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Efficient reduction of indoor exposures

Health benefits from optimizing ventilation, filtration and indoor source controls

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Foreword

Every citizen has an uncompromised right to a healthy living environment [1]. Unfortunately, as we can almost daily read from the newspapers, this is not yet reality in Finland or elsewhere in the Europe. Air pollution is estimated to be the leading cause of environmental burden of disease in Europe [2]. While more than half of this burden originates from outdoor air pollution, quite regularly many people including school children, adults and senior citizens are found living, studying and working in buildings seriously affected by moisture, dampness and mould and other problems generated by indoor sources of pollution.

In the context of a European Union research project HEALTHVENT [3, 4], aiming at defining health-based European guidelines for ventilation, we developed a quantitative model for evaluating the impacts of ventilation on the population exposures to pollution from indoor and outdoor sources. The current report presents an overview of the intrinsic gentle balance of ventilation and indoor and outdoor sources of pollution and estimates of the health effects, aiming at a quantitative understanding of the underlying mass-balance processes, and ultimately, development of informed control policies, that would allow us to reach the uncompromised safe state of our living environment.

Otto Hänninen

May 2013
Kuopio, Finland

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[2] Hänninen O, Knol A (eds.), 2011. European perspectives on Environmental Burden of Disease; Estimates for nine stressors in six countries. THL Reports 1/2011, Helsinki, Finland. . http://www.thl.fi/thl-client/pdfs/b75f6999-e7c4-4550-a939-3bccb19e41c1
[3] Project website http://www.healthvent.byg.dtu.dk
[4] http://www.efanet.org/healthvent-results-presented-at-the-european-parliament/

Contributors

This report presents an overview of results from a number of national and international studies. The report is a key contribution to the national TEKAISU project and the work has especially benefited from the work conducted in the HEALTHVENT project, but includes substantial inputs also from the following projects and persons that have had key contributions to the evaluations presented:

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Symbols and abbreviations

ACH	Air changes per hour, a measure of AER (see below)
AER, a	Air exchange rate, expressed as air changes per hour (ach, h^{-1})
CV	Coefficient of variation (CV=SD/mean)
CO, CO_2	Carbon monoxide, carbon dioxide
GSD	Geometric standard deviation
IAQ	Indoor air quality
lps	ventilation rate in litres per second
lps pp	ventilation rate litres per second per person
n_{50}	air leakage rate per hour at 50 Pa pressure test conditions
$PM_{2.5}$, PM_{10}	Particulate matter (aerodynamic size <2.5 and 10 µm, respectively)
pp	per person
SD	Standard deviation
THL	National Institute for Health and Welfare
VOC	Volatile organic compounds
WHO	World Health Organization
WP	Work Package

The following variables are used in the HEALTHVENT health impact model.

Concentration variables (µg/m^3, Bq/m^3)

C_a	Outdoor (ambient) concentration
C_i	Indoor concentration
C_{ai}	Indoor concentration of outdoor pollution
C_{ig}	Indoor concentration of indoor generated pollution
F_{inf}	Infiltration factor (fraction)
a, aer	Air exchange rate (ach or h^{-1})
P	Penetration efficiency (fraction) of outdoor pollutant entering indoors
k	Decay rate (h^{-1}) of a pollutant indoors
f	Adjustment factor (unitless) of air exchange rate
G	Indoor source strength (µg/h)
Q	Ventilation volume (m^3/h)
V	Volume of indoor space (m^3)

Burden of disease variables

BoD	Burden of disease (DALY, in years)
DALY	Disability-adjusted life years
DW	Disability weight (0=perfect health, 1=death)
L	Average length of a disease (in years)
PAF	Population attributable fraction (of a disease)
RR	Relative risk
YLD	Years lived with disability (DALY)
YLL	Years of life lost (due to premature mortality) (DALY)

Tiivistelmä

Otto Hänninen and Arja Asikainen (Eds.). Efficient reduction of indoor exposures - Health benefits from optimizing ventilation, filtration and indoor source controls. [Optimoidun ilmanvaihdon terveyshyödyt - Sisäilma-altistuksen tehokas alentaminen]. Terveyden ja hyvinvoinnin laitos (THL). 93 sivua. Helsinki 2013. ISBN 978-952-245-821-6 (painettu); ISBN 978-952-245-822-3 (verkkojulkaisu)

Epäpuhtaan sisäilman aiheuttamaksi tautikuormaksi on arvioitu vuosittain EU:ssa yli 2 miljoonaa menetettyä tervettä elinvuotta (disability-adjusted life years, DALY), joista Suomessa 13 300. Tämä tautikuorma aiheutuu osittain sisäilman epäpuhtauksista, mutta pääasiallinen tekijä ovat ulkoilman epäpuhtaudet, jotka pääsevät sisätiloihin ilmanvaihdon ja ilmavuotojen kautta. Koska epäpuhtauksien lähteinä toimii sekä sisä- että ulkoilma, on ilmanvaihdon oikeaksi säätäminen haasteellista. Tämä raportti tarjoaa viitekehyksen vaikuttavien tekijöiden tasapainottamiseksi.

Maailman terveysjärjestö (WHO) julkaisi ilmanlaadun ohjearvot kosteus- ja homevaurioiden aiheuttamille epäpuhtauksille vuonna 2009. Tästä huolimatta näiden vaurioiden aiheuttamista ongelmista raportoidaan sanomalehdissä lähes päivittäin, vahvistaen ettei ongelmaa ole onnistuttu ratkaisemaan Suomessa eikä muissakaan maissa. WHO:n ulkoilman ohjearvot ilmestyivät jo vuonna 2000, mutta arviolta 90 % eurooppalaisista asuu edelleen aluilla joissa ohjearvo pienhiukkasille (10 $\mu g/m^3$) ylitetään. Suomessa tilanne on parempi, ja WHO:n $PM_{2.5}$ vuosiohjearvo ylittyy vain suppeilla alueilla. Tästä huolimatta yli 60 % sisäympäristön aiheuttamasta tautikuormasta johtuu sisäilmaan kulkeutuneista ulkoilman saasteista myös Suomessa.

Eurooppalaiset terveysperustaiset ilmanvaihdon ohjeet koottiin EU-rahoitteisessa HEALTHVENT-projektissa (2010-2013). Tässä raportissa esitetään numeerinen menetelmä sisä- ja ulkoilman altisteiden tautikuorma-arvioiden tasapainottamiseksi merkittävimmille altisteille, ja tuotetaan tarvittavat tiedot tautikuorman vähentämiseen tähtäävien tehokkaiden rajoittamispolitiikkojen muodostamiselle. Arviot huomioivat kaikki merkittävät tiedossa olevat epäpuhtaudet, vaikkakin uutta tietoa vähemmän merkittävistä riskitekijöistä tulee jatkuvasti esille. Nämä riskitekijät voivat olla merkittäviä pienille erityisryhmille.

Tämän raportin tulokset varmistavat, että sisäilman terveysriskejä ei voida alentaa hyväksyttävälle tasolle ottamatta huomioon kaikkia altistukseen vaikuttavia tekijöitä: ulkoilman lähteet, ulkoilman epäpuhtauksien infiltraatio, sisäilmalähteet ja ilmanvaihto. Kaikkien näiden tekijöiden tehokas hallinta on ainoa keino varmistaa terveellinen sisäilma kaikissa tilanteissa.

Avainsanat: Sisäilman laatu; ilmanvaihto; sisäympäristön altistus; tautikuorma

Sammandrag

Otto Hänninen and Arja Asikainen (Eds.). Efficient reduction of indoor exposures - Health benefits from optimizing ventilation, filtration and indoor source controls. [Effektiv minskning av inomhusexponeringar - Hälsofördelar med optimerad ventilation, luftfiltrering och kontroll av inomhuskällor]. Terveyden ja hyvinvoinnin laitos (THL) (Institutet för hälsa och välfärd). 93 sidor. Helsingfors 2013. ISBN 978-952-245-821-6 (tryckt); ISBN 978-952-245-822-3 (nätpublikation)

Den årliga sjukdomsbördan orsakad av dålig inomhusluftkvalitet uppskattas motsvara en förlust av över två miljoner friska levnadsår i EU och 13 300 i Finland. Denna börda orsakas av föroreningskällor som finns i inomhusluften, men framför allt också av förorenad utomhusluft som används för ventilation. Eftersom föroreningskällor finns i både inomhus- och utomhusluften, är det utmanande att välja den bästa ventilationsstrategin. Denna rapport ger en kvantitativ ram för att hitta en balans mellan de påverkande faktorerna.

Världshälsoorganisationen publicerade år 2009 riktlinjer för inomhusluftkvalitet, för föroreningar orsakade av fukt och mögel. Trots det bekräftar nästan dagliga rapporter i tidningar att problemet inte har lösts i Finland eller någon annanstans. Luftföroreningar utomhus spelar en stor roll i uppkomsten av föroreningar inomhus. Cirka 90 % av européerna bor i områden där Världshälsoorganisationens riktvärden för $PM_{2,5}$ (10 µg/m^3) inte uppnås. I Finland är situationen bättre med bara små delar av landet som överskrider WHO:s årsriktvärde för $PM_{2,5}$. Ändå utgör föroreningarna från utomhusluften fortfarande också i Finland över 60 % av sjukdomsbördan som är orsakad av inomhusmiljön.

De hälsobaserade europeiska riktlinjerna för ventilation har utvecklats under 2010–2013 i det EU-finansierade projektet HEALTHVENT. Syftet med denna rapport är att utveckla en numerisk beräkningsmetod för sjukdomsbördan som orsakas av inomhus- och utomhuskällor och presentera nödvändig bakgrundsinformation för utvecklingen av en effektiv kontrollpolitik för att minska bördan. Alla de större kända föroreningskällorna behandlas i rapporten, men nya bevis på mindre riskfaktorer kommer kontinuerligt fram. Särskilt för vissa mindre befolkningsgrupper kan sådana nya risker spela en betydande roll.

De resultat som presenteras i denna rapport visar övertygande att de hälsorisker som orsakas av exponeringar via inomhusluften inte kan reduceras till en acceptabel nivå utan att redovisa alla viktiga faktorer som påverkar exponeringar: utomhuskällor och infiltration, inomhuskällor och ventilation. Att ha full kontroll över alla dessa faktorer är det enda möjliga sättet att ge hälsosam inomhusluft till alla.

Nyckelord: Inomhusluftkvalitet, ventilation, luftväxling, inomhusexponering, sjukdomsbörda

Abstract

Otto Hänninen and Arja Asikainen (Eds.). Efficient reduction of indoor exposures - Health benefits from optimizing ventilation, filtration and indoor source controls. Terveyden ja hyvinvoinnin laitos (THL). 93 pages. Helsinki 2013. ISBN 978-952-245-821-6 (printed) ISBN 978-952-245-822-3 (online publication)

The annual burden of disease caused by inadequate indoor air quality is estimated to correspond a loss of over 2 million healthy life years in the EU and 13 300 in Finland. This burden is caused by indoor sources of pollution, but especially also by polluted outdoor air used to ventilate indoor spaces. Because sources of pollution reside in both indoor and outdoor air, selecting the best ventilation strategy is tricky. The current report provides a quantitative framework for balancing between the influential factors.

World Health Organization published indoor air quality guidelines for dampness and mould in 2009. Nevertheless almost daily reports in newspapers painfully confirm that the problem has not been solved in Finland or elsewhere. Outdoor air pollution plays a significant role in creating the indoor exposures. Approximately 90 % of Europeans live in areas where the World Health Organization Guideline for $PM_{2.5}$ (10 µg/m^3) is not attained. In Finland the situation is better with only limited areas exceeding the annual WHO $PM_{2.5}$ Guideline. Nevertheless, still also in Finland over 60% of the burden of disease caused by indoor exposures is estimated to originate from outdoor air.

European health-based ventilation guidelines were developed in 2010-2013 in the EU-funded HEALTHVENT project. The aim of the current work is to develop a mass-balance framework for balancing the impacts of the major sources of burden of disease, providing background information for the development of efficient control policies to reduce the burden. All known major pollutants are covered; however, new evidence on smaller risk factors becomes continuously available. Especially for certain smaller population groups such emerging risks can play a significant role.

The results presented in this report show convincingly that the health risks caused by indoor exposures cannot be reduced to an acceptable level without accounting for all major factors modifying exposures: outdoor sources and infiltration, indoor sources, and ventilation. Acting efficiently on all is the only possible way forward in providing healthy indoor air to all.

Keywords: Indoor air quality; ventilation; air exchange; indoor exposures; burden of disease

Content

To the Reader

Health is a crucial prerequisite for a functional society, proper performance at school and work, and a significant determinant of life satisfaction and wellbeing. World Health Organization has defined criteria for health and has set healthy indoor environments as every a basic right (WHO, 2000a).

Recently conducted EBoDE (Hänninen & Knol, 2011; Hänninen et al., 2013) and SETURI (Pekkanen, 2010; Hänninen et al., 2010) studies, supported by the Ministry of Health and Social Affairs, have confirmed that environment is continuously a significant contributor to the burden of disease in Europe. Even in Finland, which represents the cleaner part of our continent regarding most exposures, the health risks remain unacceptably high and especially air pollutants represent substantial risks.

The importance of indoor air has been long recognized. Already in the 1980's Aino Nevalainen (1989) studied microbial indoor exposures, but only relatively recently the quantitative assessments of the health risks caused by air pollution exposures have been able to compare the relative roles of indoor and outdoor sources on the health risks. The EnVIE study (de Oliveira Fernandes et al., 2009) was the first attempt to use European wide data combined with burden of disease methodology to provide comparable risk estimates for a range of major indoor air pollutants. The work was taken forward in the IAIAQ-project (Jantunen et al., 2010) in terms of significantly improving the data coverage and exposure assessments. These studies form the ground on which the current report is built.

Efficient policies to reduce environmental health risks can only be developed, if the risks are first well known in both qualitative as well as quantitative terms. The Ministry of Health and Social Affairs is currently actively pressing forward development of policies to improve environmental health. One of the leading activities in this field is the TEKAISU-project (2011-2015), aiming at scientific prioritization of policy options in terms of their projected efficiencies. The work includes identification of alternative exposure control policies, evaluation of their efficiencies and prioritization of them according to their risk reduction potentials. The current report represents an essential part of the TEKAISU process by providing mass-balance estimates of the roles of indoor and outdoor sources and ventilation on the health risks of indoor air.

1 Introduction

Indoor air quality (IAQ) in buildings is prescribed by existing minimum standards for ventilation and the result is far too often poor. At present ventilation standards (e.g. EN15251) define ventilation in non-industrial buildings to meet comfort requirements of occupants, specified by the percentage of dissatisfied with indoor air quality and/or by the intensity of odour. While comfort is an important factor, it does not fully cover more serious health impacts like asthma, allergies, chronic obstructive pulmonary disease, cardiovascular diseases, lung cancer and acute toxication that are caused by exposures to pollutants present in indoor air. There are no European guidelines which recommend how the buildings should be ventilated for the best health of the occupants.

Large range of pollutants has been associated with health effects. In detailed carefully designed studies even small impacts can be observed with high statistical accuracy. All identified hazards, however, do not represent equal public health concerns, and legislation and standards naturally should focus on factors that have wide importance.

Figure 1. Countries included in international IAQ assessments presented in this report and referred to as EU26 (EU27 excluding Malta).

A quantitative risk assessment model for indoor exposures has been developed in a series of studies participated and coordinated by National Institute for Health and Welfare. The original EnVIE study presented a conceptual framework for linking sources to exposures and health impacts, and evaluate these from the perspective of policies (de Oliveira Fernandes et al, 2009). The EnVIE model was further elaborated in the IAIAQ-project, in which the coverage of the exposure data was substantially improved Due to the lack of exposure data Malta is missing from the assessments covering thus 99.92% of the EU27 population (Figure 1).

The exposures that were identified as playing a significant role as public health risks range from particulate matter (PM, e.g. $PM_{2.5}$ and PM_{10}) to volatile organic compounds (VOCs) (Table 1). Much larger number of pollutants have been associated with health responses, but either play a small role from the point of view of public health, or pose challenges for the exposure assessment or quantification of the burden of disease. Thus the discussion in this report is based on the assumption that the exposures listed in Table 1 represent the most important indoor air quality determining factors and should be accounted for in balancing source controls and ventilation for optimal health. Health determinants of housing in general are discussed in WHO 2011, safe levels of specific chemicals indoors in WHO 2010 and dampness and mould specifically in WHO 2009.

Table 1. Major sources of exposures occurring in indoor air and significantly contributing to the public health risks.

Major exposures	Examples of sources
Indoor origin	
Particulate matter ($PM_{2.5}$)	Cooking, cleaning, living, smoking…
Dampness and moulds	Structural moisture, humidity, biological growth
Second hand smoke (SHS)	Smoking
Radon (Rn)	Soil, (construction materials)
Carbon monoxide (CO)	Combustion devices
Volatile organic compounds (VOC) - formaldehyde, benzene, etc.	Building materials, furniture, consumer products
Outdoor origin	
Particulate matter ($PM_{2.5}$)	Traffic, combustion etc.
Bioaerosols (pollens)	Vegetation
Ozone (O_3)	Atmospheric photochemistry
Volatile organic compounds (VOC) - benzene etc.	Combustion processes etc.

1.1 Ventilation and health

Ventilation is one of the technologies used to control the quality of indoor environment, including thermal conditions and humidity, structural moisture and mould growth, extraction and dilution of emissions from indoor sources and infiltration of ambient air pollution indoors. These roles of ventilation are highlighted in the flow chart in Figure 2, developed as part of the health-based ventilation guidelines in the HEALTHVENT-project.

Emission sources are the primary causes of exposures to indoor and outdoor originating pollutants. When discussing optimal ventilation, it should be remembered that source control is almost always more efficient in controlling exposures than diluting the emissions into the occupied space. The current document aims at demonstrating the importance of the source controls in efficient protection of health.

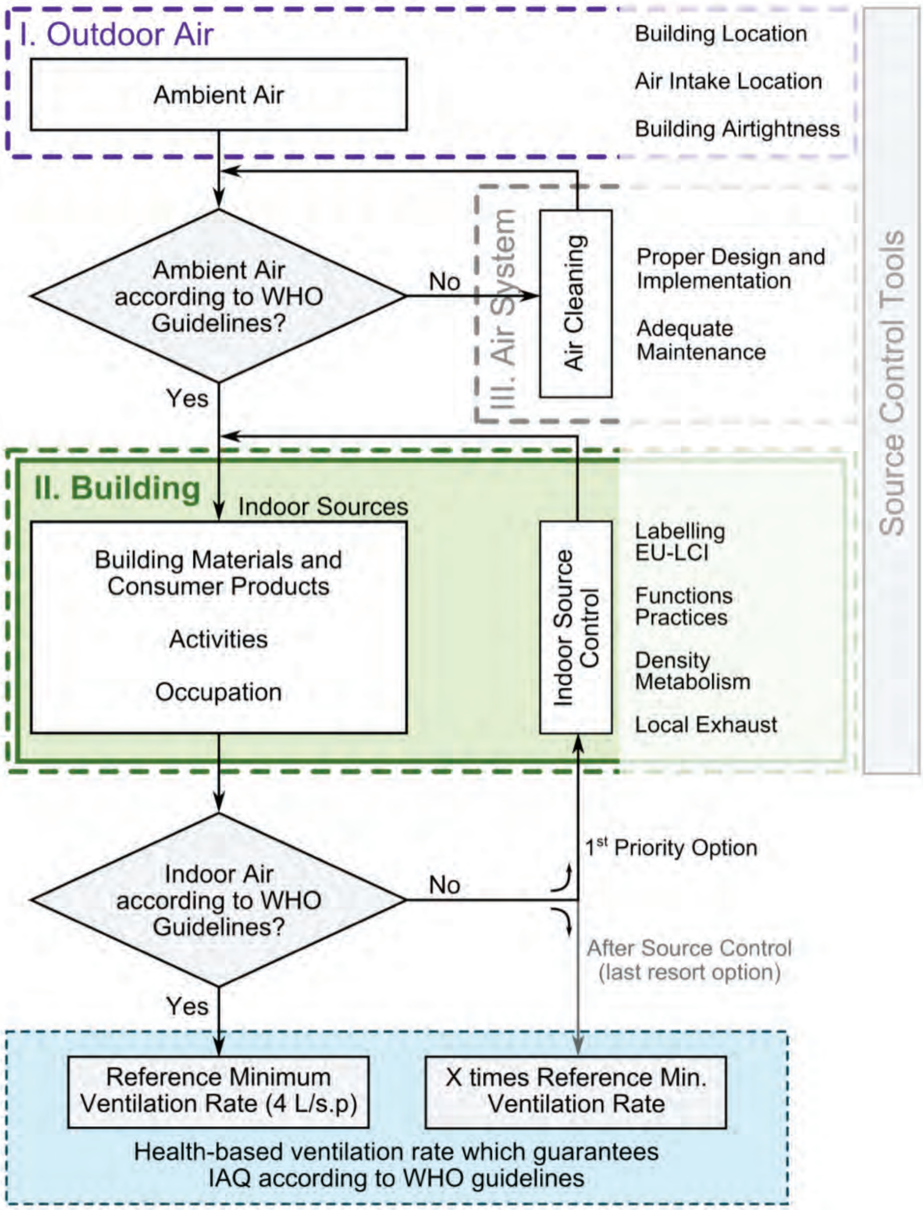


Figure 2. Flowchart of the health-based ventilation guidelines as defined in the HEALTHVENT –project (ECA, 2013)

2 Objectives of this report

Indoor air in Finland and in all studied European countries is beyond reasonable doubt associated with substantial health risks, estimated to correspond a loss of over 2 million healthy life years annually. The current work aims to summarize the current understanding of the sources of health risks in indoor environments and their relationship with ventilation levels (this part of the work was conducted in the HEALTHVENT project). The results are specifically investigated to understand and prioritize alternative strategies to control these health risks (TEKAISU project). To accomplish these tasks, we present a quantitative framework for balancing the exposures and risks in combination with their sources and ventilation.

The methods presented here allow for informed health-based optimization of efforts aimed at reducing harmful exposures and improving health of the occupants. The results are intended for development of national and international guidelines and standards, but can be used as background information also in analysing indoor air quality related issues in buildings.

Specifically, the current report has the following objectives:

1) To present an overview of the main sources of health risks present indoors and their relative magnitudes.

2) To provide a quantitative framework for estimation of long-term health effects and benefits for EU and Finnish citizens for protecting them against health risks due to poor indoor air quality in new and existing non-industrial buildings.

3) To quantify the burden of disease by exposures and by diseases in order to allow for implementation of efficient exposure reduction policies to achieve cost effective health benefits.

4) To provide information and methods for prioritization of risk management policies and resource allocation for better health, productivity and welfare, ensuring rational use of resources in Europe.

3 Indoor exposures and health effects

The heterogeneity of indoor spaces provides substantial challenges for epidemiological studies aiming at quantifying the association between indoor exposures and health. Ambient epidemiology has been extremely successful in similar task regarding outdoor air for which a small number of monitoring stations can be used to estimate exposures of large populations. In the case of indoor studies each indoor space has to be monitored separately, limiting effectively sizes of studied populations.

Moreover, many indoor studies focus mainly on acute health effects like respiratory symptoms and asthma. Investigating the association of chronic conditions, e.g. cardiovascular diseases that cause a majority of the burden of disease in the case of ambient pollution, would require long follow-up periods with corresponding exposure assessment.

For these reasons the specific evidence on the association of indoor exposures and health is much more limited than for outdoor air pollution. However, for risk assessment purposes there is no need to assume that the exposure to an identical pollutant indoors would have any different effects than exposure outdoors.

3.1 Scientific evidence on ventilation and health

Direct scientific evidence on the relationship of ventilation and health is quite limited. Recent review of epidemiological studies specifically looking at the associations between ventilation levels and health (Carrer et al, 2013) identified only few studies that observed a direct link between ventilation levels and health.

Wargocki et al. (2002) reviewed 105 papers published in peer-reviewed scientific journals, out of which 30 papers were judged to provide sufficient information on ventilation, health effects, data processing, and reporting. Ventilation was considered strongly associated with comfort (perceived air quality) and health (including sick building syndrome (SBS) symptoms, inflammation, infections, asthma, allergy, and short-term sick leaves), and that an association between ventilation and productivity (performance of office work) was indicated. The group also concluded that increasing outdoor air supply rates in non-industrial environments improves perceived air quality, but no formal cut-off point or recommendation regarding rate for control of perceived air quality was given. In some studies outdoor air supply rates below 25 l/s per person increased the risk of SBS symptoms, short-term sick leaves, and decreased productivity in office buildings. Ventilation rates above 0.5 air changes per hour (h^{-1}) in homes reduced infestation of house dust mites in Nordic countries. Wargocki et al. noted also that improper maintenance, design, and functioning of air-conditioning systems contributes to increased prevalence of SBS symptoms.

Similar results were obtained in the review by Seppänen et al. (2004). They concluded that the existing literature indicates that ventilation has a significant impact on several important human outcomes including: (1) communicable respiratory illnesses (disease prevalence or sick days); (2) sick building syndrome (SBS) symptoms; (3) task performance and productivity, and (4) perceived air quality (PAQ) as judged by building occupants or recruited sensory panels of assessors; and (5) respiratory allergies and asthma. As regards the quantitative requirements the review of Seppanen et al. (2004) showed that ventilation rate up to 20-25 L/s per person seem to decrease the prevalence of SBS symptoms. Air conditioning systems may increase the prevalence of SBS-symptoms relative to natural ventilation if not properly maintained. In residential buildings the authors conclude that the air change rate in cold climates should be at least 0.5 h^{-1}.

Li et al. (2007) performed a systematic review of the role of the built environment in the transmission of airborne infectious agents. Specifically, they examined whether there was sufficiently strong evidence in the current literature to substantiate a contributory role of ventilation rates and airflow patterns in the airborne transmission of infectious agents in different indoor settings. Li et al. concluded that there is strong evidence substantiating the association between ventilation, air movements in buildings and the transmission/spread of infectious diseases such as measles, tuberculosis, chickenpox, influenza, smallpox and SARS. However there is insufficient data to clearly define the ventilation rates that can reduce the risk of the spread of infectious diseases via the airborne route for hospitals, schools, offices, homes and isolation rooms. Very often overcrowding was identified as a factor that may be related to ventilation of buildings. However, without details of airflow rates, it was difficult to rigorously demonstrate a direct relationship between overcrowding and the airborne transmission of infection. Moreover, overcrowding may also increase disease transmission via direct contact.

Sundell et al (2011) identified 27 papers published in peer reviewed journals providing sufficient information on both ventilation rates and health effects. Multiple health endpoints showed similar relationships with ventilation rate and were biologically plausible, although the literature did not provide clear evidence on particular agents. Higher ventilation rates in offices, up to about 25 l/s per person, were shown in the reviewed literature to be associated with reduced prevalence of sick building syndrome (SBS) symptoms. Limited data suggested that inflammation, respiratory infections, asthma symptoms and short-term sick leave increase with lower ventilation rates. Home ventilation rates above 0.5 air changes per hour (h^{-1}) were shown in the reviewed papers to be associated with reduced risk of allergic manifestations among children in a Nordic climate.

None of the studies included in the reviews specifically addressed the role of outdoor air quality on indoor exposures. Neither was the existence of indoor sources systematically analysed nor exposure levels quantified. Therefore the support from these previous studies on determining the best combination of source control and ventilation levels is limited.

3.2 WHO Air Quality Guidelines

Indoor air quality has been recently lifted to focus by World Health Organization, which has reviewed the previous exposure guidelines specifically addressing exposure in indoor space (WHO 2009, 2010). Already during the previous two decades WHO had coordinated systematic reviews of scientific evidence and set Guidelines for Air Quality (WHO 2000b, 1987). These guidelines also were defined for exposures, even though indoor environments were not in particular focus.

From the evolution of the WHO Guidelines for Air Quality (Table 2) it can be seen that already in the 1980's most of the pollutants regarded hazardous today were included. Only few additions were made in the second edition released in 2000b. The Global Update in 2005 focused mainly in correcting the risk slope approach, unfortunately selected in the second edition, and adding fine particles ($PM_{2.5}$) to the guidelines. The only specific addition in the work focusing specifically on indoor exposures was naphthalene, which plays still a significant role especially in Mediterranean climate where it is used as an insecticide.

Notably, the WHO Guidelines for Indoor Air Quality do not discuss particulate matter. The previous Guideline from the Global Update (WHO, 2005) was left as it is and the potential differences in the particulate matter composition from indoor sources were not considered.

Table 2. Air pollutants recognized as hazardous to human health in the WHO Guidelines for Air Quality and the identified relevant exposure times.

	Pollutants	Edition of the WHO Guidelines (year of publication)			
		First Edition 1987	Second Edition 2000	Global Update 2006	IAQ 2010
1	1,2-Dichloroethane	**24 h**	24 h		
2	Acrylonitrile	**lifetime**	lifetime		
3	Arsenic	**lifetime**	lifetime		
4	Asbestos	**lifetime**	lifetime		
5	Benzene	**lifetime**	lifetime		lifetime
6	Cadmium	**1 a**	1 a		
7	Carbon disulfide	**24 h, 30 min**	24 h, 30 min		
8	Carbon monoxide	**15 min - 8 h**	15 min - 8 h		15 min - 8 h
9	Chromium	**lifetime**	lifetime		
10	Dichloromethane	**24 h**	**1 week, 24 h**		
11	Fluoride		**1 h**		
12	Formaldehyde	**30 min**	30 min		30 min
13	Hydrogen sulfide	**24 h, 30 min**	24 h, 30 min		
14	Lead	**1 a**	1 a		
15	Manganese	**1 a**	1 a		
16	Man-made vitreous fibres		**lifetime**		
17	Mercury	**1 a**	1 a		
18	Naphthalene				**1 year**
19	Nickel	**lifetime**	lifetime		
20	Nitrogen dioxide	**1 h**	**24 h, 1 h**	1 year, 1 h	1 year, 1 h
21	Ozone	**1 h, 8 h**	8 h	8 h	
22	PM_{10}	**24 h**	**days**	**1 year, 24 h**	
23	$PM_{2.5}$		**years**	**1 year, 24 h**	
24	Polycyclic aromatic hydrocarbons (PAH)	**lifetime**	lifetime		lifetime
25	Radon	**lifetime**	lifetime		lifetime
26	Styrene	**24 h, 30 min**	**1 week, 30 min**		
27	Sulphur dioxide	**1 hour, 10 min**	**1 year, 24 h, 10 min**	24 h, 10 min	
28	Tetrachloroethylene	**24 h, 30 min**	**1 a, 30 min**		1 year
29	Tobacco smoking (ETS)	**–**	**lifetime**		
30	Toluene	**24 h, 30 min**	**1 week, 30 min**		
31	Trichloroethylene	**24 h**	lifetime		lifetime
32	TSP	**24 h**			
33	Vanadium	**24 h**	24 h		
34	Vinyl chloride	**lifetime, 24 h**	lifetime		
Pollutants with one or more guidelines		29	32	4	9

Bold entries highlight the introduction of new/modified averaging times of the WHO guidelines.

However, in the parallel process of assessing the carcinogenicity of smoke from solid fuel use and frying, International Agency for Cancer Research clearly pointed out that the fumes from these activities are human carcinogens (IARC, 2010).

Substantial fraction of the compounds for which WHO has developed guidelines (Table 2; 10 out of 34) are volatile organic compounds (VOCs) which in the current work are included as a group only. Eight of the pollutants are metals which are not accounted here at all due to the fact that they mostly play a more significant role in the outdoor air than indoors. Asbestos and man-made vitreous fibres in general are significant occupational risks, but play a minor role for the general population.

The WHO Guidelines for Air Quality for specific pollutants are quantitative exposure levels associated with corresponding averaging times. In the Guidelines for Dampness and Mould WHO also recognized a large number of qualitative issues associated with prevention of dampness, removal and renovation of all signs of moulds, and sufficient maintenance of the building structures including ventilation systems (WHO 2009). While these qualitative guidelines are very significant tools in practical risk management, it is challenging to utilize them as risk factors in risk assessment. Therefore the current work is based on the burden of disease approach using prevalence of dampness in residences as the risk indicator without allocating the health risks to specific chemically or biologically defined exposures.

3.3 Exposure analysis

When developing the Guidelines for Air Quality, WHO adopted a quantitative approach, linking exposure levels with population health risks and considering sufficient safety margins. This approach is utilized in the current work. While the actual exposure levels in the existing building stocks are not always very well known, the quantitative relationships of indoor and outdoor sources are, however, well understood based on mass-balance.

Ventilation plays a two-sided role in formation of indoor pollutant concentrations. The main purpose of ventilation is to remove indoor generated impurities from indoor spaces by ventilating the space with fresh outdoor air. A constant indoor source leads to an inverse relationship with the ventilation rate; the higher the ventilation, the lower the corresponding indoor concentration. As the ventilation rate rises, the diluted indoor concentration decreases, but never reaches zero (Figure 3).

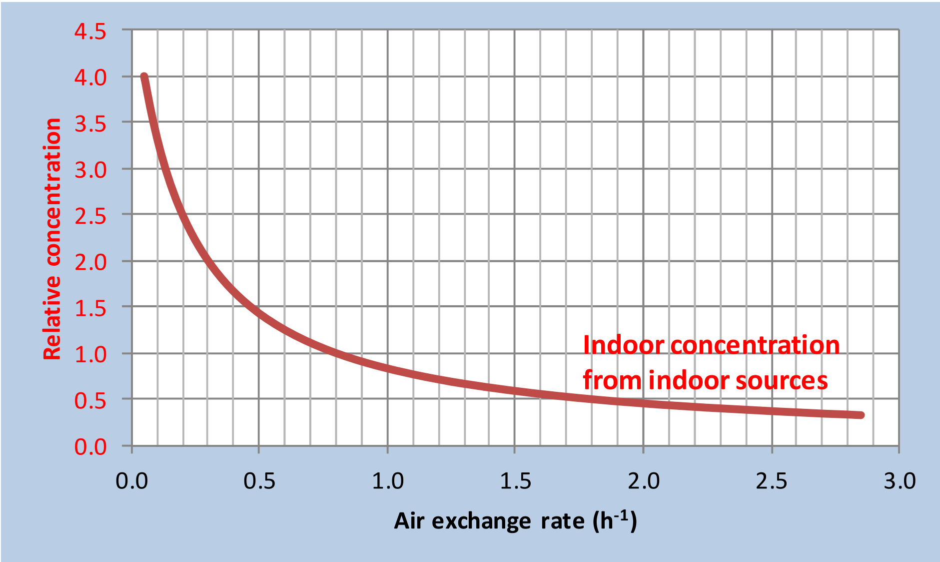


Figure 3. Relative indoor concentration from a constant indoor source as function of increasing air exchange rate.

On the other hand, while the ventilation air is taken from outdoors, ventilation introduces outdoor air pollutants indoors (Hänninen et al., 2004; Hänninen et al., 2005). Assuming a constant outdoor pollution level and constant penetration efficiency, increasing ventilation directly leads to increased indoor exposures (Figure 4).

Outdoor air has been estimated to be responsible for more than 50% of the burden of disease due to indoor exposures in European countries (Oliveira Fernandes et al., 2009, Jantunen et al., 2010). European Commission assessment based on the extensive air quality monitoring network and complementary statistical and physical modelling estimates that only 9% of European Union citizens live in areas where the WHO guideline of 10 µg m^{-3} for annual average $PM_{2.5}$ concentration (WHO, 2006) is achieved (Leeuw & Horalek, 2009).

Even in the case of efficient filtering of particles in the intake air, detailed studies have shown that a substantial fraction of the outdoor air enters indoors via windows, doors, ventilation ducts, and cracks and leaks in the building envelope, leading to much lower actual filtration efficiency (Fisk et al., 2002).

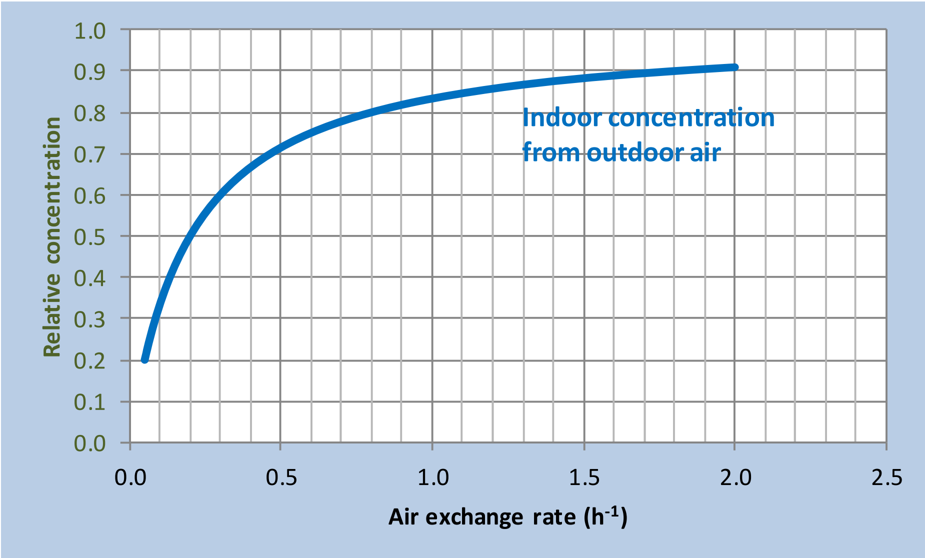


Figure 4. Relative indoor concentration from a constant outdoor level as function of increasing air exchange rate.

3.3.1 Quantification of exposures using mass-balance

Due to the counter-acting roles of indoor and outdoor sources on the exposures as function of ventilation rate a mass-balance model is needed. A commonly used approach was presented as (Dockery & Spengler, 1981):

Eq 1

$$\overline{C_i} = \frac{Pa}{a+k}\overline{C_a} + \frac{G}{V(a+k)} - \frac{\Delta C_i}{\Delta t(a+k)}$$

where C_i is the total indoor concentration (µg m^{-3}) of the pollutant in question, C_a is the concentration in the air intake, P is the probability of the pollutant remaining suspended after penetrating through the building envelope; a is air exchange rate (h^{-1}), k is the deposition rate of the pollutant indoors (h^{-1}), G is the indoor generation level (µg h^{-1}), and V is the volume of the indoor space. The third term covering the transient impacts of changing concentration can be considered zero for the sake of long-term average exposures.

Thus the total indoor concentration of a pollutant is thus effectively split into two remaining fractions, one originating from outdoor air (C_{ai}) and the other from indoor sources (C_{ig}):

Eq 2

$$C_{ai} = \frac{Pa}{a+k} C_a = F_{INF} \times C_a$$

Eq 3

$$C_{ig} = \frac{G}{V} \times \frac{1}{(a+k)}$$

As we see from these equations, the physico-chemical pollutant properties modify the both components. Infiltration is affected by both the penetration efficiency (P) and the decay (k) terms. In practice, the penetration efficiency is 1 for any component entering the building from open doors and windows or any cracks and openings that are larger than one millimetre.

The current work accounts for $PM_{2.5}$, pollen and VOC originating from outdoors. For particles the decay rate is mainly driven by thermokinetic and gravimetric deposition and thus is strongly dependent on the particle size. For the simplified approach used here the default values shown in Table 3 are used.

Table 3. Mass-balance parameters of the outdoor pollutants considered.

Pollutant	Mass balance parameters				
	Dp(eff) µm	Penetration (P) [fraction]	Density g cm^{-3}	Decay (k) h^{-1}	Finf [fraction]
$PM_{2.5}$	<2	90 %	1.5	0.14	0.55
Pollen	10	80 %	1.0	5.41	0.07
VOC	n/a	100 %	n/a	0.10	0.69

Dp(eff) = effective particle diameter; Finf = resulting infiltration factor at a=0.22 h^{-1}; in the model the actual Finf values are calculated according to the used ventilation rates.

Both ultrafine and coarse particles have much lower penetration efficiencies and higher deposition rates indoors than $PM_{2.5}$, which is therefore suitable for evaluating the health-relevant contribution of outdoor pollution indoors.

3.3.2 Determining filtration efficiencies

Long-term WHO guideline for $PM_{2.5}$ has been set at 10 µg m^{-3} as an annual average. The WHO guideline has been set based on ambient epidemiology conducted using urban background monitoring station data on outdoor levels. Depending on the building stock in each city of these studies (e.g. 6 in the Harward Six Cities study (Dockery et al., 1993); 150 in the American Cancer Society study (Pope et al., 2002), the corresponding indoor reference concentration may have varied from 4 to 8 µg m^{-3}. For the purposes of determining the filtration efficiency in the HEALTHVENT ventilation guidelines, a central value of 6 µg m^{-3} was chosen as the reference concentration (C_{ref}). Now the needed effective penetration efficiency for the building as whole can be solved from the mass-balance equation as

Eq 4

$$P_{eff} = \frac{C_{ref}}{C_a} \times \frac{a+k}{a}$$

Even in the case of mechanical ventilation systems using high quality filtering of the intake air, the effective penetration efficiency is strongly dependent on the overall tightness of the house. Penetration efficiency of particles entering indoors via windows, doors and cracks in the building envelope approaches unity, and the effective average penetration efficiency is thus determined by the filtration efficiency (P_{filter}) and fraction of air passing through the filter (*f*):

Eq 5

$$P_{eff} = 1 - f\, P_{filter}$$

Solving for the filter efficiency (P_{filter}) yields

Eq 6

$$P_{filter} = \frac{1 - P_{eff}}{f}$$

Obviously, the filter efficiency has to be balanced against the leakiness of the system as in leaky conditions the filter efficiency required may easily exceed 100%.

Thus the overall procedure for designing the building in terms of filtering outdoor air needs to account for the outdoor pollution level at the building site (C_a), air exchange rate designed for normal use (a), to solve the required effective penetration rate (P_{eff}). Additionally, in case of a mechanical ventilation system, the leakiness of the building (f) has to be balanced against the available filter efficiencies (P_{filter}). Using the $PM_{2.5}$ decay term ($k=0.14\ h^{-1}$) sufficiently covers also pollen and coarse and ultrafine particles having larger deposition velocities and typically more efficient filtration properties, too.

3.4 Risk models: Attributable burden of disease

The current enhancement of the health impact assessment with the above described mass-balance approach to account for variable ventilation is built on the previous achievements of EnVIE and IAIAQ projects (Oliveira Fernandes et al, 2009, Jantunen et al., 2010, respectively) and the corresponding models for environmental burden of disease caused by indoor air quality. These models were based on predefined population attributable burden of disease for each exposure and disease and national estimates are then calculated from national burden of disease data by scaling the attributable fraction according to the ratio of national versus European indoor concentration estimates of each pollutant. In the current work the $PM_{2.5}$, radon and dampness models were updated to the relative risk-based PAF approach (Table 4; see Hänninen & Knol, 2011, for methodological details) but keeping the IAIAQ disease classification, which for PM 2.5 slightly differs from Hänninen & Knol (2011). In addition, second hand smoke exposures were added using exposure data from EC, 2009. National exposure level estimates are presented in Appendix A, Table A2.

Exposures to environmental pollutants are associated with additional mortality and morbidity. Traditional methods estimate these separately as numbers of cases. The results from such incidence-based models are not comparable over different types of health endpoints and to improve comparability of impacts on various types of diseases and including mortality, disability adjusted life years (*DALY*) has been proposed as a common metric (Murray & Lopez, 1997).

Table 4. Diseases and exposure-response relationships included in this assessment.

Exposures	Health endpoints	WHO	RR	PAF	RR & PAF source(s)	BoD calculation[b]
$PM_{2.5}$	Asthma	W113	–[c]	f(RR, E)[d]	Pope et al. 2002	PAF(E, RR) × BoD_{2004}
	Lung cancer	W067	–[c]	f(RR, E)[d]	Pope et al. 2002	PAF(E, RR) × BoD_{2004}
	CV-diseases	W104	–[c]	f(RR, E)[d]	Pope et al. 2002	PAF(E, RR) × BoD_{2004}
	COPD	W112	–[c]	f(RR, E)[d]	Pope et al. 2002	PAF(E, RR) × BoD_{2004}
Outdoor bioaerosols	Asthma	W113	–[c]	0.1[e]	Jantunen et al., 2010	PAF × BoD_{2004}
VOC	Asthma	W113	–[c]	0.05	Jantunen et al., 2010	C/C_{EU} × PAF × BoD_{2004}
CO	Acute toxication caused by carbon monoxide	n/a	–[c]	0.9	Jantunen et al., 2010	Cases x 20 years lost/case
Radon	Lung cancer	W067	0.0014	f(RR, E)[d]	Darby et al., 2005	PAF(E, RR) × BoD_{2004}
Home dampness	Respiratory infections	W038	1.37	f(RR, E)[d]	Fisk et al., 2007	PAF(E, RR) × BoD_{2004}
	Asthma	W113	1.5	f(RR, E)[d]	Fisk et al., 2007	PAF(E, RR) × BoD_{2004}
SHS[f]	Lung cancer	W067	1.21	f(RR, E)[d]	US S.G. 2006	PAF(E, RR) × BoD_{2004}
	Ischaemic heart disease	W107	1.27	f(RR, E)[d]	US S.G. 2006	PAF(E, RR) × BoD_{2004}
	Asthma	W113	1.97	f(RR, E)[d]	Jaakkola et al., 2003	PAF(E, RR) × BoD_{2004}

a Population weighted average in EU-26
b C = National population weighted concentration, CEU = European average concentration, E = National population weighted exposure
c Expert judgment PAF from the EnVIE panel used directly (de Oliveira Fernandes et al., 2009), see column PAF
d Calculated as PAF=(f×(RR-1))/((f×(RR-1))+1), where RR = RR°E, see Hänninen & Knol, 2011, for details.
e Original value of 0.25 in Jantunen et al. (2010) adjusted to 0.1 due to separation of indoor and outdoor sources and focusing on pollen from outdoor air
f Second hand smoke exposure of non-smoking adults at home.

The burden of disease methodology is based on making years of life lost (YLL) due to premature mortality and years lived with a disability (YLD) comparable and summing them up as disability adjusted lifeyears (DALY) (Murray & Lopez, 1997):

Eq 7 $$DALY = YLL + YLD$$

The disabilities caused by various types of diseases are calculated accounting for the duration of the disease (*L*) and scaled using a disease specific disability weight (*DW*):

Eq 8 $$YLD = DW \times L$$

In the current work the fraction of disease caused by the indoor exposures to various pollutants is estimated using national statistics on the overall background burden of the target diseases (Table 4) and calculating the population attributable fraction (*PAF*) as (Hänninen & Knol, 2011):

Eq 9 $$PAF = \frac{f \times (RR - 1)}{f \times (RR - 1) + 1}$$

where *f* is the fraction of population exposed to a given factor and *RR* is the relative risk of the exposed population. Now if the background burden of disease (*BoD*) is known the environmental burden of disease (*EBD*) caused by the current exposures can be calculated as

Eq 10 $$EBD = PAF \times BoD$$

The relative risk at the current exposure level can be estimated from epidemiological relative risk (*RR°*) expressed per a standard exposure increment, e.g. 10 µg m^{-3}:

Eq 11 $$RR = e^{(E \ln RR^{\circ})} = RR^{\circ E}$$

WHO estimates for national burden of disease in 2004 were used for the background burden of disease (BoD).

4 Exposure control options for indoor air

Exposures to harmful pollutants indoors are created by the occurrence of pollution sources indoors and outdoors. The quantitative exposure levels from these sources are balanced with ventilation. In some cases specific ventilation can be used to remove the exposures (e.g. target exhaust in kitchen and bathroom), but general ventilation is rather inefficient as an exposure control and cannot be used to eliminate exposures.

This Chapter describes the selected exposure reduction scenarios for which the burden of disease benefits is evaluated in the next Chapter. The exposure reduction scenarios are based on the European building stock in 2010 and combine ventilation, filtration and source control elements.

4.1 Ventilation in current European building stock

Before it can be estimated how adjusting ventilation affects exposures, the probability distribution of national baseline ventilation itself has to be estimated. Surprisingly limited measurement data is available from only a subset of the included European countries and the population, house type and seasonal representativeness varies quite a lot from study to study.

The comprehensive review of scientific publications on residential ventilation rates in European countries by Dimitroulopoulou (2012) was complemented here with two additional approaches to adjust the non-representative datasets with available other information to obtain best possible estimates. First, a regression model was used to account for the climatological and economical differences in the building stocks. Further, as part of the HEALTHVENT project, a review of national building code requirements for ventilation was conducted (Brelih et al. 2011). These three sources of information were combined using a Bayesian subjective probability approach for generation of lognormal probability distributions for ventilation rates in each EU26 country for the baseline at 2010 (Asikainen et al. 2013). The assumption of lognormality of the air exchange rate distributions was validated against one of the most representative international datasets (Figure 5).

The estimated baseline ventilation rate distributions are listed in Appendix A.

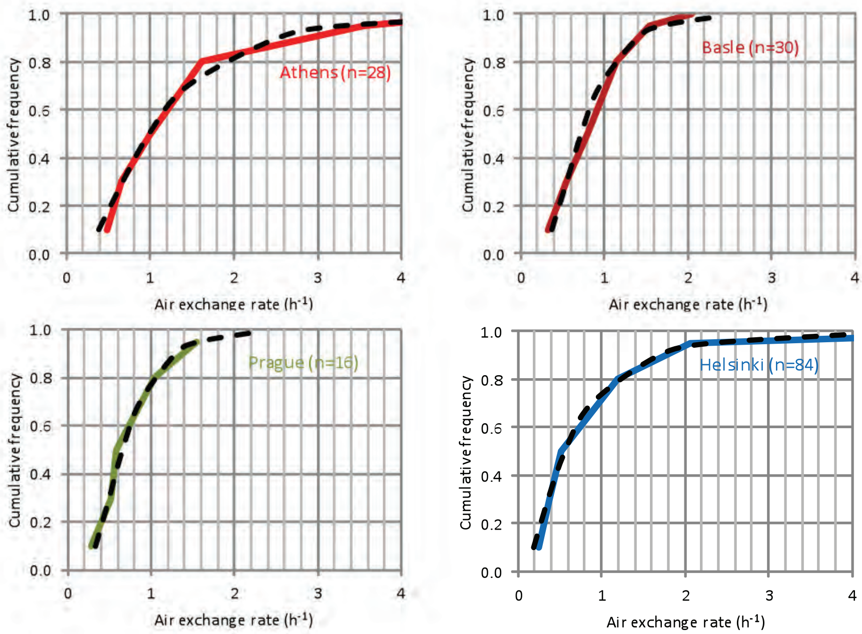


Figure 5. Validation of the overall lognormality of ventilation rate variability in four European cities (original data from Hänninen et al., 2004).

4.2 Exposure control scenarios

Three alternative exposure control scenarios were evaluated using the mass-balance enhanced burden of disease model to evaluate their efficiencies. The exposure control scenarios start from optimizing the ventilation rates only. As this proves inefficient, it is complemented first with control of filtration of outdoor pollutants and second with control of indoor sources.

4.2.1 Dilution by optimal ventilation

Ventilation is needed to remove carbon dioxide and humidity emitted by the occupants. Further, for pollutants with higher indoor than outdoor concentrations ventilation can be used to dilute the indoor levels and thus lower the exposures. However, for pollutants with higher outdoor levels, such as typically e.g. pollen and particulate matter, ventilation actually leads to their infiltration.

The first exposure reduction scenario is defined as finding the health-based optimum ventilation rate without any other changes to indoor or outdoor sources. In this scenario the pollutant concentrations from indoor and outdoor sources compete so that the pollutants of indoor sources are decreasing and the pollutants from the outdoor sources are increasing when the ventilation rate is increased. The health-based optimum level of ventilation is solved for each country by calculating the indoor and outdoor originating components of burden of disease for ventilation rates from 0.1 lps pp to 50 lps pp in 0.1 lps steps up to 9.9 lps, in 0.25 lps steps up to 20 lps pp and in 1 lps pp steps to 50 lps pp (Figure 6). The results are presented in Chapter 5.3.

The calculations assume that all indoor originating exposures follow the mass-balance dilution. This is not self-evident for several indoor originating pollutants, especially radon, dampness and mould and carbon monoxide. Radon infiltrates typically from the soil below the buildings, and the infiltration may react to the under pressure indoors, which may increase in some ventilation systems at higher ventilation rates. Dampness may also be created by condensation and may thus increase at higher ventilation rates. Carbon monoxide is lethal at high exposure levels and more efficient dilution by higher ventilation may not be sufficient. However, for all these pollutants the benefits of higher ventilation rates are calculated assuming the mass-balance for a constant source term.

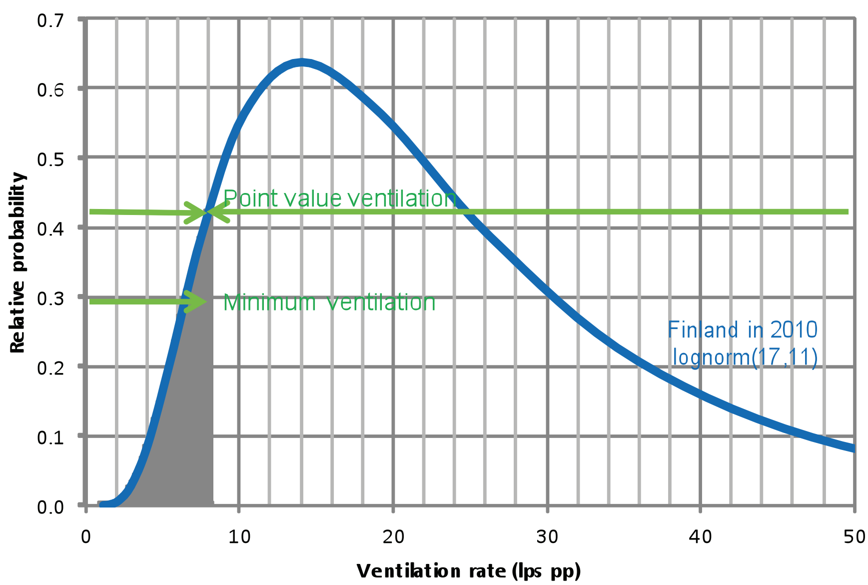


Figure 6. An example of a lognormal probability distribution of ventilation rates in Finland (blue line). The grey area represents the probability of prevailing ventilation being below a selected target value.

4.2.2 Filtration of intake air

Previous analyses of the sources of indoor exposures have shown that outdoor air is a significant source of exposures. Therefore the second scenario was determined as attempting to control the burden of disease by filtrating the exposures originating from outdoor air. Because both ultrafine and coarse particles and chemically reactive pollutants like ozone have lower infiltration factors than $PM_{2.5}$, dominated by accumulation mode particles, the filtration was specified for $PM_{2.5}$ particles.

Three levels of filtration were compared. The baseline estimates assume that 90% of the outdoor $PM_{2.5}$ mass concentration penetrates indoors. In addition, realistic but increasingly challenging penetration levels of 70% and 50% were evaluated. These correspond to effective filtration of $PM_{2.5}$ mass concentration by 27% and 45%, respectively, filtration levels that can be achieved in real buildings at least when using mechanical ventilation systems (Fisk et al., 2002). When discussing the filtration efficiencies of filters and the above mentioned penetration efficiencies, it has to be noted that the penetration efficiency is defined for the building, accounting for leaks and ventilation from windows, doors etc.

The health-based optimum ventilation was defined in this scenario also, and used when calculating the burden of disease results and the reduction potential compared to the baseline scenario. The results are presented in Chapter 5.3.

4.2.3 Source control and minimum ventilation (4 lps pp)

The third approach to optimizing ventilation for health focuses first on indoor sources of exposures. Now, instead of attempting to dilute these sources as they are, they are first assumed to be controlled by other means as much as technically feasible before optimizing the ventilation for health. The assumed control potentials for the considered pollutants were

- -90% for radon, carbon monoxide (CO) and second hand smoke (SHS)
- -50% for volatile organic componds (VOC) and dampness
- -25% for particulate matter ($PM_{2.5}$)

These hypothetical source controls were defined to approach maximum technically feasible reductions. The radon estimate assumes efficient application and control of radon safe construction in radon-prone areas combined with control of second hand smoke exposures known to act synergistically with radon. Efficient second hand smoke reductions have already been demonstrated in Finland and the SHS policies are moving forward also on the European level. The carbon monoxide controls were aimed to be implemented by compulsory alarms that will allow for identification of malfunctioning devices before the risks occur.

VOC controls can be reached by comprehensive labelling systems for product emissions. Dampness controls need to combine structural improvements with active/online and passive warning sensors. The most challenging element was considered to be particulate matter. The proposed 25% reduction can be achieved with target exhausts in kitchens, avoiding use of candles, and improved design of combustion devices.

In this scenario the ventilation levels were set to be 4 lps pp, which has been defined as minimum ventilation in cases where indoor sources are controlled and human emissions (i.e. mainly CO_2 and moisture) are the only sources (ECA, 2013). The results are presented in Chapter 5.3.

5 Reduction potential of burden of disease

The control options of indoor exposures evaluated here are compared with the baseline burden of disease in the European building stock in 2010. The health impacts are calculated for the implementation of the control options in the whole building stock.

5.1 Attributable burden in 2010

Exposures to indoor and outdoor originating pollutants were associated with a burden of disease corresponding to an annual loss of 2.1 million life-years in EU26. These estimates are calculated as disability adjusted life-years (DALY) and account for loss of life years due to premature mortality and due to years lived with disabilities (i.e. morbidity).

More than half of this burden (1.28 million DALYs) is caused by exposures to outdoor air pollution indoors. The remaining 0.74 million DALYs are associated with pollutants from various indoor sources Figure 7.

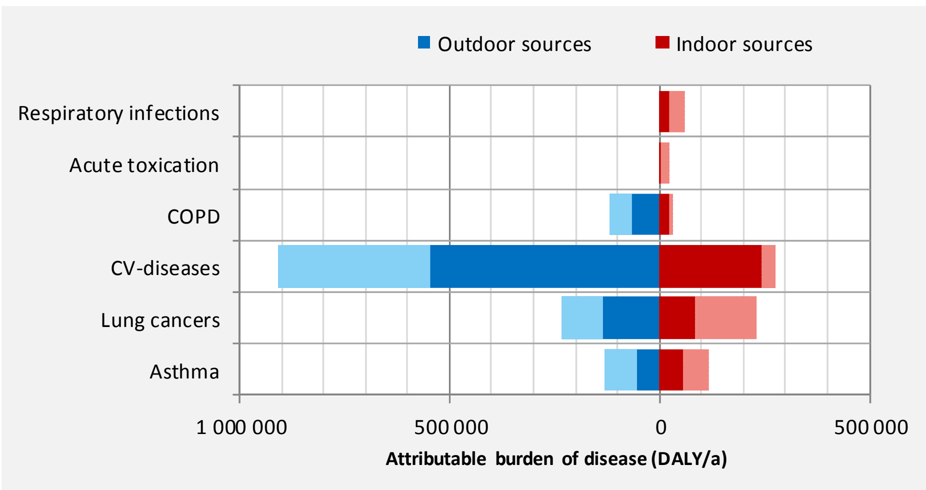


Figure 7. Attributable burden of diseases due to indoor exposures in 2010 in EU26. The lighter shade represents the maximum reducible fraction estimated in the following sub chapters.

The burden of disease caused by indoor exposures is dominated by cardiovascular (CV) diseases; 45% of the total burden comes from CV-diseases associated with outdoor particles, with an additional 12 % caused by indoor sources of exposures of particles and second hand smoke. Cardiovascular diseases are followed by asthma (total of 12%) and lung cancer (23%). The remaining 8% is divided between various respiratory symptoms and conditions.

The total burden of disease for individual countries varies between 2000 and 10 000 DALYs per million (Figure 8). The highest burden in Bulgaria is almost five times higher than that in Sweden. The higher levels in East-European countries are dominated by high contributions from outdoor sources. The contribution of outdoor sources varies between 46% (Ireland) to 75% (Bulgaria). The EU26 average burden corresponds to slightly over 4000 DALY in a year per one million population.

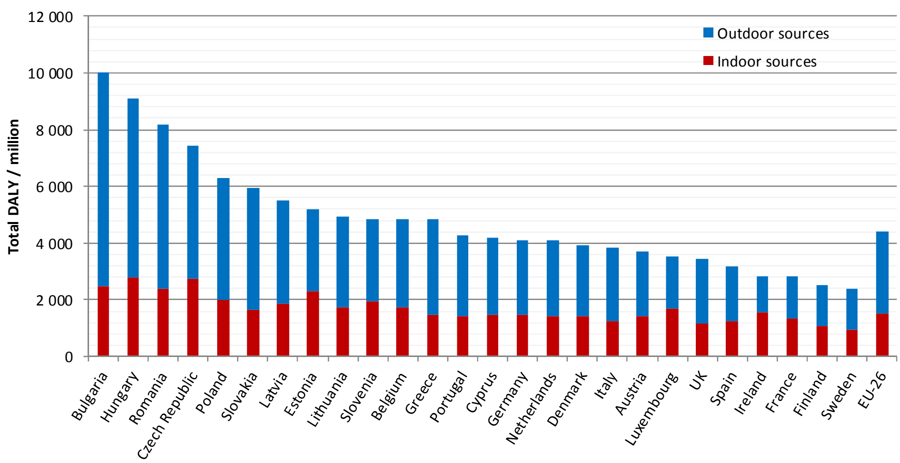


Figure 8. Total burden of disease as DALY/million population from indoor exposures in European countries with division to indoor and outdoor sources in the 2010 building stock

5.2 Source contributions

Overall in EU26, over 50% of the total annual burden of disease associated with indoor exposures (4000 DALY/million) is estimated to be caused by $PM_{2.5}$ particles originating from outdoor air, followed by particles from indoor sources, and radon (Figure 9).

The contribution of different sources to the total DALY naturally varies between countries. This can be seen when comparing the sources of the burden of disease in Finland (Figure 9) with the population-weighted mean of EU26 countries. It is readily apparent that in Finland the role of ambient particles is lower than in Europe in general, but that both bioaerosols (pollen) and radon play much more significant roles. Especially the contribution of radon is double to that of the European average, highlighting the geology of the Finnish soil. In Finland the burden of disease from lung cancer caused by radon exposures is alleviated partly by lower smoking prevalence. In EU27 31% of over 15-year olds smoke daily or occasionally. The smoking figures are lower than in Finland (25%) only in Sweden (also 25%) and Slovakia (22%) (EC, 2009), indicating the high radon exposures in Finland.

Dampness and mould problems continuously raise a lot of attention in Finland, too. Nevertheless, the burden of disease in Finland is from the lower end on the European scale, and only 3% is estimated to be caused by dampness in comparison with 5% in EU26. On the other hand, the previous estimate for the symptoms caused by dampness and mould in Finland from the national SETURI-study (Pekkanen 2010, Hänninen et al. 2010) was substantially higher than the current European wide HEALTHVENT estimate.

The country specific estimates of the burden of disease caused by exposures indoors for all EU26 countries are presented in Appendix B.

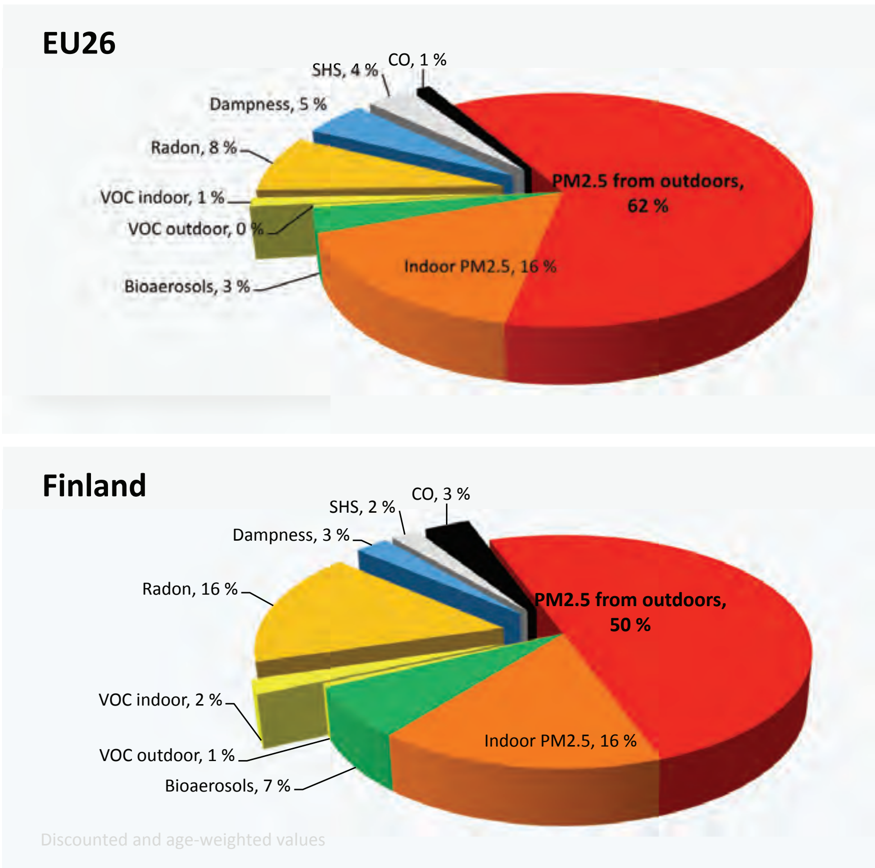


Figure 9. Burden of disease attributable to indoor exposures in EU26 (2.1 M DALY/a) and in Finland (13 k DALY/a) in 2010 divided into source contributions.

5.3 Control scenario benefits including optimal ventilation

The burden of disease caused by indoor exposures, estimated above to be over 4000 DALYs per year per a population of 1 million in EU26, is significant. However, also substantial reductions have been proposed in the earlier work (e.g. Jantunen et al., 2010). The current work made quantitative calculations to confirm the previous expert judgment estimates.

Three alternative scenarios, described in Chapter 4.2 and Table 5, were developed and tested to support policy development for controlling the risks and reducing the burden These evaluated scenarios were: (i) Dilution optimum ventilation; (ii) Filtration optimum; and (iii) Source control with 4 lps pp ventilation minimum. The scenarios are first compared below before presenting the scenario results in more detail one by one.

The first scenario assumes no changes in indoor or outdoor sources and only optimizes ventilation to find a minimum health-weighted exposure level for all pollutants. The second option assumes no changes in indoor sources, but applies variable levels of filtration to remove a part of the outdoor pollutants from indoor air. The third option applies first substantial controls on the existing major indoor sources of exposures before finding the health-based optimum of ventilation.

The overall comparison of these exposure reduction scenarios in EU26 is presented in Figure 10.

The achievable health benefits were 20 % for the dilution scenario, 38% for the filtration scenario, and 44% for the indoor source control scenario.

Each control scenario provides noteworthy health benefits. However, in the dilution-based scenario 1 the health benefits remain smallest due to the fact that the reduction of indoor originating exposures is compensated by infiltration of outdoor pollution when increasing ventilation rates. The European health optimum is found at ventilation level of 4.4 lps pp, which is lower than the baseline mean ventilation in the existing building stock. Approximately double benefits are achievable by filtration of outdoor air in scenario 2. This scenario would in practice imply substantial change towards mechanical ventilation systems in Europe. In the Nordic countries this is already the practice due to the energy efficiency norms, but in the majority of the European building stock the filtration scenario would require a substantial step towards mechanical systems.

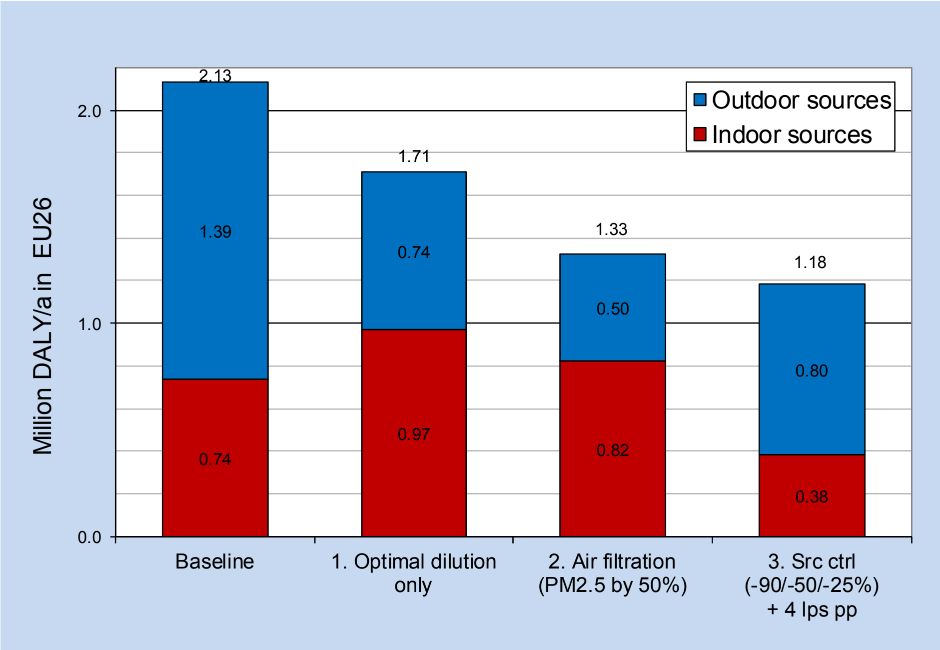


Figure 10. Burden of disease at the baseline (2010) in comparison with alternative potential control strategies in EU26 (in millions of DALYs).

However, largest health benefits can be achieved by the source control approach (scenario 3), which significantly reduces the need to control exposures by dilution Source control allows also optimizing the ventilation to the level of occupancy.

Further inspection of the contribution of indoor and outdoor sources on these scenarios shows, that with the dilution scenario the health benefit is not due to smaller proportion of the indoor contribution (i.e. the dilution of the pollutants from the indoor sources) but is based on the lower ventilation rates that actually limits the penetration of the outdoor pollutants to indoors.

In the filtration scenario the health benefits are due to filtration of the outdoor pollutants and also effective dilution of the indoor pollutants as the health-based optimal ventilation levels are higher.

Also in the source control scenario 3 the health benefit is a results of both effects; the lower indoor sources due to the source control and lower penetration of outdoor pollutants due to low level of ventilation. Minimum occupancy based value was set at 4 lps pp. The health based optimum was lower than this in some countries, but use of such low values rapidly increases the risk of humidity problems.

The ventilation levels in the dilution and filtration scenarios are country specific and based on the maximal achievable health benefits. These health-based optimum ventilation levels, burden of diseases as DALY/million and the reduction potentials of the dilution and infiltration scenarios are presented in Table 6 and Table 7. In addition the national burden of disease and the reduction potential of the source control scenario are presented in Table 8.

Table 5. Comparison of the alternative potential exposure control scenarios.

Parameters	Baseline (2010)	Sce#1 Dilution	Sce#2 Filtration	Sce#3 Src Ctrl
Ventilation				
Outdoor $PM_{2.5}$ penetration	90 %	90 %	50 %	90 %
Ventilation optimum[a] (EU26, lps pp)	19[a]	4.4	7.7	<4
Source controls				
Radon, CO, SHS	Baseline	None	None	-90 %
VOC	Baseline	None	None	-50 %
Dampness and moulds	Baseline	None	None	-50 %
Indoor-generated PM	Baseline	None	None	-25 %
Burden of disease (million DALY in EU26)	**Baseline (2010)**	**Sce#1 Dilution**	**Sce#2 Filtration**	**Sce#3 Src Ctrl**
Indoor sources	0.74	0.97	0.82	0.38
Outdoor sources	1.39	0.74	0.50	0.80
Total	2.13	1.71	1.32	1.18
%	100.0 %	80.3 %	62.0 %	55.4 %
By Disease group				
Cardiopulmonary[b]	1.27	0.94	0.72	0.78
Cancer	0.23	0.26	0.13	0.07
Asthma and allergies	0.35	0.24	0.20	0.13
Others	0.15	0.14	0.10	0.07

[a] Population weighted average ventilation rate in EU26 countries at baseline
[b] Includes CV-diseases, COPD, U&L respiratory infections/symptoms and ischaemic heart disease

Scenario 1: Dilution of indoor sources

The first scenario was defined as finding the health-based optimum ventilation rate without any other changes to indoor or outdoor sources (Chapter 4.2.1).

Modest benefits can be obtained with this approach. At maximum the reduction of the burden of disease at a ventilation rate selected commonly for all countries is approximately 20%, or 400 000 DALYs in EU26.

Figure 11 demonstrates how the increasing dilution of exposures from indoor sources is counter acted by pollutants from outdoor sources. The minimum of burden of disease is found at 4.4 lps pp. When running the health optimization of the ventilation rates by countries, the mean value is 7.5 lps pp (Table 6).

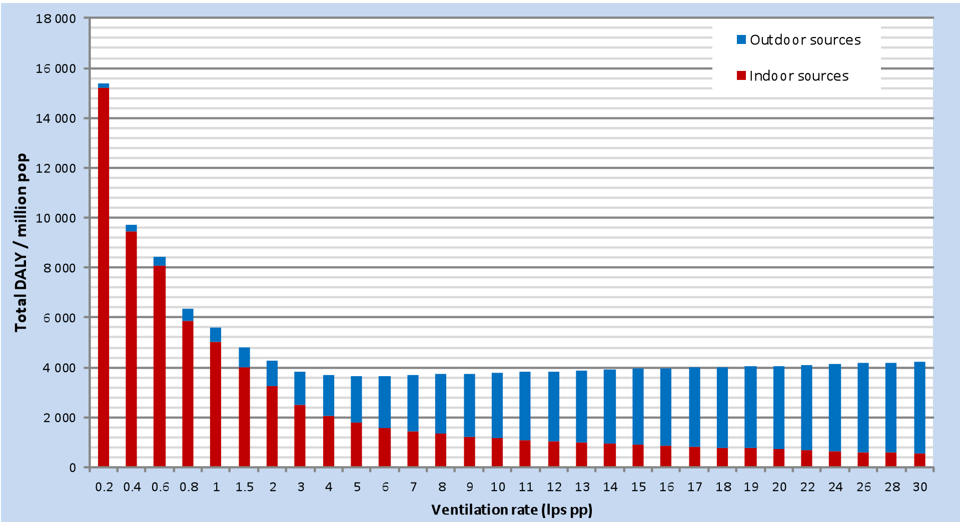


Figure 11. Burden of disease as function of residential ventilation rate per person in EU26.The national health-based optimum ventilation levels vary noticeably between countries the dilution scenario from 1 to 8.8 lps pp with EU26 being 4.4 lps pp. The reduction potentials vary between 8% and 34% with EU26 being 20%.

Table 6. National results for the residual burden of disease from indoor exposures in the dilution scenario and corresponding relative reduction potential (%).

Country	Optimum ventilation lps pp	Indoor DALY/million	Outdoor DALY/million	Total DALY/million	Reduction %
Romania	1.0	3636	2293	5929	27
Bulgaria	1.7	4080	2519	6598	34
Poland	2.4	2613	2229	4843	23
Slovakia	2.5	2397	2277	4674	21
Latvia	3.1	2209	2144	4353	21
Lithuania	3.1	2169	1872	4042	18
UK	3.2	1534	1054	2587	25
Hungary	3.9	3816	3696	7512	17
Portugal	4.0	1779	1657	3436	20
Czech Republic	4.2	3295	2925	6219	16
Slovenia	4.2	2249	1858	4107	15
Estonia	4.3	2557	1886	4443	14
Belgium	4.6	2216	1803	4019	17
Netherlands	4.6	1866	1356	3222	22
Germany	4.8	1935	1405	3340	19
Greece	4.9	2016	2065	4080	16
Italy	5.1	1749	1457	3206	17
Finland	5.4	1263	882	2145	15
Ireland	5.5	1545	840	2386	16
France	5.6	1521	919	2441	14
Spain	5.9	1550	1230	2779	13
Sweden	5.9	1174	838	2012	16
Cyprus	6.3	1924	1810	3734	11
Denmark	6.4	1868	1429	3297	16
Austria	6.9	1881	1419	3301	11
Luxembourg	8.8	2136	1132	3268	8
EU-26	**4.4**	**2003**	**1525**	**3528**	**20**

Scenario 2: Filtration of outdoor air

Outdoor air is a significant source of exposures and contributes more than 50% to the burden of disease (see e.g. Figure 7 earlier in this Chapter). Therefore the second scenario was determined as attempting to control this component by filtrating the exposures originating from outdoor air by comparing three levels of fi ltration (Chapter 4.2.2).

The results for maximum feasible filtration (P=50%) show that reduction in burden of disease approach 38 % or 800 000 DALYs in EU26 (Figure 12, Table 7.)

Average of national health optimums of ve ntilation levels is 5 .7 lps pp an d the European optimum is 7.7 lps pp. Health-optimized ventilation level in addition to the filtration produces small additional improvements.

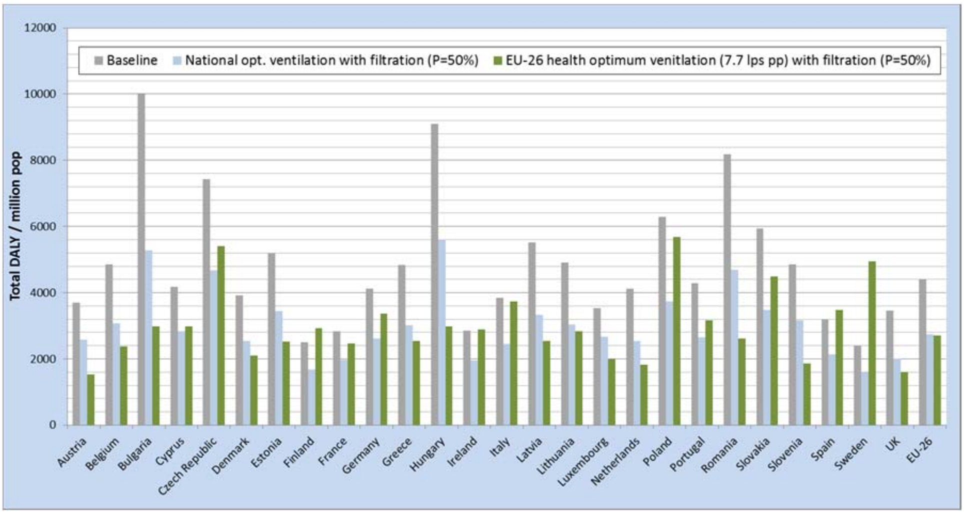


Figure 12. Burden of disease for different levels of ventilation with 50% filtration of ambient particles in 26 EU countries (numerical data in Table 7).

Table 7. National results for the residual burden of disease from indoor exposures in the filtration scenario and corresponding relative reduction potential (%).

Country	Optimum ventilation lps pp	Indoor DALY/million	Outdoor DALY/million	Total DALY/million	Reduction %
Romania	1.7	2844	1853	4697	43
Bulgaria	2.8	3242	2046	5288	47
Poland	3.4	2158	1571	3730	41
Lithuania	4.2	1778	1262	3040	38
Slovakia	4.2	1741	1747	3488	41
Latvia	4.4	1847	1488	3335	40
Portugal	4.7	1614	1033	2647	38
UK	5.0	1198	813	2011	42
Slovenia	5.1	1984	1179	3162	35
Estonia	5.2	2245	1190	3435	34
Hungary	5.2	3138	2472	5610	38
Czech Republic	5.5	2719	1947	4666	37
Netherlands	5.7	1657	885	2542	38
Belgium	5.9	1896	1188	3084	36
Germany	6.1	1684	927	2611	37
Ireland	6.2	1423	531	1954	31
Finland	6.3	1131	552	1683	33
France	6.4	1395	570	1965	31
Italy	6.4	1504	951	2455	36
Greece	6.6	1656	1372	3027	37
Sweden	6.8	1063	521	1584	34
Spain	7.1	1361	776	2137	33
Cyprus	7.5	1720	1119	2839	32
Denmark	7.7	1636	911	2547	35
Austria	8.0	1699	876	2575	31
Luxembourg	10.0	1990	683	2673	24
EU26	**7.7**	**1696**	**1042**	**2738**	**38**

In the filtration scenario the national health-based optimum ventilation levels vary between countries from 1.7 to 1 0 lps pp with EU26 being 7.7lps pp. The reduction potentials vary between 24% and 47% with EU26 being 38%.

Scenario 3: Source control

The third control approach returned the focus to indoor sources of exposures. Now, instead of attempting to dilute these sources as they are, they are first assumed to be controlled by other means as much as technically feasible before optimizing the ventilation for health (see Chapter 4.2.3 for a description on the used emission control estimates).

The source control approach provides slightly larger benefits than the filtration approach in the previous scenario; now the benefits are approximately 44% from the baseline, or 940 000 DALYs in EU26 Figure 13, Table 8.).

In this scenario the health optimums of ventilation rates are below 4 lps pp, where the bioefluent moisture emissions are becoming significant.

In comparison with the filtration-based scenario 2 the advantage is that with source control the lower dilution needs allow also for lower infiltration of outdoor particles and therefore the feasibility of the approach is better in the current building stock. Moreover, the source control approach is likely to prove also more energy efficient.

In the source control scenario ventilation rate was set to the occupancy based minimum of 4 lps pp. The risk reductions ranged from 25% to 55% with the EU26 average being 44%. For a majority of the individual countries the largest reduction is achieved with source control (Table 8).

However, e.g. Romania has almost the same reduction potential with the dilution and source control scenarios (27 and 25%) and the largest reduction is achieved with the filtration scenario (43%). Also Bulgaria and Slovakia have the largest reduction potential with the filtration scenario. This is clearly due to the larger contribution of the outdoor sources than in majority of the European countries.

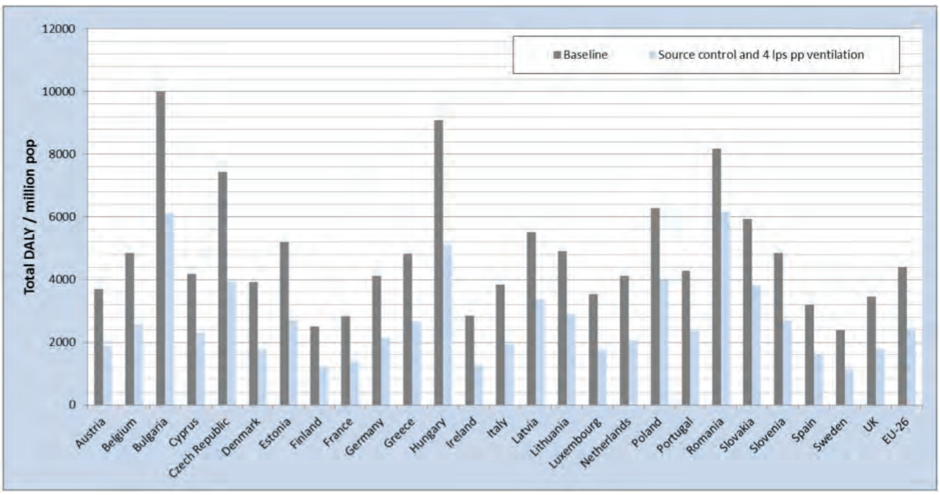


Figure 13. Burden of disease for source control and 4 lps pp in EU26.

Table 8. National results for the health benefits provided by the source control scenario with 4 lps pp.

Country	Indoor DALY/million	Outdoor DALY/million	Total DALY/million	Reduction %
Ireland	593	681	1274	55
Denmark	732	1033	1765	55
Sweden	463	643	1106	54
Finland	486	725	1211	52
France	662	737	1400	51
Luxembourg	1096	669	1765	50
Spain	630	967	1596	50
Netherlands	832	1231	2063	50
Italy	693	1245	1937	50
Austria	885	1004	1889	49
Germany	894	1242	2136	48
Estonia	896	1807	2703	48
UK	574	1230	1805	48
Czech Republic	1101	2838	3939	47
Belgium	935	1650	2585	47
Cyprus	898	1412	2310	45
Portugal	708	1657	2364	45
Greece	843	1833	2675	45
Slovenia	896	1806	2702	44
Hungary	1358	3753	5110	44
Lithuania	702	2179	2881	41
Latvia	868	2500	3368	39
Bulgaria	1544	4574	6117	39
Poland	941	3033	3974	37
Slovakia	823	2999	3821	36
Romania	1071	5100	6171	25
EU26	792	1656	2448	44

6 Impacts on energy use

Residential energy use represents roughly a quarter of the total energy consumed in Europe (Figure 14). The total energy balance is led by transportation sector (34% of energy and 39% of CO_2 emissions), followed by the residential sector and industrial contributions.

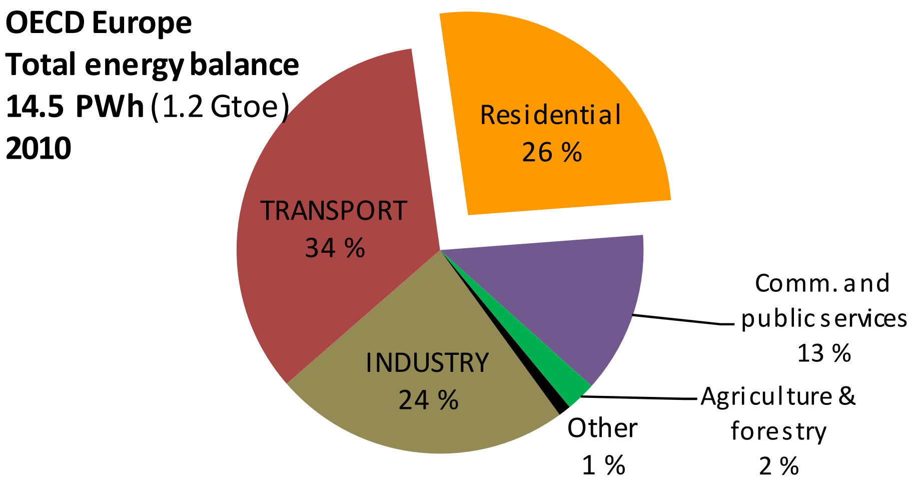
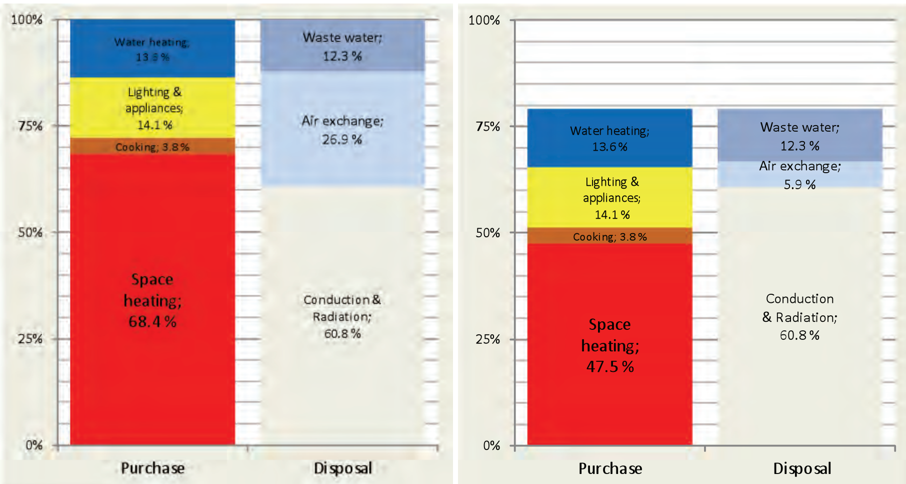


Figure 14. Overview of energy use in OECD Europe countries in 2010 (IEA, 2012). Transport includes international aviation and navigation.

The residential energy use includes space heating, lighting and electric appliances, cooking and water heating. Air exchange, consisting of intentionally ventilated air as well as building leakages, directly affects the heating energy needs during the cold season and, optionally, cooling needs in summer. In EU27 approximately 68% of energy consumed by the residential sector is used for heating. Additional heat is produced by cooking (3.8%) and lighting and other electrical appliances (14%). Water heating represents over 13% of the total residential energy use, but this energy is mostly lost with waste water and water evaporation (Figure 15a). In comparison with the energy used for space heating (nearly 2.5 PWh in EU27), air exchange represents almost 40%.

In the future building stocks, where the insulation of buildings is improved for better energy efficiency, the role of air exchange as an energy sink is expected to increase. However, if the ventilation is optimized according to the health-based ventilation guidelines proposed by the HEALTHVENT project, energy savings are possible meanwhile decreasing health risks (Figure 15b).



(a) Baseline (b) Src Ctrl scenario in 2010 buildings

Figure 15. Structure of residential energy use (left columns; total in 2010 3.6 PWh/a ≈ 7,45 TWh/a per million inhabitants) and corresponding energy disposal (right columns) in EU27 at the baseline (part a) and assuming source controls and the HEALTHVENT ventilation guidelines completely implemented (part b) (minimum ventilation of 4 lps pp with 100% ventilation effectiveness).

6.1 Contribution of air exchange to residential energy use

Using the European ventilation model (Asikainen et al., 2013), we calculated the national fractions of residential energy use consumed by ventilation in 2010 (Figure 16). Higher energy consumptions occur in the Nordic countries and e.g. in Luxembourg, where the living space is larger than in many other countries per capita. The energy consumption is highest in Finland.

The potential for energy consumption reduction by ventilation by applying the HEALTHVENT ventilation guidelines is shown in Figure 17. Denmark and Luxembourg, representing the most spacious living, have the highest baseline ventilation energy consumptions followed by Sweden and Finland, with their cold climate.

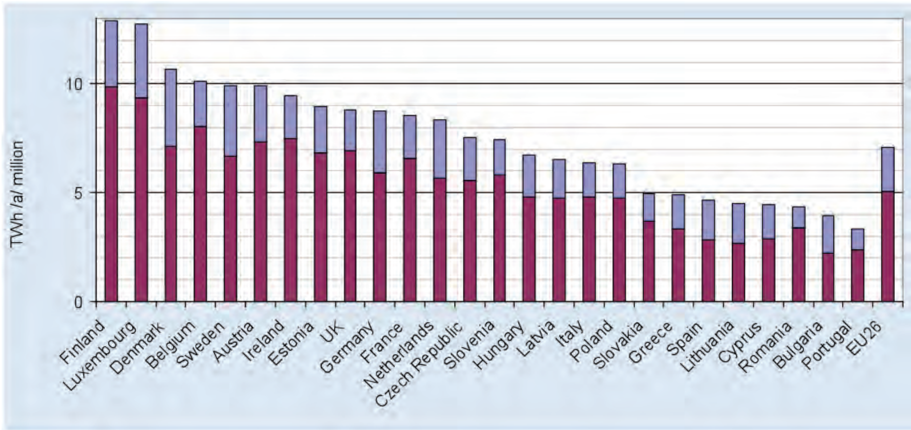


Figure 16. Total residential energy use and the fraction consumed by air exchange (ventilation and air leakages; in blue) in 2010 (for six countries missing 2010 data is replaced EEA data for 2009 (EEA, 2012).

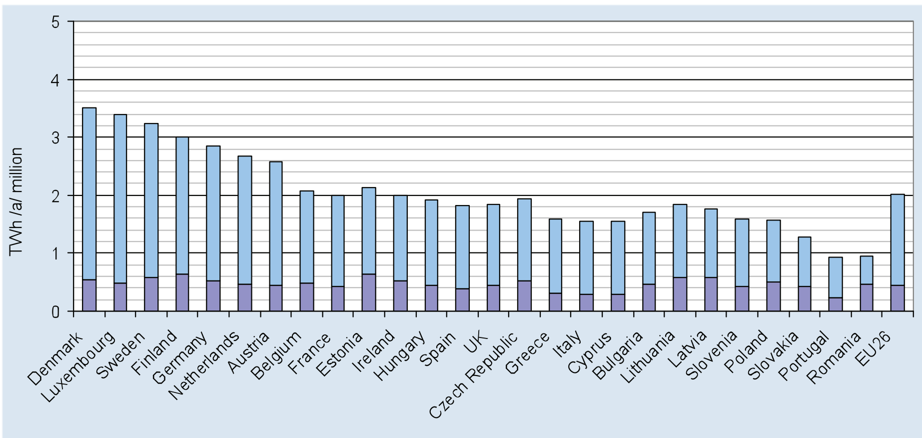


Figure 17. Residential air exchange energy consumption at the baseline (light blue) and the remaining fraction (darker blue) at minimum ventilation 4 lps pp and assuming fully effective source controls.

6.2 Air exchange energy use

Impact of ventilation on residential energy use was estimated in simulations that compared in energy consumptions in three European climates, Helsinki, Paris and Lisbon in existing buildings and using modern ventilation technology in future buildings (Santos & Leal, 2012). The compared energy use scenarios were:

(i) Baseline: existing building stock and prevailing ventilation in 2010
(ii) Guideline: HEALTHVENT minimum ventilation with corresponding indoor source control in the existing building stock
(iii) New building stock built according to current building codes
(iv) Potential future building stock with advanced technologies

The results projected substantial energy savings for the current building codes and estimated additional energy savings by applying novel energy efficient ventilation techniques in the future (Figure 18). The results suggest that the implications of ventilation for heating energy needs (shown in Figure 16) can be almost removed. The implications of tighter buildings and better insulation on the cooling needs were not considered, but are likely to counter-balance some of the suggested energy savings.

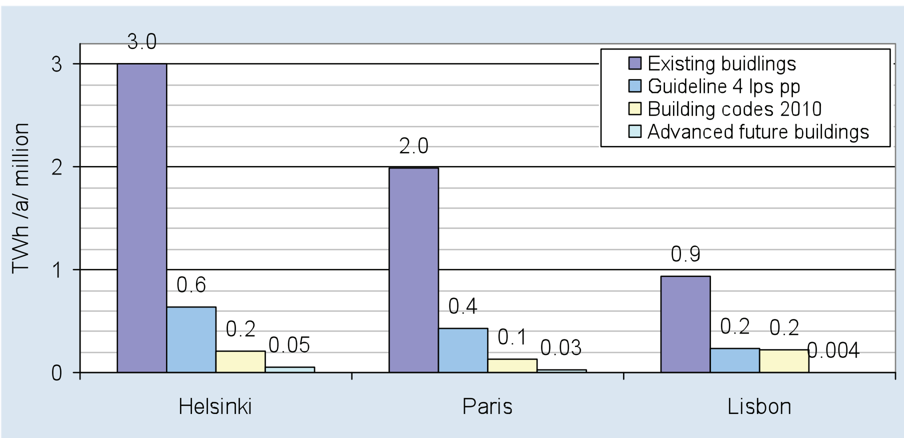


Figure 18. Comparison of the energy needs of ventilation at the baseline (2010) and guideline minimum ventilation (assuming fully implemented source controls) in future buildings as simulated by Santos & Leal (2012) in three cities.

7 Discussion of limitations and uncertainties

The results from the studies summarized in this report suggest that (i) there is a substantial burden of disease associated with inhalation exposures taking place indoors and that (ii) these risks have a substantial reduction potential by various policies that apply a range of controls affecting indoor sources, infiltration of outdoor pollutants, and ventilation levels. The suggested prioritization of the policies depends naturally, besides the estimated health benefits and policy implementation costs, also on the uncertainties in the estimates. The main uncertainties are discussed here.

7.1 Attributing health effects

Epidemiological studies on health effects caused by indoor exposures typically cover acute symptoms like wheeze and cough, headache etc. (Carrer et al., 2012). Chronic effects are well known for lung cancer and asthma incidence, but are to large extent lacking for cardiovascular and COPD effects. In the current work the chronic health endpoints were included using exposure-based risk assessment models, where the association between individual exposures and health has been obtained from more general epidemiological studies, using larger populations and specific exposure indicators like residential radon concentration (e.g. Darby et al., 2005, 2006) or ambient $PM_{2.5}$ concentration (e.g. Pope & Dockery, 2006).

Variable degree of uncertainty exists in the exposure-response response relationships based on epidemiological studies. For some of the included pollutants, like $PM_{2.5}$ originating from outdoor air, this data is based on a large number of studies, representing very large populations in different climatological regions. The exposure-response relationship of ambient particles has also been used for indoor generated particles. The indoor generated particles have partly the similar composition, originating from combustion processes or being resuspended particles originating from soil, for which it is reasonable to assume similar toxicity as for the ambient particles. Some particle fractions, especially the particles from cooking of food, from the occupants, and from textiles, have a different chemical composition with limited direct evidence on their toxicity.

Further, in some cases the population representativeness, number of studies, control of confounding and other sources of uncertainties in epidemiological designs are much less convincing than in the case of ambient particle, radon, or second hand smoke. Health effects and exposures with weaker evidence have been excluded from the models at this point and therefore it is likely that the results are underestimates. However, as those factors that are considered most important are included, the order of magnitude of the results should be sufficiently reliable for cost effectiveness analyses and policy development. Future refinements will allow for including also less dominating effects in the estimates.

7.2 Technical feasibility of lowering the health risks

Three main approaches were investigated to control the health risks caused by indoor exposures in Finland and in other EU26 countries. Each of these approaches poses questions affecting both the technical feasibility as well as potential failures in implementation of the necessary components for achieving the projected health benefits. These are discussed shortly in this section. Additionally, maintenance and other factors affecting the safety of ventilation systems were also elaborated in detail in the HEALTHVENT project (Seppänen et al., 2012).

7.2.1 Controlling ventilation

A vast majority of the European residential buildings were ventilated naturally in 2010. In natural ventilation systems the main factors determining the ventilation rates are the temperature differences between indoor spaces and outdoor air, wind speed, tightness of the building envelope, and availability of openings for ventilation. Seasonal and daily variations in temperature differences and wind speed have to be accounted for by adjusting the ventilation openings. Such manually operated adjustment systems require occupant attention and activity and are not always optimal in controlling the exposures. In mechanical ventilation systems electronic control units can be programmed to adjust ventilation according to the environmental changes and the ventilation demand.

In the future the need to integrate energy optimization of ventilation with energy efficient tight building envelopes and advanced technologies for energy conservation like heat pumps and heat recovery units set pressure on equipping more buildings with mechanical systems.

7.2.2 Filtration of ambient particles

More than 90% of Europeans lived in 2005 in areas where outdoor air quality does not meet the WHO Guidelines for $PM_{2.5}$ (de Leeuw & Horalek, 2009). European policies for improving outdoor air quality are constantly developed, but it is extremely challenging to lower particle concentrations rapidly. Therefore filtration of the outdoor particles from the indoor air remains a major technology to improve healthiness of indoor spaces.

Infiltration of ambient particles depends on air exchange rates, size distribution of the outdoor particles, and filtration of the intake air. At lower air exchange rates the prolonged residence time of air indoors and corresponding deposition of particles on indoor surfaces reduces indoor exposures even when the outdoor air is not filtrated. Using window frames and other sedimentation chambers allows for filtrating particles even in gravimetric ventilation systems. Nevertheless, active filtration becomes efficient only in mechanical systems using high quality (above FP7) filters.

Advanced systems for energy efficiency include heat exchangers and heat pumps, which can be integrated with balanced mechanical ventilation including filtration of intake air. Further reduction of indoor particle levels can be achieved by using filters in air recirculation.

7.2.3 Controlling indoor sources

Largest health benefits were projected for the source control policies. It is obvious that the benefits are achievable only if the source controls work as efficiently as proposed in Chapter 4.2.3 and that the efficiency of the source controls must be confirmed with follow-up of exposure levels after the policy enforcement.

7.2.4 National averages versus individual buildings

The current ventilation rate estimates per occupant (lps pp) are calculated using average residence sizes and average numbers of occupants in each country. Population weighted average outdoor concentrations have also been used in estimating the indoor exposures. It is clear that the air filtration needs for a specific building have to be defined using the ambient air quality at the selected building location. In all countries included there are locations where the outdoor levels exceed the WHO guidelines much more than the national averages used here indicate. When the current methods proposed for determining the potential filtration needs, they have to be applied with worst case estimates for the actual building site, accounting for the whole service life.

7.3 Risk of insufficient ventilation

Current burden of disease calculations suggest that low ventilation levels ranging from 4 to 8 lps pp provide benefits in public health. As presented in more detail in this report, these results are based on various alternative controls affecting indoor and outdoor sources of pollution. In the 1970s the tightening of buildings as a response to the 1974 energy crisis rapidly led to high exposures from indoor sources and massive symptoms of occupants. When applying these ventilation rate estimates, strict caution has to be taken to make sure that the exposure control assumptions are fulfilled to avoid the repetition of such problems.

7.3.1 Controlling dampness in residences

Additional risk assessment has to be conducted regarding dampness. Water is intimately integrated with our living environments, affected by both weather from outdoors as well as living indoors. Water is emitted by the metabolism of persons, pets and plants, but also by natural human activities like dishwashing, showering, laundry and cleaning. Presence of water in the form of dampness or humidity is sufficient to lead to rapid proliferation of moulds and other biological organisms such as house dust mites.

World Health Organization (2009) clearly recognizes numerous qualitative indicators including any signs of moisture, dampness or moulds as risk factors and recommends to take immediate action to remediate the conditions. Discussion of minimum health-based ventilation rates have to be taken exactly as such: (1) they are minimum levels that cannot ever be left unattained; and (2) in the presence of additional sources such as humidity, the ventilation has to be adjusted accordingly.

To highlight this the following simple example is considering very normal household type of activities, including showering and drying laundry, leading to the need of typically 1-5 litres of water to be evaporated and transported away from the bathroom or drying room.

The capacity of air to carry water depends strongly on the temperature. As the room temperatures are almost always in the order of 20-22 °C, mostly not differing from this value more than few degrees, the main variables affecting the drying capacity of air are the temperature and humidity of outdoor air.

Figure 19 presents the amount of air in cubic meters needed to transport (dry) one litre of evaporated water from indoors. In winter conditions the air entering indoors is relatively dry after being heated to the normal room temperature, and thus 50-100 m^3 is sufficient to dry one litre of water. However, when the outdoor temperature rises – and if the air outdoors remains humid – the amount of drying air increases rapidly.

Now, the time needed for the ventilation system to provide the requested amount of air naturally depends on the ventilation rate. Figure 20 demonstrates this by calculating the drying times, again per one litre of water, at typical ventilation rate at the 2010 baseline, 0.5 air changes per hour. In a two-room apartment this correspond to roughly 60 m^3 of fresh air in an hour and assuming that one third of this is available for the dried space like bathroom, the drying time in winter conditions is in the order of 3-5 hours (blue curve). However, if the same apartment is designed for one occupant with ventilation of 4 lps pp, as shown by the red curve in the figure), the drying times increase substantially. For a full washing machine load (5 kg of water) the winter drying time would become already almost prohibitively high 60 hours, but especially in the humid summer conditions would request more than 240 hours. Such periods of more than ten days with full humidity indoors would beyond any doubt make sure that the space would rapidly become uninhabitable.

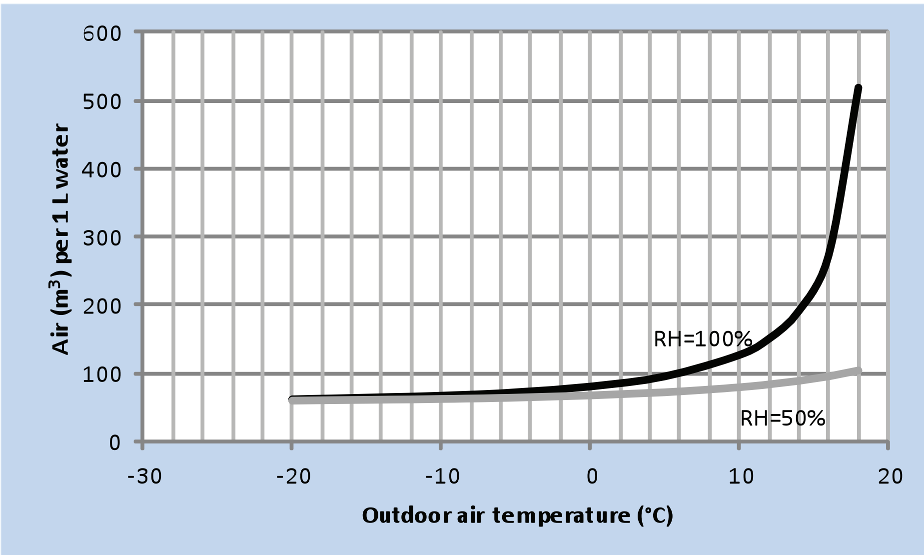


Figure 19. Volume of fresh outdoor air needed to transport one litre of water as function of outdoor air temperature and outdoor relative humidity (RH) at indoor temperature of +20 °C.

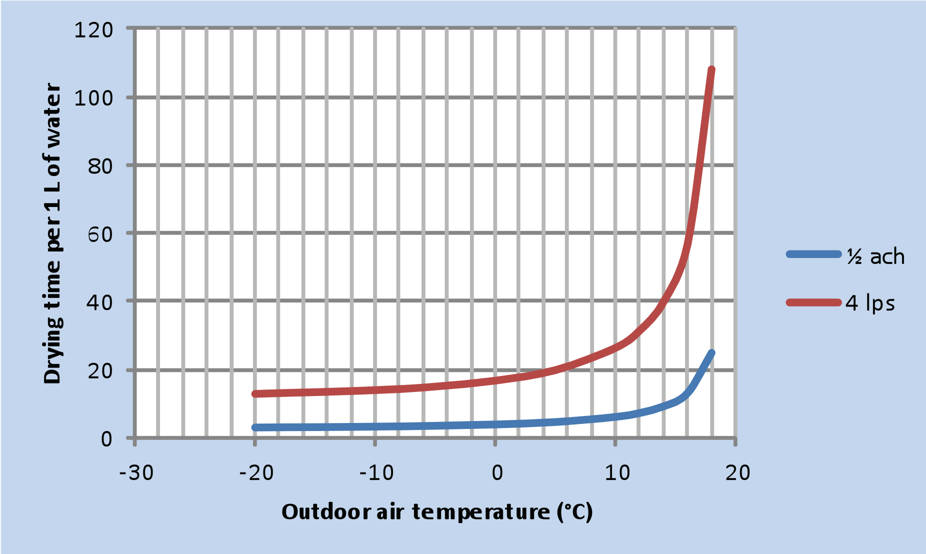


Figure 20. Time needed to transport 1 litre of water by ventilation at two discussed ventilation levels and assuming 1 third of the air is affecting the space.

Accounting for especially sensitive population groups needs therefore careful handling of occupant generated humidity and water from normal household activities. New sensor techniques and online systems will allow recognizing violations of the good practices in handling humidity. However, common sense cannot yet be replaced by intelligent houses.

In addition to the presence of 'normal' occupant generated humidity there is a obviously multitude of other sources for excess moisture indoors, leading to adverse health as reviewed by World Health Organisation in 2009. While it is conceivable that ventilation may not help to reduce indoor moisture generated by rain- or groundwater leakages into the enclosure or plumbing leaks, it is plausible that higher ventilation rates support buildings to cope with certain insufficiency in building structures etc. that would – at lower ventilation rates - lead to accumulation and ultimately excess moisture and subsequent microbial proliferation indoors. It is unclear and difficult to predict whether lowering current ventilation guidelines would result in an increase of dampness and mould in the building stock.

7.3.2 Microbial exposures

Indoor exposure to microbes and the impact of these exposures on human health is highly active field of research, even beyond the discussion of moisture damage, dampness and mould, in particular referring to studies on the role of indoor exposures on the development of asthma and allergy. Microbes, their structural components and secondary metabolites have been suggested to be involved in both protective and adverse mechanisms in particular in respiratory health and allergy development.

Multiple factors, such as timing of exposure, the quantity, quality and potentially diversity of microbial exposures are relevant for explaining the observed health outcomes. Ventilation and the impact of ventilation rates on indoor microbial content and levels have not been studied systematically. It is evident, however, that ventilation rates and types affect indoor microbial exposure.

The sources for indoor microbes relate to outdoors – e.g. ambient air, outdoor particles tracked in on shoes, clothes, etc. – but also have a strong indoor context, as in the case of human shedding of microbes, pets, moisture and subsequent microbial proliferation. Occupancy is a major determinant of indoor microbial levels, both through the occupants themselves being an active source of mainly bacteria, and through resuspension of microbes from reservoirs, such as floors and other surfaces. Ventilation affects the concentrations of airborne microbial components directly, but also to large extent modifies the indoor environmental conditions leading to microbial growth.

7.4 Uncertainties of the health risk model

Besides the considerations on the parameter uncertainties affecting the risk assessments discussed above, additional sources of uncertainties can be grouped into two categories:

(i) Uncertainties in the model
(ii) Uncertainties in defining the future scenarios.

Model uncertainties are causing the largest concerns here. They include the selection of pollutants and health end-points associated with them and it is clear that also in the current context a substantial uncertainty raises from here: it is not clear how much the burden of disease estimates are underestimated due to dozens of ignored exposures or missing health endpoints for the included exposures. At best the model uncertainties can be qualitatively judged by experts. As part of the TEKAISU work, THL is evaluating the potential impact of missing pollutants on the overall environmental burden of disease. Some of the pollutants considered may affect also inhalation exposures indoors.

In the current work a previously developed burden of disease model from EnVIE and IAIAQ studies was used as the platform for the current work. Several improvements were added for the exposure data for the baseline year 2010, including detailed population based outdoor levels of $PM_{2.5}$, estimated with 10 km spatial resolution for 2005 (de Leeuw & Horalek, 2009). The model was also supplemented with second hand smoke exposures from a harmonized recent European survey (EC, 2009). To estimate the impacts of ventilation on the burden of disease the model was integrated with a single compartment complete mixing mass-balance model for the estimation of exposures. The mass-balance model has been validated in experimental datasets earlier with good results (e.g. Hänninen et al., 2004).

Parameter uncertainties are the easiest to be estimated and evaluated. Standard methods applied to the observed data handle sufficiently statistical errors. More care and expert judgment is needed to cover problems in non-representativeness of various population groups. Quantification of the exposure-response relationships and mass-balance model for exposures belong also to the parameter uncertainties. Even though the mass-balance model, assuming e.g. complete mixing and using a single compartment approach does not capture short-term variations in the actual exposure concentrations very well, from the point of view of quantifying the overall exposure processes the accuracy is considered good.

Scenario uncertainties are inherent for any future forecasts; we may not know all changes in the systems under scrutiny and therefore must rely on assumptions. When selecting policies for implementation, the implementation timeframe should also be considered. In the case of the national building stocks it is clear that it takes years and decades before any new policy may have been fully implemented.

Most significant element in the scenario uncertainties is related to the development of building stocks in the future. The current ventilation guidelines provide some elements that contribute to the need for development in the standard building construction technologies. The guidelines are intentionally formulated so that the focus is in the key parameters in terms of health, the exposures, and there is as little as possible elements that require specific technical solutions. An example of such an issue is the filtration of outdoor air pollution, especially $PM_{2.5}$, but also pollen, other biological particles, ozone, ultrafine traffic particles and so on. Cleaning of ventilation air seems to imply using filters and therefore a mechanical ventilation system. However, as shown also in the estimates presented in this report, low infiltration of ambient particles can be partly obtained by optimizing the balance of ventilation rates and indoor sources. It is also possible to develop methods to reduce infiltration of outdoor pollutants in traditional ventilation systems. This certainly requires more applied research and technology development as well as careful control of design and implementation.

8 Conclusions

Over 2 million disability adjusted life years (DALY) are annually lost in the European Union due to compromised indoor air quality including morbidity and mortality due to cardiovascular diseases, lung cancer, asthma and allergies, acute toxication and respiratory diseases caused by particulate matter, pollen, radon, second hand smoke, dampness and mould, volatile organic compounds, and carbon monoxide exposures that take place in indoor environments.

Several strategies can be used to reduce this burden. Results from the quantitative comparison of thee main approaches were presented here: (i) adjusting ventilation only; (ii) filtration of air intake; and (iii) source control approaches. All approaches are able to provide substantial reductions in the health risks, but in the listed order the reduction potential of the strategies increases from approximately 20 % to almost 50%, corresponding to 400 000 and 900 000 saved DALYs in EU26. Thus selection of strategies has substantial impact on the expected benefits.

The projected health benefits can be achieved if the controls on ventilation and sources are fully implemented as defined in the scenario descriptions. In the case of selecting some of the proposed strategies for implementation, a careful follow-up plan has to be developed for ensuring that the controls are affective and match the requirements of the benefit calculations.

THL is currently developing methods for quantitative prioritization of environmental health protection policies in the TEKAISU project. The current analyses on the health risk reduction potential of policies focusing on indoor air quality in an important input to the wider analysis of environmental health risk control policies.

The health-based ventilation guidelines, when combined with the proposed efficient control of indoor sources, was estimated to allow reducing the energy consumption required by ventilation by 760 TWh/a, or 78 % in comparison to the 2010 situation, corresponding 125 MtCO_2/a reduction in the carbon dioxide emissions in EU27. However, it is essential to consider especially risks in handling and removing humidity to avoid similar problems that occurred in the 1970s when attempting to reduce energy needs. At that time the haphazardly selected approaches resulted in an enormous increase in indoor air quality problems and associated health risks.

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Appendix A – Baseline ventilation and exposure levels

Table A.1. Estimated ventilation rate distributions in European countries.

	Air exchange rate			Ventilation rate per occupant		
Country	Mean	Median	One-GSD range[a]	Mean	Median	One-GSD range[a]
	h^{-1}	h^{-1}	h^{-1}	lps pp	lps pp	lps pp
Austria	0.85	0.70	(0.4-1.3)	25	21	(11.1-39.1)
Belgium	0.71	0.58	(0.3-1.1)	17	14	(7.6-26.7)
Bulgaria	0.71	0.58	(0.3-1.1)	15	12	(6.4-22.3)
Cyprus	1.22	1.00	(0.5-1.9)	24	20	(10.6-37.2)
Czech Republic	0.62	0.51	(0.3-1.0)	14	11	(6.0-21.1)
Denmark	0.66	0.54	(0.3-1.0)	24	20	(10.4-36.6)
Estonia	0.66	0.54	(0.3-1.0)	13	10	(5.5-19.4)
Finland	0.65	0.53	(0.3-1.0)	17	14	(7.5-26.3)
France	0.64	0.53	(0.3-1.0)	18	14	(7.7-27.1)
Germany	0.68	0.56	(0.3-1.0)	20	17	(8.8-31.0)
Greece	0.96	0.79	(0.4-1.5)	20	17	(8.8-30.9)
Hungary	0.75	0.62	(0.3-1.2)	16	13	(6.8-24.0)
Ireland	0.57	0.47	(0.3-0.9)	14	12	(6.2-21.9)
Italy	0.76	0.62	(0.3-1.2)	21	17	(9.2-32.4)
Latvia	0.65	0.53	(0.3-1.0)	11	9.2	(4.9-17.2)
Lithuania	0.67	0.55	(0.3-1.0)	11	9.2	(4.9-17.3)
Luxembourg	0.87	0.71	(0.4-1.3)	32	26	(14.1-49.5)
Netherlands	0.67	0.55	(0.3-1.0)	21	17	(9.1-32.1)
Poland	0.69	0.57	(0.3-1.1)	11	8.9	(4.8-16.7)
Portugal	0.73	0.60	(0.3-1.1)	15	12	(6.6-23.1)
Romania	0.78	0.64	(0.3-1.2)	7.2	5.9	(3.2-11.1)
Slovakia	0.78	0.64	(0.3-1.2)	12	10	(5.1-17.9)
Slovenia	0.72	0.59	(0.3-1.1)	13	11	(5.9-20.7)
Spain	0.80	0.65	(0.3-1.2)	20	17	(8.9-31.3)
Sweden	0.64	0.52	(0.3-1.0)	20	17	(9.0-31.5)
UK	0.61	0.50	(0.3-0.9)	15	13	(6.8-23.8)
EU26	**0.70**	**0.58**	**(0.3-1.1)**	**16.6**	**13.7**	**(7.3-25.6)**

[a] (median/GSD, median x GSD)

Table A.2. Exposure levels in European countries.

	$PM_{2.5}$ C_{out} µg m^{-3}	$PM_{2.5}$ C_{in} µg m^{-3}	VOC C_{out} µg m^{-3}	VOC C_{in} µg m^{-3}	Radon C_{in} Bq m^{-3}	Damp homes %	SHS non-smokers %
Austria	17.2	5.3	103	298	97	8	14
Belgium	18.7	5.3	103	298	69	14	18
Bulgaria	22.3	5.0	103	298	30	n/a	23
Cyprus	22.6	4.0	103	298	7	30	31
Czech Republic	23.1	5.0	116	334	140	16	16
Denmark	13.3	2.9	103	298	53	11	17
Estonia	10.8	2.9	103	298	120	23	16
Finland	9.1	2.9	64	226	120	5	2
France	12.3	5.3	77	223	89	14	9
Germany	16.0	5.3	103	297	50	13	13
Greece	20.8	4.0	155	345	55	19	28
Hungary	24.6	5.0	103	298	107	19	12
Ireland	7.6	2.9	103	298	89	15	14
Italy	19.6	4.0	181	489	70	21	11
Latvia	12.4	2.9	103	298	0	26	12
Lithuania	13.6	2.9	103	298	55	25	28
Luxembourg	12.1	5.3	52	148	115	15	8
Netherlands	18.7	5.3	46	134	30	18	15
Poland	22.2	5.0	103	298	49	37	21
Portugal	18.3	4.0	38	213	86	20	13
Romania	22.6	5.0	103	298	45	29	23
Slovakia	23.1	5.0	103	298	87	6	13
Slovenia	16.8	5.0	103	298	87	17	14
Spain	16.4	4.0	103	298	90	18	20
Sweden	10.4	2.9	77	223	108	6	3
UK	13.3	2.9	85	245	20	15	7
EU26	**17.0**	**4.5**	**104**	**297**	**64**	**18**	**13.9**

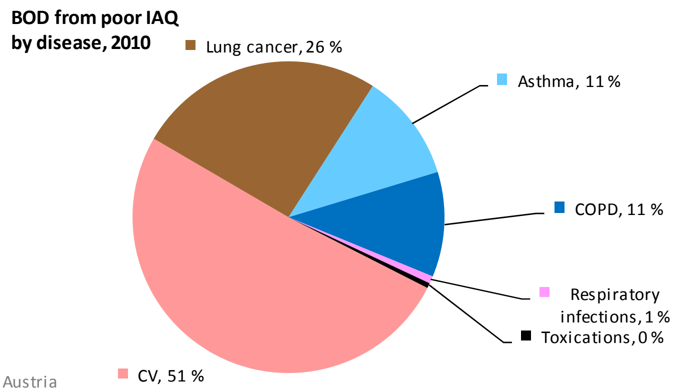
Appendix B – Country results on baseline burden

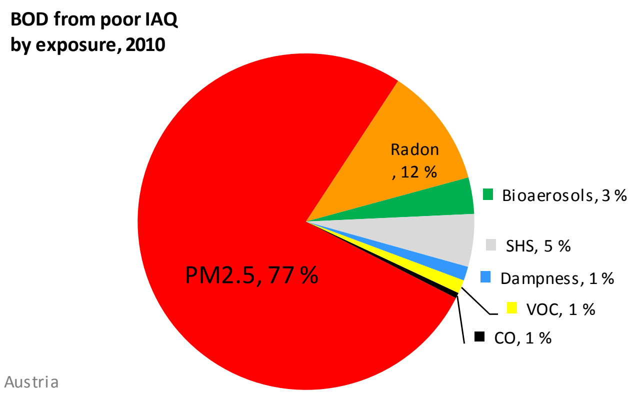
This section presents the national results on burden of disease attributable to exposures to pollutants present in residential indoor air at the baseline in 2010. The results are subdivided by diseases and by exposures.

Austria

Disease	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
Austria	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	1 887	15 309	11.6 %	36.5 %	50.9 %
Lung cancer	953	7 728	15.1 %	10.6 %	25.7 %
Asthma (& allergy)	416	3 374	4.7 %	6.5 %	11.2 %
COPD	404	3 280	2.6 %	8.3 %	10.9 %
U&L respiratory infections	28	230	0.8 %	0.0 %	0.8 %
Acute CO toxication	19	156	0.5 %	0.0 %	0.5 %
Total	**3 708**	**30 077**	**35 %**	**62 %**	**100.0 %**

Exposure	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
	DALY/million	DALY	%	%	%
PM2.5	2 832	22 969	18.5 %	58.2 %	76.7 %
Radon	426	3 458	11.6 %	-	11.6 %
Bioaerosols	129	1 049	-	3.5 %	3.5 %
Second hand smoke (SHS)	187	1 516	5.1 %	-	5.1 %
Dampness and mould	50	403	1.3 %	-	1.3 %
Volatile organic cmpounds (VOC)	48	389	1.3 %	-	1.3 %
Carbon monoxide (CO)	19	156	0.5 %	-	0.5 %
Total	**3 691**	**29 941**	**38.3 %**	**61.7 %**	**100.0 %**

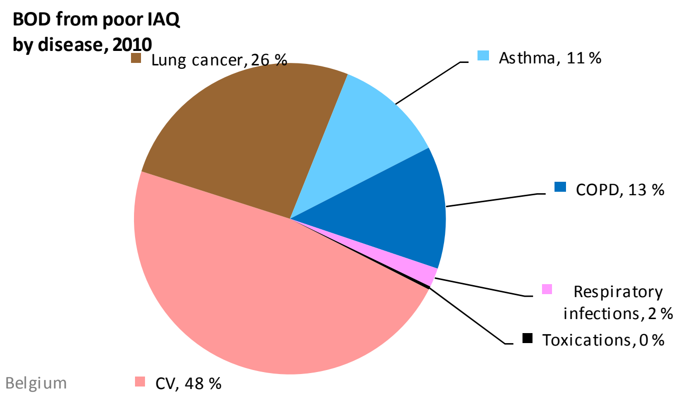


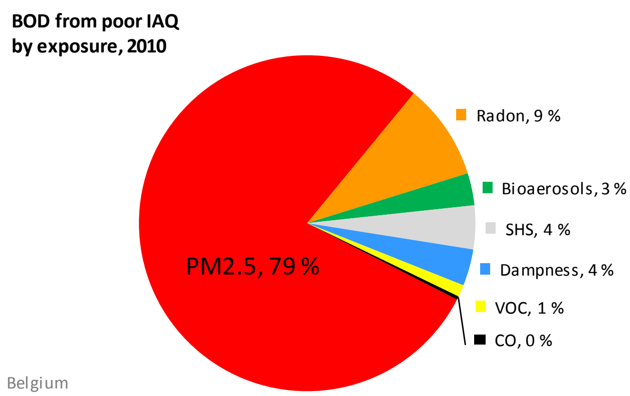


Belgium

Disease	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
Belgium	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	2 301	23 689	10.3 %	35.1 %	47.4 %
Lung cancer	1 267	13 045	13.2 %	12.9 %	26.1 %
Asthma (& allergy)	553	5 698	5.4 %	6.0 %	11.4 %
COPD	618	6 359	2.9 %	9.9 %	12.7 %
U&L respiratory infections	96	992	2.0 %	0.0 %	2.0 %
Acute CO toxication	15	159	0.3 %	0.0 %	0.3 %
Total	**4 851**	**49 943**	**34 %**	**64 %**	**100.0 %**

Exposure	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
	DALY/million	DALY	%	%	%
PM2.5	3 790	39 016	17.8 %	60.6 %	78.4 %
Radon	447	4 606	9.3 %	-	9.3 %
Bioaerosols	150	1 543	-	3.1 %	3.1 %
Second hand smoke (SHS)	203	2 095	4.2 %	-	4.2 %
Dampness and mould	170	1 752	3.5 %	-	3.5 %
Volatile organic cmpounds (VOC)	56	573	1.2 %	-	1.2 %
Carbon monoxide (CO)	15	159	0.3 %	-	0.3 %
Total	**4 831**	**49 744**	**36.3 %**	**63.7 %**	**100.0 %**

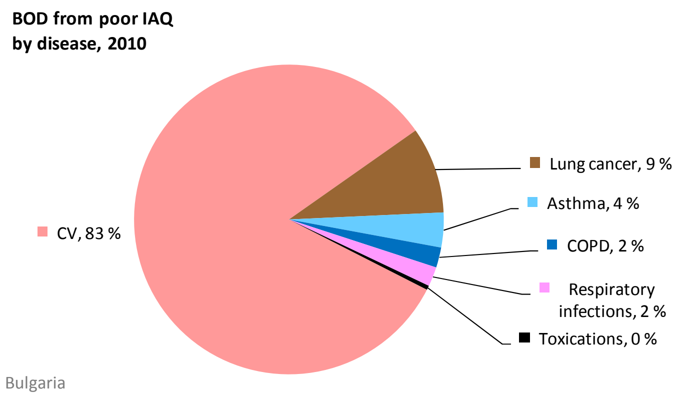


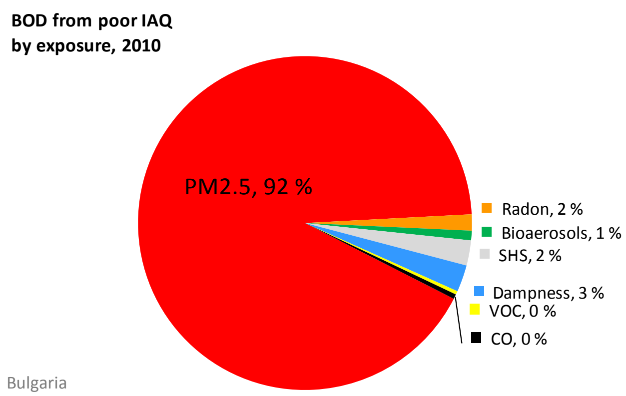


Bulgaria

Disease	Burden of disease in 2010		Source contributions Indoor	Outdoor	Percentage of National BoD
Bulgaria	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	8 280	65 953	15.3 %	65.7 %	82.7 %
Lung cancer	904	7 199	3.1 %	6.0 %	9.0 %
Asthma (& allergy)	363	2 890	1.7 %	1.9 %	3.6 %
COPD	212	1 690	0.4 %	1.7 %	2.1 %
U&L respiratory infections	202	1 612	2.0 %	0.0 %	2.0 %
Acute CO toxication	45	362	0.5 %	0.0 %	0.5 %
Total	**10 007**	**79 705**	**23 %**	**75 %**	**100.0 %**

Exposure	Burden of disease in 2010		Source contributions Indoor	Outdoor	Percentage of National BoD
	DALY/million	DALY	%	%	%
PM2.5	9 162	72 974	17.4 %	74.3 %	91.7 %
Radon	157	1 251	1.6 %	-	1.6 %
Bioaerosols	93	741	-	0.9 %	0.9 %
Second hand smoke (SHS)	243	1 933	2.4 %	-	2.4 %
Dampness and mould	260	2 074	2.6 %	-	2.6 %
Volatile organic cmpounds (VOC)	35	275	0.3 %	-	0.3 %
Carbon monoxide (CO)	45	362	0.5 %	-	0.5 %
Total	**9 995**	**79 610**	**24.8 %**	**75.2 %**	**100.0 %**

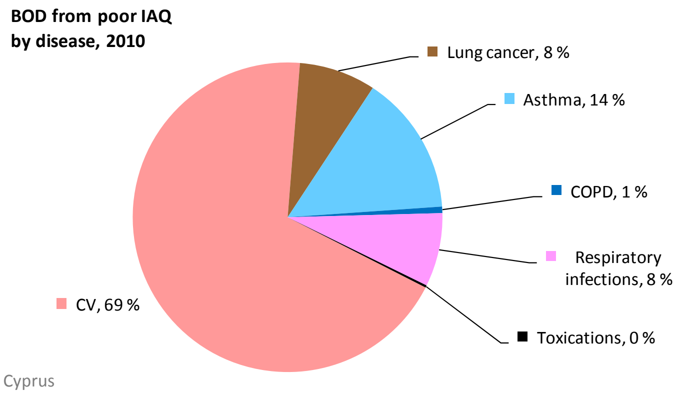


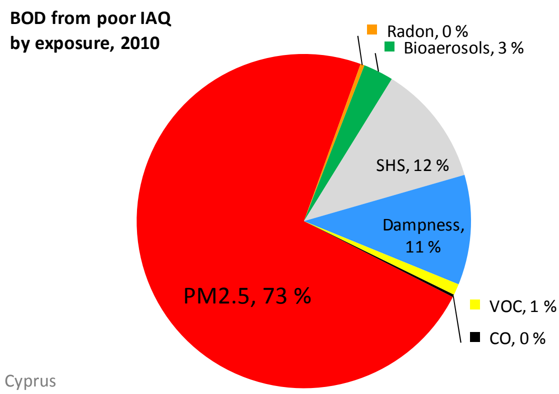


Cyprus

Disease	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
Cyprus	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	2 878	2 290	9.6 %	51.8 %	68.8 %
Lung cancer	334	266	1.8 %	6.2 %	8.0 %
Asthma (& allergy)	612	487	8.6 %	6.1 %	14.6 %
COPD	28	23	0.1 %	0.6 %	0.7 %
U&L respiratory infections	322	256	7.7 %	0.0 %	7.7 %
Acute CO toxication	10	8	0.2 %	0.0 %	0.2 %
Total	**4 185**	**3 331**	**28 %**	**65 %**	**100.0 %**

Exposure	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
	DALY/million	DALY	%	%	%
PM2.5	3 044	2 423	11.4 %	61.6 %	73.0 %
Radon	16	13	0.4 %	-	0.4 %
Bioaerosols	122	97	-	2.9 %	2.9 %
Second hand smoke (SHS)	489	389	11.7 %	-	11.7 %
Dampness and mould	443	353	10.6 %	-	10.6 %
Volatile organic cmpounds (VOC)	45	36	1.1 %	-	1.1 %
Carbon monoxide (CO)	10	8	0.2 %	-	0.2 %
Total	**4 169**	**3 318**	**35.5 %**	**64.5 %**	**100.0 %**

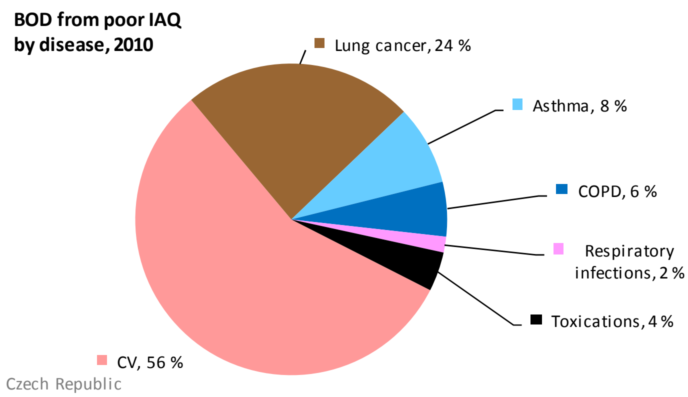


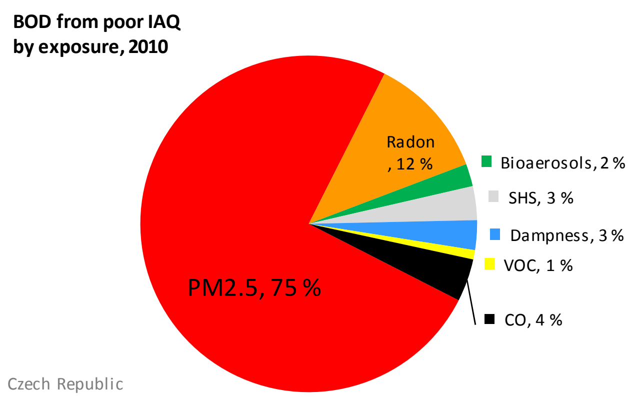


Czech Republic

Disease	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
Czech Republic	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	4 193	42 960	10.0 %	44.3 %	56.4 %
Lung cancer	1 782	18 254	14.1 %	9.9 %	24.0 %
Asthma (& allergy)	613	6 281	3.7 %	4.6 %	8.2 %
COPD	421	4 315	1.0 %	4.6 %	5.7 %
U&L respiratory infections	122	1 252	1.6 %	0.0 %	1.6 %
Acute CO toxication	304	3 112	4.1 %	0.0 %	4.1 %
Total	**7 435**	**76 175**	**35 %**	**63 %**	**100.0 %**

Exposure	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
	DALY/million	DALY	%	%	%
PM2.5	5 555	56 911	13.8 %	61.1 %	74.9 %
Radon	873	8 945	11.8 %	-	11.8 %
Bioaerosols	160	1 642	-	2.2 %	2.2 %
Second hand smoke (SHS)	242	2 475	3.3 %	-	3.3 %
Dampness and mould	212	2 170	2.9 %	-	2.9 %
Volatile organic cmpounds (VOC)	67	683	0.9 %	-	0.9 %
Carbon monoxide (CO)	304	3 112	4.1 %	-	4.1 %
Total	**7 412**	**75 938**	**36.7 %**	**63.3 %**	**100.0 %**

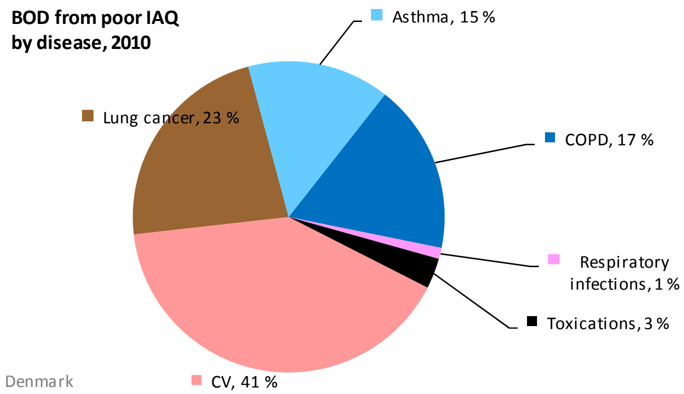


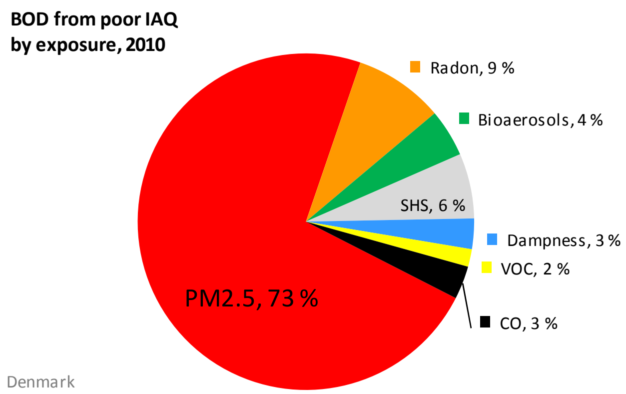


Denmark

Disease	Burden of disease in 2010		Source contributions Indoor	Outdoor	Percentage of National BoD
Denmark	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	1 597	8 547	6.9 %	30.8 %	40.7 %
Lung cancer	887	4 746	11.3 %	11.3 %	22.6 %
Asthma (& allergy)	580	3 104	7.0 %	7.8 %	14.8 %
COPD	690	3 692	3.2 %	14.4 %	17.6 %
U&L respiratory infections	45	240	1.1 %	0.0 %	1.1 %
Acute CO toxication	124	663	3.2 %	0.0 %	3.2 %
Total	**3 923**	**20 992**	**33 %**	**64 %**	**100.0 %**

Exposure	Burden of disease in 2010		Source contributions Indoor	Outdoor	Percentage of National BoD
	DALY/million	DALY	%	%	%
PM2.5	2 837	15 184	13.3 %	59.4 %	72.8 %
Radon	335	1 794	8.6 %	-	8.6 %
Bioaerosols	178	955	-	4.6 %	4.6 %
Second hand smoke (SHS)	244	1 305	6.3 %	-	6.3 %
Dampness and mould	115	614	2.9 %	-	2.9 %
Volatile organic cmpounds (VOC)	66	354	1.7 %	-	1.7 %
Carbon monoxide (CO)	124	663	3.2 %	-	3.2 %
Total	**3 900**	**20 869**	**36.0 %**	**64.0 %**	**100.0 %**

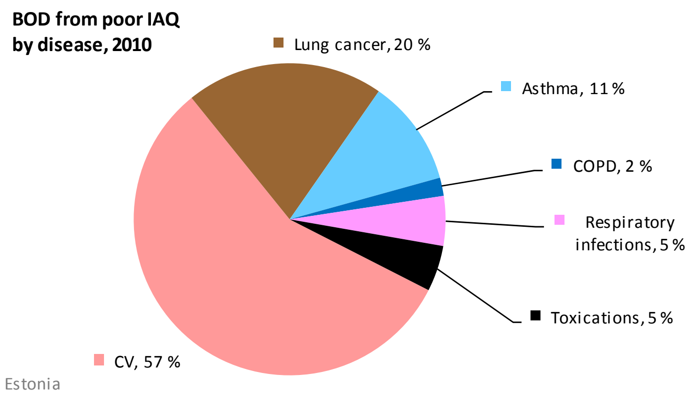


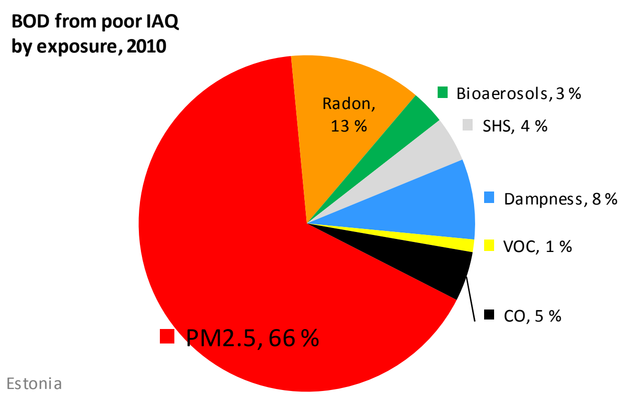


Estonia

Disease	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
Estonia	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	2 943	3 937	11.6 %	42.5 %	56.7 %
Lung cancer	1 065	1 425	14.4 %	6.1 %	20.5 %
Asthma (& allergy)	572	765	5.8 %	5.2 %	11.0 %
COPD	98	131	0.4 %	1.5 %	1.9 %
U&L respiratory infections	268	359	5.2 %	0.0 %	5.2 %
Acute CO toxication	246	329	4.7 %	0.0 %	4.7 %
Total	**5 192**	**6 946**	**42 %**	**55 %**	**100.0 %**

Exposure	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
	DALY/million	DALY	%	%	%
PM2.5	3 412	4 565	14.2 %	51.8 %	66.0 %
Radon	658	880	12.7 %	-	12.7 %
Bioaerosols	168	225	-	3.3 %	3.3 %
Second hand smoke (SHS)	224	299	4.3 %	-	4.3 %
Dampness and mould	400	535	7.7 %	-	7.7 %
Volatile organic cmpounds (VOC)	62	83	1.2 %	-	1.2 %
Carbon monoxide (CO)	246	329	4.8 %	-	4.8 %
Total	**5 170**	**6 917**	**44.9 %**	**55.1 %**	**100.0 %**

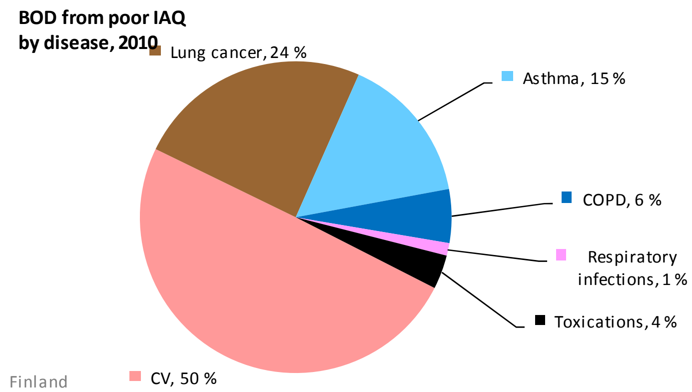


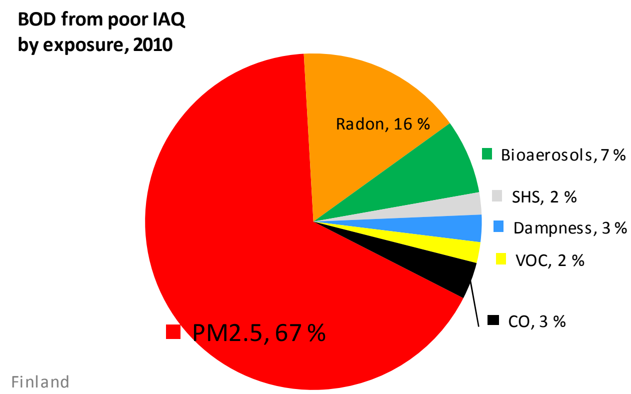


Finland

Disease	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
Finland	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	1 250	6 495	11.8 %	36.6 %	49.7 %
Lung cancer	614	3 192	18.0 %	6.4 %	24.4 %
Asthma (& allergy)	389	2 023	5.0 %	10.5 %	15.5 %
COPD	140	726	1.4 %	4.2 %	5.6 %
U&L respiratory infections	33	172	1.3 %	0.0 %	1.3 %
Acute CO toxication	89	460	3.5 %	0.0 %	3.5 %
Total	**2 514**	**13 067**	**41 %**	**58 %**	**100.0 %**

Exposure	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
	DALY/million	DALY	%	%	%
PM2.5	1 665	8 653	16.3 %	50.3 %	66.6 %
Radon	399	2 073	16.0 %	-	16.0 %
Bioaerosols	178	927	-	7.1 %	7.1 %
Second hand smoke (SHS)	54	278	2.1 %	-	2.1 %
Dampness and mould	65	340	2.6 %	-	2.6 %
Volatile organic cmpounds (VOC)	50	261	2.0 %	-	2.0 %
Carbon monoxide (CO)	89	460	3.5 %	-	3.5 %
Total	**2 500**	**12 994**	**42.5 %**	**57.5 %**	**100.0 %**



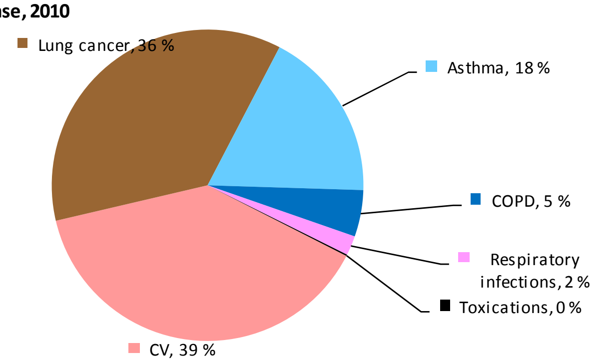


France

Disease	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
France	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	1 102	65 974	11.7 %	26.7 %	38.8 %
Lung cancer	1 031	61 680	23.4 %	12.9 %	36.3 %
Asthma (& allergy)	507	30 353	7.9 %	9.9 %	17.9 %
COPD	137	8 226	1.5 %	3.4 %	4.8 %
U&L respiratory infections	57	3 428	2.0 %	0.0 %	2.0 %
Acute CO toxication	4	246	0.1 %	0.0 %	0.1 %
Total	**2 839**	**169 907**	**47 %**	**53 %**	**100.0 %**

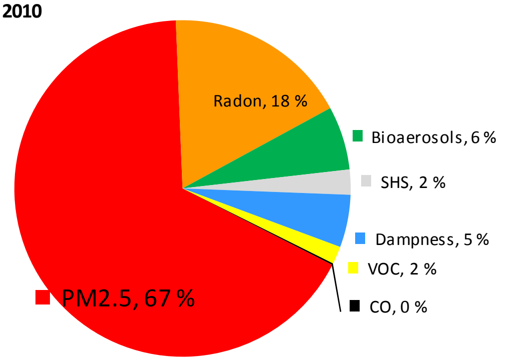
Exposure	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
	DALY/million	DALY	%	%	%
PM2.5	1 887	112 931	20.4 %	46.5 %	66.9 %
Radon	500	29 902	17.7 %	-	17.7 %
Bioaerosols	173	10 352	-	6.1 %	6.1 %
Second hand smoke (SHS)	68	4 080	2.4 %	-	2.4 %
Dampness and mould	142	8 527	5.0 %	-	5.0 %
Volatile organic cmpounds (VOC)	48	2 872	1.7 %	-	1.7 %
Carbon monoxide (CO)	4	246	0.1 %	-	0.1 %
Total	**2 822**	**168 910**	**47.4 %**	**52.6 %**	**100.0 %**

BOD from poor IAQ by disease, 2010



France

BOD from poor IAQ by exposure, 2010

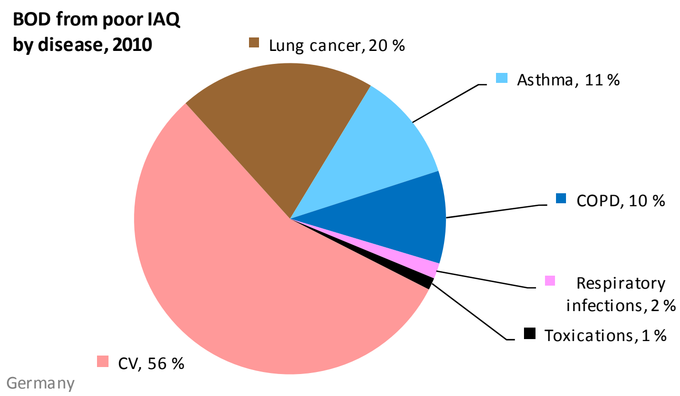


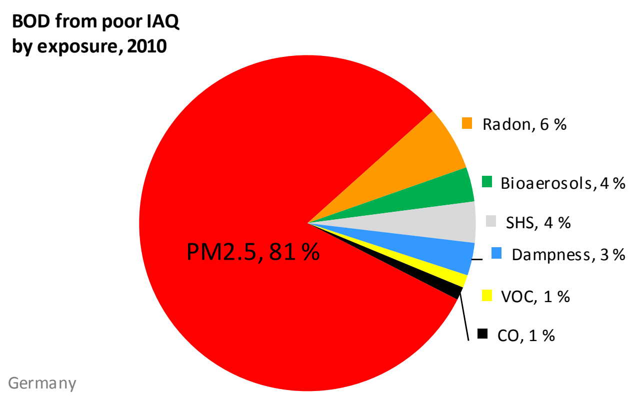
France

Germany

Disease	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
Germany	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	2 298	189 409	13.6 %	40.2 %	55.8 %
Lung cancer	838	69 099	9.9 %	10.4 %	20.4 %
Asthma (& allergy)	467	38 528	5.3 %	6.0 %	11.4 %
COPD	397	32 678	2.4 %	7.2 %	9.6 %
U&L respiratory infections	66	5 452	1.6 %	0.0 %	1.6 %
Acute CO toxication	51	4 217	1.2 %	0.0 %	1.2 %
Total	**4 118**	**339 382**	**34 %**	**64 %**	**100.0 %**

Exposure	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
	DALY/million	DALY	%	%	%
PM2.5	3 315	273 235	20.5 %	60.4 %	80.9 %
Radon	256	21 116	6.2 %	-	6.2 %
Bioaerosols	137	11 255	-	3.3 %	3.3 %
Second hand smoke (SHS)	162	13 334	3.9 %	-	3.9 %
Dampness and mould	129	10 617	3.1 %	-	3.1 %
Volatile organic cmpounds (VOC)	51	4 163	1.2 %	-	1.2 %
Carbon monoxide (CO)	51	4 217	1.2 %	-	1.2 %
Total	**4 100**	**337 937**	**36.3 %**	**63.7 %**	**100.0 %**

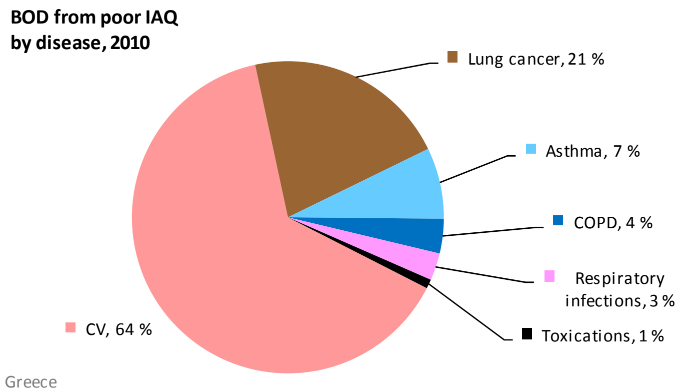


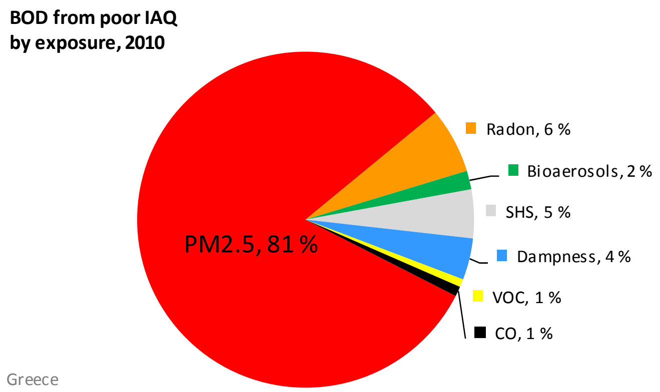


Greece

Disease	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
Greece	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	3 098	33 989	10.1 %	50.9 %	64.1 %
Lung cancer	1 023	11 219	9.0 %	12.2 %	21.2 %
Asthma (& allergy)	356	3 905	3.7 %	3.7 %	7.4 %
COPD	173	1 901	0.6 %	3.0 %	3.6 %
U&L respiratory infections	136	1 493	2.8 %	0.0 %	2.8 %
Acute CO toxication	45	498	0.9 %	0.0 %	0.9 %
Total	**4 832**	**53 005**	**27 %**	**70 %**	**100.0 %**

Exposure	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
	DALY/million	DALY	%	%	%
PM2.5	3 925	43 059	13.6 %	67.9 %	81.5 %
Radon	303	3 323	6.3 %	-	6.3 %
Bioaerosols	86	946	-	1.8 %	1.8 %
Second hand smoke (SHS)	226	2 475	4.7 %	-	4.7 %
Dampness and mould	193	2 114	4.0 %	-	4.0 %
Volatile organic cmpounds (VOC)	37	407	0.8 %	-	0.8 %
Carbon monoxide (CO)	45	498	0.9 %	-	0.9 %
Total	**4 815**	**52 822**	**30.3 %**	**69.7 %**	**100.0 %**



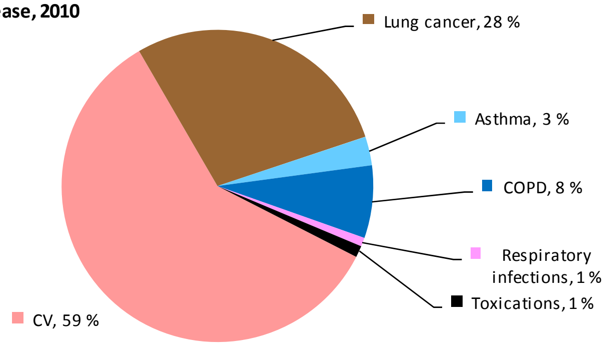


Hungary

Disease	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
Hungary	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	5 377	53 352	10.2 %	48.0 %	59.1 %
Lung cancer	2 572	25 518	14.7 %	13.6 %	28.3 %
Asthma (& allergy)	271	2 690	1.3 %	1.7 %	3.0 %
COPD	685	6 796	1.3 %	6.2 %	7.5 %
U&L respiratory infections	83	826	0.9 %	0.0 %	0.9 %
Acute CO toxication	107	1 064	1.2 %	0.0 %	1.2 %
Total	**9 095**	**90 246**	**30 %**	**70 %**	**100.0 %**

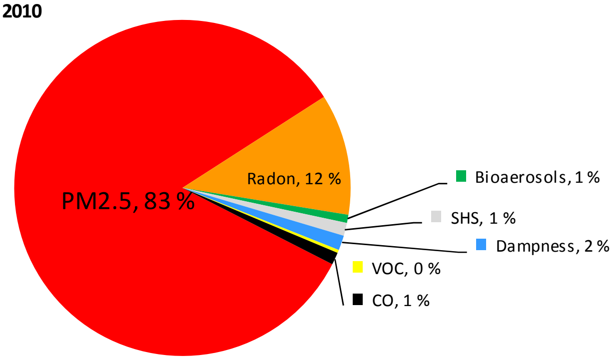
Exposure	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
	DALY/million	DALY	%	%	%
PM2.5	7 577	75 183	14.7 %	68.7 %	83.4 %
Radon	1 061	10 524	11.7 %	-	11.7 %
Bioaerosols	72	710	-	0.8 %	0.8 %
Second hand smoke (SHS)	113	1 118	1.2 %	-	1.2 %
Dampness and mould	130	1 292	1.4 %	-	1.4 %
Volatile organic cmpounds (VOC)	27	263	0.3 %	-	0.3 %
Carbon monoxide (CO)	107	1 064	1.2 %	-	1.2 %
Total	**9 086**	**90 154**	**30.5 %**	**69.5 %**	**100.0 %**

BOD from poor IAQ by disease, 2010



Hungary

BOD from poor IAQ by exposure, 2010

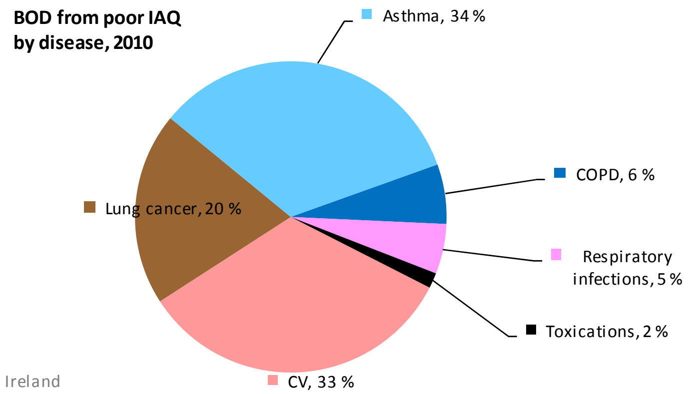


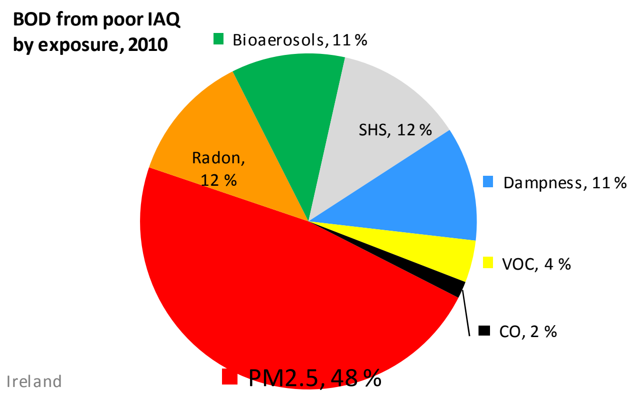
Hungary

Ireland

Disease	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
Ireland	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	950	3 715	7.9 %	20.3 %	33.4 %
Lung cancer	571	2 234	14.5 %	5.6 %	20.1 %
Asthma (& allergy)	956	3 740	17.8 %	15.7 %	33.6 %
COPD	176	690	1.7 %	4.5 %	6.2 %
U&L respiratory infections	147	576	5.2 %	0.0 %	5.2 %
Acute CO toxication	45	178	1.6 %	0.0 %	1.6 %
Total	**2 847**	**11 133**	**49 %**	**46 %**	**100.0 %**

Exposure	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
	DALY/million	DALY	%	%	%
PM2.5	1 339	5 239	13.3 %	34.4 %	47.7 %
Radon	347	1 355	12.3 %	-	12.3 %
Bioaerosols	307	1 200	-	10.9 %	10.9 %
Second hand smoke (SHS)	346	1 355	12.3 %	-	12.3 %
Dampness and mould	309	1 207	11.0 %	-	11.0 %
Volatile organic cmpounds (VOC)	114	445	4.1 %	-	4.1 %
Carbon monoxide (CO)	45	178	1.6 %	-	1.6 %
Total	**2 807**	**10 978**	**54.7 %**	**45.3 %**	**100.0 %**

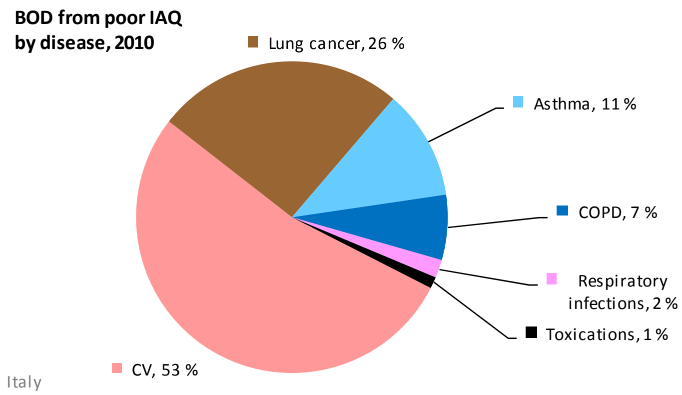


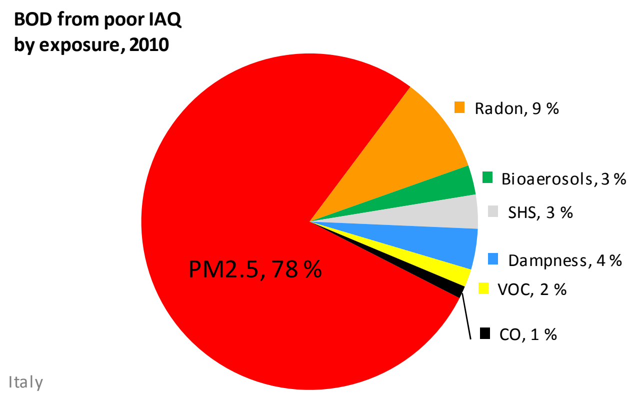


Italy

Disease	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
Italy	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	2 041	117 297	8.9 %	42.3 %	53.0 %
Lung cancer	991	56 952	12.3 %	13.4 %	25.7 %
Asthma (& allergy)	438	25 199	5.6 %	5.8 %	11.4 %
COPD	261	14 978	1.2 %	5.6 %	6.8 %
U&L respiratory infections	72	4 149	1.9 %	0.0 %	1.9 %
Acute CO toxication	45	2 610	1.2 %	0.0 %	1.2 %
Total	**3 848**	**221 185**	**31 %**	**67 %**	**100.0 %**

Exposure	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
	DALY/million	DALY	%	%	%
PM2.5	2 972	170 810	13.6 %	64.1 %	77.7 %
Radon	358	20 586	9.4 %	-	9.4 %
Bioaerosols	108	6 197	-	2.8 %	2.8 %
Second hand smoke (SHS)	125	7 192	3.3 %	-	3.3 %
Dampness and mould	150	8 617	3.9 %	-	3.9 %
Volatile organic cmpounds (VOC)	66	3 776	1.7 %	-	1.7 %
Carbon monoxide (CO)	45	2 610	1.2 %	-	1.2 %
Total	**3 824**	**219 789**	**33.1 %**	**66.9 %**	**100.0 %**

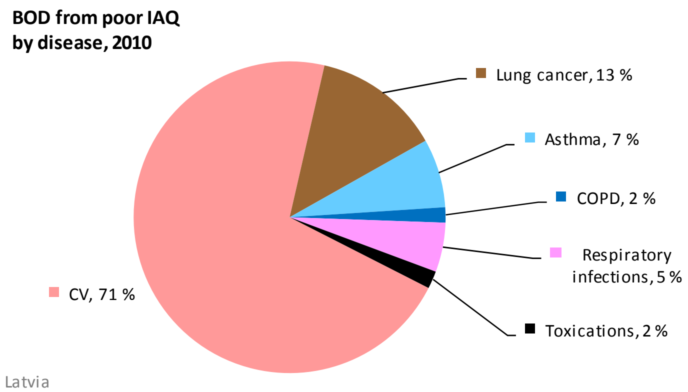


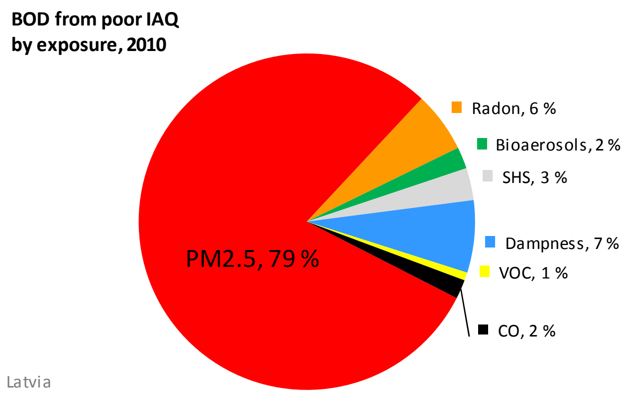


Latvia

Disease	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
Latvia	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	3 926	9 145	13.3 %	55.6 %	71.1 %
Lung cancer	731	1 703	7.3 %	5.9 %	13.2 %
Asthma (& allergy)	395	919	3.7 %	3.5 %	7.1 %
COPD	87	203	0.3 %	1.3 %	1.6 %
U&L respiratory infections	283	658	5.1 %	0.0 %	5.1 %
Acute CO toxication	101	234	1.8 %	0.0 %	1.8 %
Total	**5 523**	**12 863**	**32 %**	**66 %**	**100.0 %**

Exposure	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
	DALY/million	DALY	%	%	%
PM2.5	4 376	10 192	15.4 %	64.1 %	79.5 %
Radon	320	746	5.8 %	-	5.8 %
Bioaerosols	115	268	-	2.1 %	2.1 %
Second hand smoke (SHS)	170	395	3.1 %	-	3.1 %
Dampness and mould	383	893	7.0 %	-	7.0 %
Volatile organic cmpounds (VOC)	43	99	0.8 %	-	0.8 %
Carbon monoxide (CO)	101	234	1.8 %	-	1.8 %
Total	**5 508**	**12 828**	**33.8 %**	**66.2 %**	**100.0 %**

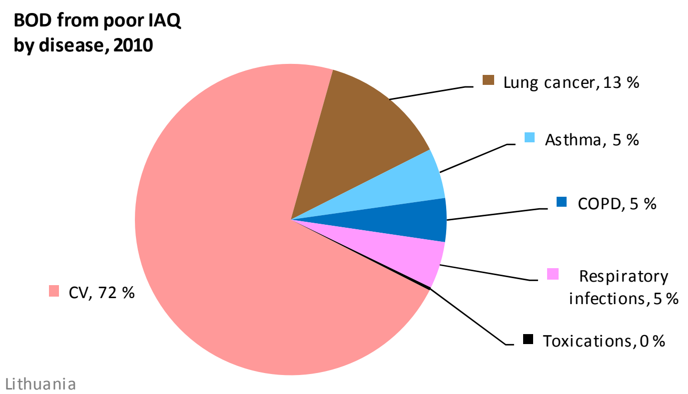


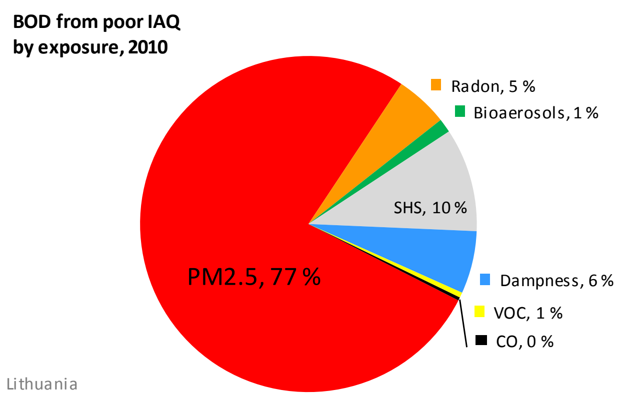


Lithuania

Disease	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
Lithuania	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	3 531	12 236	11.3 %	51.8 %	71.9 %
Lung cancer	648	2 247	6.6 %	6.6 %	13.2 %
Asthma (& allergy)	256	889	2.9 %	2.3 %	5.2 %
COPD	223	772	0.8 %	3.7 %	4.5 %
U&L respiratory infections	240	831	4.9 %	0.0 %	4.9 %
Acute CO toxication	15	51	0.3 %	0.0 %	0.3 %
Total	**4 914**	**17 026**	**27 %**	**64 %**	**100.0 %**

Exposure	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
	DALY/million	DALY	%	%	%
PM2.5	3 768	13 056	13.8 %	63.0 %	76.8 %
Radon	247	857	5.0 %	-	5.0 %
Bioaerosols	66	229	-	1.3 %	1.3 %
Second hand smoke (SHS)	489	1 694	10.0 %	-	10.0 %
Dampness and mould	296	1 025	6.0 %	-	6.0 %
Volatile organic cmpounds (VOC)	25	85	0.5 %	-	0.5 %
Carbon monoxide (CO)	15	51	0.3 %	-	0.3 %
Total	**4 905**	**16 996**	**35.6 %**	**64.4 %**	**100.0 %**

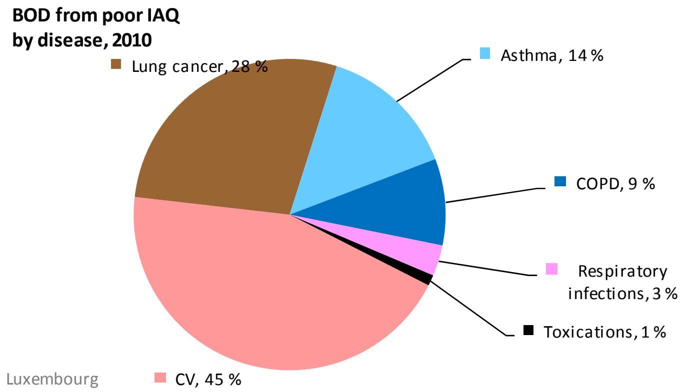


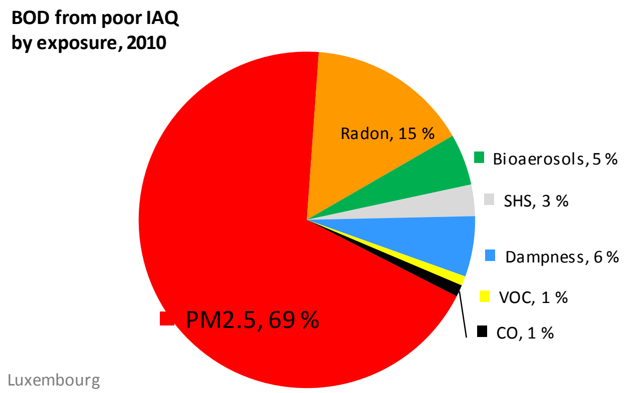


Luxembourg

Disease	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
Luxembourg	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	1 567	701	13.3 %	29.9 %	44.3 %
Lung cancer	992	444	19.4 %	8.6 %	28.1 %
Asthma (& allergy)	506	226	6.4 %	7.9 %	14.3 %
COPD	317	142	2.8 %	6.2 %	9.0 %
U&L respiratory infections	113	51	3.2 %	0.0 %	3.2 %
Acute CO toxication	40	18	1.1 %	0.0 %	1.1 %
Total	**3 535**	**1 581**	**46 %**	**53 %**	**100.0 %**

Exposure	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
	DALY/million	DALY	%	%	%
PM2.5	2 418	1 082	21.1 %	47.5 %	68.6 %
Radon	547	245	15.5 %	-	15.5 %
Bioaerosols	175	78	-	5.0 %	5.0 %
Second hand smoke (SHS)	106	48	3.0 %	-	3.0 %
Dampness and mould	205	92	5.8 %	-	5.8 %
Volatile organic cmpounds (VOC)	32	14	0.9 %	-	0.9 %
Carbon monoxide (CO)	40	18	1.1 %	-	1.1 %
Total	**3 524**	**1 576**	**47.5 %**	**52.5 %**	**100.0 %**

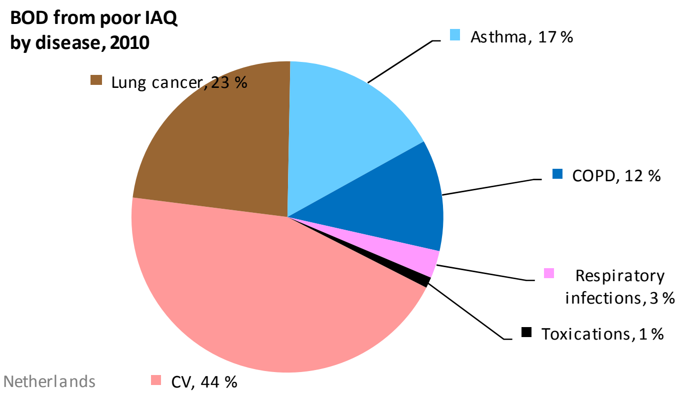


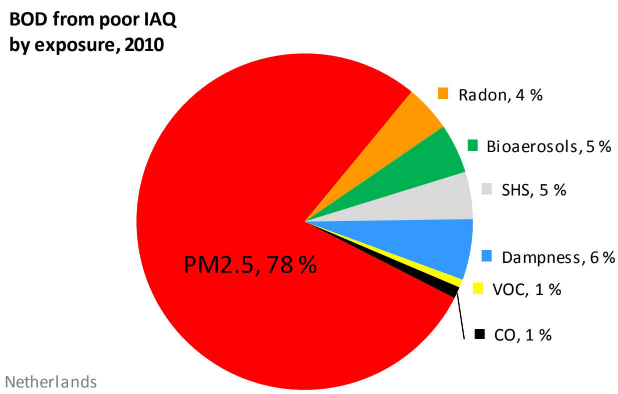


Netherlands

Disease	Burden of disease in 2010		Source contributions Indoor	Outdoor	Percentage of National BoD
Netherlands	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	1 830	29 409	9.7 %	33.3 %	44.5 %
Lung cancer	959	15 403	8.9 %	14.4 %	23.3 %
Asthma (& allergy)	684	10 995	7.8 %	8.8 %	16.6 %
COPD	477	7 670	2.6 %	9.0 %	11.6 %
U&L respiratory infections	118	1 894	2.9 %	0.0 %	2.9 %
Acute CO toxication	45	730	1.1 %	0.0 %	1.1 %
Total	**4 114**	**66 100**	**33 %**	**66 %**	**100.0 %**

Exposure	Burden of disease in 2010		Source contributions Indoor	Outdoor	Percentage of National BoD
	DALY/million	DALY	%	%	%
PM2.5	3 219	51 719	17.8 %	60.7 %	78.5 %
Radon	184	2 954	4.5 %	-	4.5 %
Bioaerosols	196	3 143	-	4.8 %	4.8 %
Second hand smoke (SHS)	186	2 994	4.5 %	-	4.5 %
Dampness and mould	240	3 856	5.8 %	-	5.8 %
Volatile organic cmpounds (VOC)	33	523	0.8 %	-	0.8 %
Carbon monoxide (CO)	45	730	1.1 %	-	1.1 %
Total	**4 103**	**65 919**	**34.6 %**	**65.4 %**	**100.0 %**



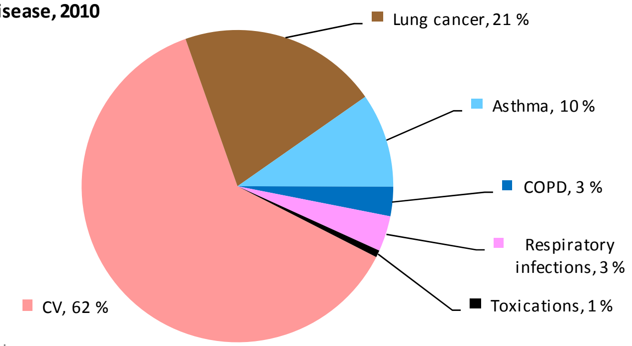


Poland

Disease	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
Poland	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	3 901	150 658	11.4 %	48.9 %	62.1 %
Lung cancer	1 301	50 252	8.4 %	12.4 %	20.7 %
Asthma (& allergy)	612	23 642	5.2 %	4.5 %	9.7 %
COPD	192	7 402	0.6 %	2.5 %	3.1 %
U&L respiratory infections	231	8 921	3.7 %	0.0 %	3.7 %
Acute CO toxication	45	1 754	0.7 %	0.0 %	0.7 %
Total	**6 282**	**242 629**	**30 %**	**68 %**	**100.0 %**

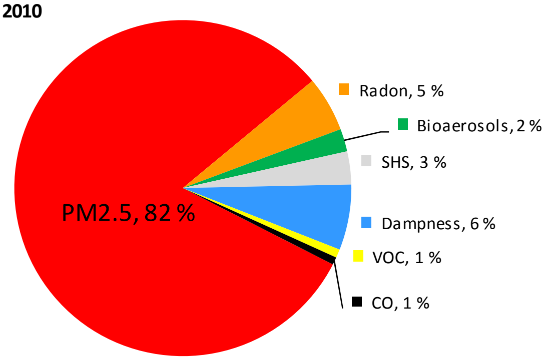
Exposure	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
	DALY/million	DALY	%	%	%
PM2.5	5 104	197 116	15.5 %	66.0 %	81.5 %
Radon	334	12 903	5.3 %	-	5.3 %
Bioaerosols	136	5 268	-	2.2 %	2.2 %
Second hand smoke (SHS)	199	7 689	3.2 %	-	3.2 %
Dampness and mould	395	15 264	6.3 %	-	6.3 %
Volatile organic cmpounds (VOC)	51	1 955	0.8 %	-	0.8 %
Carbon monoxide (CO)	45	1 754	0.7 %	-	0.7 %
Total	**6 265**	**241 950**	**31.8 %**	**68.2 %**	**100.0 %**

BOD from poor IAQ by disease, 2010



Poland

BOD from poor IAQ by exposure, 2010

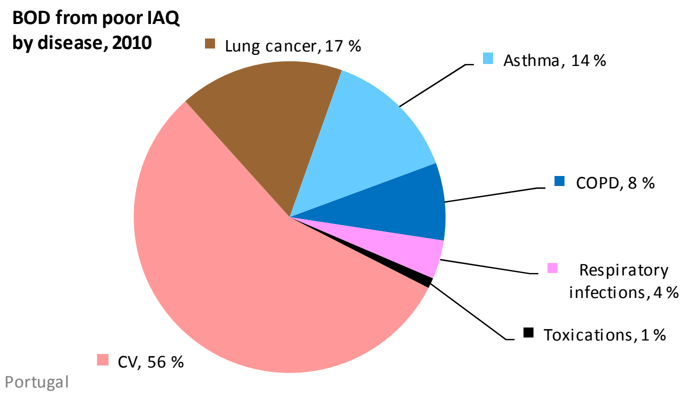


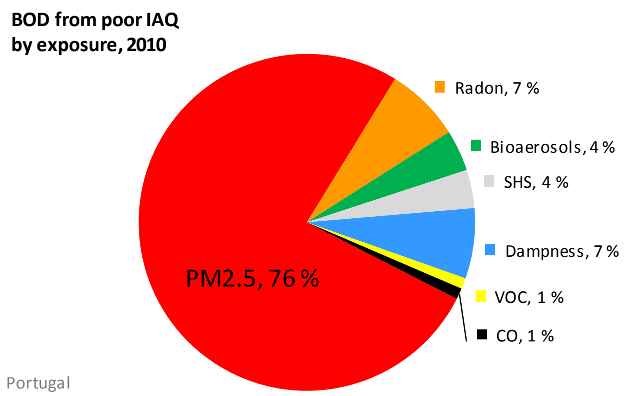
Poland

Portugal

Disease	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
Portugal	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	2 390	24 021	10.0 %	44.5 %	55.8 %
Lung cancer	733	7 362	9.2 %	8.0 %	17.1 %
Asthma (& allergy)	596	5 991	6.7 %	7.2 %	13.9 %
COPD	345	3 463	1.5 %	6.6 %	8.0 %
U&L respiratory infections	172	1 727	4.0 %	0.0 %	4.0 %
Acute CO toxication	45	456	1.1 %	0.0 %	1.1 %
Total	**4 281**	**43 021**	**32 %**	**66 %**	**100.0 %**

Exposure	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
	DALY/million	DALY	%	%	%
PM2.5	3 260	32 758	14.0 %	62.2 %	76.3 %
Radon	308	3 096	7.2 %	-	7.2 %
Bioaerosols	169	1 700	-	4.0 %	4.0 %
Second hand smoke (SHS)	157	1 582	3.7 %	-	3.7 %
Dampness and mould	288	2 898	6.7 %	-	6.7 %
Volatile organic cmpounds (VOC)	45	450	1.0 %	-	1.0 %
Carbon monoxide (CO)	45	456	1.1 %	-	1.1 %
Total	**4 273**	**42 941**	**33.8 %**	**66.2 %**	**100.0 %**

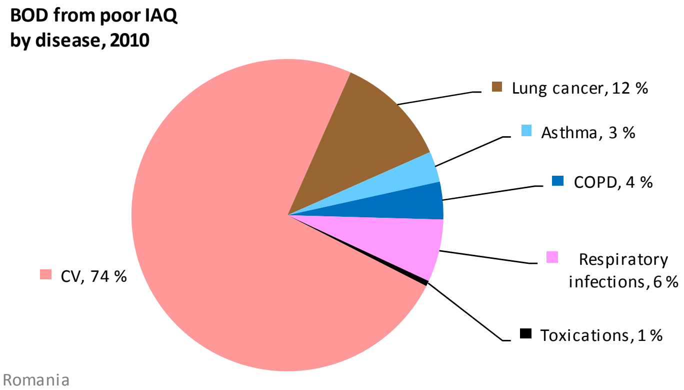


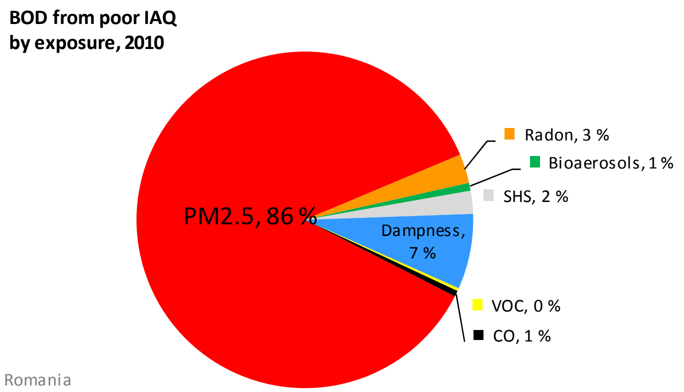


Romania

Disease	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
Romania	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	6 061	135 700	13.6 %	58.9 %	74.1 %
Lung cancer	960	21 484	4.6 %	7.2 %	11.7 %
Asthma (& allergy)	259	5 800	1.6 %	1.6 %	3.2 %
COPD	318	7 120	0.7 %	3.2 %	3.9 %
U&L respiratory infections	532	11 902	6.5 %	0.0 %	6.5 %
Acute CO toxication	45	1 017	0.6 %	0.0 %	0.6 %
Total	**8 175**	**183 023**	**28 %**	**71 %**	**100.0 %**

Exposure	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
	DALY/million	DALY	%	%	%
PM2.5	7 038	157 566	16.1 %	70.0 %	86.2 %
Radon	229	5 117	2.8 %	-	2.8 %
Bioaerosols	61	1 365	-	0.7 %	0.7 %
Second hand smoke (SHS)	181	4 051	2.2 %	-	2.2 %
Dampness and mould	591	13 225	7.2 %	-	7.2 %
Volatile organic cmpounds (VOC)	23	507	0.3 %	-	0.3 %
Carbon monoxide (CO)	45	1 017	0.6 %	-	0.6 %
Total	**8 167**	**182 847**	**29.2 %**	**70.8 %**	**100.0 %**



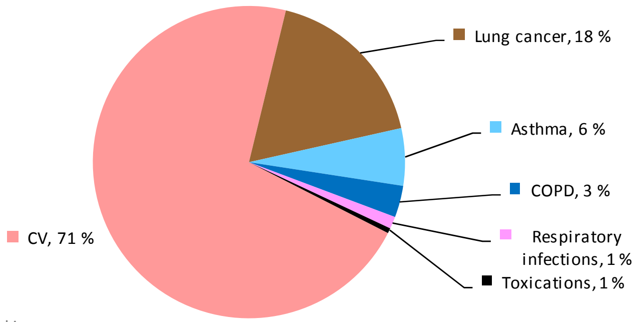


Slovakia

Disease	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
Slovakia	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	4 236	22 865	12.7 %	56.6 %	71.3 %
Lung cancer	1 051	5 673	8.7 %	9.0 %	17.7 %
Asthma (& allergy)	353	1 904	2.2 %	3.7 %	5.9 %
COPD	195	1 051	0.6 %	2.7 %	3.3 %
U&L respiratory infections	75	403	1.3 %	0.0 %	1.3 %
Acute CO toxication	31	170	0.5 %	0.0 %	0.5 %
Total	**5 940**	**32 066**	**26 %**	**72 %**	**100.0 %**

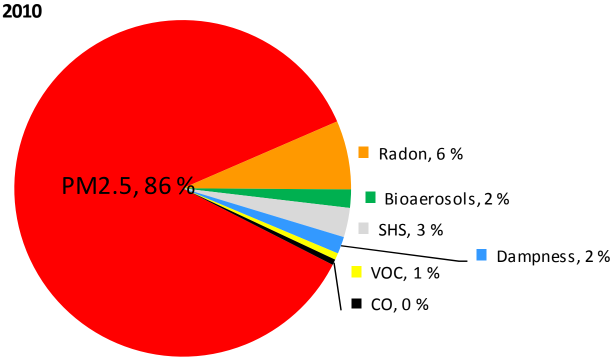
Exposure	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
	DALY/million	DALY	%	%	%
PM2.5	5 096	27 507	15.8 %	70.1 %	86.0 %
Radon	393	2 119	6.6 %	-	6.6 %
Bioaerosols	104	563	-	1.8 %	1.8 %
Second hand smoke (SHS)	167	901	2.8 %	-	2.8 %
Dampness and mould	97	525	1.6 %	-	1.6 %
Volatile organic cmpounds (VOC)	39	209	0.7 %	-	0.7 %
Carbon monoxide (CO)	31	170	0.5 %	-	0.5 %
Total	**5 927**	**31 993**	**28.1 %**	**71.9 %**	**100.0 %**

BOD from poor IAQ by disease, 2010



Slovakia

BOD from poor IAQ by exposure, 2010

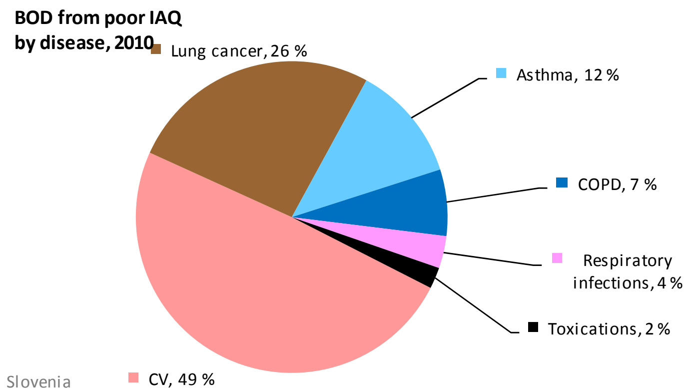


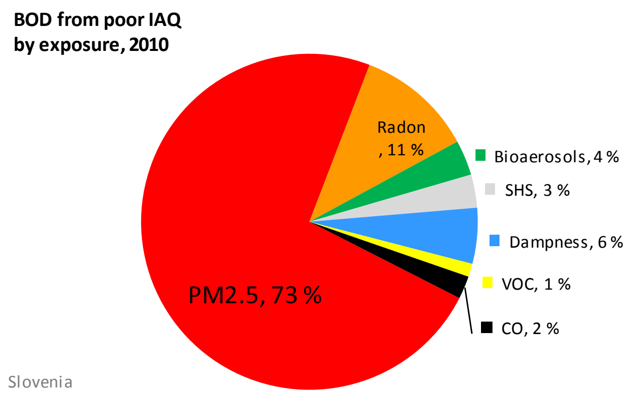
Slovakia

Slovenia

Disease	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
Slovenia	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	2 391	4 749	11.2 %	36.9 %	49.3 %
Lung cancer	1 270	2 522	14.9 %	11.3 %	26.2 %
Asthma (& allergy)	588	1 168	5.8 %	6.3 %	12.1 %
COPD	334	664	1.6 %	5.3 %	6.9 %
U&L respiratory infections	163	323	3.4 %	0.0 %	3.4 %
Acute CO toxication	106	211	2.2 %	0.0 %	2.2 %
Total	**4 852**	**9 636**	**39 %**	**60 %**	**100.0 %**

Exposure	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
	DALY/million	DALY	%	%	%
PM2.5	3 542	7 034	17.2 %	56.1 %	73.3 %
Radon	544	1 081	11.3 %	-	11.3 %
Bioaerosols	164	326	-	3.4 %	3.4 %
Second hand smoke (SHS)	154	306	3.2 %	-	3.2 %
Dampness and mould	260	516	5.4 %	-	5.4 %
Volatile organic cmpounds (VOC)	61	121	1.3 %	-	1.3 %
Carbon monoxide (CO)	106	211	2.2 %	-	2.2 %
Total	**4 831**	**9 595**	**40.5 %**	**59.5 %**	**100.0 %**

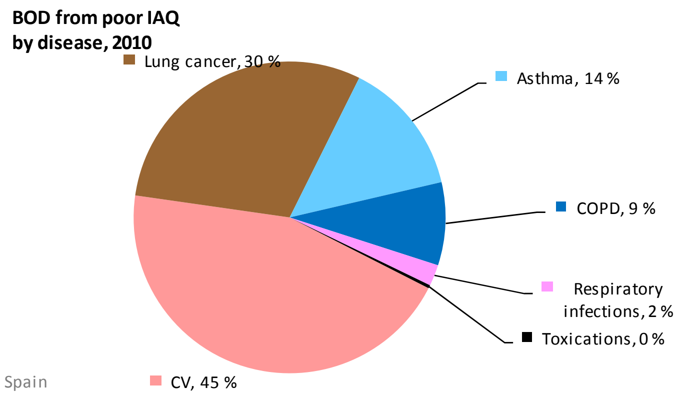


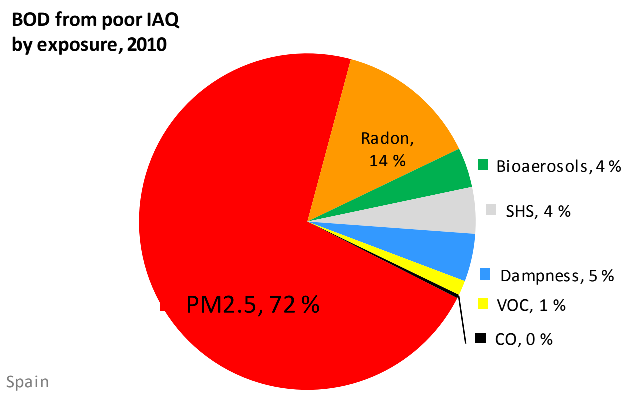


Spain

Disease	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
Spain	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	1 428	58 517	8.6 %	34.5 %	44.8 %
Lung cancer	961	39 378	17.2 %	12.9 %	30.1 %
Asthma (& allergy)	447	18 298	7.0 %	7.0 %	14.0 %
COPD	275	11 257	1.7 %	6.9 %	8.6 %
U&L respiratory infections	70	2 881	2.2 %	0.0 %	2.2 %
Acute CO toxication	11	431	0.3 %	0.0 %	0.3 %
Total	**3 191**	**130 762**	**37 %**	**61 %**	**100.0 %**

Exposure	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
	DALY/million	DALY	%	%	%
PM2.5	2 276	93 252	14.4 %	57.2 %	71.7 %
Radon	435	17 823	13.7 %	-	13.7 %
Bioaerosols	121	4 966	-	3.8 %	3.8 %
Second hand smoke (SHS)	142	5 824	4.5 %	-	4.5 %
Dampness and mould	146	5 982	4.6 %	-	4.6 %
Volatile organic cmpounds (VOC)	45	1 843	1.4 %	-	1.4 %
Carbon monoxide (CO)	11	431	0.3 %	-	0.3 %
Total	**3 175**	**130 122**	**38.9 %**	**61.1 %**	**100.0 %**

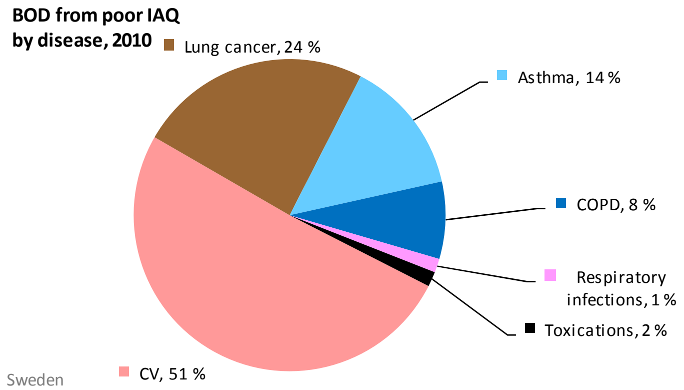


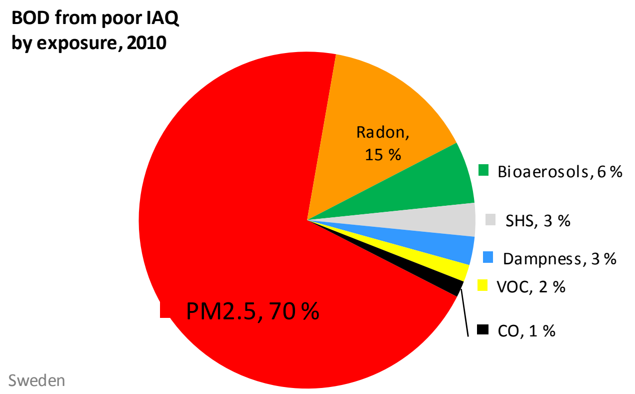


Sweden

Disease	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
Sweden	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	1 213	10 753	10.8 %	38.0 %	50.8 %
Lung cancer	578	5 123	16.8 %	7.4 %	24.2 %
Asthma (& allergy)	334	2 962	4.8 %	9.2 %	14.0 %
COPD	191	1 694	1.8 %	6.2 %	8.0 %
U&L respiratory infections	34	302	1.4 %	0.0 %	1.4 %
Acute CO toxication	37	326	1.5 %	0.0 %	1.5 %
Total	**2 386**	**21 160**	**37 %**	**61 %**	**100.0 %**

Exposure	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
	DALY/million	DALY	%	%	%
PM2.5	1 667	14 781	15.6 %	54.7 %	70.3 %
Radon	347	3 080	14.6 %	-	14.6 %
Bioaerosols	141	1 252	-	6.0 %	6.0 %
Second hand smoke (SHS)	76	678	3.2 %	-	3.2 %
Dampness and mould	65	574	2.7 %	-	2.7 %
Volatile organic cmpounds (VOC)	39	347	1.7 %	-	1.7 %
Carbon monoxide (CO)	37	326	1.5 %	-	1.5 %
Total	**2 373**	**21 039**	**39.4 %**	**60.6 %**	**100.0 %**

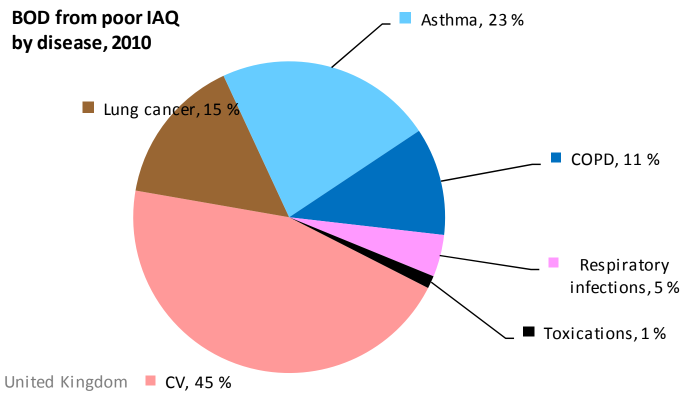


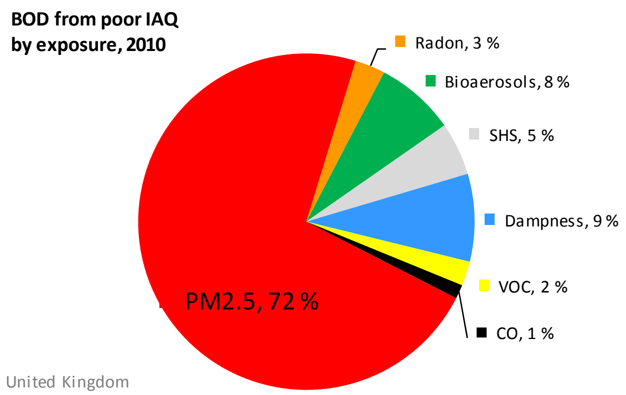


United Kingdom

Disease	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
United Kingdom	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	1 563	92 335	7.8 %	34.9 %	45.2 %
Lung cancer	531	31 338	5.2 %	10.1 %	15.4 %
Asthma (& allergy)	780	46 072	9.8 %	12.8 %	22.6 %
COPD	386	22 793	2.0 %	9.1 %	11.2 %
U&L respiratory infections	151	8 908	4.4 %	0.0 %	4.4 %
Acute CO toxication	45	2 682	1.3 %	0.0 %	1.3 %
Total	**3 456**	**204 129**	**30 %**	**67 %**	**100.0 %**

Exposure	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
	DALY/million	DALY	%	%	%
PM2.5	2 476	146 273	13.2 %	59.1 %	72.2 %
Radon	99	5 868	2.9 %	-	2.9 %
Bioaerosols	263	15 522	-	7.7 %	7.7 %
Second hand smoke (SHS)	175	10 331	5.1 %	-	5.1 %
Dampness and mould	289	17 070	8.4 %	-	8.4 %
Volatile organic cmpounds (VOC)	80	4 737	2.3 %	-	2.3 %
Carbon monoxide (CO)	45	2 682	1.3 %	-	1.3 %
Total	**3 428**	**202 485**	**33.3 %**	**66.7 %**	**100.0 %**

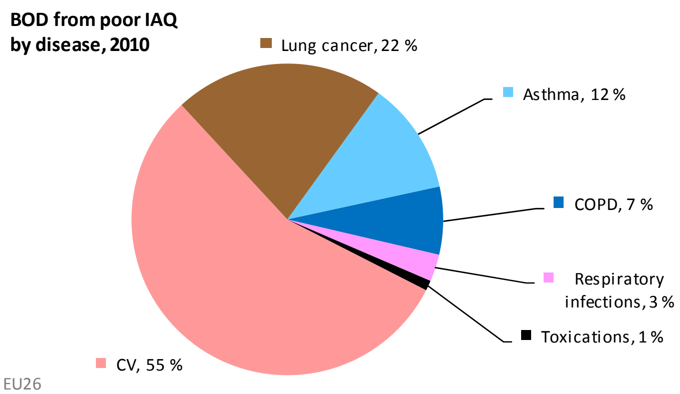


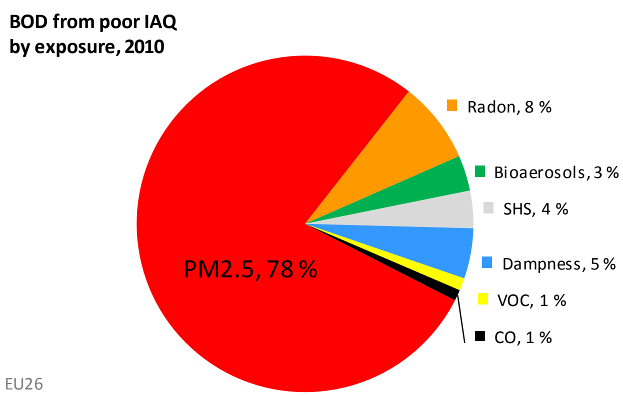


EU26

Disease	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
EU26	DALY/million	DALY	%	%	%
Cardiovascular (CV) diseases	2 449	1 184 005	11.1 %	42.7 %	55.6 %
Lung cancer	963	465 487	10.9 %	11.0 %	21.9 %
Asthma (& allergy)	513	247 903	5.5 %	6.2 %	11.6 %
COPD	310	149 715	1.5 %	5.5 %	7.0 %
U&L respiratory infections	124	59 839	2.8 %	0.0 %	2.8 %
Acute CO toxication	46	22 141	1.0 %	0.0 %	1.0 %
Total	**4 403**	**2 129 090**	**33 %**	**65 %**	**100.0 %**

Exposure	Burden of disease in 2010		Source contributions		Percentage of
			Indoor	Outdoor	National BoD
	DALY/million	DALY	%	%	%
PM2.5	3 424	1 655 488	16.3 %	61.8 %	78.1 %
Radon	343	165 717	7.8 %	-	7.8 %
Bioaerosols	150	72 519	-	3.4 %	3.4 %
Second hand smoke (SHS)	158	76 336	3.6 %	-	3.6 %
Dampness and mould	212	102 537	4.8 %	-	4.8 %
Volatile organic cmpounds (VOC)	53	25 474	1.2 %	-	1.2 %
Carbon monoxide (CO)	46	22 141	1.0 %	-	1.0 %
Total	**4 385**	**2 120 212**	**34.8 %**	**65.2 %**	**100.0 %**





REPORT

Otto Hänninen and Arja Asikainen (Eds.)

Efficient reduction of indoor exposures

Health benefits from optimizing ventilation, filtration and indoor source controls

Indoor exposures to air pollutants are associated with a significant burden of disease. In EU-27 the burden is estimated to be over 2 million healthy life years annually. This report investigates how this burden can be mitigated and in particular presents health based estimates for ventilation, including discussion of necessary control strategies for indoor sources and filtration needs for polluted outdoor air.

The report allows for construction engineers, health professionals and legislators to weight the benefits of various strategies for optimal control of the health risks. Energy efficiency impacts are also shortly covered.

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