HealthVent

Health-Based Ventilation Guidelines for Europe

Deliverable 8

Report on the impact of guideline implementation on health and energy

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HEALTHVENT

HEALTH-BASED VENTILATION GUIDELINES FOR EUROPE

WORK PACKAGE 8

IMPACT OF THE IMPLEMENTATION OF THE VENTILATION GUIDELINES ON BURDEN OF DISEASE

FINAL REPORT 2013-JANUARY-31

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Kuopio, Finland, December 2012

HEALTHVE NT Deliverable D8
Final report of Work Package 8 - Implementation and impact assessment of the guidelines

Evaluation of the impacts of implementation of guidelines on health indicators, energy, and on the development of new trends in the built environments suggesting research needs

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Air exchange rate (AER), normally expressed as air exchanges per hour (ach or h^{-1}). Volume fraction of ventilated air per hour (m^3 m^{-3} h^{-1}). This parameter is relvant for estimating infiltration of outdoor air pollution indoors and diluting indoor space emissions.

Ventilation rate, volume of fresh air introduced into the space per hour (m^3 h^{-1}, l s^{-1} or lps). Often also scaled per person (lps pp). This is the target parameter for the occupancy-based ventilation guidelines and accounts for the bioefluents emitted by occupants and the need of fresh air.

Ventilation per area (lps m^{-2}) is useful in estimating dilution need of emissions from surfaces.

Table 1. Typical occupancy levels (floor area and space volume per person) in various building types.

Space type	Area pp m^2	Height m	Volume pp m^3
School	2	2.5	5
Office	10	2.5	25
Residential	20	2.5	50
Spacious	50	2.5	125

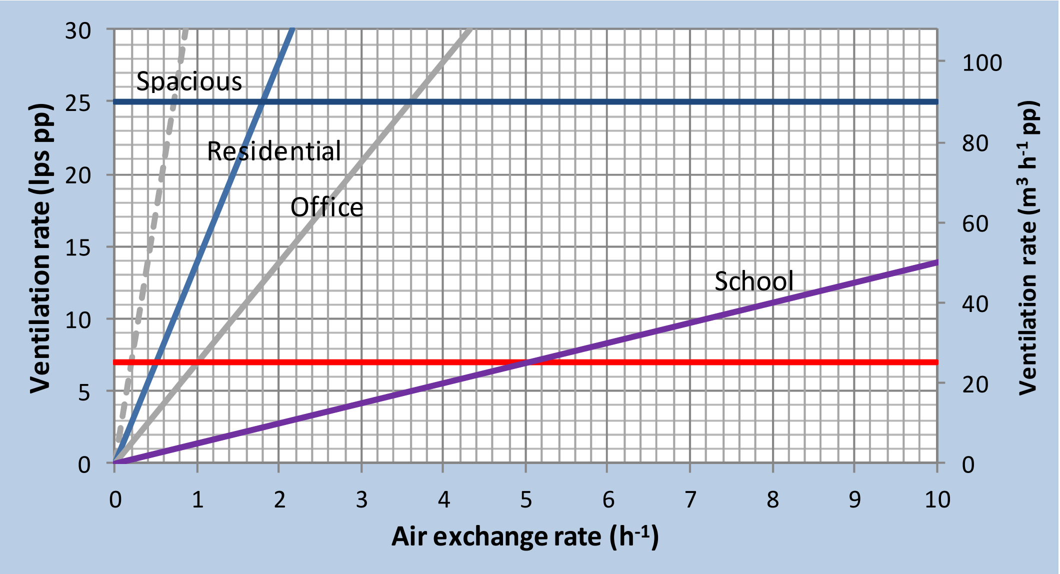


Figure 1. Relationships between measures of ventilation in different building types using parameters tabulated above.

SYMBOLS AND ABBREVIATIONS

Abbreviation	Meaning
ACH	Air changes per hour, a measure of AER (see below)
AER, a	Air exchange rate, normally expressed as air exchanges per hour (ach or h^{-1})
CV	Coefficient of variation (CV=SD/mean)
GSD	Geometric standard deviation
IAQ	Indoor air quality
lps	ventilation rate 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
pp	per person
SD	Standard deviation
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)

Ca	Outdoor (ambient) concentration
Ci	Indoor concentration
Cai	Indoor concentration of outdoor pollution
Cig	Indoor concentration of indoor generated pollution
Finf	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

RR	Relative risk
PAF	Population attributable factor (fraction)
BoD	Burden of disease (DALY, in years)
YLL	Years of life lost (due to premature mortality) (DALY, in years)
YLD	Years lived with disability (DALY, in years)

Energy and CO_2 emission variables

TWh	Terawatt-hour
$MtCO_2$	Megaton of CO_2

PREFACE

This report summarizes the results of Work Package 8 of the HEALTHVENT –project. It provides a summary of the work conducted for estimation of the health and energy implications of the health-based ventilation guidelines developed for Europe.

As an instrumental part of the work, recent reviews of ventilation rate measurements in European countries were combined with the systematic collection of national regulations collected in WP5 coordinated by REHVA and climatological data for estimation of overall statistical distributions of prevailing ventilation rates in the 26 European countries included in HEALTHVENT. Due to the limited data available from Malta, it could not be included in the assessment.

The main focus in the work of WP8 was on health. The previously developed burden of disease models from EnVIE and IAIAQ projects was complemented with a mass-balance –based evaluation of the impact of changes in ventilation on the exposures and health risks. The model was used to evaluate alternative approaches for improvement of health, including merely optimizing ventilation rates, improving filtration of outdoor pollution from air intake, and source control of indoor sources. The results were then used in the formulation of the ventilation guidelines for obtaining maximal benefits in health. The minimum ventilation approach selected as the main format of the guidelines requires careful attention in the implementation: the minimum level is an absolute minimum, which cannot in any conditions when the space is occupied, be left unattained.

While the detailed simulations on the impacts of ventilation on energy use of contemporary state of art as well as advanced future buildings were evaluated in WP6 by University of Porto, the energy implications of the guidelines in comparison with the current European building stock were shortly evaluated in WP8 and are reported here. Special thanks are due to Dr Stylianos Kephalopoulos from the EC Joint Research Center, Ispra, Italy, and Dr Matthias Braubach and Marie-Eve Heroux from the World Health Organization, who have actively participated in the HEALTHVENT work as collaborators and contributed also to the evaluation of health impacts of indoor exposures.

Kuopio, December 2012

Otto Hänninen
Coordinator of the health impact assessment work

EXECUTIVE SUMMARY

Previous studies have estimated that the burden of disease caused by inadequate indoor air quality causes an annual loss of 2 million healthy life years in EU. Main factors responsible for this are (i) polluted outdoor air used to ventilate indoor spaces and (ii) indoor sources of pollution. Ventilation is a key factor determining the indoor air quality. The aim of DG Sanco funded HEALTHVENT –project was to evaluate in detail how ventilation should be defined in terms of achieving optimal health in Europe.

The previously developed burden of disease model was upgraded in the current work with a single compartment complete mixing mass-balance model for estimation of changes in exposures and health risks due to alternative ventilation guidelines. Using the upgraded HEALTHVENT model, the counterbalancing roles of indoor and outdoor pollution sources on health were confirmed: by optimizing ventilation rates for minimum health risks produced only modest health benefits (22 % in comparison with the 2010 baseline).

Outdoor air pollution plays a significant role for the indoor exposures. Efficient filtration of outdoor air allows for specific control of this component dominated by particles. Ultrafine and coarse particles have lower penetration efficiencies and residence times than accumulation mode particles and therefore PM2.5 was chosen as the critical parameter for filtration. Using advanced filtration allows for reduction of the burden of disease by 42 %.

While the main reason for the need of increased ventilation rates is the presence of indoor sources, and the health benefits if enhanced dilution by higher ventilation rates are counterbalanced by infiltration of outdoor pollutants, efficient control of indoor sources of radon, carbon monoxide, volatile organic compounds, moisture and fine particles was identified as the most efficient way to reduce exposures. Combined with health-based optimization of ventilation this was estimated to reduce the burden of disease by 48 %.

Overall the health implication results confirm that health risks are reduced at ventilation rates lower than the 2010 baseline. Main reason for this is the fact that over 90 % of Europeans live in areas where WHO Guidelines for $PM_{2.5}$ are not attained.

Lower ventilation rates allow for lower energy consumption and lower CO_2 emissions. All estimated health-based optimal ventilation rates proposed lower ventilation rates than at the baseline, suggesting that energy savings are readily combined with health benefits. These results are based on the key assumption that indoor sources remain at the 2010 level or are substantially reduced from that level. If this assumption cannot be ensured, using the estimated optimal ventilation rates could lead to tragic increase in health risks. Therefore control of the sources and exposures remains a key element in the risk management process.

Energy consumption was estimated for the baseline building stock for 2010 using prevailing ventilation and minimum guideline ventilation assuming full implementation of proposed source controls. Additionally, more detailed simulations for Lisbon, Paris and Helsinki were used to estimate the changes in the ventilation energy in the future building stocks.

1 INTRODUCTION

Indoor air quality is associated with several health effects and discomfort experienced by people staying in environments with poor IAQ (e.g. Seppänen et al., 1999, Wargocki et al., 2002, Sundell et al., 2011). Previous risk assessments conducted for European countries in the EnVIE (Oliveira Fernandes et al., 2009) and IAIAQ (Jantunen et al., 2010) studies estimated that the burden of disease caused by inadequate indoor air quality in EU causes an annual loss of 2 million healthy life years.

At present ventilation standards (e.g. EN15251) and guidelines define ventilation in non-industrial buildings to meet comfort requirements of building 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 consider more serious health impacts like asthma, allergies, chronic obstructive pulmonary disease, cardiovascular diseases, lung cancer and acute toxication. HEALTHVENT project was launched in 2010 to specifically quantitatively and qualitatively study the relationship between ventilation and health (Wargocki et al., 2012).

Ventilation, however, plays only a mediating role. Emission sources are the primary cause of exposures to indoor and outdoor originating pollutants and therefore source control is almost always more efficient in controlling exposures than diluting the emissions into the occupied space. Nevertheless, ventilation plays a substantial role in determining the exposure levels and therefore adjusting the health risks. The current work aims at quantitatively studying the exposures and risks in combination with their sources. Six key elements were considered for determining health-based ventilation guidelines:

(1) Emission of human bio effluents with carbon dioxide and moisture as markers;

(2) Results from epidemiological studies on the relationship between ventilation and health in non-industrial indoor environments using published peer-reviewed and conference papers as a reference;

(3) Health effects of outdoor air pollutants using particulate matter, pollens and ozone as markers;

(4) Toxicological data on indoor air pollutants using World Health Organization Guidelines for Air Quality and other international sources;

(5) Existing data showing the relationship between concentrations (emissions) of pollutants and ventilation; and

(6) Current normative documents

1.1 OBJECTIVES

The current work package 8 was defined to cover two key aspects of optimizing ventilation for health. Changes in health impacts of indoor air exposures due to changes in ventilation are quantified in disability adjusted lifeyears (DALYs). Additionally, the corresponding changes in energy needs are expressed also as CO_2 emissions, accounting for national energy production profiles in 2010.

Specific objectives were defined in the description of work of the core workpackages as:

(i) Update and application of the previous models for burden of disease caused by inadequate quality of indoor air.

(ii) Evaluation of the health impacts of alternative scenarios to optimize ventilation for health in DALYs.

(iii) Assessment of the health benefits of the proposed ventilation guidelines.

(iv) Assessment of the energy consequences of the proposed ventilation guidelines.

(v) Evaluation of the technical feasibility and effectiveness of the guidelines.

For the implementation of the analyses needed to reach these objectives a substantial upgrade of the previous burden of disease models was designed to cover pollutant specific factors, such as decay and infiltration parameters.

2 BURDEN OF DISEASE APPROACH

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. To improve comparability of impacts on various types of diseases and including mortality, World Health Organization has been promoting the use of disability adjusted life years (*DALY*) as a common metric (e.g. Murray & Lopez, 1996).

Disability adjusted life years are expressed as

Eq 1 $DALY = YLL + YLD$

where *YLL* is the number of years of life lost due to premature mortality and *YLD* the years lived with disability. 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 2 $YLD = DW \times L$

A complementary approach can be used to estimate the burden of disease by utilizing existing information on the national background burden of disease caused by a given health endpoint and epidemiological estimation of the population attributable fraction (*PAF*) (Hänninen & Knol, 2011):

Eq 3 $$PAF = \frac{f \times (RR - 1)}{f \times (RR - 1) + 1}$$

where *f* is the fraction of population exposed to a given factor and *RR* is the relative risk of the exposed. 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 4 $EBD = PAF \times BoD$

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 5 $$RR = e^{(E \ln RR^{\circ})} = RR^{\circ E}$$

The health impact assessment for the HEALTHVENT ventilation guidelines is built on the previous achievements of EnVIE and IAIAQ projects and the corresponding models for environmental burden of disease caused by indoor air quality. Both these models are 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 (de Oliveira Fernandes et al, 2009, Jantunen et al., 2010).

This approach ensures a maximum comparability of the results with these two earlier major studies on environmental burden of disease attributable to indoor air pollution. However, for model evaluation and confirmation of the results also the EBoDE approach will be used when applicable.

In the HEALTHVENT project the burden of disease model was updated and upgraded according to the process shown in Figure 2. Specifically, the following components were updated or included:

1) National background burden of disease values were updated to the latest available data from 2004 (WHO, 2012); changes to EnVIE/IAIAQ version were small (see Table 2).

2) Outdoor $PM_{2.5}$ concentrations were updated to latest available population based estimates; population representativity was improved by using the methods described by de Leeuw & Horalek (2009).

3) Indoor $PM_{2.5}$ concentration data was updated based on the EXPOLIS study (Hänninen et al., 2004); the population representativity remains limited due to extrapolation from four countries.

4) Second hand smoke (SHS) was included as a new indoor source using exposures from EC (2009) and health end-points from Hänninen & Knol (2011); impact on the overall burden of disease was not dramatic.

5) Data on housing was improved including information on size of the residences (Dol and Hafner, 2010) and on baseline (2010) ventilation rates (Asikainen et al., 2012, 2013).

6) A mass balance was integrated into the model to calculate the exposure changes when changing the ventilation rates.

7) Acute non-intentional CO toxication deaths were updated from a recent study by Braubach et al. (2012).

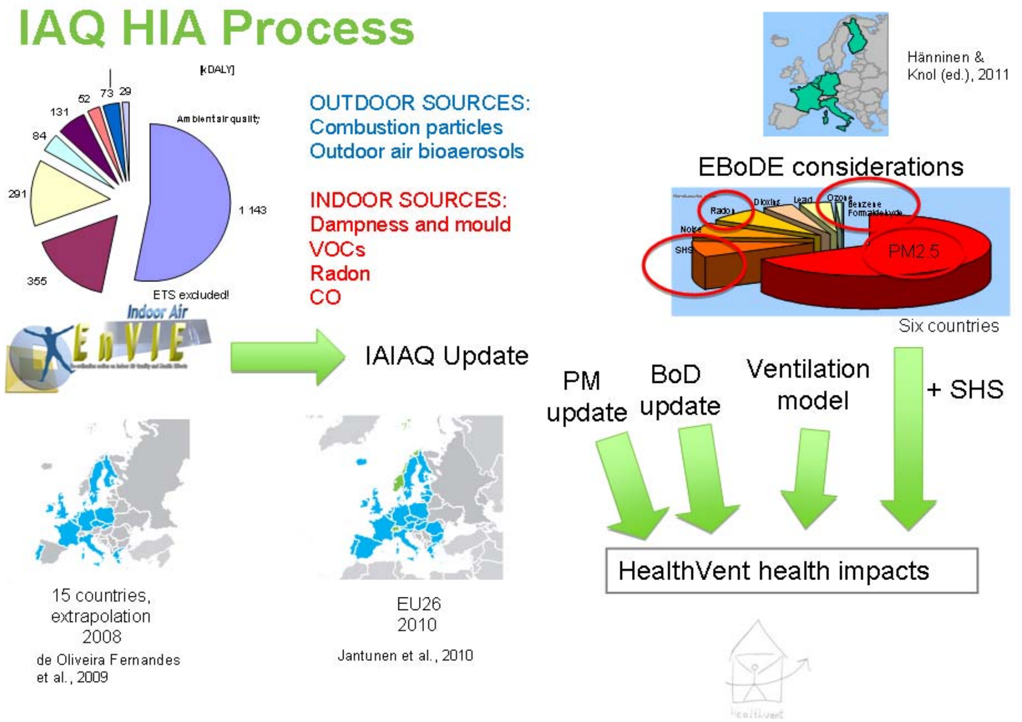


Figure 2. A schematic presentation of the features of the three health impact models (EnVIE, IAIAQ and HEALTHVENT).

Table 2. The background burden of disease data as DALY / 100 000 population for EU-26 countries used in IAIAQ model and updated for HEALTHVENT model

Disease (WHO Disease ID)	2002 (DALY / 100 000)	2004 (DALY / 100 000)
Asthma (symptoms) - W113	158	150
Lung (trachea & bronchus) cancer - W067	427	426
Cardiovascular disease -W104	2525	2432
Chronic obstructive pulmonary disease - W112	182	341
Upper and lower respiratory disease symptoms - W038	388	143
Acute CO toxication - W151	27	5

3 BASELINE VENTILATION IN EUROPE

Central part of estimating the impacts of changing ventilation on health and energy needs is estimation of the baseline ventilation itself. Limited measurement data is available from only a subset of the included European countries and the population, house type and seasonal representativity varies from study to study. Therefore the estimation of the baseline ventilation rates was not a trivial task. The studies with measured AERs usually provide information only for a limited set of target buildings, which does not provide nationally representative information at the country level. Therefore three different approaches were combined for best possible estimates: **(i)** compilation of existing national measurement data for each country based on a literature reviews; **(ii)** regression modelling to account for geographical, climatological and economic factors and to smooth artefacts caused by small studies an variable representativity; and **(iii)** review of national building code requirements for ventilation. These three sources of information, described in more detail below, were then 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.

As a result the selected approach was used to estimate national air exchange distributions in all countries; to fill in the data gap that currently exists due to scarce information of measured AERs; to utilize international data to support national measurements; to be robust against insufficient statistical representatives of small studies and potentially affected by specific seasons; to consider also the regulations, but allowing for the fact that regulation is not always completely enforced.

3.1 REVIEW OF MEASUREMENTS

Data on the existing studies measuring air exchange rates are previously collected in EU FP6 project HEIMTSA (2010) and in the recent comprehensive review by Dimitroulopoulou (2012). The review by Dimitroulopoulou (2012) generated an up-to-date summary of existing data on air exchange rates in Europe identifying 96 journal papers, including specific data from 12 European countries. Additionally Dimitroulopoulou (2012) reviewed the current status of residential ventilation standards and regulations in Europe and compared them with the measured ventilation rates and summarized the studies relating ventilation to the human health showing the impact of ventilation on several health responses. The review of building regulations and the measured ventilation rates showed that ventilation requirements receive major attention in building regulations across Europe, but that the ventilation rates are in practice often reduced.

Dozens of air exchange rate measurement studies were identified by the reviews, but overall, seasonal coverage and population representativeness were limited for many of the countries for which data existed. For a substantial number of European countries no national data were available and in general it’s evident that there is no central survey of AERs in most countries. Some of the data found in literature were based on building envelope leakiness tests, which in principle could be related to annual AER by crude ratio of 10-30 (Jokisalo et al., 2009). However, when this method was tested, part of the resulting values were clearly too small (below 0.1) and we decided to leave these estimates out. Altogether we ended up of having measured mean air exchange rate values expressed as ach only for 11 European countries. Furthermore, only part of them provided data on the distributions of the values (e.g. mean and standard deviation).

For some countries there were values from several different studies, and for these data expert judgement was used to define a one mean value of air exchange rate to be used in the modelling. In cases where a comprehensive national study was available, the results obtained in this single study were directly used. In cases with several smaller national studies, each result was taken into account by using a weighting factor that was defined on the basis of the representativeness of the study (i.e. the number of measured houses, and seasonal coverage). Practically, the studies with a higher number of measured residences received higher weighting compared with the studies with low number of measured residences when estimating the national mean AER based on the study results.

3.2 NATIONAL BUILDING CODES

Some European countries have defined the required air exchange rates in the national building regulations and these were used to enhance our model as we assumed that the presence and levels of the regulations influence the actual levels of the air exchange rates. The up-to-date data in national legislation and codes were collected from 15 European countries by questionnaire as a part of the HEALTHVENT project (Seppänen et al., 2012). Additionally, Sweden and Denmark were added based on oral communication from the authors. The ventilation rate required were given in different units depending on the country, such as per number of persons, flow rate per floor area, flow rate per number of rooms, fixed flow rate per room type, number of air changes per hour, or combination of different units. In order to compare ventilation rates the test cases of real-life design situations were introduced and the air exchange rates were simulated for 50m^2 and 90m^2 apartments with 2 rooms and 2 persons and with 4 rooms and 4 persons, respectively. The ventilation rates were simulated for the whole dwelling as air changes per hour, and for the kitchen, bathroom, and toilet as ventilation rate per room (Brelih and Seppänen, 2011).

We used these two simulation results to produce a linear equation (Eq 6, Eq 7) which was used to calculate the regulation based air exchange rate for all 26 countries based on the national average size of residences.

Eq 6 $$ß = \frac{a_{90} - a_{50}}{90m^2 - 50m^2}$$

Where a_{50} and a_{90} are the simulated air exchange rates for 50 and 90 m^2 apartments, respectively and *ß* is the slope. Now the national air exchange rate (a_2) can be calculated using the national mean apartment size (A) as

Eq 7 $$a_2 = a_{50} + ß(\overline{A} - 50m^2)$$

The national measured air exchange rates based on the literature review, the simulated values based on the regulations for two sized apartment and the calculated values based on regulations for average sized residences are presented in Table 3.

Table 3. Summary of air exchange rates from measurements and from simulations for 50 and 90 m² residences based national on regulations.

Country	Measured		Regulations		Average residence
	Mean h^{-1}	SD h^{-1}	$50m^2$ h^{-1}	$90m^2$ h^{-1}	h^{-1}
Austria					0.44
Belgium					0.47
Bulgaria			0.23	0.26	0.24
Cyprus					0.59
Czech Republic	0.75	0.45	0.30	0.30	0.30
Denmark	0.62	0.59	0.50	0.50	0.50
Estonia					0.50
Finland	0.62	0.54	0.66	0.50	0.54
France			0.48	0.40	0.40
Germany	0.66	0.52[a]	0.60	0.51	0.51
Greece	1.22	1.10	0.70	0.70	0.70
Hungary			0.60	0.60	0.60
Ireland					0.43
Italy			0.30	0.30	0.30
Latvia					0.50
Lithuania			0.50	0.50	0.50
Luxembourg					0.39
Netherlands	0.90	0.52[a]	1.01	0.67	0.60
Norway	0.68	0.52[a]			
Poland			0.64	0.44	0.54
Portugal	0.75	0.52[a]	0.60	0.60	0.60
Romania			0.48	0.54	0.46
Slovakia					0.50
Slovenia			0.50	0.50	0.50
Spain					0.44
Sweden	0.59	0.30	0.50	0.50	0.50
Switzerland	0.83	0.46			
UK	0.53	0.20	0.43	0.43	0.43
Europe-26[b]					**0.45**

[a] Missing variation estimated using coefficient of variation from other studies.
[b] Population weighted average of the individual countries

3.3 LOG-NORMALITY OF THE DISTRIBUTIONS

Modelling of the probability distributions of air exchange rates from non-continuous data, variable sample sizes and variable temporal and spatial representativity required supportive assumptions on the type of the distribution. Previous data, shown in Figure 3 for four cities from the EXPOLIS study (Hänninen et al., 2004) supports the approach that lognormality can be assumed.

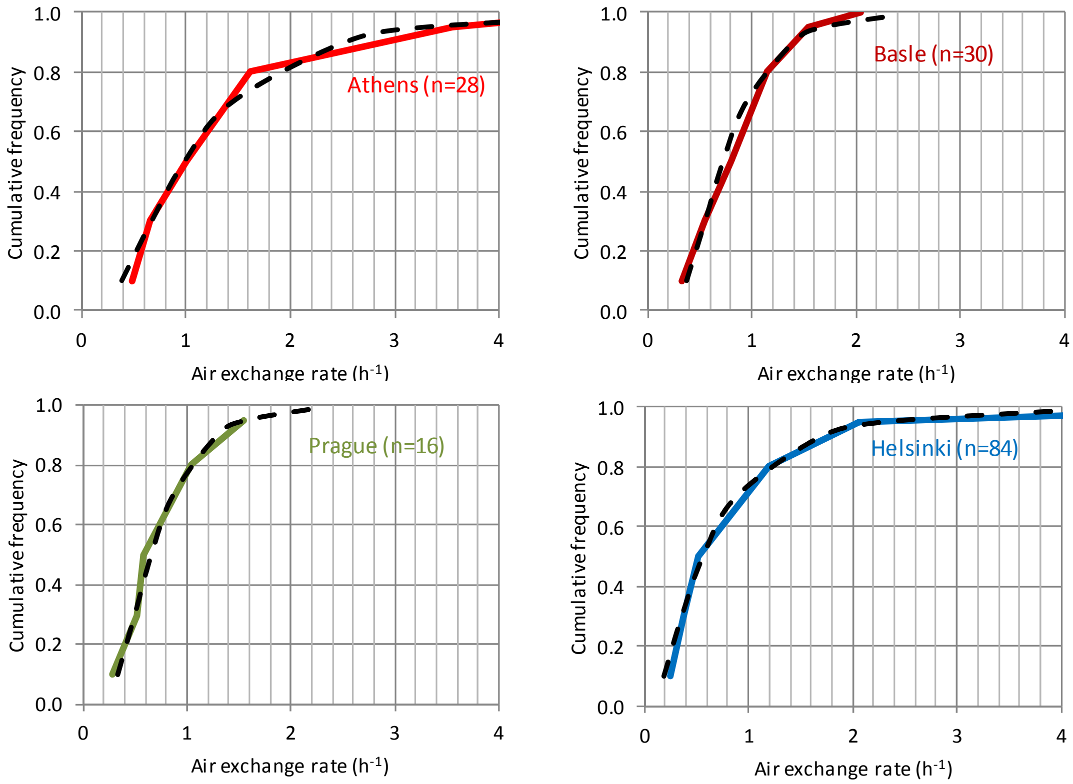


Figure 3. Observed cumulative air exchange rate distributions in four EXPOLIS cities and corresponding lognormal fits (black lines) (original data: Hänninen et al., 2004).

3.4 REGRESSION MODELLING

The air exchange rates based on the literature review were used in the regression analysis to produce national distributions of air exchange rates for 26 European countries. The model is based on the assumption that the most important factors that influence between country variability in air exchange rate are the climate (annual mean temperature) and the geographical location of the country, both affecting the building tightness and operation.

Different combinations of independent variables were tested to explain the variation in the AER. The geographical location was defined with the longitude and latitude of the capital of each country. Using these variables the R^2 of the model was 0.69. We also tested the case where the longitude was left out, but this lowered the predictive capability of the model noticeably (R^2= 0.50). We also tested the use of the GPD per capita as independent variable to describe the wealth of the country, which could be linked to the sizes of the residences and also to the technical level of the ventilation systems. The performance of the model was slightly increased by this combination giving R^2 = 0.76 for the mean of AER. The last option was selected as the final one. The equation produced by the regression model is presented in Eq 8

Eq 8

$$a_{regression} = 1.268 + (-0.018 * N_{\deg}) + 0.011 * E_{\deg} + 0.016 * T + 0.003 * GDP$$

Later on we received measured AER values for France with 450 measured residences. This data was used for validation of our regression model to see how well the measured values were in line with our model.

3.5 BAYESIAN WEIGHING OF ESTIMATES

The measured national air exchange rates exhibited a lot of variation between studies when several ones were available. This can be explained by the seasonal differences in sampling of buildings, sample sizes and air exchange rate measurement methods. Due to these differences it was clear that the national estimates were not comparable and therefore a European average was calculated and used for all countries as an uninformative prior (i.e. the first guess for the AER), which was then enhanced by the Bayesian model to create the final distributions of air exchange rates.

The regression-modelled national air exchange rates (a_1), the regression-modelled population-weighted European average (a_2) and the air exchange rates based on the national regulations (a_3) were included in the model by using weighting factors. The steps of the modelling are presented schematically in Figure 4 and the calculations were performed according to the Eq 9.

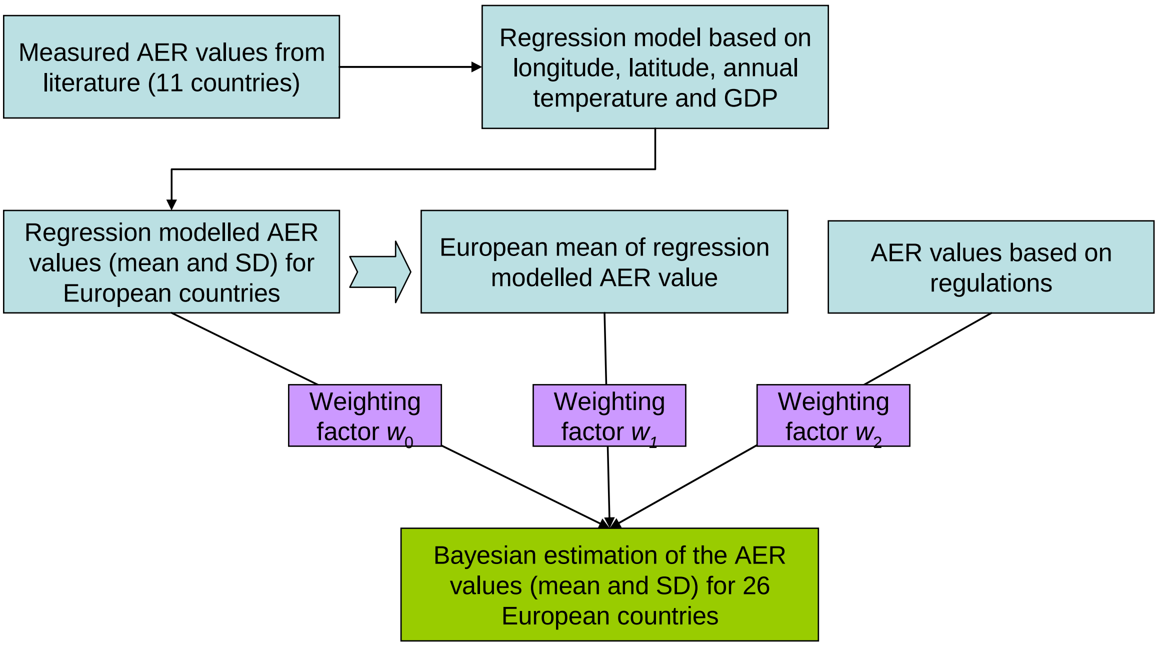


Figure 4. Schematic presentation of the Bayesian method to model national distributions of air exchange rates for residences in European countries.

Eq 9 $$a = f_1 a_1 + f_2 a_2 + f_3 \frac{a_3}{a_3} a_1$$

where f_1 = weighting factor for the population weighted European mean based on the regression modelling, a_1 = Population weighted European mean of AER based on the regression modelling, f_2 = weighting factor for the national AER based on the regression modelling, a_2 = National AER based on the regression modelling, f_3 = weighting factor of the AER based on the regulations, a_3 = AER value based on the national regulations.

The variation (SD) for the Bayesian modelled mean of air exchange rates was calculated using the coefficient of variation from the regression model.

Due to the relatively small number of residences covered in the measurement studies and variable seasonal coverage of individual studies, the European mean distribution was used as the *a priori* distribution in the Bayesian analysis and was given a weight of 0.5. The *a priori* distribution was then adjusted by the two national factors, the regression estimate and the building regulation based simulation scaled for the average residence size, both with a weight of 0.25.

3.6 BASELINE AIR EXCHANGE RATES

The air exchange rates (mean and SD) produced by the regression modelling and the final air exchange rates based on the Bayesian model are presented in Table 4 and in **Error! Reference source not found.** and Figure 5.

Table 4. Comparison of regression estimates of air exchange rates with the Bayesian estimates that incorporate also national regulations.

Country	Regression model		Bayesian estimate			
	Mean h^{-1}	SD h^{-1}	Mean h^{-1}	SD h^{-1}	Mean lps pp	SD lps pp
Austria	0.9	0.7	0.8	0.6	24	17
Belgium	0.7	0.4	0.7	0.5	18	12
Bulgaria	0.9	0.8	0.8	0.5	15	11
Cyprus	1.4	1.3	1.1	0.8	22	16
Czech Republic	0.7	0.5	0.7	0.5	15	10
Denmark	0.7	0.5	0.7	0.5	27	19
Estonia	0.6	0.5	0.7	0.5	14	10
Finland	0.6	0.5	0.7	0.5	20	14
France	0.7	0.4	0.7	0.5	20	14
Germany	0.7	0.5	0.8	0.5	23	16
Greece	1.2	1.0	1.1	0.8	23	16
Hungary	0.8	0.7	0.9	0.6	18	12
Ireland	0.5	0.2	0.6	0.4	16	11
Italy	1.0	0.8	0.8	0.6	23	16
Latvia	0.6	0.5	0.7	0.5	12	8
Lithuania	0.7	0.5	0.8	0.5	13	9
Luxembourg	0.9	0.6	0.8	0.6	30	21
Netherlands	0.7	0.4	0.8	0.5	24	17
Poland	0.7	0.6	0.8	0.5	12	9
Portugal	0.8	0.4	0.8	0.6	17	12
Romania	0.9	0.8	0.9	0.6	8	6
Slovakia	0.8	0.6	0.8	0.6	12	8
Slovenia	0.8	0.6	0.8	0.6	15	10
Spain	0.8	0.5	0.8	0.5	20	14
Sweden	0.6	0.5	0.7	0.5	23	16
UK	0.6	0.4	0.7	0.5	17	12
Europe-26[a]	0.8	0.5	0.8	0.5	19	13

[a] Population weighted average

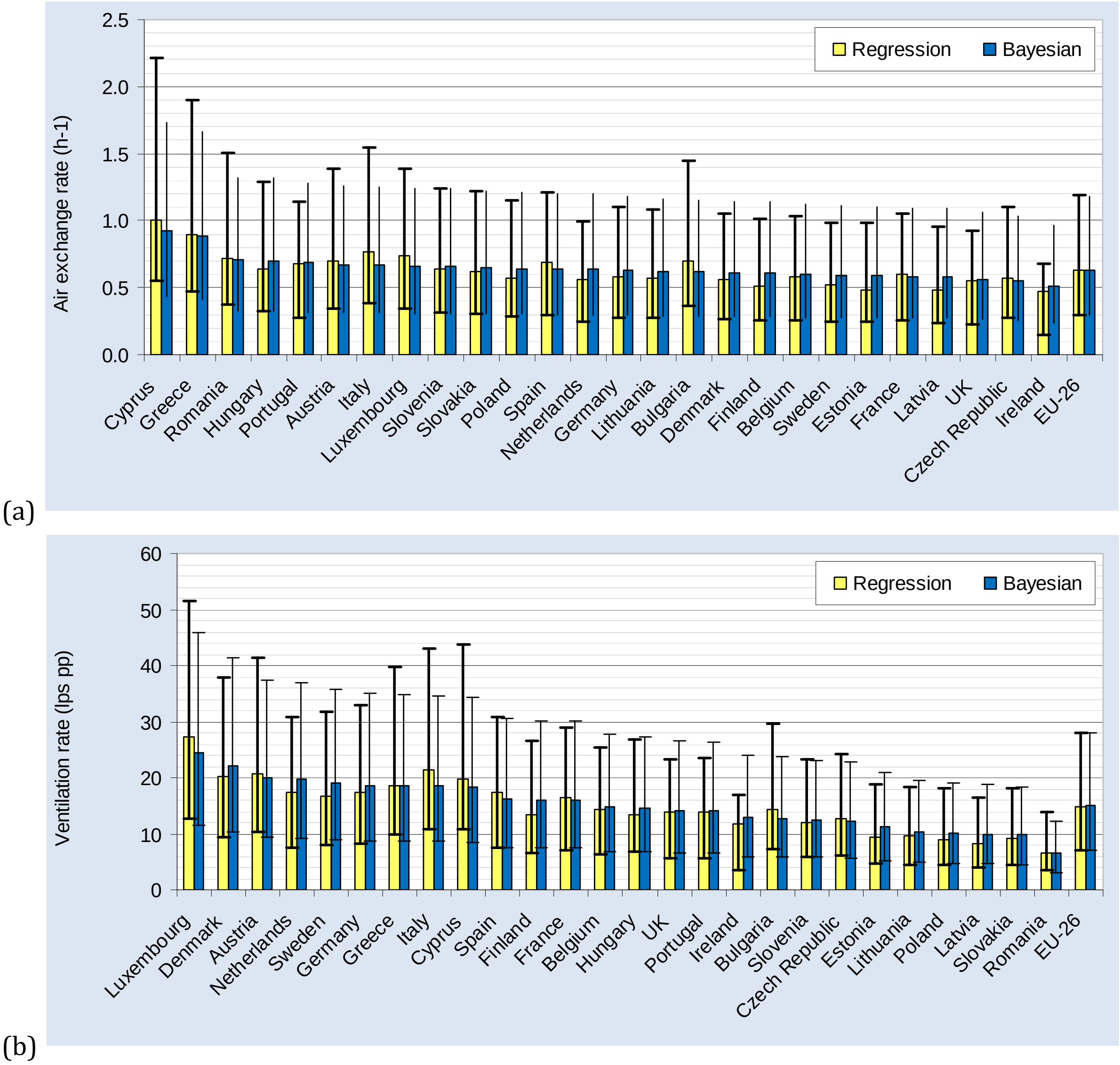


Figure 5. Comparison of regression and Bayesian estimates of national (a) air exchange rates (h^{-1}) and (b) ventilation rates as per person (lps pp). Bars represent median and error bars GSD.

The mean of Bayesian estimates of national air exchange rates vary from 0.6 (SD 0.4) in Ireland to 1.1 (0.8) in Cyprus and Greece. The population weighted mean of the 26 countries does not change that much when using the Bayesian model, which takes into account the national regulations, but changes can be seen in the level of individual countries.

4 EXPOSURE MODELLING

The current evaluation of health impacts of various ventilation guideline options as national and European burden of disease is based on the EnVIE framework. For the purposes of HEALTHVENT project the EnVIE burden of disease model (Oliveira Fernandes et al., 2009), further developed in the IAIAQ-project (Jantunen et al., 2010), was supplemented with a single compartment complete mixing mass-balance model (Hänninen et al., 2004) for adjusting exposures as function of ventilation.

4.1 SINGLE COMPARTMENT COMPLETE MIXING MASS-BALANCE MODEL

The modelling approach is based on a single compartment complete mixing mass-balance equation (Dockery and Spengler, 1981):

Eq 10 $$\overline{C_i} = \frac{Pa}{a+k}\overline{C_a} + \frac{G}{V(a+k)} - \frac{\Delta C_i}{\Delta t(a+k)}$$

The current work focuses on long-term average concentrations in indoor spaces in general, so the third term in the right side of the equation, representing the transient mass-balance adjustment when the indoor air concentration is changing, is ignored. The total indoor concentration of a pollutant is thus effectively split into two fractions, one originating from outdoor air (C_{ai}) and the other from indoor sources (C_{ig}):

Eq 11 $$C_{ai} = \frac{Pa}{a+k}C_a = F_{INF} \times C_a$$

Eq 12 $$C_{ig} = \frac{G}{V} \times \frac{1}{(a+k)}$$

Ventilation plays a two-sided role in formation of indoor pollutant concentrations. On the other hand, main purpose of ventilation is to remove indoor generated impurities from indoor spaces by ventilating the space with fresh outdoor air. Assuming constant source strength of an indoor source, the generated indoor concentration has an inverse relationship to the ventilation rate; the higher the ventilation, the lower the corresponding indoor concentration, which approaches zero as the ventilation rate increases (Figure 6).

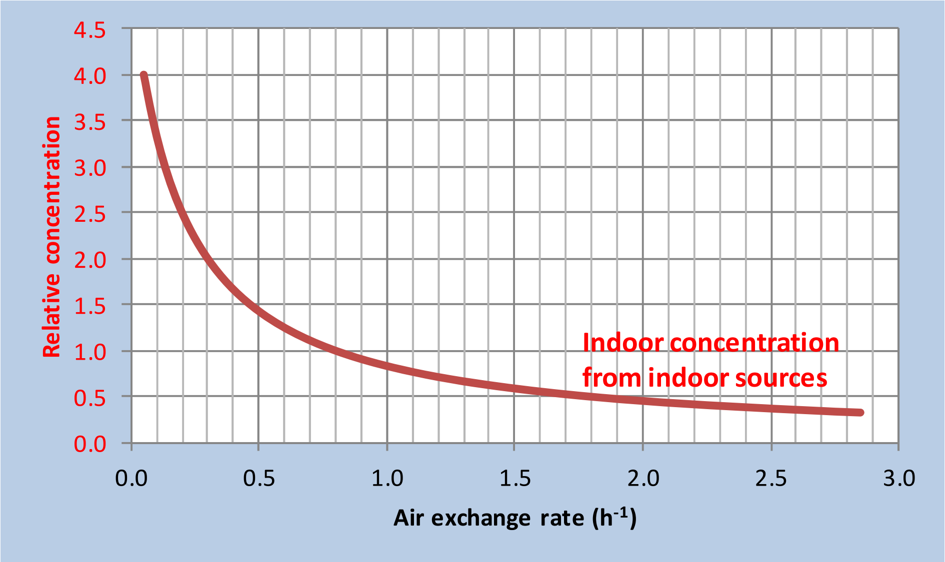


Figure 6. Relative indoor concentration from a constant indoor source as function of increasing air exchange rate.

On the other hand, while the fresh ventilation air is taken from outdoors, ventilation at the same time also is prone to introducing outdoor air pollutants indoors. The ventilation system may include filtering of intake air, but practice has shown that in real world situations even in cases when the intake air is carefully filtered, substantial fraction of the outdoor pollution level actually enters indoors via windows, doors, ventilation ducts, and cracks and leaks in the building envelope (Fisk et al., 2002). Assuming a constant outdoor pollution level and a constant penetration efficiency, the increasing indoor concentration as function of increasing air exchange rate is seen in Figure 7.

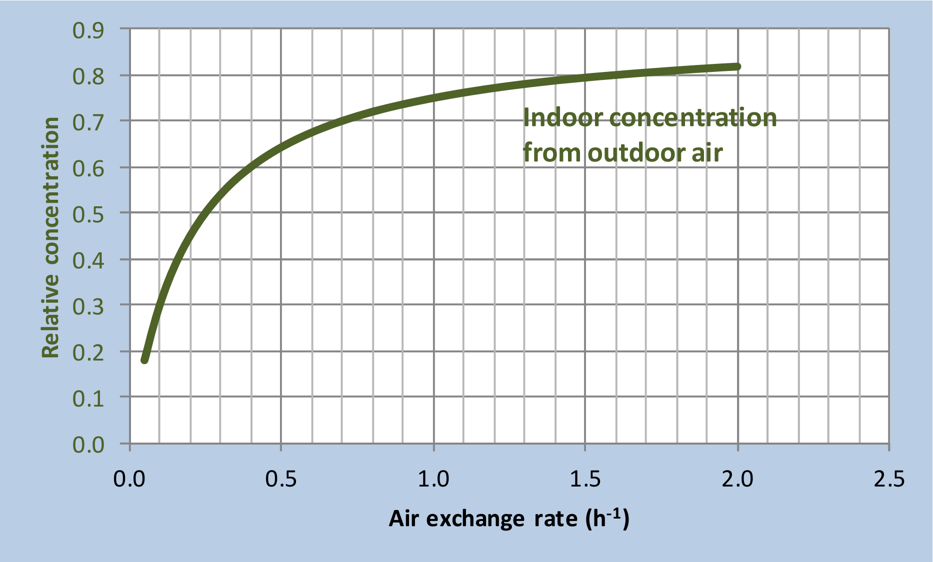


Figure 7. Relative indoor concentration from a constant outdoor level as function of increasing air exchange rate.

The total level of pollutants indoors is affected by the penetration of pollutants from outdoors and decay of the pollutants indoors.

4.1.1 IMPACT OF DECAY TERM ON CONCENTRATION CHANGES

Pollutant decay, typically gravimetric settling of particles leading to deposition on horizontal, upward facing surfaces, slowly removes pollutants from indoor spaces. Only gaseous inert compounds like carbon dioxide do not have decay. For reactive gases the decay rate may vary significantly due to the availability of reacting compounds in the air.

The decay term decreases the maximum indoor concentration created by indoor sources. For an inactive gas (k=0) with an indoor source the indoor concentration approaches infinity when air exchange approaches zero (C_{ig}~1/(a+k)= 1/a). However, the larger the decay term, the lower the maximum concentration, still occurring at a=0, remains ($Cmax$~1/k).

The impact of decay term on the relationship of indoor concentration when adjusting ventilation by a given factor f can be solved from the mass balance equation. The average concentration indoors caused by an outdoor concentration can be estimated using Eq 11, when air exchange rate is $a = a_0$. Now the relative change in indoor concentration can be written for an adjusted ventilation rate $a = a_1 = f \times a_0$ as

Eq 13 $$\frac{C_{ai1}}{C_{ai0}} = \frac{\frac{Pfa}{fa+k}}{\frac{Pa}{a+k}} = \frac{Pfa(a+k)}{Pa(fa+k)} = \frac{f(a+k)}{fa+k} = \frac{a+k}{a+\frac{k}{f}}$$

The special case for inert gases with decay rate k=0 can be solved as

$$\frac{C_{ai1}}{C_{ai0}} = \frac{a+k}{a+\frac{k}{f}} = \frac{a}{a} = 1$$

Eq 14

thus, for inert gases adjusting the ventilation has no effect on indoor concentrations from outdoor sources. Correspondingly, when ventilation is adjusted from a_0 to $a_1 = f \times a_0$, the impact on concentrations caused by indoor sources can be expressed as

Eq 15 $$\frac{C_{ig1}}{C_{ig0}} = \frac{\frac{1}{fa+k}}{\frac{1}{a+k}} = \frac{a+k}{fa+k}$$

From the equation we can see that the impact on concentrations with large decay rates will be less profound than on inert pollutants. In the special case of an inert gas with decay rate k=0 the solution becomes:

Eq 16 $$\frac{C_{ig1}}{C_{ig0}} = \frac{a+k}{fa+k} = \frac{a}{fa} = \frac{1}{f}$$

indicating that in this case the change in concentration is inversely proportional to the change in ventilation.

4.1.2 MASS-BALANCE TERMS FOR THE TARGET POLLUTANTS

The mass-balance parameters for the target pollutants were determined by using literature data and physical characteristics. In the case of particulate matter, second hand smoke, mould particles and outdoor air bioaerosols gravimetric and thermokinetic deposition rates in typical indoor space geometries were used. For radon the radiological decay was used (Table 5).

Table 5. Pollutants considered and their mass-balance parameters.

	Sources		Mass balance parameters							
Pollutant	Out	In	Out Dp(eff) µm	Penetration [fraction]	Density ρ g cm^{-3}	Decay k h^{-1}	Finf	Indoors Dp(eff) µm	Density ρ g cm^{-3}	Decay k h^{-1}
PM	x	x	<2	90 %	1.5	0.14	0.55	2.5	1.5	0.51
Bio	x		10	80 %	1.0	5.41	0.07	n/a	n/a	n/a
SHS		x	n/a	n/a	n/a	n/a	n/a	0.1	1.0	0.001
Mold		x	n/a	n/a	n/a	n/a	n/a	5	1.0	1.4
Radon		x	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.01
CO		x	n/a	n/a	n/a	n/a	n/a	n/a	n/a	<0.01
VOC	(x)	x	n/a	1	n/a	<0.1	0.9	n/a	n/a	<0.1

Note: Radon decay calculated based on half life. Outdoor PM2.5 decay term estimated from ambient size distribution data from Helsinki..

The impact of the particle size on the terminal gravimetric settling velocity and decay rate is demonstrated in Figure 8 for particles of density 1.5, found for ambient particles in a number of studies. It can be readily seen that the deposition rate increases rapidly as function of increasing particle diameter and therefore ventilation rates are significant for the concentrations of fine particles only.

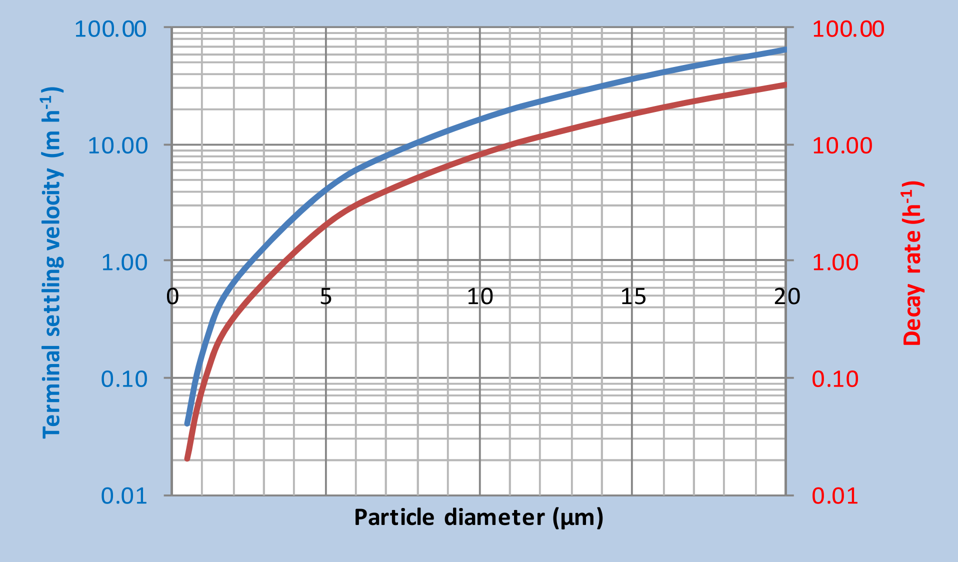


Figure 8. Depencency of gravimetric settling velocity and corresponding particle decay rate as function of particle diameter (rho=1.5 g cm^{-3}, effective deposition height 2 m).

For the indoor generated particles the theoretical maximum concentration depends on the decay term. As can be seen in Figure 9, the deposition rates of indoor resuspension PM and mould particles limit the maximum concentration strongly. The lower decay rates of second hand smoke (ETS) particles and radon, however, lead to orders of magnitude higher maximum levels in the case of low air exchange rates.

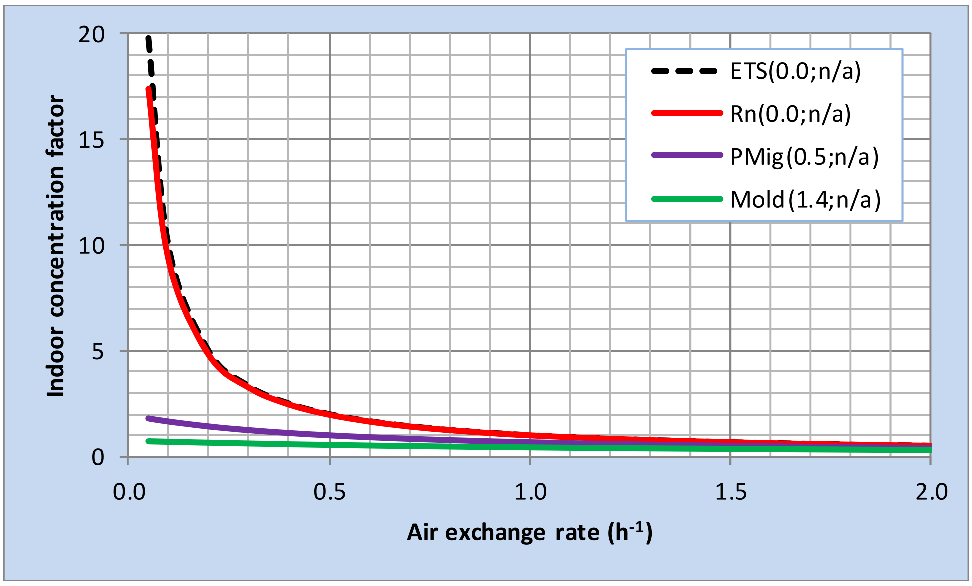


Figure 9. Impact of decay term on indoor concentrations of the three EnVIE indoor source pollutants + ETS.

In the case of outdoor particles the indoor decay reduces infiltration of coarse particles (Figure 10) for bioaerosols, modelled as 10µm pollen particles. PM2.5 particles, on the other hand, have a substantial infiltration when the air exchange rate approaches values above 0.1 – 0.2 changes per hour.

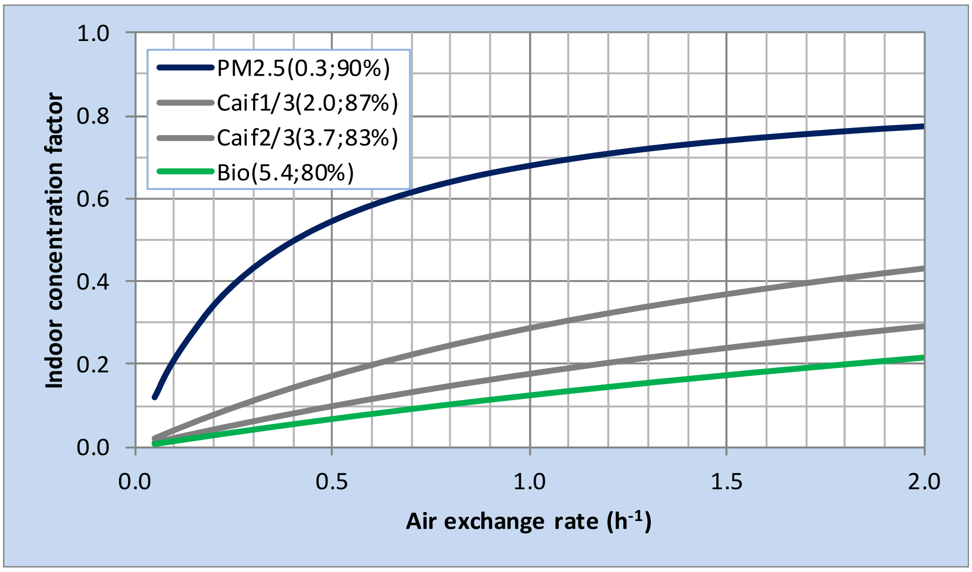


Figure 10. Impact of decay term on indoor concentrations of the two EnVIE outdoor source pollutants.

Increasing air exchange rate by 10% at different levels affects indoor and outdoor originating pollutants differently as can be seen in Figure 11 and Figure 12, respectively. In both cases larger decay rates decrease the relative impacts of changing ventilation.

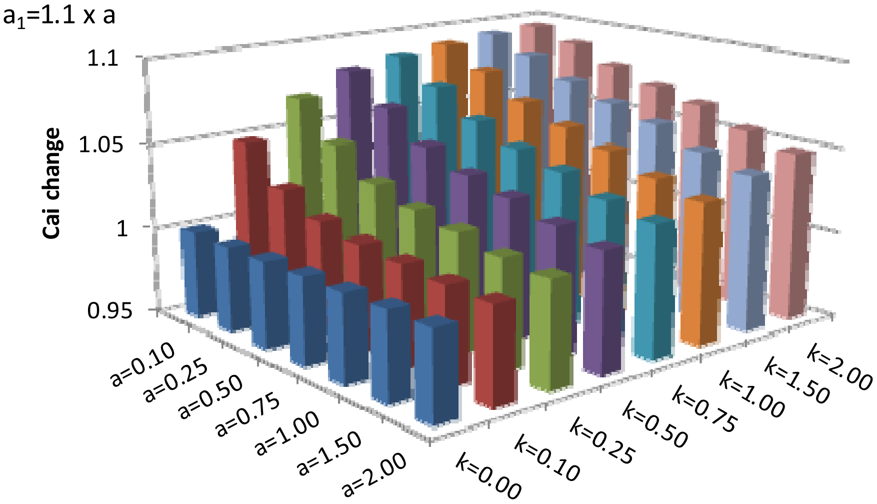


Figure 11. Relative effect of decay rate on indoor concentration from outdoor sources as function of air exchange rate, adjusted 10% upwards. 1 represents the original concentration, which stays the same if k=0. The higher decay rate k, the higher the relative increase in concentration.

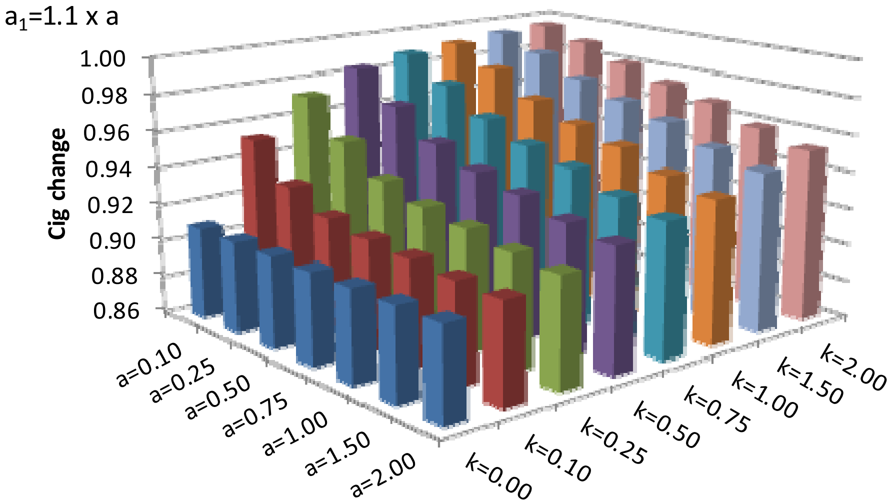


Figure 12. Relative effect of decay rate on relative change in indoor concentration from indoor sources as function of air exchange rate, adjusted upwards by 10%.

4.1.3 FILTRATION OF OUTDOOR AIR

Outdoor air is a major source of health risks manifested from indoor exposures (Hänninen et al., 2004, 2005, Oliveira Fernandes et al., 2009, Jantunen et al., 2010). This is due to the fact that the fresh ventilation air is taken from outdoors, introducing outdoor air pollutants indoors. Even in the cases of theoretically efficient filtering of intake air, detailed studies have shown that in real world situations 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). Moreover, European Commission assessment based on the extensive air quality monitoring network and complementary statistical and physical modelling has shown that only 9% of European Union citizens live in areas where the WHO guideline of 10 µg m-3 for annual average PM2.5 concentration (WHO, 2006) is achieved (Leeuw & Horalek, 2009).

Definition of needed filtration efficiency for the protection of public health must be based mainly on long-term average contribution of outdoor sources to the indoor concentrations. These can be quantitatively described using the mass-balance equation (Dockery and Spengler, 1981):

Eq 17
$$\overline{C_i} = \frac{Pa}{a+k}\overline{C_a} + \frac{G}{V(a+k)} - \frac{\Delta C_i}{\Delta t(a+k)}$$

According to the mass-balance, the indoor concentration of a pollutant originating from outdoor air (Cai) depends on penetration efficiency (P; probability of a particle to be carried through the building envelope with air intake), air exchange rate (a; h-1) and decay rate of particles indoors (k, h-1):

Eq 18 $$C_{ai} = \frac{Pa}{a+k} C_a = F_{INF} \times C_a$$

In the case of particulate matter the decay rate is mainly driven by thermokinetic and gravimetric deposition. The decay rate is strongly dependent on the particle size and for the simplified approach used here the default values shown in Table 5 are used.

Table 6. Mass-balance parameters of the outdoor pollutants considered.

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

According to the mass-balance, when assuming constant outdoor pollution and penetration efficiency, the indoor concentration originating from outdoors increases as function of air exchange rate. Filtration of outdoor air is necessary for protecting health of the occupants in cases when the outdoor air is contaminated. Because both ultrafine and coarse particles have much lower penetration efficiencies and higher deposition rates indoors, $PM_{2.5}$ is suitable for controlling the contribution of outdoor pollution indoors. Further, the current approach is using the long-term WHO guideline for $PM_{2.5}$, set at 10 µg m^{-3} as an annual average, for quantifying the needed efficiency of filtration of outdoor particles at a given location. This guideline was 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 of the whole building can be solved from the mass-balance equation as

Eq 19 $$P_{eff} = \frac{C_{ref}}{C_a} \times \frac{a+k}{a}$$

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 bypassing the filter (f)

Eq 20 $$P_{eff} = 1 - fP_{filter}$$

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

Eq 21 $$P_{filter} = \frac{1-P_{eff}}{f}$$

Obviously, the filter efficiency has to be balanced against the leakiness of the system as 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.

4.2 MINIMUM AND POINT VALUE VENTILATION

The national distributions of ventilation were defined as log-normal probability distributions, demonstrated in Figure 13. The ventilation guidelines could in principle be defined either as minimum values or as target (point) values.

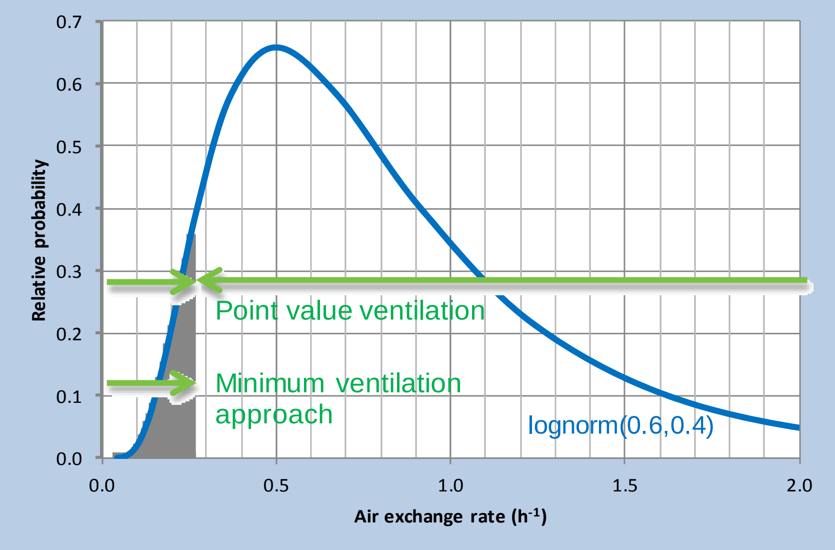


Figure 13. An example of a lognormal distribution of ventilation rates (blue line). The grey area represents the probability of prevailing ventilation being lower than 0.36 ach.

The impact of a proposed ventilation guideline on exposures is calculated for indoor concentrations from indoor and outdoor sources separately. In the case of indoor sources the adjusted ventilation removes the highest indoor concentrations (Figure 14). The minimum ventilation guideline approach would replace the lowest part of the solid red curve by the dotted line. The target value approach would replace the whole curve with the exposure value circulated. Correspondingly, the exposures to outdoor pollutants are modified as shown in the part b of the figure.

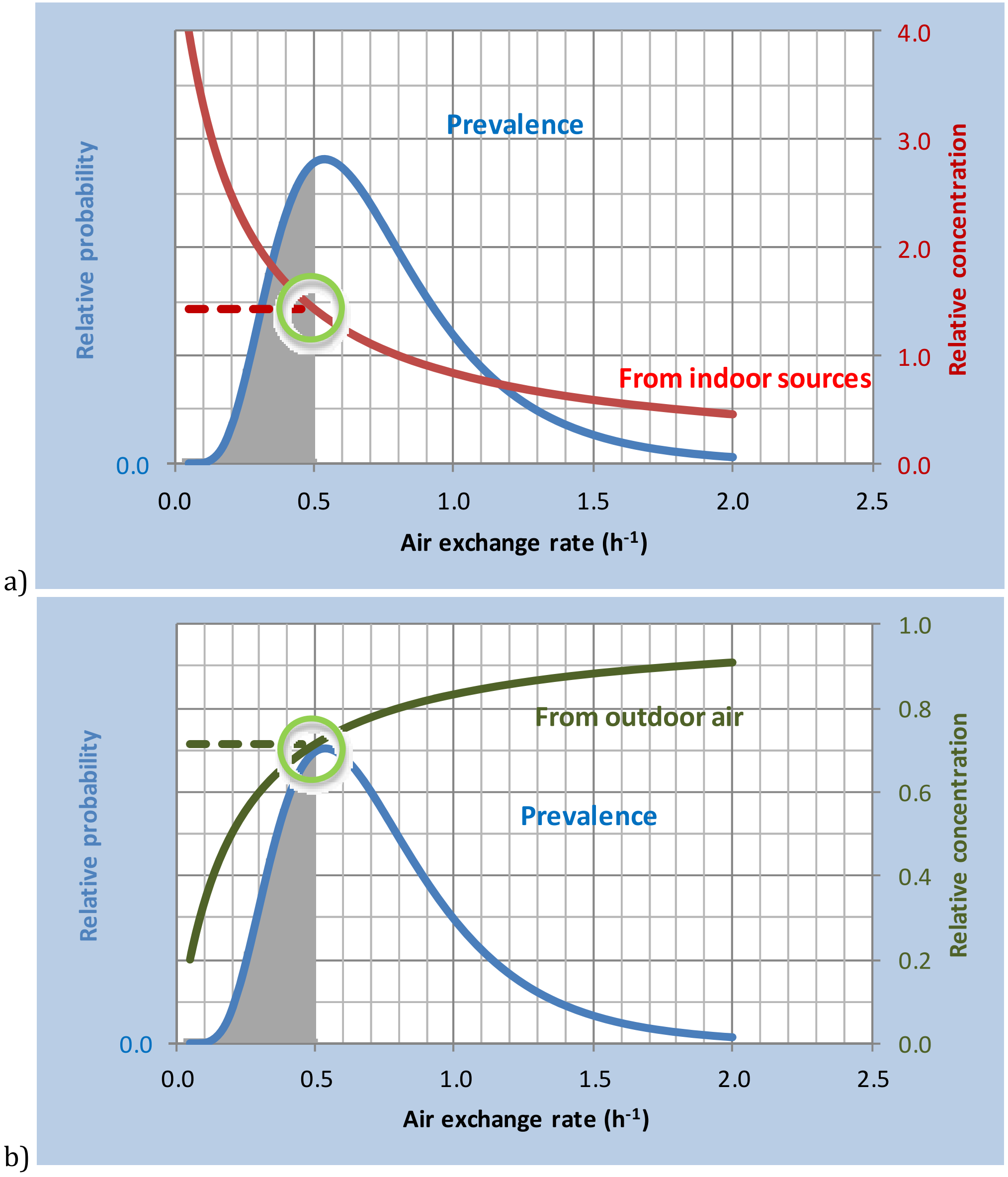


Figure 14. Effect of ventilation guideline on a concentration for (a) indoor and (b) outdoor sources.

5 HEALTH GAINS OF VENTILATION GUIDELINES

Exposures to indoor and outdoor originating pollutants are associated with significant health effects. Previous studies have estimated the burden of disease caused by exposures in indoor spaces to be 2 million disability adjusted life-years (DALY) in EU26. The HEALTHVENT update of the model estimates that 1.3 million DALYs are caused by exposures to outdoor air pollution indoors and 0.7 million DALYs by exposures to indoor originating pollutants (Figure 15). Both parts are dominated by cardiovascular diseases followed by asthma and allergies and lung cancer in contrasting order.

The current work used these estimates as a starting point to evaluate how various approaches to health-based ventilation guidelines could be used reduce this burden. Three alternative scenarios were developed for testing to support the final definition of guidelines. (i) Dilution optimum; (ii) Filtration optimum; and (iii) Source control optimum. The first approach 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 a substantial but feasible level of indoor source controls before finding the health-based optimum of ventilation.

This chapter presents the results on the efficiency of these three approaches in controlling the health effects caused by indoor exposures in comparison with the baseline:

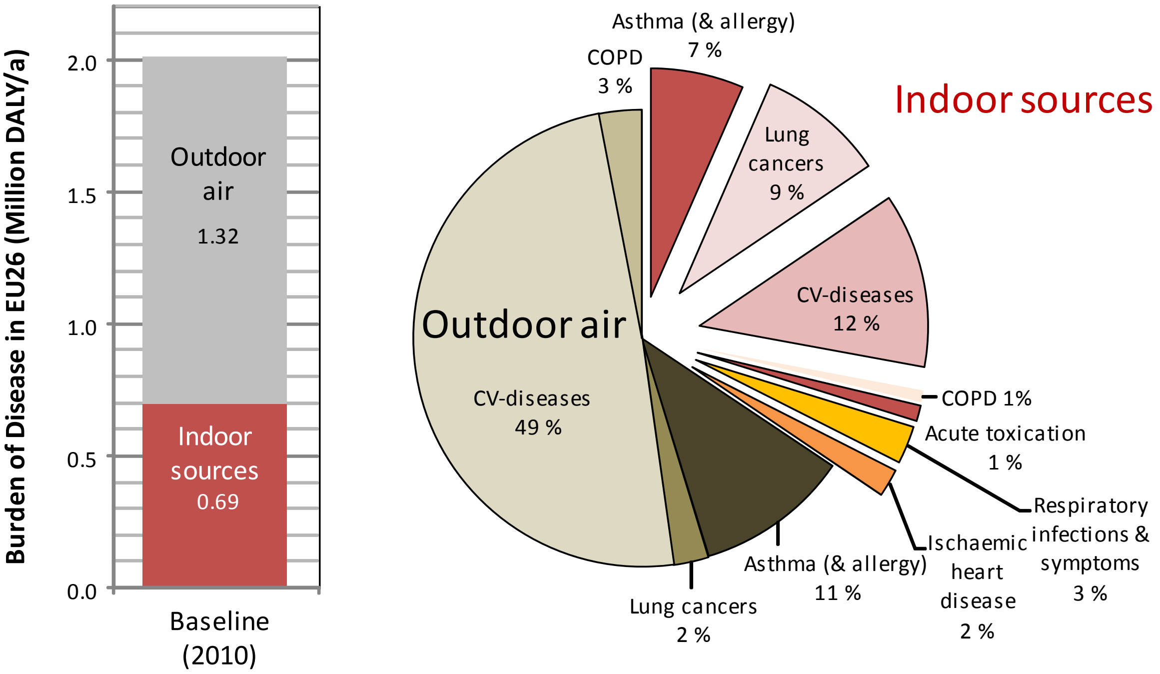


Figure 15. Burden of disease at the baseline (2010) in EU-26 divided into indoor and outdoor source components (left) and fractions associated with different diseases (right).

Comparison of the results from the alternative scenarios shows that each scenario can be used to provide 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 6 lps pp, which is lower than the baseline mean ventilation in the existing building stock. Somewhat larger benefits are produced by filtration of outdoor air in scenario 2, especially at higher filtration efficiencies. However, largest health benefits can be achieved by source control approach, which significantly reduces the need to control exposures by dilution and allows for avoiding extraneous infiltration.

Table 7. Comparison of the alternative potential guideline scenarios.

	Baseline 2010	Scenario 1 Dilution	Scenario 2 Filtration	Scenario 3 Src cntrl
Ventilation				
Penetration of outdoor $PM_{2.5}$	90 %	90 %	50 %	90 %
Ventilation optimum (EU26, lps pp)	19[a]	6	14	<4
Source controls				
Radon, CO, SHS	-	-	-	-90 %
VOC	-	-	-	-50 %
Moisture and moulds	-	-	-	-50 %
Indoor-generated PM	-	-	-	-25 %
Burden of disease (MDALY in EU26)				
Indoor sources	692 129	770 841	475 303	357 524
Outdoor sources	1 315 753	804 029	679 940	694 133
Cardiopulmonary	1 274 999	941 480	718 150	776 971
Cancer	231 394	255 940	134 130	72 673
Asthma and allergies	348 144	240 924	204 223	129 199
Other (COPD, infections, toxications)	153 345	136 526	98 741	72 814

[a] Population weighted average ventilation rate in EU26 countries at baseline

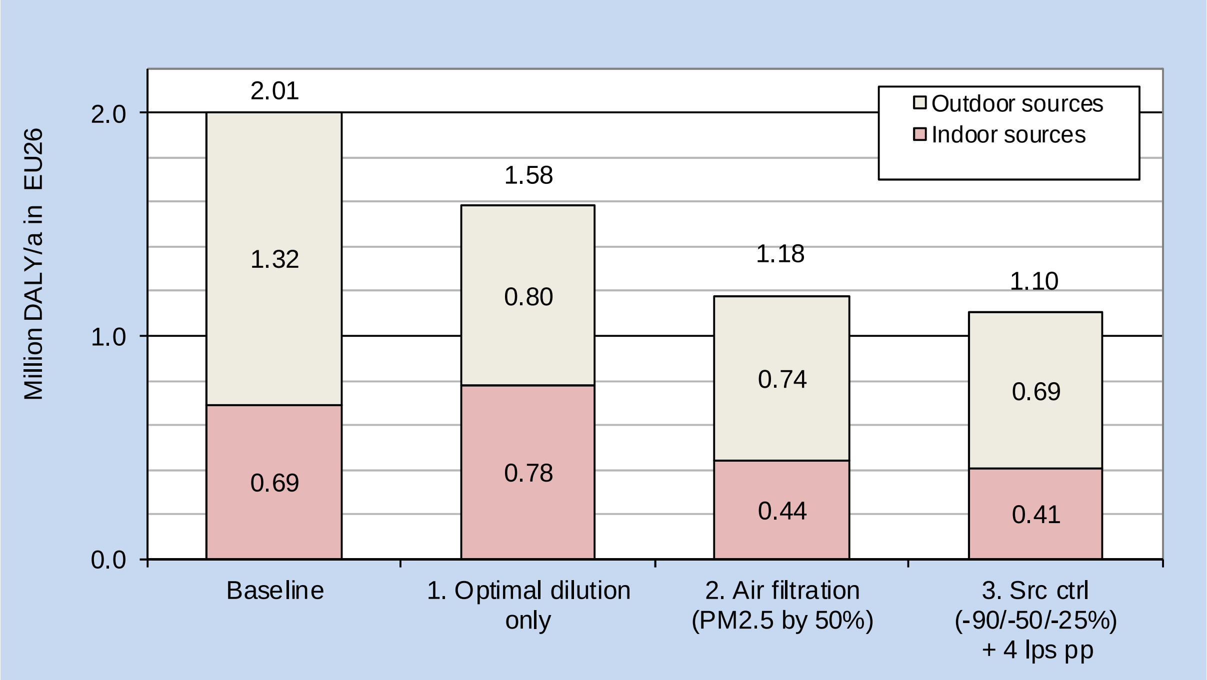


Figure 16. Burden of disease at the baseline (2010) in comparison with alternative potential ventilation guideline definitions in EU-26 (in millions of healthy lifeyears lost).

Each of the potential guideline scenarios is described in more detail in the sections below.

5.1 SCENARIO 1: DILUTION OF INDOOR SOURCES

Primary motivation for ventilation is the removal of indoor generated pollutants. This occurs by diluting indoor emissions with outdoor air. Traditionally in this context it was assumed that the outdoor air is clean, which is not the case. Nevertheless, in the calculations the baseline outdoor air quality in Europe, estimated at 10 km spatial resolution was used and the impacts of ventilation rate were calculated as discussed in Chapter 4 above. Thus the first scenario is defined as finding the health-based optimum ventilation rate without any other changes to indoor or outdoor sources.

In the dilution scenario the adjustment of ventilation is the only thing affecting the concentrations of the pollutants. 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 0.25 lps pp to 50 lps pp in 0.25 lps steps to 4 lps and in 1 lps steps up to 50 lps pp.

Only 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 17 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 6 lps pp. When running the health optimization of the ventilation rates by countries, the mean value is 7.5 and standard deviation 3.9.

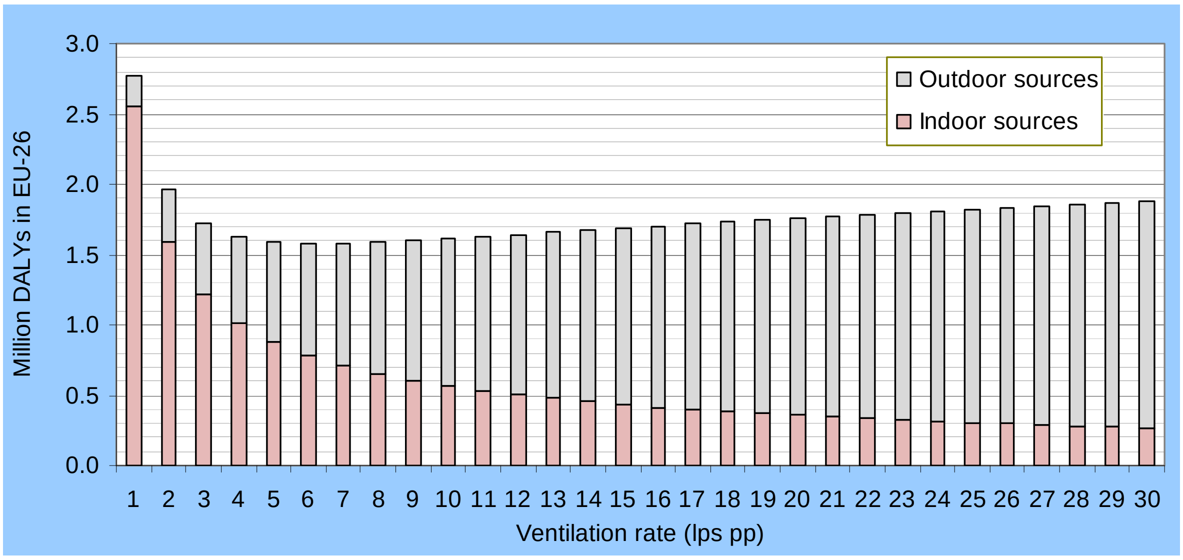


Figure 17. Burden of disease as function of residential ventilation rate per person in EU-26.

5.2 SCENARIO 2: FILTRATION OF OUTDOOR AIR

Previous analyses of the sources of indoor exposures in the EnVIE and IAIAQ studies have shown that outdoor air is a significant source of exposures and contributes more than 50% to the burden of disease (see e.g. Figure 15 earlier in this Chapter). 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 rates 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 results for maximum feasible filtration (P=50%) show that reduction in burden of disease approach 40 % or 800 000 DALYs in EU26 (Figure 18). This approach would by default imply the use of mechanical ventilation systems. Average of national health optimums of ventilation levels is 15.5 lps pp (SD 6.6 lps pp) and the European optimum is 14 lps pp. Figure 18 shows that using health-optimized ventilation level in addition to the filtration produces small improvements in comparison to the baseline ventilation with improved filtration.

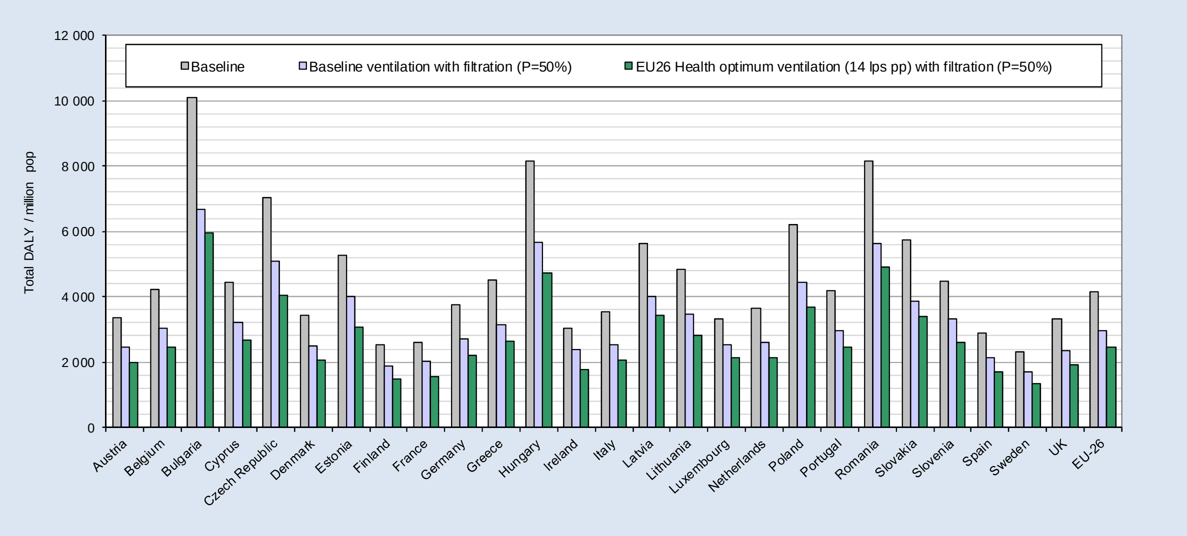


Figure 18. Burden of disease for different levels of filtration of ambient particles in EU-26.

5.3 SCENARIO 3: SOURCE CONTROL

The third approach to optimizing ventilation for health returns 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.

The source control approach provides even slightly larger benefits than the filtration approach in the previous scenario; now the benefits are approximately 45% from the baseline, or 900 000 DALYs in EU26 (Figure 19). 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.

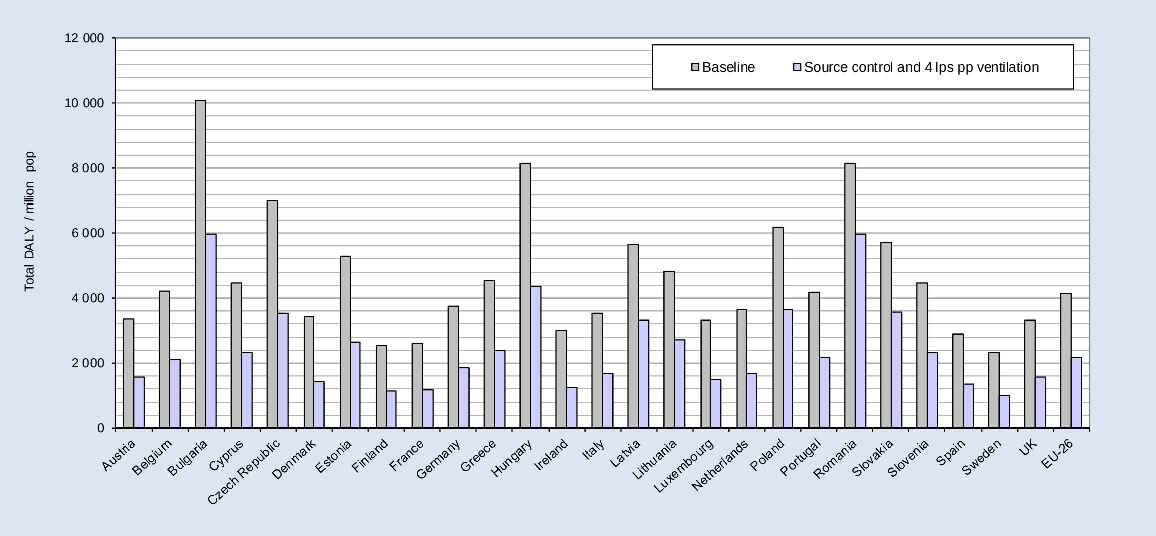


Figure 19. Burden of disease for source control optimum in EU-26.

6 IMPLICATIONS ON ENERGY USE AND CO_2 EMISSIONS

Residential energy use represents roughly a quarter of the total energy consumed in Europe and almost identical share of the corresponding greenhouse gas emissions (Figure 20). The total energy balance is lead by transportation sector (34% of energy and 39% of CO2 emissions), followed by the corresponding residential sector and industrial contributions.

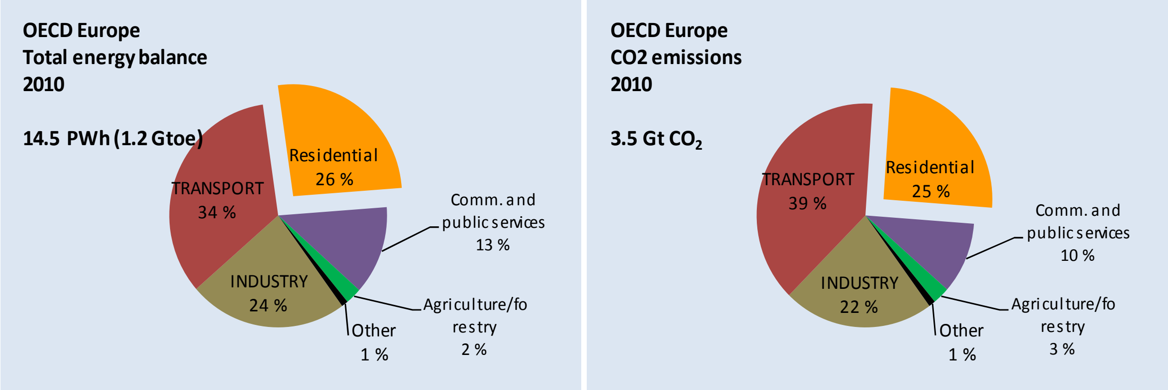
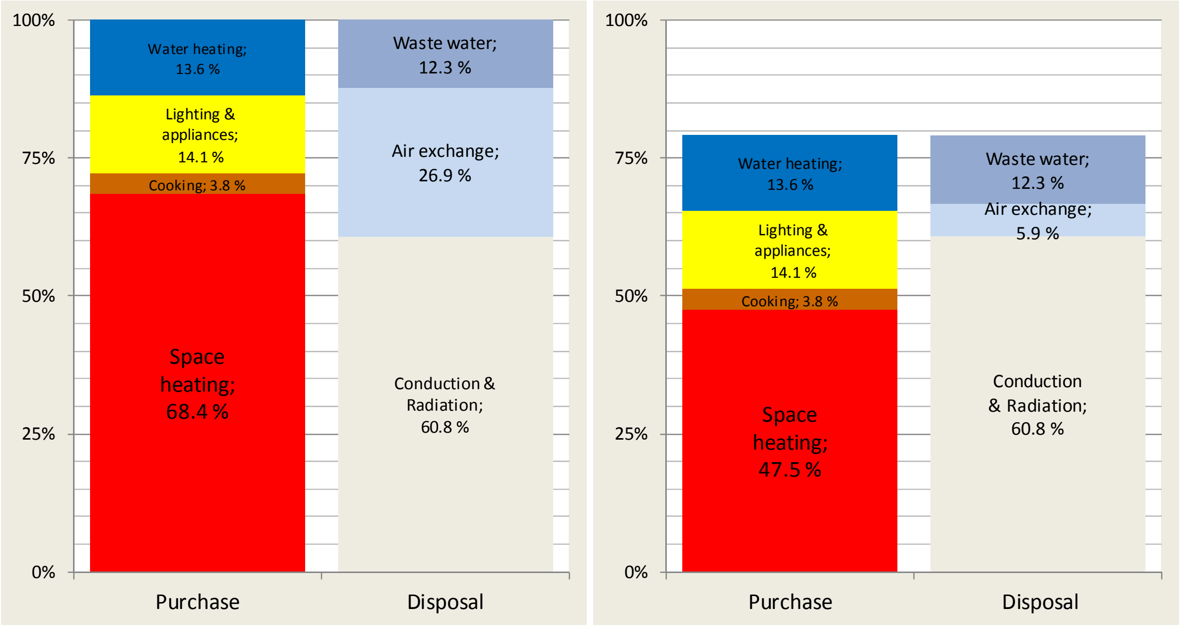


Figure 20. Overview of energy use in OECD Europe countries in 2010 (IEA, 2012) and corresponding CO_2 emissions. Transport includes international aviation and navigation. Residential use represents 26% of the total energy used.

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 EU-27 over 68% of energy consumed by the residential sector was 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. The relative contributions of these components are depicted in the left columns of Figure 21. The right columns show the fate of the energy, dominated by conductivity and radiation losses of the buildings, followed by the energy losses due to air exchange. In comparison with the energy used for space heating (nearly 2.5 PWh in EU27 in 2008), 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. Therefore the current evaluation of the health-based ventilation guidelines was designed to consider also the corresponding energy implications and changes in the carbon dioxide emissions.



(a) Baseline (b) Src Ctrl Guideline in 2010 building stock

Figure 21. 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 and the HEALTHVENT guideline scenario assuming source control approach completely implemented and minimum ventilation of 4 lps pp with 100% ventilation effectiveness.

6.1 CONTRIBUTION OF AIR EXCHANGE IN RESIDENTIAL ENERGY USE AND CO_2 EMISSIONS

EU-26 Residential energy components (heating, water, cooking, electrical appliances) and fraction consumed by air exchange.

Baseline ventilation energy need by country in comparison with the total residential energy use (stacked bar)

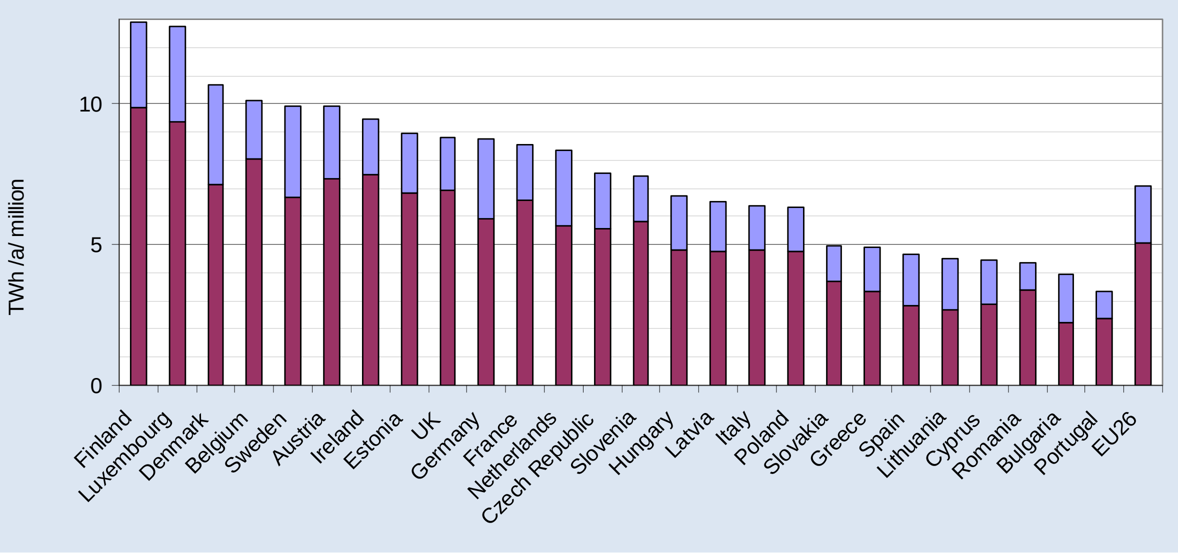


Figure 22. Total residential energy use and the fraction consumed by air exchange (ventilation and air leakages; in blue) in 2010 (for six countries missing 2010 data is replaced EEA data for 2009 (EEA, 2012).

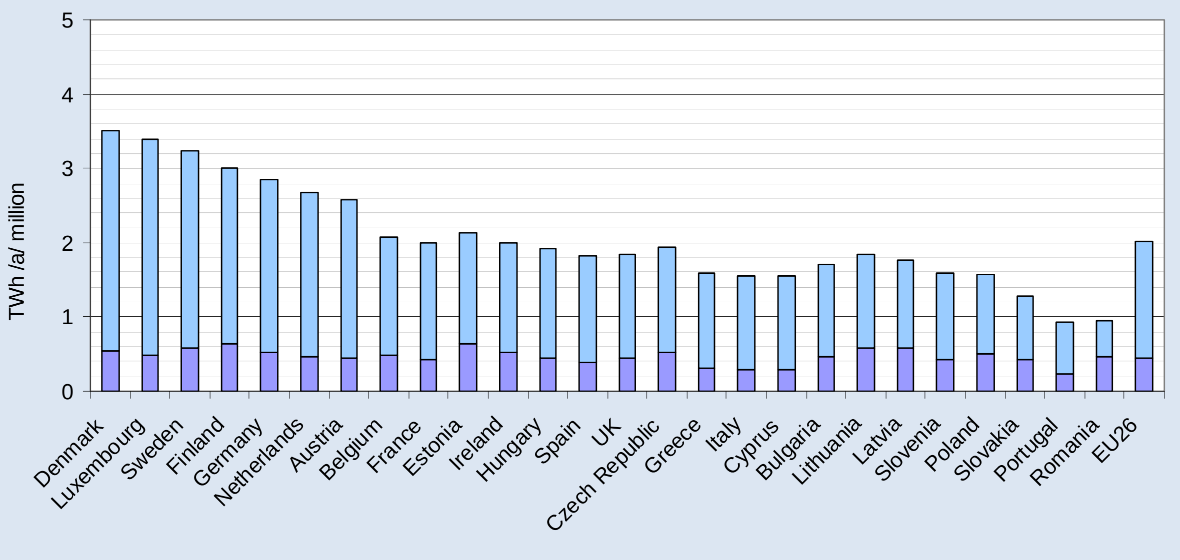


Figure 23. Residential air exchange energy consumption at the baseline (blue) and the remaining fraction at minimum ventilation 4 lps pp (=assuming fully effective source controls as specified for Scenario 3).

6.2 IMPACT OF VENTILATION GUIDELINES ON AIR EXCHANGE ENERGY USE

The baseline and guideline energy use estimates are based on the current building stock. To contrast the current building stock with more energy efficient buildings built according to the current building codes and pertaining to future, two future building stock scenarios were created in HEALTHVENT Workpackage 6 (Santos & Leal, 2012a,b):

(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 (Santos & Leal, 2012a,b)

(iv) Potential future building stock with advanced technologies (Santos & Leal, 2012a,b)

Comparison of the energy use in baseline with the implementation of the ventilation guidelines in the current building stock and when using 2010 technology in all buildings or advanced systems for energy efficiency.

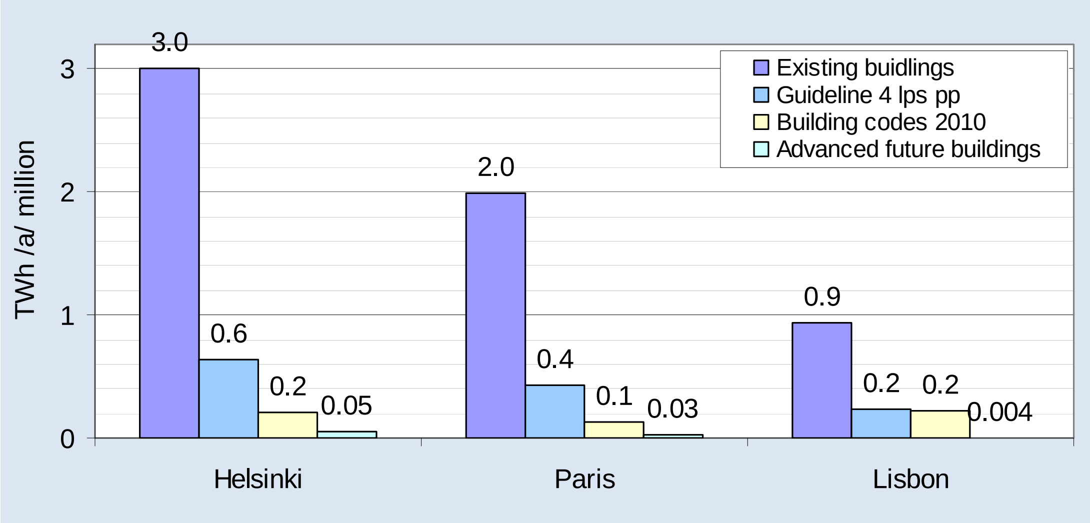


Figure 24. Comparison of the energy needs of ventilation at the baseline (2010) and guideline minimum ventilation (assuming fully implemented source controls) with modern and future buildings as simulated by Santos & Leal (2012a,b) in three cities.

7 DISCUSSION AND UNCERTAINTIES

The current work used mainstream burden of disease and energy models to estimate the overall magnitude of health and energy implications of alternative approaches for health-based ventilation guidelines. The calculations were conducted first for the baseline building stock representing year 2010. In several cases data from nearby years were used to characterize the baseline situation in lack of actual 2010 data. Most importantly, the best population-based European outdoor $PM_{2.5}$ pollution field was available for 2005 (de Leeuw & Horalek, 2009) and was used as such. The temporal trends in $PM_{2.5}$ concentrations have been estimated to be very modest, in the order of -1 … -2 % per year; thus the error is expected to be in the order of +5 %.

The energy implications were estimated for the heating energy needs. Increasing building tightness and insulation levels is likely to lead to a need for mechanical cooling during the summers, which will partly compensate the projected improvements in energy efficiencies.

This section will discuss some specific aspects affecting the interpretation and use of the results.

7.1 SOURCES OF UNCERTAINTIES

Sources of uncertainties in modelled estimates are traditionally grouped into three categories: (i) Uncertainties in the input data (parameter uncertainty); (ii) uncertainties in the model, and (iii) uncertainties in defining the future scenarios. Normally the parameter uncertainties are the easiest to handle using standard statistical methods and observed data. Model uncertainties can be sometimes evaluated against observed data in special settings, but the applicability of the model in new settings remains uncertain and can only be qualitatively judged by experts. 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.

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 PM2.5, 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).

Variable degree of model uncertainty exists in the exposure-response response relationships based on epidemiological studies. For some of the included pollutants, like PM2.5 originating from outdoor air, this data is based on a large number of studies, representing very large populations in different climatological regions. On the other hand, in some cases the population representativity, number of studies, control of confounding and other sources of uncertainties in epidemiological designs are much less convincing. Nevertheless, the evidence on the association of the included pollutants and the health endpoints is strong. 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.

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 PM2.5, 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.

7.2 HEALTHVENT UPDATE OF THE IAIAQ MODEL

The baseline model describes the burden of disease of indoor exposures for the current situation. The total BoD (DALY / million pop) calculated with IAIAQ and HEALTHVENT models for the baseline are presented in Figure 25. As it can be seen the BoD in Bulgaria and Romania is quite different between these models and the explanation is the updated PM concentrations in the HEALTHVENT model. The levels of PM were drastically lower for these countries when the data was updated. In addition of updating the PM data, the changes between the models are caused by the updated background BoD values and addition of SHS to the list of sources.

Evaluation of the sources indicates that the outdoor sources are contributing more to the exposures and causing more health effects than the indoor sources. The total DALY/million population in each country distributed between indoor and outdoor sources in IAIAQ and HEALTHVENT baseline scenarios are presented in Table 8.

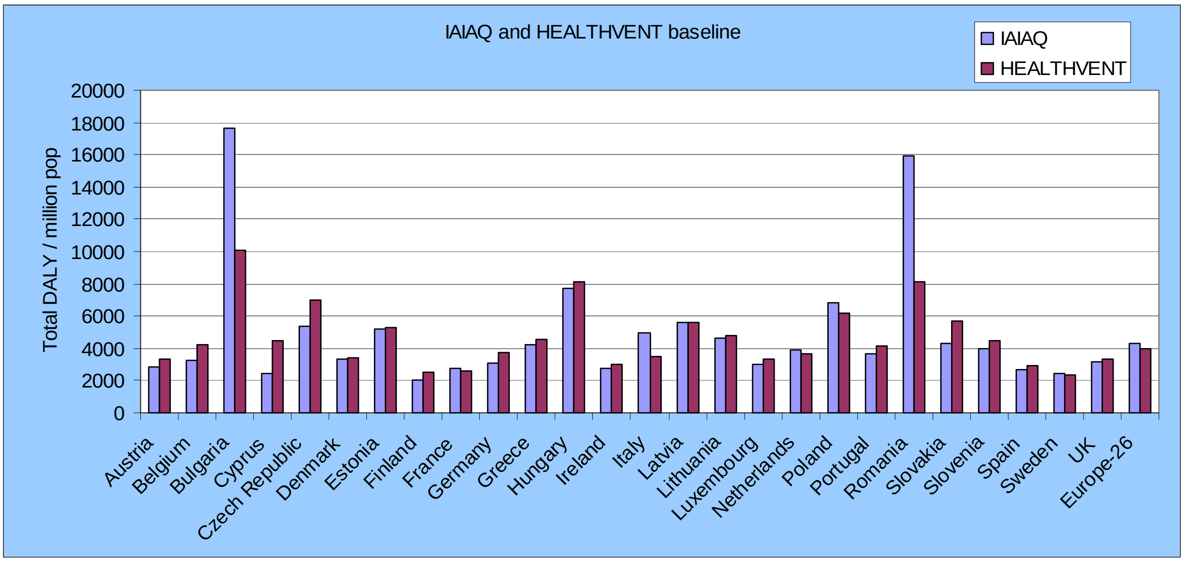


Figure 25. Total burden of disease (DALY / million pop) for the baseline models of IAIAQ and HEALTHVENT.

Table 8. Comparison of baseline burden of disease as estimated by IAIAQ and HEALTHVENT models.

	Indoor sources				Outdoor sources			
	IAIAQ		HEALTHVENT		IAIAQ		HEALTHVENT	
Country	DALY/M	%	DALY/M	%	DALY/M	%	DALY/M	%
Austria	971	34	1262	38	1904	66	2097	62
Belgium	1221	38	1524	36	2002	62	2690	64
Bulgaria	5511	31	2392	24	12137	69	7696	76
Cyprus	768	31	1629	37	1671	69	2826	63
Czech Republic	1863	35	2564	37	3486	65	4457	63
Denmark	1516	45	1241	36	1845	55	2201	64
Estonia	2352	45	2340	44	2818	55	2943	56
Finland	755	38	968	38	1257	62	1561	62
France	968	35	1183	45	1803	65	1435	55
Germany	999	32	1318	35	2109	68	2439	65
Greece	1146	27	1368	30	3122	73	3157	70
Hungary	2300	30	2545	31	5449	70	5596	69
Ireland	1234	45	1448	48	1529	55	1569	52
Italy	1425	29	1200	34	3550	71	2336	66
Latvia	1778	32	1918	34	3838	68	3723	66
Lithuania	1317	28	1743	36	3318	72	3088	64
Luxembourg	1250	42	1510	46	1756	58	1803	54
Netherlands	1630	42	1252	34	2266	58	2389	66
Poland	1853	27	2150	35	4976	73	4039	65
Portugal	1185	33	1396	33	2455	67	2786	67
Romania	6534	41	2439	30	9392	59	5724	70
Slovakia	1038	24	1517	26	3234	76	4214	74
Slovenia	1427	36	1787	40	2558	64	2676	60
Spain	1232	46	1147	40	1441	54	1752	60
Sweden	694	28	840	36	1746	72	1479	64
UK	960	30	1026	31	2236	70	2296	69
Europe-26	1333	31	1415	35	2938	69	2599	65

7.3 CHRONIC DISEASES, ACUTE SYMPTOMS

Epidemiological studies on health effects caused by indoor exposures typically cover acute symptoms like wheeze and cough, headache etc. (Carrer et al., 2012). It is challenging to collect data on the association of chronic or rare conditions without acute symptoms associated with the exposures, like cancer or cardiovascular diseases. Therefore the review of literature specifically focusing on the association of ventilation and health was able to identify only a small number of studies showing an association between acute effects and ventilation.

However, main stream risk assessment models have consistently shown that the burden of disease from the chronic effects like lung cancer, cardiovascular diseases, and especially from mortality, are driving the overall environmental burden of disease (e.g. Hänninen & Knol, 2011).

The chronic health endpoints were included in the current work based on 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). In the current work a mass-balance model has been used to quantify the association of ventilation and indoor exposures and combined with these main stream risk assessment models to estimate the impact of chronic effects on health. The results confirm the earlier finding that the chronic effects are more significant than acute effects.

7.4 TECHNICAL FEASIBILITY OF THE GUIDELINES

Energy efficiency needs are a strong factor influencing the future building stock. Therefore in the current work the impact of the ventilation guidelines were estimated first for the current building stock assuming minimal changes in the building stock. The possibilities for improved energy efficiency by using state of art technologies were then evaluated separately. In these scenarios it is assumed that the whole building stock in Europe and in all member states of EU will comply to the alternative definitions; such a change in the building stock will take a long time to be possible even in theory; the change will involve substantial investments (that may partly or completely be offset by energy savings; and the schedule of such a change is among the largest uncertainties.

Ensuring sufficient ventilation and controlling indoor and outdoor pollution sources requires technical resources. The factors affecting the functionality of ventilation systems are elaborated in depth in the HEALTHVENT WP5 report (Seppänen et al., 2012).

In the current situation a vast majority of the European buildings are ventilated naturally. Throughout the HEALTHVENT guideline development process care has been taken to avoid recommendations that would specifically require application of a certain technology. The focus has been kept, instead of technical solutions, in the definition of key parameters determining the health risks. Nevertheless, it is a technical challenge to ensure a proper minimum ventilation, or minimum filtration of outdoor air pollution.

7.4.1 CONTROLLING VENTILATION

Majority of European residential buildings were ventilated naturally in 2010. In natural ventilation systems the driving forces determining the ventilation rates are the temperature differences between indoor spaces and outdoor air and wind speed. 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 active informed decisions and are not optimal in controlling the exposures. In mechanical ventilation systems electronic control units can be programmed to adjust ventilation according to the environmental changes and 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 and more buildings with mechanical systems.

7.4.2 FILTRATION OF AMBIENT PARTICLES

More than 90% of Europeans live in areas where outdoor air quality does not meet the WHO Guidelines for $PM_{2.5}$. 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 of course on 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 systems. Nevertheless, active filtration becomes efficient only in mechanical systems using high quality (FP7 and above) filters and optionally combination of coarse and fine filters in sequence.

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. However, also techniques applicable in natural ventilation systems can be used to reduce infiltration of ambient particles.

7.4.3 HEAT RECOVERY AND OTHER ADVANCED TECHNOLOGIES

Santos and Leal (2012a,b) simulated the ventilation related energy consumption of modern buildings pertaining to the building codes in force in 2010 (labelled as base case in their report) and advanced systems that take the energy efficiency even further by simultaneously applying heat recovery, very high building air tightness, demand-control of ventilation and free-cooling (ventilating the building when it needs cooling and outdoor air is enough cool, conditions typically met during summer nights and early mornings).

In Nordic countries due to the cold winters many of the technologies are already in use in new buildings, including mechanical systems with heat recovery. In comparison with the existing building stock in Central and Southern Europe these requirements are further from the current state of art situation. The energy simulations conducted in HEALTVENT WP6 demonstrate the potential of these new technologies on energy conservation.

7.5 BALANCING HEALTH AND ENERGY

The current work demonstrates that the health can be promoted most efficiently by giving serious attention to controlling indoor sources of exposures. When indoor sources are left on the baseline (2010) level, only marginal health benefits can be achieved on European scale by optimizing ventilation rates. Moreover, even in this case, the optimal ventilation rate is substantially reduced from the baseline (6 lps pp vs. 19 lps pp) due to the contribution of outdoor sources to the burden of diseases. Reduction of ventilation rates of course is of a major concern in cases where indoor sources are present.

Energy implications of ventilation can be divided into three components: (i) heating, (ii) cooling, and (iii) fan energy. The latter two are generally applicable only in case of mechanical systems. Cooling techniques in natural systems are mainly based on shading.

7.5.1 CO_2 EMISSIONS PER DALY -INDEX

The project plan anticipated health benefits at increased ventilation rates due to improved dilution of indoor sources and therefore included a component to estimate the energy and CO_2 costs of improved population health. The idea was to evaluate various approaches to improve health in terms of green house gas emissions. However, in the detailed implementation of the work, it turned out that due to the effects of outdoor air pollution, on population level and in Europe as whole, health benefits are actually achieved at lower ventilation rates than the baseline at 2010. Therefore saving lives and DALYs is associated also with saving CO_2 emissions – a win-win setting for health and energy.

As described in Chapter 5 above, there are different approaches to better health. In the dilution-based Scenario 1 lowering ventilation rates from 19 lps pp, the European baseline mean to 6 lps pp yielded 20 % savings in burden of disease, assuming that the indoor sources remained constant. Even in the filtration-based Scenario 2 the European health optimum ventilation rate was 14 lps pp, thus below the mean baseline. The source control –based Scenario 3 produced the lowest health-based optimum ventilation rates, approaching the level where humidity emission from the occupants become critical. Thus in all approaches health benefits were associated with decreased ventilation and energy savings and the logic in developing the CO_2 emissions per DALY –index was reversed.

The ratio of CO2 emissions to burden of disease (MtCO2/MDALY) increases in the guideline scenario for the current building stock due to the fact that the health benefits of the guidelines exceed those of energy and greenhouse gas savings when accounting for the whole residential sector (Table 9). If looking at ventilation energy and corresponding CO_2 emissions, this ratio is reversed due to the fact that the energy savings on ventilation energy needs are expected to exceed 70% and therefore are in relative terms larger than the projected health benefits.

Table 9. Estimation of burden of disease, energy and CO_2 emissions in the baseline building stock at current ventilation and at minimum guideline ventilation assuming fully effective source controls.

		Baseline (2010)	**Guideline** (2010)
	Burden of disease (MDALY/a)	2.01	1.05
Total residential energy use			
	Energy (TWh)	3608.7	3065.7
	CO_2 (Mt)	829.2	704.4
	$MtCO_2$/MDALY	413	671
Residential ventilation energy use			
	Energy (TWh)	971	210
	CO_2 (Mt)	223.1	48.3
	$MtCO_2$/MDALY	111	46

7.6 IMPLEMENTATION RISKS OF THE GUIDELINES

The minimum ventilation requirement approach is implemented and evaluated based on the source control approach, assuming that in the future building stock all major indoor sources of CO, radon, dampness and mould, volatile organic compounds and particulate matter can be substantially reduced from the baseline situation in 2010. If such a guideline would be carelessly implemented as such, without rigidly confirming the functionality and implementation of the corresponding source controls, the proposed energy efficient low ventilation rates might lead to high indoor exposures. In the case of especially sensitive population groups this would lead to exponential increase of indoor air related health problems. Therefore it is of utmost importance to handle the ventilation guidelines, especially the basic bioeffluent based minimum ventilation limits as such, absolute minimums that never can be compromised, and in combination with a complete handling of indoor air quality and human exposures. In the lack of confirmation of successful source controls, as requested by the guidelines, the ventilation rates have to be adjusted accordingly, as described in the guideline definition.

8 CONCLUSIONS

Previous assessments have evaluated that over 2 million healthy life years are annually lost in the European Union due to compromised indoor air quality. The aim of the HEALTHVENT Workpackage 8 was to evaluate the impact of various approaches to define health based ventilation guidelines for Europe on health. The work was conducted by developing three main approaches to reduce the burden of disease by optimizing ventilation for health and adjusting other exposure parameters. First scenario assumed that the sources of exposures both indoors and outdoors stay constant and adjusted ventilation to find minimum burden of disease. The second approach attempted to reduce the burden of disease primarily by filtrating outdoor originating particles from the air intake. The third approach was based on maximal feasible control of indoor emissions before optimizing ventilation rates for health.

Each of the evaluated approaches produced substantial reduction of burden of disease. The relative reduction ranged from 20 to 40%, representing 400 000 to 900 000 saved DALYs in Europe (EU26). Adjusting ventilation only was least efficient while applying filtration to all buildings or removing a feasible fraction of all major indoor emission sources both produced rather comparable health gains. The source control approach proved to be slightly more efficient. Moreover, the filtration approach would be likely to require mechanization of ventilation systems in Europe for realization of the benefits.

The health-based ventilation guidelines, when combined with the proposed efficient control of indoor sources, allow to reduce the energy consumption required by ventilation by 760 TWh, or 78 %, corresponding 125 $MtCO_2$ reduction in the carbon dioxide emissions in Europe.

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