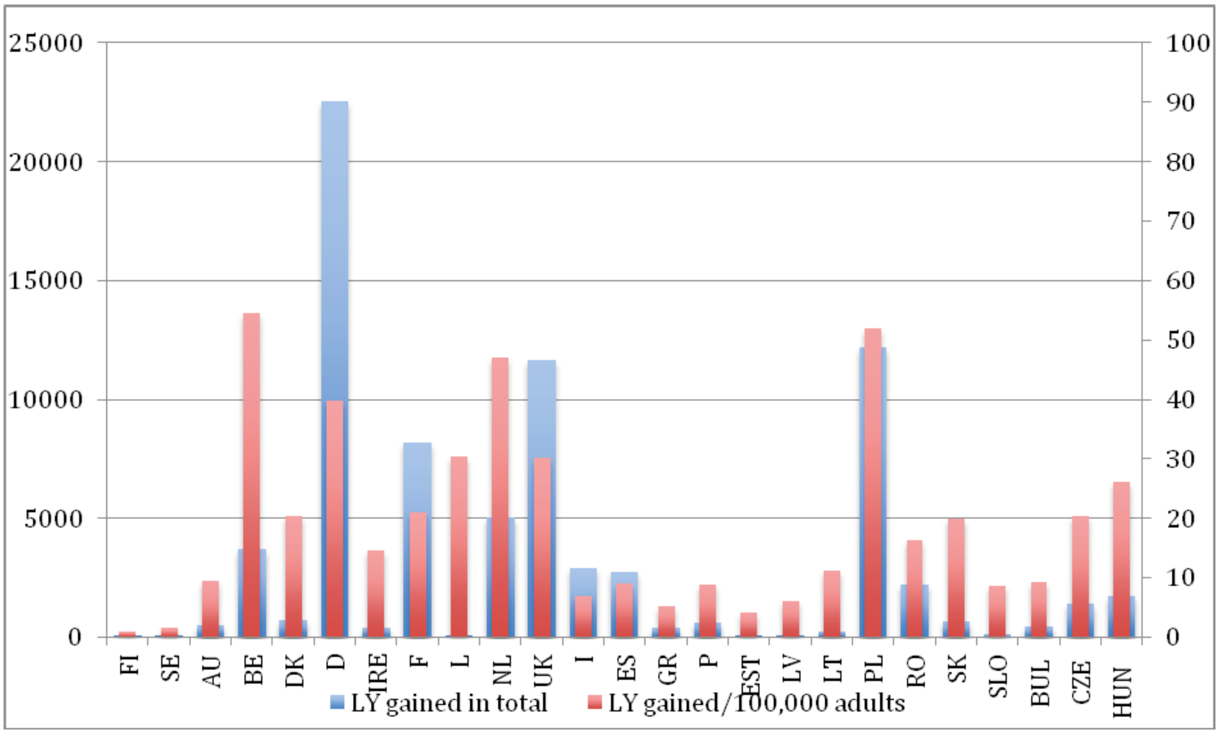

Figure 2. Annual changes (gains) in life-years (LY) following the improved building insulation scenario in the EU-25 states. In blue : totals (left axis); in red : per 100 000 adults (right axis).
Changements dans les nombres d'années de vie gagnées dans les 25 pays européens avec le programme d'isolation des bâtiments. En bleu (axe de gauche), les nombres totaux ; en rouge (axe de droite), les nombres pour 100 000 adultes.

m^3 increase in annual $PM_{2.5}$ suggested to the EPA by a panel of experts (US-EPA, 2006) was applied.

For the remaining health end-points the 95% CI as given by HEIMTSA were used for sensitivity analyses.

3. Results

The population in the 25 EU states totaled 495.7 million of which 4.9 million were infants and 324.5 million were adults aged 30+ years - the ages in which changes in mortality from air pollution was calculated.

The changes in main pollutant concentrations that have previously only been published by region are visualised in Figure 1. The mean annual change in $PM_{2.5}$ caused by the insulation scenario varied almost two orders of magnitude between –0.008 µg/m^3 (Finland) and –0.538 µg/m^3 (Belgium).

Accordingly the number of LY gained among adults 30+ years varied greatly from 0.9/100000 persons/year in Finland to 54.5/100000 persons/year in Belgium - the unweighted 25-country mean being 24.3/100000/year.

As table II shows, the total number of LY gained annually varied to an even greater extent from 31 in Finland to 22524 in Germany, totaling 78678 LY in the EU-25.

In figure 2 this is further illustrated by including LY/100000 inhabitants/year. The value of saved LY among adults in Europe was 4.25 billion €/year (table IV).

Among infants the total number of avoided deaths was 7/year. The societal costs saved amounted to 10.4 million €/year (table IV).

A total of 7173 cases of persistent chronic bronchitis were avoided annually, varying from 3 in Finland and Estonia to 2000 in Germany. The annual net gain from this reduction was 1.49 billion €/year.

A total of 1142 emergency admissions were avoided annually, of which 1/4 would have occurred in Germany. The saved costs amounted to 2.7 million €/year.

Regarding changes in number of RAD among adults and days with LRS among children and adults, these totaled –6.6E+06/year, –94.4 E+06/year, and –152.6 E+06/year respectively.

The changes in number of days with bronchodilator use among children and adults totaled –25398/year and –840994/year respectively and resulted in total savings of 866,391 €/year.

The sum of societal costs saved by declining morbidity amounted to 2.38 billion €/year (table IV). Detailed information with 95% CI and split by nation is given in table III.

In total, summing up mortality and morbidity effects among all age groups, the total economical savings in the 25 states due to the insulation scenario was 6.64 billion €/year.

The projected changes in ground ozone were infinitesimal and the effects on life expectancy and economy similarly indiscernible from zero.

Table III. Annual change in morbidity in the EU-25 states due to the insulation scenario.
Les changements de morbidité dans les 25 pays européens avec le programme d'isolation des bâtiments.

	Chronic bronchitis[a]	Emergency admissions	RAD[b]	Days on medication[c]	LRS[d]
Finland	-3 (0,-5)	0 (0,-1)	-2.6 (-2,-3)	-0.3 (0,-1)	-2.3 (-1,-4)
Sweden	-10 (-1,-18)	-2 (-1,-2)	-9.1 (-8,-10)	-1.2 (1,-4)	-8.4 (-2,-14)
Austria	-52 (-5,-94)	-8 (-5,-10)	-47.6 (-42,-54)	-6.3 (7,-20)	-41.8 (-10,-72)
Belgium	-344 (-31,-625)	-56 (-37,-72)	-315.3 (-277,-354)	-41.7 (46,-130)	-295.9 (-76,-504)
Denmark	-66 (-6,-121)	-11 (-7,-14)	-62.5 (-55,-70)	-8.1 (9,-25)	-59.8 (-16,-101)
Germany	-2011 (-183,-3656)	-310 (-203,-397)	-1773 (-1557:-1991)	-242.9 (263,-754)	-1557 (-356,-2689)
Ireland	-45 (-4,-82)	-8 (-5,-10)	-45.2 (-40,-51)	-5.5 (6,-17)	-42.4 (-12,-72)
France	-765 (-70,-1391)	-126 (-83,-162)	-705 (-619,-792)	-92.6 (103,-291)	-676 (-177,-1147)
Luxembourg	-11 (-1,-20)	-2 (-1,-2)	-10.4 (-9,-12)	-1.3 (2,-4)	-9.6 (-3,-16)
Netherlands	-534 (-49,-972)	-87 (-57,-112)	-503.3 (-442,-565)	-64.8 (72,-203)	-466.4 (-121,-793)
United Kingdom	-1123 (-102,-2042)	-184 (-120,-225)	-1042.1 (-915,-1170)	-135.6 (150,-425)	-960 (-244,-1637)
Italy	-291 (-26,-528)	-45 (-30,-58)	-258.1 (-227,-290)	-35.1 (38,-109)	-226 (-52,-390)
Spain	-295 (-27,-536)	-46 (-30,-59)	-275.9 (-242,-310)	-35.7 (39,-111)	-231.1 (-54,-399)
Greece	-41 (-4,-74)	-6 (-4,-8)	-36.7 (-32,-41)	-4.9 (5,-15)	-31.6 (-7,-55)
Portugal	-59 (-5,-108)	-9 (-9,-12)	-54.3 (-48,-61)	-7.2 (8,-22)	-48.1 (-12-83)
Estonia	-2 (0,-5)	0 (0,-1)	-2.3 (-2,-3)	-0.3 (0,-1)	-2 (-1,-3)
Latvia	-6 (-1,-11)	-1 (-1,-1)	-5.4 (-5,-6)	-0.7 (1,-2)	-4.4 (-1,-8)
Lithuania	-15 (-1,-28)	-2 (-1,-3)	-14.5 (-13,-16)	-1.9 (2,-6)	-12.6 (-3,-22)
Poland	-988 (-90,-1796)	-157 (-103,-202)	-963.9 (-846,-1083)	-118.7 (130,-370)	-802 (-193,-1375)
Romania	-169 (-15,-307)	-27 (-17,-34)	-161.6 (-142,-181)	-20.4 (22,-64)	-135.9 (-33,-233)
Slovakia	-58 (-5,-106)	-9 (-8,-12)	-58 (-51,-65)	-7 (8,-22)	-47.6 (-12,-82)
Slovenia	-11 (-1,-20)	-2 (-1,-2)	-10.3 (-9,-12)	-1.3 (1,-4)	-8.5 (-2,-15)
Bulgaria	-33 (-3,-60)	-5 (-3,-7)	-30.8 (-27,-35)	-4 (4,-12)	-25.3 (-6,-44)
Czech Republic	-126 (-11,-229)	-20 (-13,-25)	-120.5 (-106,-135)	-15.1 (16,-47)	-96.7 (-22,-167)
Hungary	-114 (-10,-208)	-18 (-12,-23)	-106.7 (-94,-120)	-13.8 (15,-43)	-91.4 (-22,-157)
All states	-7173 (-652,-13041)	-1142 (-750,-1464)	-6615 (-5808,-7429)	-866.4 (949,-2701)	-5882 (-1433, -10081)

95% CI in brackets. [a] Change in annual incidence of the disease. [b] Restricted activity days x 1000. [c] x 1000; all ages included. [d] Days with lower respiratory symptoms; all ages included.

Table IV. Saved societal costs (€) in the EU-25 states due to the insulation scenario.
Coûts économisés (€) dans les 25 pays européens avec le programme d'isolation des bâtiments.

	Adult life-years	Infant death	Chronic bronchitis	Emergency admissions	RADs[a]	LRS[b]	All health effects[c]
Finland	1.68E+06	2.77E+03	5.76E+05	1.06E+03	2.48E+05	9.81E+04	2.6E+06
Sweden	5.28E+06	1.17E+04	2.09E+06	3.85E+03	8.78E+05	3.51E+05	8.61E+06
Austria	2.84E+07	5.49E+04	1.08E+07	1.93E+04	4.62E+06	1.75E+06	4.56E+07
Belgium	1.99E+08	5.45E+05	7.15E+07	1.32E+05	3.06E+07	1.24E+07	3.14E+08
Denmark	3.82E+07	2.19E+05	1.38E+07	2.60E+04	6.06E+06	2.51E+06	6.08E+07
Germany	1.22E+09	1.8E+06	4.18E+08	7.32E+05	1.72E+08	6.54E+07	1.87E+09
Ireland	2.00E+07	7.1E+04	9.42E+06	1.83E+04	4.39E+06	1.78E+06	3.56E+07
France	4.42E+08	1.11E+06	1.59E+08	2.98E+05	6.84E+07	2.84E+07	6.99E+08
Luxembourg	5.07E+06	9.03E+03	2.25E+06	4.20E+03	1.01E+06	4.03E+05	8.75E+06
Netherlands	2.71E+08	5.95E+05	1.11E+08	2.06E+05	4.88E+07	1.96E+07	4.51E+08
United Kingdom	6.29E+08	2.1E+06	2.34E+08	4.34E+05	1.01E+08	4.03E+07	1.01E+09
Italy	1.57E+08	2.69E+05	6.05E+07	1.06E+05	2.5E+07	9.49E+06	2.53E+08
Spain	1.49E+08	3.7E+05	6.14E+07	1.09E+05	2.68E+07	9.71E+06	2.47E+08
Greece	2.12E+07	4.52E+04	8.44E+06	1.49E+04	3.56E+06	1.33E+06	3.46E+07
Portugal	3.38E+07	7.68E+04	1.23E+07	2.21E+04	5.26E+06	2.02E+06	5.35E+07
Estonia	1.90E+06	4.42E+03	5.19E+05	9.34E+02	2.24E+05	8.24E+04	2.73E+06
Latvia	4.79E+06	1.69E+04	1.20E+06	2.14E+03	5.2E+05	1.85E+05	6.72E+06
Lithuania	1.25E+07	3.77E+04	3.21E+06	5.83E+03	1.41E+06	5.28E+05	1.77E+07
Poland	6.58E+08	1.76E+06	2.05E+08	3.72E+05	9.35E+07	3.37E+07	9.93E+08
Romania	1.20E+08	6.93E+05	3.51E+07	6.30E+04	1.57E+07	5.71E+06	1.77E+08
Slovakia	3.58E+07	1.59E+05	1.21E+07	2.20E+04	5.63E+06	2,00E+06	5.57E+07
Slovenia	6.30E+06	9.08E+03	2.29E+06	4.03E+03	1,00E+06	3.56E+05	9.96E+06
Bulgaria	2.54E+07	1.22E+05	6.91E+06	1.22E+04	2.99E+06	1.06E+06	3.65E+07
Czech Republic	7.58E+07	1.45E+05	2.62E+07	4.65E+04	1.17E+07	4.06E+06	1.18E+08
Hungary	9.26E+07	1.72E+05	2.37E+07	4.25E+04	1.04E+07	3.84E+06	1.31E+08
All states	4.25E+09	1.04E+07	1.49E+09	2.7E+06	6.42E+08	2.47E+08	6.64E+09

[a] *Restricted activity days.*
[b] *Days with lower respiratory symptoms; all ages included.*
[c] *including days on medication.*

Table V. Sensitivity analysis on adult mortality from $PM_{2.5}$ exposure.
Life years gained annually due to insulation scenario.
Analyse de sensibilité sur la mortalité des adultes due aux $PM_{2.5}$. Nombre d'années de vie gagnées avec le programme d'isolation des bâtiments.

	Sens	Core	Sens	Sens	Sens
	COMEAP lower bound suggetion 0.1%/µgm-3	0.6%/µgm-3	US EPA lower bound judgment 0.7%/µgm-3	COMEAP upper bound sugges-tion 1.2%/µgm-3	US EPA upper bound judgment 1.6%/µgm-3
Finland	5	31	36	60	79
Sweden	17	98	114	190	249
Austria	90	526	610	1022	1338
Belgium	630	3684	4277	7156	9363
Denmark	121	708	822	1375	1801
Germany	3850	22524	26149	43763	57277
Ireland	63	370	429	719	941
France	1397	8178	9494	15896	20811
Luxembourg	16	94	104	182	239
Netherlands	857	5014	5820	9738	12742
United Kingdom	1990	11643	13517	22627	29618
Italy	498	2913	3382	5665	7418
Spain	470	2752	3195	5351	7006
Greece	67	392	456	763	999
Portugal	107	626	726	1216	1593
Estonia	6	35	41	68	89
Latvia	15	89	103	172	226
Lithuania	39	231	268	449	589
Poland	2083	12187	14148	23767	30986
Romania	379	2217	2574	4310	5644
Slovakia	113	662	769	1288	1686
Slovenia	20	117	136	227	297
Bulgaria	80	471	547	916	1199
Czech Republic	240	1404	1630	2730	3574
Hungary	293	1714	1990	3332	4363
All states	13446	78678	91339	152983	200126

Table VI. Sensitivity analyses on societal costs from adult mortality from $PM_{2.5}$ exposure. € saved annually with insulation scenario.
Analyse de sensibilité sur les coûts économisés (€ par an) dus au nombre d'années de vie gagnées avec le programme d'isolation des bâtiments.

	Sens	Core	Sens	Sens	Sens
	COMEAP lower bound suggestion 0.1%/µgm^{-3}	**0.6%/µgm^{-3}**	**US EPA lower bound judgment 0.7%/µgm^{-3}**	**COMEAP upper bound suggestion 1.2%/µgm^{-3}**	**US EPA upper bound judgment 1.6%/µgm^{-3}**
Finland	2.86E+05	1.68E+06	1.95E+06	3.26E+06	4.27E+06
Sweden	9.02E+05	5.28E+06	6.13E+06	1.03E+07	1.34E+07
Austria	4.85E+06	2.84E+07	3.30E+07	5.52E+07	7.23E+07
Belgium	3.40E+07	1.99E+08	2.31E+08	3.86E+08	5.06E+08
Denmark	6.53E+06	3.82E+07	4.44E+07	7.43E+07	9.72E+07
Germany	2.08E+08	1.22E+09	1.41E+09	2.36E+09	3.09E+09
Ireland	3.41E+06	2.00E+07	2.32E+07	3.88E+07	5.08E+07
France	7.54E+07	4.42E+08	5.13E+08	8.58E+08	1.12E+09
Luxembourg	8.66E+05	5.07E+06	5.64E+06	9.84E+06	1.29E+07
Netherlands	4.63E+07	2.71E+08	3.14E+08	5.26E+08	6.88E+08
United Kingdom	1.07E+08	6.29E+08	7.30E+08	1.22E+09	1.60E+09
Italy	2.69E+07	1.57E+08	1.83E+08	3.06E+08	4.01E+08
Spain	2.54E+07	1.49E+08	1.73E+08	2.89E+08	3.78E+08
Greece	3.62E+06	2.12E+07	2.46E+07	4.12E+07	5.40E+07
Portugal	5.77E+06	3.38E+07	3.92E+07	6.57E+07	8.60E+07
Estonia	3.24E+05	1.90E+06	2.20E+06	3.69E+06	4.83E+06
Latvia	8.17E+05	4.79E+06	5.56E+06	9.31E+06	1.22E+07
Lithuania	2.13E+06	1.25E+07	1.45E+07	2.43E+07	3.18E+07
Poland	1.12E+08	6.58E+08	7.64E+08	1.28E+09	1.67E+09
Romania	2.04E+07	1.20E+08	1.39E+08	2.33E+08	3.05E+08
Slovakia	6.11E+06	3.58E+07	4.15E+07	6.95E+07	9.10E+07
Slovenia	1.08E+06	6.30E+06	7.32E+06	1.23E+07	1.60E+07
Bulgaria	4.34E+06	2.54E+07	2.95E+07	4.95E+07	6.48E+07
Czech Republic	1.3E+07	7.58E+07	8.8E+07	1.47E+08	1.93E+08
Hungary	1.58E+07	9.26E+07	1.07E+08	1.8E+08	2.36E+08
All states	7.26E+08	4.25E+09	4.93E+09	8.26E+09	1.08E+10

3.1. Sensitivity analyses

In the sensitivity analysis performed with median rather than mean VOLY, the saved societal cost associated with adult mortality amounted to 9.84 billion €/year, a 48% increase from the core analysis. In the analyses based on mean and median VSL the saved societal costs amounted to 13.67 and 6.69 billion €/year respectively; i.e. either a doubling or no significant change from the core analysis.

The sensitivity analyses performed with the mean rather than median value of a saved infant's life resulted in a 2-fold increase, i.e. saved costs of 20 million €/year, increasing to 26 million €/year when using the mean marginal rate of substitution of 2.0.

The sensitivity analyses performed with the CRF ranges for adult mortality suggested by the COMEAP and EPA expert panels resulted in saved costs of 726 million €/year with a CRF of 0.1% per µg/m^3 increase in annual $PM_{2.5}$ and 10807 million €/year with a CRF of 1.6% per µg/m^3 increase in annual $PM_{2.5}$. These extremes correspond to 11-163% of the core analysis costs.

Details on the sensitivity analyses are provided in tables V and VI. The extreme ranges of the sensitivity analyses obtained by combining the smallest CRF with the lowest valuation and the biggest CRF with the highest valuation yielded a range between 1.5 and 40 billion € saved annually, i.e. 23-602 % of the core analysis valuation.

4. Discussion

Our analysis of health effects associated with an improved insulation scenario compared with a business as usual scenario in Europe from 2005 to 2020 revealed substantial benefits and particularly so regarding the number of LY lost in Central Europe. Effects, however, were discernible in all of the 25 EU states studied except Finland and Sweden. The annual health benefits within the EU-25 included 78,678 saved LY and societal cost savings of 6.64 billion €. The study provided detailed results for health effect known to be associated with air pollution on the country level as well as sensitivity analyses assuming different impacts and costs. The analyses covered a population of almost 0.5 billion and a large region, relied on suggested ranges of impacts and costs provided by CAFE/HEIMTSA (Hurley et al., 2005; HEIMTSA, 2011) and by expert elicitations for core and sensitivity analyses in accord with suggested methods (Pervin et al., 2008). In addition, we applied life-table analyses at the national level that account for population dynamics caused by historical exposure. Changes in criteria air pollutant concentrations on a per country basis was derived from an air-quality model, and were found to be in line with results from other state-of-the-art regional air-quality models (Korsholm et al., 2012). Uncertainties in relation to the insulation levels, energy sources and consumption, the scenario, and the models used are discussed in detail therein.

Our analysis is a one-year picture, assuming 2009 meteorology and 2009 populations (or as close as possible in states without 2009 data) of a sustained improved insulation scenario policy from 2005-2020. Economic valuation is expressed in 2005 value. It is conservative, including only health effects and costs agreed upon in the CAFE/HEIMTSA reports (Hurley et al., 2005; HEIMTSA, 2011). Thus it is an investigation of the health effects and associated costs that would have occurred some years from 2005 if an improved insulation scenario had been implemented in new and existing houses rather than a study of the effects in a particular real year.

Sufficient time for the health effects to change fully after exposure reduction is inherently assumed in the study and we did not include lag-times. This assumption is reasonable considering that there is "a fair amount of evidence for a good proportion of the benefits from a reduction in $PM_{2.5}$ appearing in the first few years" (Walton, 2011). We did not convert the changes in LY into numbers of avoidable deaths although this is commonly used to express mortality effects. As stated by COMEAP LY gained or lost is "the most comprehensive way of capturing the full effects" and "is the most relevant index for policy analysis". A factor of 1/10.6 can be used to convert LY lost or gained into number premature deaths as done in the CAFE reports (Watkiss et al., 2005) although greater accuracy would require country-based disease-specific mortality rates.

We also did not include interest rates, as it would require focusing on specific spans of years and because there is no commonly agreed upon interest rate for use in environmental health impact studies across the EU-25 states. Applying interest rates can change the economic consequences of projected changes significantly. If, in our case, we assume the full effect in 2009 (from 2005) and we apply a 3% interest rate, the saved costs would be 6.06 rather than 6.64 billion €. Extending this into 2020, the final year of our scenario, would reduce the saved costs substantially as would higher interest rates applied in some EU states. To what degree such an extension would be counterbalanced by an increased population of elderly particularly susceptible to the effect of air pollution is unpredictable.

A full cost-benefit analysis was out of scope of the paper as were effects of pollutants on crops and constructions. Effects on air pollution, and thus on health, from possible energy scenarios other than the improved insulation scenario were not considered. Therefore, and in contrast to Levy et al. (2003), we did not consider production of the insulation material or costs of the improved insulation scenario. Nishioka et al. (2006) investigated insulation from current practice to the levels recommended by the 2000 International Energy Conservation Codes (IEE, 2000) in new and existing housing in the U.S., considering energy reduction in the homes, energy for production of mineral wool, economic impacts for the homeowners, and interest rates and observed that "the total disease-adjusted life years saved from the fuel supply chain is four times larger than the total disease-adjusted life years added from the mineral wool supply chain". We have no reason to believe that this would be substantially different in the region of the EU-25. Atmospheric chemistry interactions are non-linear and without running the model for each scenario it is unpredictable how concentrations of air pollutants would change given other projected changes to emission than the improved insulation scenario. An example is that the amount of secondary ammoniated sulfate and nitrate formed is dependent on the available atmospheric ammonia that changes with farming practices (Yim et al., 2013).

Considerations on how to best calculate costs associated with loss of LY and morbidity endpoints are clearly also out of scope of this paper. Such considerations are, however, important and revisions of the valuation conducted as part of the CAFE program almost a decade ago are possibly warranted. The diversity of the EU-25 economies further complicates the issue. Our cost-evaluation approach with application of similar costs per outcome across Europe was based on EU programs such as CAFE (Holland et al., 2005) and HEIMTSA (HEIMTSA, 2011) and in line with the OECD guidance on environmental cost benefit analysis (OECD, 2006).

The CAFE analysis reported that the annual societal cost of the total amount of air pollution in the EU-25 states were approx. 513 billion € in 2000 (using VOLY mean as in the present study) (Watkiss et al., 2005). Our model suggests that 1.3% could be saved with the proposed insulation program.

The CAFE quantification of health impacts and subsequent valuation was done for the European Commission DG Environment and aimed at consistency with the WHO "Systematic Review of Health Aspects of Air Quality in Europe" (Holland et al., 2005). It has formed the basis of previous European quantifications of effects of air pollution. The HEIMTSA report from 2011 was based on the CAFE results but reviewed the CRF extensively and was used for our study (HEIMTSA, 2011). However, only the CRF for chronic bronchitis and respiratory hospital admissions changed from CAFE to HEIMTSA. Valuation of mortality and morbidity was dealt with extensively in the CAFE reports (Holland et al., 2005) and included a substantial discussion of the use of the VSL versus the VOLY approach. To our knowledge no extensive work has been published on this issue in Europe since the CAFE report suggestion of comparing median and mean costs from both VSL and VOLY. These methods and estimates are widely used, e.g. by the European Environment Agency (EEA, 2011).

Several other adverse health effects than those considered in this study have been sufficiently documented for inclusion in evaluations of air pollution related health effects and costs (Bickel and Friedrich, 2005; HEIMTSA, 2011). Additional effects on, e.g. restricted activity days, lung cancer, or asthma are commonly included in similar studies, e.g. (Wong et al., 2004; Brandt et al., 2013). In addition, effects on intrauterine growth intelligence and lung development in childhood, and associations with diseases including diabetes, appendicitis, airway infections, and rheumatoid arthritis have been reported, e.g. in (Medina-Ramon et al., 2006; Gauderman et al., 2007; Brauer et al., 2008; Hart et al., 2009; Kaplan et al., 2009; Puett et al., 2011; Andersen et al., 2012; Bellinger, 2013). In addition, some of the CRF applied in our study are probably underestimating the health effects. This particularly regards the calculations on hospitalizations as these are based on studies of short term changes in air pollution. It has consistently been shown that long-term effects of PM on mortality are several times stronger than short-term effects. It is unlikely that hospitalization rates should differ in that respect. In addition $PM_{2.5}$ effects on mortality are usually stronger per µg than are effects of PM_{10} (reflecting the fact that $PM_{2.5}$ makes up part of PM_{10}). In the case of infant mortality the CRF was available only for PM_{10} although in this study the entire change in PM_{10} was caused by changes in $PM_{2.5}$ - probably underestimating the effect.

The changes in air pollutant concentrations in this study are mean changes based on a 15-year long period assuming application of the improved insulation scenario. During such a period a likely occurrence is a substantial increase of elderly people in the region under study, resulting in a larger group of vulnerable people and thus greater potential for positive effects of decreased pollution. Other changes in lifestyle and in disease prevalences are predictable. Consideration of such demographic changes was recently demonstrated to have significant impact on long-term studies of health and social cost impacts from air pollution (Flachs et al., 2013).

Despite its widespread use in other studies, the CRF used for adult mortality (of 0.6% per µg/m^3 $PM_{2.5}$) could also be an underestimate. Re-analyses of the Harvard Six Cities Study as well as some analyses on the American Cancer Society Study have suggested greater effects, in particular when taking into account socio-economic determinants (Krewski et al., 2000).

Accordingly, a CRF higher than 0.6% has been applied in recent studies (Levy et al., 2010; Anenberg et al., 2012; Shindell et al., 2012; Yim et al., 2013). The fact that our core estimate of 6.6 billion € is in the lower sixth of the range of the sensitivity analyses based on expert elicitations partly corroborates this view (US-EPA, 2006). In a report by the UK Committee on the Medical Effects of Air Pollutants (COMEAP, 2009) a plausibility distribution based on Members' consolidated views was developed suggesting the use of the coefficients 1% and 12% for use in sensitivity analysis. In an expert elicitation from the United States Environmental Protection Agency (US-EPA, 2006) median estimates ranged from a 0.7 to 1.6 % decrease in annual, adult, all-cause mortality per 1 µg/m^3 decrease in annual average $PM_{2.5}$. We considered these ranges for sensitivity analyses more appropriate than the confidence intervals provided in a single study. Yet the core change in mortality that we calculated is not negligible and it corresponds to approximately 0.1% of the total mortality in the considered states. This figure is 10 times higher than in the study by Levy et al. (2003) on retrofit of insulation in the US. Several methodological differences between the studies may explain the difference. Most importantly Levy et al. assessed an IEE 2000 insulation scenario that may be less strict than our improved insulation scenario; the U.S. energy supply differs from the European; the study only considered retrofitting existing houses; and it passed from emission changes over intake fraction to health rather than modeling atmospheric chemistry and passing from concentrations in ambient air to health effects.

Changed quality of indoor air as a result of increased insulation, of changed concentrations of pollutants penetrating from outdoors, or from less indoor emissions in homes heated with wood stoves would be likely additional effects of the improved insulation scenario. Without changes to ventilation, houses become tighter with increased insulation which results in deteriorating indoor air quality due to increased humidity but also in greater thermal comfort and less infiltration of polluted ambient air in cities. Although indoor air quality can significantly affect health (Pekkanen et al., 2007) it was out of scope to estimate these very complex effects.

A model of a household energy efficiency program in the UK, focusing on indoor air effects from increased insulation, phasing out of indoor fossil fuel combustion, and average temperature reduction revealed that more than 115 disease-adjusted life years could be saved per million population for each of the 33 megatons CO_2 saved from just the insulation improvements (Wilkinson et al., 2009). However, the study also demonstrated the importance of improved ventilation, which if not ensured when insulation improves may increase indoor radon, secondhand tobacco and mold problems. On the other hand, improved insulation can also help protecting dwellers from thermal stress in a warming climate (Haines and Dora, 2012). However, if adequate ventilation is not built into energy efficient building projects and indoor pollutants increase as a result, the negative health effects may end up dominating the positive effects.

5. Conclusions

This analysis showed that an ambitious building insulation scenario of new houses and with a 2% annual retrofit ratio of existing houses in Europe could result in 78678 saved LY with the strongest effects in Central Europe and in reductions to morbidity and societal costs that would not be trivial. Sensitivity analyses indicate that the effects may be underestimated. Health effects associated with decreased carbon emissions as well as from changed indoor air quality were not considered. Our results suggest that climate mitigation costs associated with housing insulation will be partly counterbalanced by societal savings.

Abbreviations used

CAMx, Comprehensive Air-Quality Model with extensions; CAFE, Clean Air for Europe, CO_2, carbon dioxide; CRF, concentration-response function; EPA, Environmental Protection Agency; EU, European Union; IEE 2000, the 2000 International Energy Conservation Codes; HEIMTSA, Health and Environment Integrated Methodology and Toolbox for Scenario Development; ICD, International classification of disease; LRS, lower respiratory symptoms; LY, life-years; OECD, Organisation for Economic Co-operation and Development; PM, particulate matter; RAD, restricted activity days; RR, relative risk; VOLY, value of a life-year; VSL, value of a statistical life; WHO, World Health Organization.

Competing financial interests declaration

The sponsors of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication. None of the authors had any other perceived or actual competing financial interests. In particular, no optional future funding from any of the sponsors has been proposed during this research which could depend on the current results.

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