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Promoting healthy and highly energy performing buildings in the European Union

National implementation of related requirements of the Energy Performance Buildings Directive (2010/31/EU)

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Abstract

Promoting healthy and highly energy performing buildings in the European Union

EU Member States have been developing policies and measures to generally reduce the actual energy use of their buildings. Member States are called to properly implement and enforce the Energy Performance of Buildings Directive (2010/31/EU) without compromising the comfort, health and productivity of their occupants.

The objective of this report is three-fold: (a) to present the outcome of the review carried out concerning the implementation status by the EU MS of provisions relating to ventilation, indoor air quality and energy performance criteria and requirements; (b) assess whether the current implementation status can ensure avoiding possible negative effects on the comfort, health and productivity conditions of the buildings' occupants in EU; (c) formulating policy and technical related recommendations to enable the effective implementation of healthy and highly energy performing buildings in the EU.

This work was performed in the context of Task 13.3 of the Administrative Arrangement TSSEED between DG ENER and JRC no. ENER/C3/2014-554/SI2.693948 (2015-2017) with the aim to directly inform the review process of the EU energy efficiency legislation in 2016.

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National implementation of related requirements of the Energy Performance Buildings Directive (2010/31/EU)

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Executive summary

Policy context

The Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy[1] considers energy efficiency as one of the pillars to deliver the Energy Union and identify buildings as a sector with an important potential for further efficiency increase.

Most of the energy used in buildings aims at guaranteeing conditions of well-being, comfort and health for the buildings' occupants. This creates the need and challenging endeavour to reconcile energy savings ambitions with the obligation to guarantee the conditions of growing-up, living working and learning in healthy indoor environments.

EU MS have been developing policies and measures to generally reduce the actual energy use of their buildings. They are called to properly implement and enforce the requirements of the Energy Performance of Buildings Directive (2010/31/EU)[2] without compromising the comfort, health and productivity of their occupants.

The objective of this report is three-fold: (a) to present the outcome of the review carried out concerning the implementation status in the EU MS of the EPBD relating to ventilation, indoor air quality (IAQ) and energy performance criteria and requirements; (b) assess whether the current implementation status can ensure avoidance of possible negative effects on the comfort, health and productivity conditions of the buildings' occupants in EU; (c) formulating policy and technical related recommendations to enable the effective implementation of healthy and highly energy performing buildings in the EU.

This work was performed in the context of Task 13.3 of the Administrative Arrangement TSSEED between DG ENER and JRC no. ENER/C3/2014-554/SI2.693948 (2015-2017) with the aim to directly inform the review process of the EU energy efficiency legislation in 2016.

Key conclusions

The key conclusions drawn from the review performed in the context of Task 13.3 and recommendations made to help promoting and enabling the effective implementation of healthy and highly energy performing buildings in EU are reported below.

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[1] EC. (2015). Energy Union Package, A Framework Strategy for Resilient Energy Union with a Forward-Looking Climate Change Policy, European Energy Security Strategy. Communication from the Commission to the European Parliament and the Council. http://ec.europa.eu/priorities/energy-union/docs/energyunion_en.pdf

[2] EPBD. DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 May 2010 on the energy performance of buildings (recast). Official Journal of the European Union, OJ L 153/13, 18.6.2010.

Conclusions on the implementation status in the EU MS of the EPBD relating to ventilation, indoor air quality (IAQ) and energy performance criteria and requirements

- Most EU MS have introduced minimum ventilation requirements but these are in most cases based on comfort criteria and use health based criteria[3] to a lesser extent. In some cases the minimum ventilation requirements are below the generally accepted levels for comfort. In some cases no legally binding requirements exist at all.
- Other than minimum ventilation rates, IAQ related requirements in EU MS, such as acceptable levels of pollutants (according to national or international IAQ guidelines) and building airtightness, are largely differentiated in terms of mandatory or recommended values for new and existing residential buildings. In several cases, there is a mismatch of the IAQ related requirements that are set for new and existing buildings.
- As energy efficiency related measures are often applied without any mandatory requirements for a subsequent assessment of their impact on the levels of ventilation and other Indoor Environment Quality (IEQ) related parameters such as thermal comfort, lighting (including day lighting), noise and indoor air pollution levels, in several cases values for these parameters are reported to be below the required or recommended levels by national regulations and international standards. This situation could further deteriorate given the current trend in renovation measures resulting in more airtight building envelopes.
- Several European countries do not allow or do not recognise the possibility of reducing ventilation rates when less polluting materials are used or when ventilation efficiency is improved. Also they do not provide the possibility of controlling ventilation rates based on the outdoor air quality (with the exception of those EU MS that have adopted and currently apply the EN 15251:2007[4] and EN 13779:2007[5] standards in their national regulations).
- In the on-going revision of standard EN 15251:2007 (prEN 16798-1)[6] the IAQ and health aspects related to the design and criteria of ventilation rates have a greater emphasis than in the former version of the standard but the concepts, targets, tools and methods proposed do not yet fully match the framework of the health

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[3] The health based ventilation criteria are defined in the context of the health based guidelines framework that was developed within the EU funded HEALTHVENT project (ECA report, 2015). The "health based ventilation rate" for a specific building is defined when the WHO air quality guidelines are met through an integrated approach following the principles of primary prevention, which combines source control measures and health based ventilation practices that guarantee the protection of health. Both indoor and outdoor air pollution sources should be tackled through coordinated actions and treated as equally important for human health.

[4] EN 15251:2007. Indoor environmental parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. European Committee for Standardization (CEN), 2007.

[5] EN 13779:2007. Ventilation for non-residential buildings - Performance requirements for ventilation and room-conditioning systems. European Committee for Standardization (CEN), 2007.

[6] CEN. European Committee for Standardization, prEN 16798-1 "Energy performance of buildings – Part 1: Indoor environmental input parameters for design and assessment of the energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics (EN 15251 rev: 2015). CEN/TC 156 WG19-N68, May 2015.

based ventilation guidelines that was developed within the EU funded HEALTHVENT project[7].

- Compliance check procedures in EU currently focus mainly on structural analysis, safety and energy performance aspects during the buildings' design stage. During the construction of new or renovated buildings compliance procedures are limited to aspects such as thermal transmittance of building elements (U-values), installation of heating and air conditioning equipment (but not their operation nor any guaranteeing of the quality of the supplied air), airtightness, availability of Energy Performance Certificates (EPCs), etc.
- Compliance with building and installation aspects related to indoor air quality (e.g. ventilation and Heating, Ventilating and Air Conditioning - HVAC systems) or thermal comfort (in particular risk of overheating) is rarely checked by the designated control bodies and if so, mainly at the design stage based on calculations rather than by performing onsite controls. In a few countries only, there is an effective penalty system in case of non-compliance. During the operation phase of existing buildings, compliance checks are only carried out for aspects such as energy performance, safety (e.g. resistance to fire, structure defects such as cracks, etc.) and occupational health and safety, while systematic indoor air quality or thermal comfort verification procedures have been rarely identified and even less practiced.

To understand the potential impact (improvement or deterioration) of comfort and health conditions in new or renovated buildings in the EU as result of the interplay among various factors (e.g., IAQ sources, ventilation practices and systems, building characteristics and operational conditions, regional climate differences etc.), data collection initiatives and projects (e.g. national monitoring surveys in EU MS, EU funded projects, etc.) on IAQ, comfort and health in highly energy performing buildings were also reported and analysed.

Moreover, evidence from measured data was further supported by a review of modelling simulations demonstrating that IEQ and energy are linked in many ways and, if proper measures are applied, energy performance improvements may result in IAQ and thermal comfort improvements, i.e. energy and IEQ problems can be solved concurrently.

Conclusions from data monitoring surveys and modelling simulations at EU and national levels on indoor environment quality, comfort and health conditions in highly energy performing buildings

- To date, only a very limited number of studies investigating IAQ, health and comfort in low-energy buildings have been conducted in the EU and other parts of the globe. The outcomes of these studies contribute to the knowledge about IEQ and occupants' comfort and health in energy performing buildings. However, due to the limited sample size of buildings and occupants included in the investigations and also considering the diversity of climate conditions, cultures and economic

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[7] ECA (European Collaborative Action "Urban Air, Indoor Environment and Human Exposure"). Report no. 30. Framework for health based ventilation guidelines in Europe. European Commission. Joint Research Centre. EUR 27640 EN (2015).

status, caution must be applied when assessing outcomes and the findings should not be generalised.

- The reviewed studies show limited evidence about the impact of energy efficiency strategy and retrofits on IEQ, comfort and health in Europe and beyond. The initial work underway in some EU MS to understand and quantify this impact is promising but still limited. There is a need to investigate further and produce more data to fully understand the implications of highly energy performing buildings on the relationships between energy efficiency measures, IEQ and comfort conditions, ventilation and health in Europe.
- A number of studies have explored occupants' health in energy performing homes. The majority of these studies report that highly energy performing homes are associated with health benefits although there have also been reports of an increase in health problems in some cases for this type of buildings. Recipients on low incomes experience greater improvements in health following energy efficiency interventions, supporting the inclusion of energy efficiency measures in strategies to tackle social issues like fuel poverty and health inequity.
- The studies that were reviewed in this report show that improving buildings' energy performance generally improves the indoor environment and IAQ. However, if energy sufficiency and energy efficiency measures[8] are implemented incorrectly then the health based ventilation conditions may not be fulfilled. If the building itself and its systems and components are not adequately designed, installed and maintained, negative impacts on IAQ and consequently on the occupants' health, comfort and performance might be expected. Several studies have shown that a substantial performance gap is emerging between the design expectations and the measured performance in terms of energy consumption and IAQ in both new and refurbished buildings, reflecting the related lack of proper design and commissioning procedures.
- The reviewed studies show that mechanical ventilation systems in highly energy performing buildings, if properly operated and maintained, lead to an increased removal of pollutants, and thus to an overall improvement of the IAQ and reduction of reported comfort and health related problems. In the case of poor design, operation and/or maintenance, there are a number of concerns about potential failures associated with these systems. The most frequently mentioned concerns are: wrong airflow rates, excess noise, draughts, poor hygiene of the air handling system and low humidity indoors due to elevated outdoor air rates (especially during winter when the outdoor humidity is low). In practice, design, installation and operation of mechanical ventilation systems is not an equally preferred solution across the entire building stock of the EU MS due to climatic, cultural and social characteristics and economic possibilities (e.g. different practices observed among Northern and Southern European countries).
- Demand controlled ventilation can significantly decrease the energy needs for heating and cooling in buildings by fine-tuning ventilation rates to the strict needs. Additionally, when applicable, heat recovery can further reduce those energy needs

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[8] Energy sufficiency, energy efficiency and supply from renewable sources are key drivers in the transition to a sustainable, cost-effective, secure and contributing to the planet as a low-carbon energy system (IEA/UNDP, 2013).

by lowering the energy impact associated with ventilation. In cases where higher ventilation rates are required, modelling simulations show that the use of any or both of these strategies enables meeting health based ventilation needs without necessarily having a negative impact on the energy consumption. However, the benefits from the use of heat recovery may be offset in scenarios of low building airtightness which might be a technical and especially a cultural challenge in countries in which natural ventilation practices prevail and buildings mostly have low airtightness (e.g. Southern European countries).

- With the increasing demand for minimising energy consumption in residential buildings, the relationship between building characteristics and operation, occupant behaviour and the quality of the indoor environment in low-energy and high-energy performing dwellings requires further attention.
- Detailed comparative analysis of building energy consumption data and IEQ data accounting for the interactions between six factors (i.e., climate; building envelope; building services and energy systems; building operation; building maintenance; occupants' activities and behaviour) would provide essential guidance to identifying opportunities for energy saving while safeguarding the occupant's health, comfort and productivity conditions.
- Building occupants' behaviour, equipment performance and quality of the building envelope during the building operation phase are essential drivers for energy consumption and indoor environment quality (IEQ) (i.e., thermal comfort, IAQ, acoustical and lighting conditions) in buildings. Therefore, the building's design, commissioning and operational phases including maintenance aspects should be given the same level of prominence in the evolution of existing building codes and related standards and regulations in the EU and Member States.
- Studies showed that the use of low-emitting construction and decoration products, furniture and consumer products would help limit the episodic indoor air pollution events observed in buildings and therefore reduce the exposure to pollutants linked to human activities. This is an important consideration that could significantly reduce some of the health based ventilation demand in highly energy performing buildings. In some European countries building materials labelling has been systematically used over many years (e.g. in Finland since 1995 with over 3000 labelled construction materials) which has incentivised the process of producing and progressively using low-emitting materials throughout EU.
- Many of the reviewed studies focussed primarily on measuring CO_2 concentration (as a 'proxy' of IAQ) and general comfort parameters (i.e. relative humidity and temperature). Only a few studies have also included measurements of IAQ parameters known to be associated to health risks (i.e. physical, chemical and biological pollutants including those with WHO guidelines).

The aforementioned conclusions suggest that, in order to guarantee that highly energy performing buildings in the EU will also be healthy for their occupants, a number of IEQ related issues should be considered as part of the review of the Energy Performance Building Directive (EPBD). These should be implemented in the EU MS within a holistic approach to building's sustainability, which should consider optimising buildings' energy performance and associated costs without compromising the implementation and enforcement of the health based ventilation concept in EU buildings.

It should be noted that the EPBD already provides a “whole building” approach by promoting the improvement of the energy performance (i.e. energy efficiency and renewable energy use) of buildings, taking into account both outdoor climatic and indoor climate requirements and cost-effectiveness. In addition, according to the EPBD the energy performance of buildings should be calculated on the basis of a methodology that includes, in addition to thermal characteristics, other factors that play an increasingly important role including indoor air-quality.

To this purpose the following specific policy/legislative/regulatory and research/technical/implementation oriented recommendations are made.

Policy/ legislative/ regulatory oriented recommendations

- Careful policy design, combined with adequate regulation and enforcement regimes, can strike a balance between good IEQ and the rational use of energy in buildings, while also avoiding the potential pitfalls of introducing energy efficiency measures into the complex system that buildings represent.

  In such context and perspective, the existing overarching EU policy framework to buildings’ energy performance needs to be supported by a comprehensive, integrated and flexibly implemented approach of consistent standards and regulations at both EU and national levels.
- The conception, integration and efficient implementation of building related policies, regulations and standards in EU should be performed considering the multi-dimensional concept of buildings’ sustainability which encompasses socioeconomic, energy, health, safety of constructions and sustainability aspects.
- The best approach for designing effective building codes from an energy point of view and for successfully reducing building related energy consumption patterns in the long term is by properly combining energy sufficiency, energy efficiency and supply from renewable energy sources.
- IEQ and health aspects should be considered to a greater extent in European building codes than in the current practice. While indoor climate is mentioned in the EPBD, the importance of indoor air quality, thermal comfort, daylight and noise has to be strengthened. Inclusion of requirements for indoor air quality in the national regulations of all European countries should be reinforced, including specific pollutants to be measured and their associated limit levels in line with the WHO guidelines (or EU or other international standards).
- A co-ordinated and coherent implementation of IEQ related requirements in building related policies in EU is still missing as from a regulatory point of view this remains under the competencies and responsibilities of the EU MS with no binding requirements at EU level. This creates obstacles for the implementation of an integrated performance-based approach for buildings’ related energy and IEQ issues in Europe.

  Consequently, within the holistic view and approach of buildings’ sustainability, it is recommended that the definition of the boundaries and implementation of the requirements of each of the building related sectorial policies, regulations and standards should be co-ordinated and optimised via an overarching and balanced approach at EU level which fully considers energy, environmental, health and resource efficiency aspects as well as national characteristics and constraints (economic, social, cultural and climatic).

Such an approach would help avoid 'conflicting overlaps' in terms of environmental and health impacts and costs as well as the potential fragmentation of the European market by ensuring consistency in criteria and coherence of objectives among the various EU policy and regulatory instruments addressing the energy, environmental and IEQ related performances of products and buildings. It would also help industries and SMEs producing construction products complying with the requirements of several different regulations and policies for the same product(s) by reduced burdensome conditions and more affordable costs.

- The most feasible, technically robust, flexible and cost-optimised solutions satisfying minimum mandatory requirements across the issues of safety, health, energy, and sustainability in the EU MS should be pursued and investigated. This could be enabled by developing a "head standard" and setting mandatory minimum performance requirements for each of the seven Essential Requirements of the Construction Products Regulation (CPR)[9] which should be aligned with: (a) the principles and requirements of the overarching European standard on energy performance of buildings (EN 15603)[10]; (b) with the recently launched (by the European Commission) development of a common EU framework for building environmental performance indicators to drive improvements in both new and refurbished buildings.

  Provided that this could be successfully undertaken and implemented it would then pave the way for the development of a *common set of building's sustainability metrics* and *labelling system* at EU level to use for rating buildings for their performance jointly in terms of energy performance, IEQ, structural and fire safety and sustainability.

  The common building's sustainability metrics and labelling system could be accompanied by a *building passport* to follow a building for its entire life cycle. Building passports, on a voluntary basis, include tailor-made information to building owners on long term investments and financing mechanisms in renovation measures over the lifetime of the building and could also include relevant information about ventilation systems characteristics and IEQ related aspects, and traceability of expected cost and benefits in terms of improved energy savings, IEQ, comfort and health conditions. Building passports should not replace the role of existing EPC schemes across MS.

  The progression towards meeting the targets for Nearly Zero-Energy Buildings (NZEB) by 2020 has involved a stepwise tightening of minimum energy performance requirements in EU MS. To avoid this resulting in deterioration of IEQ and health conditions in the European building stock, measures related to energy sufficiency/efficiency and renewable energy supply should be implemented in an

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[9] EC. (2011). Construction Products Regulation. Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC; 2011.

[10] prEN 15603:2013 standard. Energy performance of buildings - Overarching standard EPBD and related technical reports (TR 2013, prEN 15603, May 2013).

integrated fashion together with appropriate strategies dealing with indoor and outdoor pollution sources, ventilation, thermal comfort, acoustics and lighting.

In this respect, it is recommended that the health based guidelines framework that was developed within the EU funded HEALTHVENT project be consulted and properly implemented in building related policies, regulations and standards at both EU and EU MS levels.

According to the HEALTHVENT health based ventilation guidelines concept, to ensure that energy efficiency measures are properly combined with health based ventilation it is necessary to consider controlling the outdoor and indoor pollution sources, reduce the emissions from the materials used, and take account of the type and level of occupancy and the activities taking place in buildings during their lifetime (including changes in use) when health based ventilation rates are defined and calculated.

All relevant key stakeholders (EU MS, policy makers, building designers and constructors to building managers and users) should ensure that in the entire building stock (existing buildings and new highly energy performing buildings) the buildings' design, maintenance and operation respect the HEALTHVENT framework's concept and other relevant EU policies, standards and WHO guidelines.

In this context, there is a need to provide *common health based ventilation guidance in Europe* that will reinforce the definition and setting of ventilation requirements and metrics based on health criteria to be applied after all possible control strategies of indoor and outdoor pollution sources have been exploited.

Harmonisation of *ventilation metrics* and *calculation practices* among countries is also recommended. The guidance should focus on methods covering aspects such as controlled ventilation (accounting for occupancy, activities, and outdoor and indoor air quality), improved ventilation efficiency, localised ventilation, air cleaning, adjusting the ventilation rates according to the indoor and outdoor air pollution conditions, use of clean HVAC components, balancing the ventilation based on the actual use of the building, selection of low pressure drop equipment to reduce electricity use, heat recovery, etc. The guidelines should also cover the quality of the air handling system as described in the HEALTHVENT WP 5 report. These issues are partly dealt with in the standard prEN 16798-3 [11] but not exhaustively.

- EU and national policies are recommended to promote sustainable buildings that can adapt to variations in outdoor and indoor pollution sources as well as featuring passive/active control for moisture/dampness and avoidance of particles. The IEQ issues (IAQ, thermal comfort, noise, daylight, etc.) should be given more emphasis in the labelling criteria of sustainable buildings.
- The Construction Products Regulation (CPR) targets the performance of construction products and not buildings. Further work is required to provide guidance at EU level on how to effectively implement the requirement under paragraph 6 of Annex I (2) of the Commission Delegated Regulation (EU) No.

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[11] EN 16798-3:2014. Energy performance of buildings Part 3: Ventilation for non-residential buildings - Performance requirements for ventilation and room-conditioning systems. European Committee for Standardization (CEN), 2014.

244/2012[12] (associated to the EPBD implementation) concerning the compatibility of the energy efficiency related measures and requirements with the basic requirements for construction works as listed in Annex I to CPR.

- With the increasing energy performance (EP) requirements towards NZEBs, the compliance checking of the energy performance of new buildings becomes increasingly important and should be seen within the holistic concept and implementation perspective of building's sustainability (i.e. exploring the potential of energy efficiency in relation to the climate conditions and performance requirements, optimising over energy performance and costs without compromising the enforcement of the health based ventilation concept).
- There is a need to provide guidance at EU level on proper design, construction, installation, maintenance and inspections of ventilation systems. Inspection and compliance checks of ventilation systems are recommended to become part of energy and IAQ auditing under the EPBD.

  The review of the EPBD and of national ventilation regulations could consider including requirements for IEQ inspection and audit in the operational phase of buildings to monitor and ensure that the IEQ related requirements are met. This can be based on the outcomes and experience gained in the development of the harmonisation framework for indoor air monitoring by the European Commission (DG SANCO and DG JRC) in the context of the PILOT INDOOR AIR MONIT[13] project (2010-2012).
- Clear provisions and criteria in the buildings' energy performance calculation methodology (including cost-optimality calculations) should be introduced so that the simulated scenarios for various buildings' typologies and climates and the subsequent energy efficiency measures shall guarantee good indoor air quality and comfort conditions for the buildings' occupants at the design and operation phases of new and renovated buildings during their entire lifespan while also optimising energy savings and costs. This will help achieving better acceptance of energy related measures and labelling systems among the public and all other relevant stakeholders.
- It is also recommended to model and systematically assess the total buildings' performance at the EU level (i.e. energy performance, adequate ventilation, IEQ, occupants' health, comfort and performance) and the associated socio-economic implications under various scenarios representing different climatic zones, building typologies and operation practices and regimes of various building systems (e.g. HVAC systems), quality of building products (e.g. low-emitting construction materials) and occupants behaviour in EU MS. In addition to considering and including the construction and operational cost of buildings, this would also allow provision of consolidated figures to compare the economic benefits from improved health, comfort and performance against those from energy-efficiency saving measures alone.

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[12] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:081:0018:0036:en:PDF

[13] PILOT INDOOR AIR MONIT project's final report (2013). Administrative arrangement between DG SANCO and DG JRC (contract no. SI 2582843) (Kephalopoulos et al., 2013).

In this context and perspective, the EPBD Comparative Methodology Framework could incorporate *key performance indicators* for *energy use, health, comfort and IEQ* in buildings. These would need to be integrated with a proper cost indicator for estimating the co-benefits of energy-efficiency measures, health and comfort in indoor environments in the context of cost-optimal calculations at the macroeconomic level especially in the case of renovation measures related to the existing EU building stock (i.e. gains from energy savings, less health care costs, less absenteeism rates from work, increased productivity).

- It is recommended to create an information resource at EU level with best practice examples in the EU MS, contextualised in their respective climate, cultural tradition and values, technological and economic contexts, to show buildings' compliance and certification performance rates jointly for energy use and performance levels, IEQ and associated costs within a perspective of economy of scale.
- It is recommended to establish rewarding mechanisms for best performing EU MS as to the degree of compliance and performance of their building stock jointly in terms of energy performance (in its broader sense), IAQ, thermal comfort and ventilation. This would create incentives for better performance at the EU MS level, which could extend also to building owners (e.g. reduction of their annual taxes, exception of the EPC issuing fee, etc.) when they manage to improve the energy performance and IEQ of their buildings either through major renovation and/or applying the EPC recommendations. Conversely, in case of non-compliance penalties should be activated.

Research/Technical/implementation oriented recommendations

- A key issue is to progressively start building up a consolidated picture of energy-efficiency measures, IAQ, thermal comfort, ventilation and health via co-ordinated, systematic and centralised large scale longitudinal studies with data collection and reporting mechanism at the EU level.

  Population representative measurement campaigns should be planned and carried out on indoor exposures for various typologies of buildings to fill the gaps in knowledge about the effects of ventilation and indoor air exposures on health. These measurement campaigns should include a much better characterisation of exposures and ventilation than has been previously done. They should also investigate in detail the role and impact of indoor and outdoor sources on chronic diseases. Particular emphasis should be given to vulnerable groups such as children, elderly and patients with allergies and chronic respiratory diseases.

  In such context and perspective, it is recommended to set up monitoring campaigns to collect information and data in EU MS on the performances of ventilation systems and the IEQ levels achieved in relation to indoor and outdoor pollution sources, energy sufficiency and energy efficiency measures in the EU building stock. The information and data should be streamlined and made available via the European Commission's relevant data portals and knowledge systems (i.e. the DG JRC's European Energy Efficiency Platform Portal and the DG ENV's IPCHEM[14] module 4 on 'Products and Indoor Air Monitoring' data).

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[14] https://ipchem.jrc.ec.europa.eu/RDSIdiscovery/ipchem/index.html

- IEQ and comfort parameters should become an integral part of all building related performance standards and regularly monitored after building completion and during building use (i.e. at both building commissioning and occupation phases).

- Ventilation energy demand should be calculated and expressed in a transparent way according to health based ventilation requirements and should be clearly separated from the total heating and cooling demand.

- Ventilation systems should undergo mandatory and periodic inspection by qualified professionals and be subject to periodic maintenance as per the related technical prescriptions. When seen and implemented according to the health based ventilation concept and approach, this will increase the chances of achieving the designed ventilation rates and encourage maintenance of proper health based ventilation conditions in relation to real pollution sources load and changes occurring during building occupancy for the entire building life cycle.

- Harmonized criteria for construction products' labelling are recommended to be used as a part of the design specification of ventilation requirements and be aligned with the principles and requirements of the Construction Products Regulation. This can take advantage of the two harmonisation frameworks for indoor products labelling and health based evaluation of product emissions which were developed by the European Commission (DG GROW and DG JRC) (ECA Reports n°27[15], 2012 and n°29[16], 2013 respectively).

- It is recommended to develop a common, flexible and comparative framework methodology in the EU that includes guidelines for compliance checks related to energy efficiency, energy sufficiency and IEQ. Such compliance checks should ensure proper levels of IAQ and adaptive comfort behaviour to avoid health risks of the buildings' occupants while optimising actual energy expenditures. The methodology should be developed and implemented via a comprehensive and holistic approach which properly considers pollution source based strategies and lighting, HVAC and ventilation practices (such as those proposed by the HEALTHVENT and AIRLESS[17] projects), in line with the criteria and parameters specified in relevant CEN standards, and considering integration of various IAQ monitoring typologies (e.g. such as those elaborated by the EC's PILOT INDOOR AIR MONIT[18] and AIRLOG[19] projects). Moreover, it is recommended to preferably cover all stages of compliance checking and quality control during the building's design and construction phases and, ultimately, prior to and also during the building's occupation and operation.

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[15] ECA (European Collaborative Action "Urban Air, Indoor Environment and Human Exposure"). Report no. 27. Harmonisation Framework for Indoor Products Labelling Systems in EU. European Commission. Joint Research Centre. EUR 25276 EN (2012).

[16] ECA (European Collaborative Action "Urban Air, Indoor Environment and Human Exposure"). Report no. 29. Harmonisation framework for health based evaluation of indoor emissions from construction products in the European Union using the EU-LCI concept. European Commission. Joint Research Centre. EUR 26168 EN (2013).

[17] AIRLESS: A European project to optimise Indoor Air Quality and Energy consumption of HVAC-systems (Bluyssen et al., 2003).

[18] PILOT INDOOR AIR MONIT project's final report (2013). Administrative arrangement between DG SANCO and DG JRC (contract no. SI 2582843) (Kephalopoulos et al., 2013).

[19] HEALTHY INDOOR LIFE - Integrated platform for intelligent indoor air quality audit management (http://www.iaq-airlog.eu/)

- One possible option for consideration would be extending the EPC to include ventilation systems characteristics (where applicable) and IEQ related aspects related to occupants. Such an extended EPC could also include recommendations (as foreseen by the EPBD) about the overall building's improvement potential. For issuing such an extended certificate and enable monitoring of the implementation of the recommendations via proper auditing procedures at an affordable cost, it is important to find a trade-off between standard recommendations generally applicable to the entire building stock and tailor-made recommendations that may be more effective for specific buildings.

In conclusion, to guarantee that highly energy performing buildings in the EU will also be healthy for their occupants, a number of IEQ related issues should be considered as part of the review of the EPBD within a holistic view of building's sustainability that should consider optimising buildings' energy performance and associated costs without compromising the implementation and enforcement of the health based ventilation concept in EU buildings.

Disclaimer: The conclusions and recommendations of this report do not imply any policy position of the European Commission.

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1. Introduction

The 2030 policy framework for climate and energy proposed by the European Commission on 22 January 2014 aims to make the European Union's economy and energy systems more competitive, secure and sustainable.

A European strategy for the sustainable competitiveness of the construction sector has been defined for the next decade (EC, 2012). As part of the short term measures related to this strategy, particular emphasis should be put on encouraging the activity of building renovation and infrastructure maintenance, which represents an important share of total construction employment and production.

Energy sufficiency, energy efficiency and supply from renewable sources are key drivers in the transition to a sustainable, cost-effective and secure future and contribute to the planet becoming a low-carbon energy system (IEA/UNDP, 2013). The Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy (EC, 2015) considers highly energy performing buildings as one of the pillars to deliver the Energy Union.

EU MS have been developing policies and measures to generally reduce the actual energy use of their buildings but a number of challenges need to be addressed in terms of the impact of high-energy performance on the quality of the indoor climate of buildings without compromising the comfort, health and productivity of their occupants. EU MS are called to properly implement and enforce the Energy Performance of Buildings Directive. In some EU MS, a low level of ambition and a failure to enforce building energy codes hamper energy efficiency in buildings and thus fail to stimulate the construction sector.

Traditional building energy codes focus mainly on improving the efficiency of the energy used to achieve the same level of energy services (e.g. heating, cooling and lighting). However, a new wave of building energy codes provides a comprehensive and effective path to low-energy and to low-carbon buildings by requiring: (a) energy sufficiency measures, designed to reduce the needs for energy services needed to operate and maintain the required comfort level in a building; (b) energy efficiency measures, which reduce the amount of energy needed to fulfil the energy services; and (c) the use of renewable energy sources, notably resources generated at the building premises or as part of the energy supplied to the building.

A great deal of intervention is still to be done concerning the energy sufficiency of buildings to integrate provisions that ensure maintenance of healthy indoor air quality and the required level of adaptive thermal comfort while reducing the requirement for use of equipment providing energy services. Due regard must be given to potential developments of the architecture and construction technologies appropriate for the differences between current climatic zones.

In this context and perspective, Article 4 of the EPBD requires MS to set and ensure minimum energy performance requirements which "shall take account of general indoor climate conditions, in order to avoid possible negative effects such as inadequate ventilation, as well as local climatic and surrounding environment conditions and the designated function and the age of the building". There is a need to investigate the extent to which the provisions in EPBD related to indoor climate and indoor air quality conditions have been implemented by the EU MS and whether these could guarantee avoiding deterioration of the air quality in highly energy performing buildings in the EU (due to inadequate air pollution source control, pollution entrapment and inadequate ventilation) and consequently avoid possible negative effects to the buildings' occupants thermal comfort, health and overall performance conditions. In this context, local climatic conditions and cultural specificities should not be overlooked and recognition of new concepts such as the adaptive comfort should be fully considered in parallel and properly implemented.

The European Commission's Joint Research Centre (JRC) provides scientific/technical assistance to the Directorate General for Energy (DG ENER) for the implementation of the Directive 2012/27/EU on Energy Efficiency (EED) and of the EPBD. JRC also contributes to the development of concepts for the strengthening of the overall EU legislative framework for energy saving (Administrative Arrangement TSSEED between DG ENER and JRC no. *ENER/C3/2014-554/SI2.693948*, (2015-2017)).

In the context of this administrative arrangement, the effective implementation of the EED and EPBD by EU MS and the monitoring of the MSs' progress towards achieving the 2020 energy reduction targets will be assessed and evaluated.

Among the various tasks to perform, JRC was charged with carrying out a review of existing literature on studies, reports and investigations which have been examining the status of indoor air quality in highly energy performing buildings in EU and also assessing the implementation status of relevant criteria in EPBD by the EU MS. The ultimate objective is to summarise the main consequences and provide recommendations on how to establish healthy and highly energy performing buildings in EU (Task 13.3 'Relation between high-energy performance and indoor air quality').

More specifically, the objectives of Task 13.3 are:

1. Assessing the implementation status of the EPBD by EU MS in terms of ventilation, indoor air quality and energy efficiency criteria and requirements, and investigating what is needed to guarantee that renovated or new highly energy performing buildings will not create health risks for their occupants.
2. Performing literature review and data collection on the impact of highly energy performing buildings (residential and non-residential) to indoor air quality via assessing indoor air quality in relation to ventilation and energy performance before and after improvement of energy performance of buildings.
3. Formulating policy and technical related recommendations to enable the effective implementation of healthy and highly energy performing buildings in the EU especially in connection to the on-going evaluation of the EPBD and its review due for completion in 2016.

This report intends to provide the European Commission with the knowledge base and recommendations about potential options to consider in order achieving healthy indoor air in highly energy performing buildings in the short term and, in longer term, safe, healthy, highly energy performing and sustainable buildings in EU within the context of a global implementation strategy. Such a strategy should account for actual differences in the building stock arising from cultural aspects, regional climatic conditions and economic conditions. It should include actions to ensure the efficient implementation and compliance-checking and enforcement of building codes and take advantage of technological developments along a path which includes requirements on control of indoor and outdoor pollution sources, energy sufficiency measures, energy efficiency measures and the use of renewable energy sources.

In chapter 2 is emphasised the importance of various facts related to buildings and related policies (i.e. socioeconomic facts, energy facts, health facts, sustainability and safety of constructions facts). All should be accounted for when talking about and dealing within a holistic concept of building's sustainability. Then this concept is defined and developed along its dimensions (energy sufficiency and efficiency, safety of constructions, comfort and healthy conditions of the buildings' occupants and sustainability of constructions within a Life Cycle Assessment (LCA) context). This represents an upfront definition and implementation of building's performance which then is framed, narrowed and focused to the target dimensions to be dealt with (i.e. energy efficiency and health) according to the specific objectives of Task 13.3. In this context the relationship and interplay among IAQ pollution sources, ventilation strategies and energy sufficiency/efficiency are demonstrated as essentially interlinked/interacting issues to conceptualise and implement in practice in relation to major EU related instruments (e.g. EPBD, international and national standards and regulations) as supported by projects and initiatives at EU and MS level and other relevant stakeholders.

Chapter 3 includes an analysis about how and to what extent the provisions and requirements of the EPBD were implemented in EU MS and whether the manner and degree of implementation can ensure reduced health risks of the building's occupants in highly energy performing buildings in EU.

This analysis will formulate a comparative picture of the implementation status of EPBD across the EU MS including: commonalities and differences in focal (to the purposes of Task 13.3) parameters (e.g. those related to energy sufficiency and efficiency, indoor climate and air quality, thermal comfort and ventilation) and performance indicators (and their metrics) considered; degree of alignment of national standards and regulations to those at EU and/or international level; reporting about EU MS experiences concerning the effect of the interdependency of the focal parameters with other parameters pertaining to the holistic concept of buildings' sustainability (e.g. air conditioning and cooling, heat recovery systems, daylight, acoustics, etc.). It will consider both the design and operational phases of a highly energy performing building bearing in mind that at both phases the health risks to the buildings' occupants should be minimised.

Last but not least, some best practice examples of national building related regulations giving prominence to IAQ issues in relation to energy performance of buildings are reported.

Chapter 4 provides a review about the lessons learned from the EU MS experiences during the implementation of the EPBD and some best practice examples of EU MS that have set up compliance and quality control for both energy efficiency and IAQ and pollution requirements in existing and new highly energy performing buildings. Information on IAQ related indicators (i.e. pollutants source control, ventilation, indoor air priority pollutants) used in Green Building Certifications world-wide is also provided to show the progressive consideration of these indicators in existing Green Building Certifications systems as well as their percentage of coverage in each of the systems compared to the non-chemical based indicators (i.e. environmental indicators). Then these indicators are compared against the most commonly considered priority pollutants in the WHO ambient air quality and IAQ guidelines. This analysis will boost a potential future extension of energy-performance audits by including monitoring of a minimum common set of indoor air chemical pollutants.

In Chapter 5 data collection initiatives and projects (e.g. national monitoring surveys) in EU MS and other relevant stakeholders on IAQ, comfort and health in highly energy performing buildings are reported and analysed to demonstrate the potential impact (improvement or deterioration) of comfort and health conditions in new or renovated highly energy performing buildings in the EU. Moreover, evidence from measured data is further supported by modelling simulations demonstrating that IAQ and energy are linked in many ways and, if proper measures are applied, energy performance improvements may result in IAQ and thermal comfort improvements, i.e. energy and IAQ problems can be solved concurrently.

Chapter 6 describes succinctly the existing Comparative Methodology Framework for Energy Performance in the EU MS and makes recommendations about its potential extension to include IAQ aspects and related minimum requirements in order to achieve healthy and highly energy performing buildings in EU while boosting its flexible and efficient implementation in the EU MS.

Chapter 7 refers to a number of building related policies, standards and regulations which are cross-cutting aspects of energy efficiency, safety, health and sustainability (e.g. EPBD, EED, Construction Products Regulation, Energy Labelling Directive, Eco-design Directive, EC Ambient Air Quality Directive, WHO guidelines, CEN standards, etc.). This aims to emphasise and reinforce the need for their synergistic implementation and alignment in order to enable the effective take-up and implementation of the holistic concept of buildings' sustainability in EU.

The 'Conclusions and Recommendations' chapter includes the conclusions drawn from the review performed in the context of Task 13.3 and the recommendations made to help the promoting and enabling of the effective implementation of healthy and energy-efficient buildings in EU.

The conclusions on the implementation status in the EU MS of the EPBD relating to ventilation, indoor air quality and energy efficiency criteria and requirements are reported separately from those drawn from the review of data monitoring surveys and modelling simulations at EU and national levels on IEQ, energy efficiency and comfort and health conditions in highly energy performing buildings. This will help the reader to distinguish these two distinct categories of conclusions drawn.

Following the same spirit and logic, the recommendations made in this report are reported separately according to their affinity and content (i.e. whether they are more policy/legislative/regulatory oriented or research/technical/implementation oriented).

2. A holistic concept of buildings' sustainability for Europe

SETTING UP THE SCENE

The construction sector is among the main pillars of the European Union, as evidenced by the following facts:

- **Socio-Economic facts:**
    - The construction sector plays an important role in the European economy. It generates almost 10% of GDP and provides 20 million jobs, mainly in micro and small enterprises [20]. Poor indoor air and environmental quality can create significant economic loss due to elevated absence rates, reduced premiums, retention of lessors and lower market value, as well as due to reduced worker performance[21,22]. For the United States of America potential annual savings of $20-60 billion are estimated from direct improvements in workers performance and productivity that unrelated to health[23].
    - Renovating the European Union's building stock for improving its energy performance will save €80 to €153 billion of investment costs into the bloc's power system by 2050[24]. The savings, estimated after deep renovation, are at grid and production level. They are in addition to the lower costs delivered from reduced consumption caused by the efficiency measures.
    - The typical breakdown of operating costs of a business building is 1% for energy, 9% rental costs and 90% staff costs (in terms of salaries and benefits)[25]. The full costs of installation and running of the building's systems can be offset by 10% increase in productivity[26].

- **Energy facts:**
    - Buildings contribute to about 30% of global annual greenhouse gas emissions (GHG) in the atmosphere[27] and accounts for 40% of total energy consumption in Europe[28]. Buildings have the potential to reach a 90 % reduction in their greenhouse gas emissions by 2050[29].

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[20] COM (2012) 433. Strategy for the sustainable competitiveness of the construction sector and its enterprises

[21] Fisk, W. and Seppänen, O. Providing Better Indoor Environmental Quality Brings Economic Benefits. Proceedings of Clima 2007 Well Being Indoors, June 10-14, 2007, Helsinki.

[22] Fisk, W.J., D. Black and G. Brunner (2011), "Benefits and costs of improved IEQ in U.S. offices", *Indoor Air*, Vol. 21, No. 5, Blackwell, Oxford, pp. 357–367.

[23] The business case for green buildings, (2013); http://www.worldgbc.org/activities/business-case/

[24] http://www.euractiv.com/sections/energy/renovation-could-save-billions-grid-investment-say-researchers-318517

[25] Health, Wellbeing & Productivity in Offices – The next chapter for green building (World Green Building Council);http://www.worldgbc.org/files/6314/1152/0821/WorldGBC__Health_Wellbeing__productivity_Full_Report.pdf

[26] Wargorcki P. (ed.), Seppänen O. (ed.), Andersson J., Boerstra A., Clements-Croome D., Fitzner K., Hanssen SO. (2006). REHVA Guidebook: Indoor Climate and Productivity in Offices.

[27] Buildings and Climate Change – Summary for Decision Makers. UNEP Sustainable Buildings & Climate Initiative (2009); http://www.unep.org/sbci/pdfs/SBCI-BCCSummary.pdf

[28] DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 May 2010 on the energy performance of buildings (recast).

http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010L0031&from=EN

[29] The European construction sector. A global partner (2014). European Commission;

http://ec.europa.eu/growth/tools-databases/newsroom/cf/itemdetail.cfm?item_id=7426&lang=en&title=The-European-construction-sector%3A-a-global-partner

- **Health facts:**

  - According to the World Health Organisation (WHO), in 2012, 99000 deaths in European low and middle income countries and 17000 in European high income countries were attributable to household (indoor) air pollution[30]. 2.2 million estimated DALYs (Disability Adjusted Life Years) are lost each year in Europe due to exposures to pollutants in buildings[33]. This would amount to € 99 billion per year if a common DALY value of € 45,000 per life year is applied[21]. The estimated socio-economic costs of indoor air pollution in France amounts approximately to around 20 billion EUR annually[31] (based on an estimated cost of a DALY of € 115, 000 [32]) due to premature deaths, medical costs, lost productivity, and related impacts. For analogy, road traffic in EU costs 3.6 million DALYs annually.
  - More than 300,000 DALYs per year are the estimated health gains in EU-26 which are attributed to the efficient implementation of EPBD which integrates indoor air quality criteria and auditing[33].
  - It is estimated that at least 110 million citizens in EU live in buildings with elevated concentrations of hazardous and toxic pollutants due to operating ventilation which does not meet current regulation limits[34].
  - Substantial health benefits from improved indoor climate from improved energy performance renovation of buildings are estimated in the order of €33 - 73 billion annually in 2020 in the low-energy performance scenario and to €64 - 140 billion in the high-energy performance scenario through improved life quality, less public health spending and fewer missed days of work. These figures are the same order of magnitude as those estimated when considering the energy savings alone [35].
  - Good indoor environmental quality of buildings (i.e. thermal, illumination (lighting), ventilation and acoustic conditions) can improve overall work and learning performance and reduce absenteeism[36]. There is a comprehensive body of research evidence demonstrating that the design of office buildings impacts the health, wellbeing and productivity of its occupants. Productivity improvements of 8-11% are not uncommon as a result of better air quality in office buildings[37]. Directly related to health, potential annual savings and productivity gains in the United States are estimated in the order of $6-14 billion from reduced respiratory disease, $1-4 billion from reduced allergies and asthma and $10-30 billion from

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[30] World Health Organization, "Burden of disease from Household Air Pollution for 2012". Available at: http://www.who.int/phe/health_topics/outdoorair/databases/HAP_BoD_results_March2014.pdf?ua=1

[31] Kopp, P., G. Boulanger, T. Bayeux, C. Mandin, S. Kirchner, B. Vergriette, and V. Pernelet-Joly. 2014. Socio-economic costs due to indoor air pollution: a tentative estimation for France. Proc. Indoor Air 2014, Hong Kong. HP0955.

[32] Quinet, E., Baumstark, L., Bonnet, J., Croq, A., Ducos, G., Meunier, D., Rigard-Cerison, A,. Roquigny, Q, (2013) L'évaluation socioéconomique des investissements publics. Commissariat Général à la Stratégie et à la Prospective: 352 p.

[33] Jantunen M., de Oliveira Fernandes E., Carrer P., Kephalopoulos S., 2011. Promoting actions for healthy indoor air (IAIAQ). European Commission Directorate General for Health and Consumers. Luxembourg. ISBN 978-92-79-20419-7.

[34] Asikainen A., Hänninen O., Brelih N., Leal V., Allard F., Wargocki P., 2012b. Proportion of residences in European countries with ventilation rates below the limit defined by regulations. Ventilation 2012 Conference, Paris, 17-19 September, 2012.

[35] Multiple benefits of investing in energy efficient renovation of buildings. Copenhagen Economics, 5 October 2012.

[36] Seppänen, O., Fisk, W.J., Lei, Q.H. Ventilation and performance in office work, *Indoor Air 16* (2006) 28-36.

[37] World Green Building Council. Health, Wellbeing & Productivity in Offices - The next chapter for green building (2014). http://www.worldgbc.org/files/6314/1152/0821/WorldGBC__Health_Wellbeing__productivity_Full_Report.pdf

reduced health, well-being and productivity of workers due to buildings' insufficiency from environmental, comfort and health standpoints[38].

- Improved indoor air quality has significant impact on increased property value and longer tenant occupancy and lease renewals. It also significantly reduces the sick absence among employees: lost employee costs about 1.5 to 2 annual salaries[39].
- The average pay-back time of investments to improve indoor air quality of buildings are less than 2 years and frequently less than 1 year due to benefits from improved performance and reduced sick-leave [26, 40, 41].

➢ **Sustainability facts:**

- 50% of all materials extracted from the earth's crust are transformed into construction materials and products[42].
- Construction and use of buildings in the EU gives rise to about 35% of total generated waste material[43].

➢ **Safety of constructions facts:**

- 80% of European citizens live and work in cities, many of which are located in hazard prone areas (e.g. fires, earthquakes, floods) and with potential high air pollution entering into buildings through openings, cracks and airing and ventilation systems.

The holistic concept of Building's Sustainability

The facts and associated figures reported in the above box clearly establishes the importance of the multifaceted dimension of buildings in terms of socioeconomic, energy, health, safety of constructions and sustainability aspects which all should be accounted for in the conception and implementation of building related policies. This strengthens the importance of shifting from the largely prevailing paradigm of considering the aforementioned dimensions in an almost uncorrelated fashion to a new paradigm that deals with a holistic view of building's sustainability and concisely implementing all relevant aspects in an integrated and efficient manner.

This multi-dimensional based approach of buildings' performance concerns an upfront definition and implementation of building's sustainability which at EU level was for first time presented, discussed and widely supported in the context of the European Forum for Science and Industry round table on scientific support to energy performance of

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[38] The business case for green buildings, (2013), http://www.worldgbc.org/activities/business-case/

[39] Sivunen, M., Kosonen, R., Kajander, J-K. (2014). Good indoor environment and energy efficiency increase monetary value of buildings. REHVA Journal 06/2014.

[40] Wargocki, P. and Djukanovic, R. (2005). Simulations of the potential revenue from investment in improved indoor air quality in an office building. ASHRAE Transactions, Vol. 111 (pt. 2), pp. 699-711.

[41] Dorgan, C.B., Dorgan, C.E., Kanarek, M.S., and Willman, A.J. 1998. Health and productivity benefits of improved indoor air quality. ASHRAE Transactions, Vol. 104, Part 1A, pp. 658-666.

[42] European Working Group for Sustainable Construction, Sustainable construction final report, (2001)

[43] BIO Intelligence Service (2011). Management of construction and demolition waste in the EU. European Commission (DG ENV) service framework contract (ENV.G.4/FRA/2008/0112). Final report Task 2. http://ec.europa.eu/environment/waste/pdf/2011_CDW_Report.pdf

buildings which was organised by the European Commission's Joint Research Centre (JRC) on 29 November 2013 in Brussels[44] and is graphically represented in Figure 1.1.

The first dimension of buildings' performance, in the holistic view of building's sustainability, considers and implements in practice the buildings' structural safety, stability and durability. The Eurocodes [45] are a series of well-consolidated and implemented European Technical Standards for structural design of buildings, civil engineering works and construction products. Their creation and implementation started in the 1970s, with the decision of the Commission of the European Communities to implement an action programme to progressively eliminate technical obstacles to trade in the field of construction. In this respect, EN Eurocodes contribute to the establishment and functioning of an Internal Market for construction products and services. They also ensure a uniform level of safety in construction in Europe.

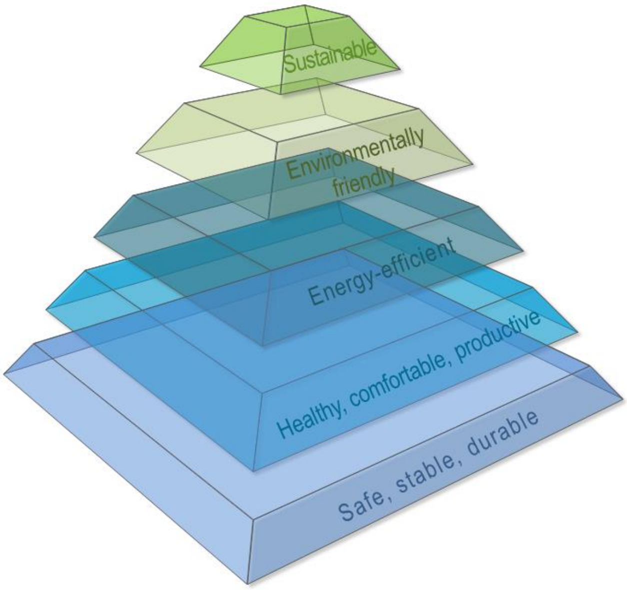

Figure 1.1 The holistic concept of a "Sustainable Building" (©Porto University)

Concerning the energy dimension of the holistic concept of buildings' sustainability, building codes have been instrumental in reducing the overall energy consumption of buildings in the last two decades in EU, with the entity of energy savings depending on the stringency of energy requirements and the approach used in the design of building energy codes (i.e. prescriptive or performance-based approach). A prescriptive approach sets minimum energy performance requirements for each component of the building (e.g. windows, walls, lighting and ventilation systems, heating and cooling equipment) while the performance-based approach requires an integrated design and requirements set for the building's overall energy consumption (either minimum energy performance requirements based on the building's size or with standard energy performance requirements for all building sizes).

In Europe, in the context of the EPBD implementation, requirements have gradually started shifting from prescriptive to a performance-based approach, which is regarded as

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[44] https://ec.europa.eu/jrc/sites/default/files/events/20131129-eeb-roundtable/20131129-eeb-roundtable-report.pdf

[45] http://eurocodes.jrc.ec.europa.eu

a major change in the building code trends. In practice, the single-element approach is preferred in major renovation projects while the performance-based in new constructions, although a mixed approach has been adopted for a number of EU MS.

Concerning the evolution of building energy codes, in addition to the aforementioned paradigm shift that is related to provisions targeting energy performance improvements, progressively, there is also a new wave of codes which are also addressing in parallel energy performance and energy supply from renewable sources aspects (e.g. The French building energy code[46]) and including corresponding requirements.

The purpose of *energy sufficiency* measures is to reduce the amount of energy needed to operate and maintain a building. Energy sufficiency measures include requirements for the orientation of the building vis-a-vis the sun, its form, volume, placement with respect to surrounding buildings, and general daylight and sunshine requirements based on bio-climatic design principles.

By integrating *renewable energy sources* into buildings, they can be transformed from energy consumers to power generators capable of supplying energy to the grid. Renewable energy sources could also be supplied from surrounding buildings or through district heating and cooling systems.

Combing energy sufficiency, energy efficiency and supply from renewable energy sources represents the best approach for designing effective building codes from an energy point of view and are important drivers for successfully reducing building related energy consumption patterns on the long term.

Considering the buildings' long lifespans, when in addition to the energy dimension of the holistic concept of building's sustainability the economic dimension is added, increasing stringency of energy performance requirements in the building codes (i.e. reaching the nearly zero-energy target by 2020) is an unavoidable consequence to secure long-term economic and energy security solutions. The EPBD already requires EU MS to set minimum energy performance requirements for buildings with a view to achieving cost-optimal levels, namely the energy performance level which leads to the lowest cost during the estimated economic lifecycle.

Concerning the buildings' energy consumption two other important aspects to consider are the building related embodied energy (i.e. the energy required to produce building materials and to construct buildings) and usage patterns (i.e. how buildings are used by their occupants). This represents the 'sustainability' dimension of the holistic concept of buildings' sustainability. In fact, life-cycle analysis of energy consumption of existing low-energy buildings shows that the share of embodied energy from the overall energy consumption of a low-energy building over its lifetime is much higher than that of an inefficient building (IEA/UNDP, 2013). In the perspective of the entire buildings' lifespan, these two aspects represent important drivers of the buildings' energy consumption, which should be fully considered together with any other energy efficient, energy-sufficient and renewable energy supply measures if a successful energy reduction policy is sought. The main focus for sustainable buildings is the reduction of the environmental impact of resources such as materials, water and embodied energy, throughout the life cycle of buildings, from the extraction of building materials to demolition and the recycling of materials.

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[46] www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000022959397&dateTexte=&categorieLien=id

As the energy consumption in buildings shall be primarily meant to guarantee conditions of well-being, comfort and health for their occupants, integrating this dimension into the holistic concept of buildings' sustainability, creates the need for the challenging endeavour of reconciling energy savings ambitions with the obligation to guarantee the conditions of growing-up, living, working and learning in healthy indoor environments. This latter represents a right for every person that has been already clearly stated by WHO back in 2000 (WHO, 2000).

It should be noted, that health, comfort and productivity of buildings' occupants as affected by indoor environmental quality are issues that have been included in the context of the dramatic broadening of the definition of sustainability especially during the last decade. This enlarged scope and definition of sustainability, in addition to the sustainable design that takes care of resource conservation, energy, water and material resources, also includes assurances for mobility and access, as affected by land use and transportation, for health and productivity, as affected by indoor environmental quality, and for the protection of regional strengths in the context of pursuing a more globally shared quality of life (Loftness et al., 2006; EC, 2014). The occupants of sustainable buildings enjoy better health and well-being and productivity gains that translate into cost savings (see also relevant figures in the Box 'Setting up the scene' above).

The holistic concept of building's sustainability, in terms of implementation, represents a difficult task for building related policy makers, designers, managers, owners and occupants reflecting the complexity of a number of interlinked and interacting factors related to: the building itself and its systems (i.e. building's design, volume, orientation, openings, heating, ventilation and air conditions systems, lighting conditions, products and materials used); the long term maintenance and operational conditions of the building and its systems; the building's location in terms of climatic zone and surrounding land use and environmental conditions (e.g. ambient air pollution levels) and, last but not least, the behaviour of the building's occupants who can significantly intervene and influence both the building's energy consumption related patterns and indoor environmental conditions (depending on their socioeconomic status and cultural driven habits and other factors).

The implementation of the holistic concept of building's sustainability should be seen in close relation with the life cycle performance of buildings (Famuyibo et al., 2013). It is important to fully account for and measure the energy use and emissions of a building throughout its life cycle which encompasses all the supply chain processes required for its production, operation and removal so as to assist policy makers and designers in understanding the true national, regional and global impacts of buildings on the environment. This will lead to more effective decision making.

This complexity translates into interplay among indoor and outdoor air quality pollution sources, ventilation, thermal comfort, acoustic and lighting strategies and energy sufficiency/efficiency/renewable energy supply measures which should be all conceptualised and implemented in an integrated fashion in relation to major related policy objectives and instruments at EU MS levels (e.g. energy, environmentally- and chemically-based labelling schemes for buildings, buildings components, equipment and appliances; international and national standards, regulations and building energy codes; land-use policies; sustainable policies; economic development, environmental protection and energy security objectives and boundaries and technology advancements).

Concerns about buildings’ energy consumption and savings and indoor air pollution as significant factor in human health were developed in parallel during the last decades, with the challenging issue being how to meet the increased energy saving requirements (especially those linked to highly energy performing and nearly zero-energy buildings) while maintaining indoor environments that are conducive to occupant comfort, health and performance.

Following the initial requirements of the EPBD, the action plans of EU MS for progression to NZEB by 2020 include minimum energy performance requirements with a stepwise tightening for both residential and non-residential buildings. Buildings are progressively built in EU with much higher airtightness requirements in order to prevent uncontrolled ventilation heat losses. In order to satisfy energy performance and ventilation requirements, mechanical ventilation systems are increasingly used. Moving from buildings with infiltration rate by air leakage to airtight buildings mainly mechanically ventilated is a large step change in terms of culture. There are increasing concerns regarding the impact of airtight constructions on health, comfort and productivity of the occupants such as the possible degradation of the indoor environment quality (IEQ), the effectiveness of the mechanical ventilation system in maintaining healthy indoor environment and the potential impact of occupants behaviour on the operation of the buildings’ equipment (ventilation, heating, cooling, etc.). To date few data on indoor air quality (IAQ) and health in highly energy performing buildings are available. Before reviewing and analysing the extent that the provisions and requirements of the EPBD were implemented in EU MS and whether the way and degree of their implementation can ensure reduced health risks of the building’s occupants in highly energy performing buildings in EU, we will first outline how the challenging interplay among ventilation, IAQ, pollution sources, health and rational use of energy should be handled based on state-of-art scientific and technical developments and knowledge.

In this perspective, in the remaining part of this chapter, the aforementioned holistic concept and approach of buildings’ sustainability will be framed and focused on those of the target dimensions according to the specific objectives of Task 13.3 (i.e. energy efficiency, IAQ, pollution sources, ventilation and health) to pave the ground for the subsequent analysis included in the remaining parts of the report. However, the overall holistic concept should be always kept in mind.

Ventilation, IAQ, pollution sources, health and rational use of energy: a challenging interplay

The impact of IAQ and ventilation on occupant health, comfort and productivity has been widely and extensively documented in the scientific literature over the last two decades. The EU funded EnVIE (de Oliveira-Fernandes et al., 2009) and IAIAQ (Jantunen et al., 2011) projects estimated the annual burden of disease (BoD) related to inadequate IAQ is ca. 2 million disability adjusted life years (DALYs) in EU-27 (except Malta) and also attributed major health effects to pollutants and their sources (excluding smoking). Reducing this BoD is a high priority for the EU health policies. More than half of this BoD is attributable to indoor exposure to pollutants originating outdoors, in particular those related to traffic and the combustion of solid fuels. The rest is attributable to pollutants originating from indoor sources including building materials, furnishing, building equipment, combustion and consumer products, as well as people and their activities and any processes occurring indoors that can become a source of indoor pollutants (i.e. can cause the release of pollutants).

In order to effectively tackle and manage the challenging interplay among ventilation, IAQ, pollution sources, health and rational use of energy within the holistic approach of building's sustainability, we have first to understand that this interplay is the result of the interaction of three main systems (Figure 1.2).

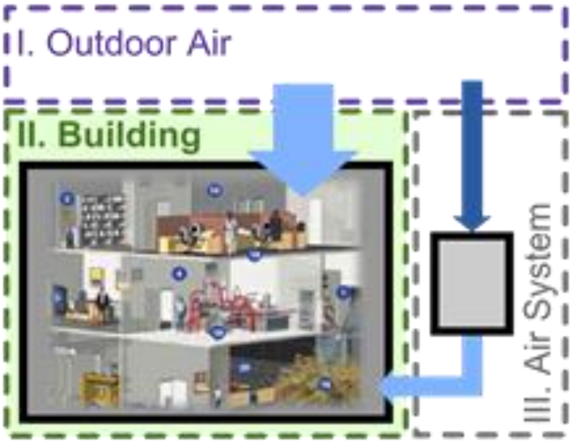

Figure 1.2 Relationship between the systems affecting indoor air quality in buildings

(I) the *ambient air*, that is the outdoor air around the building which is introduced into the building either by natural or mechanical ventilation; (II) *the building as an air system*, i.e., an enclosure by itself or a cluster of several interconnected enclosures with their own indoor air dynamics and relationships with the outdoor air; and (III) the *ventilation system*, understood here as an extra technical solution (device or equipment) to control, whenever needed, the quantity and the quality of the outdoor air brought into the building. The first two systems are responsible for the source control of IAQ in a given building or a space while the ventilation system must be seen as an auxiliary system to provide service under specific requirements and therefore shall be treated separately from the building system.

(I) Ambient Air

The quality of ambient or outdoor air has been studied for more than 50 years involving significant efforts in research and development (R&D) dedicated to the management of air pollutants emissions and the modelling of their transport and dispersion at local, regional and global scales. Despite the fact that the science behind the quality of the ambient air has progressed considerably, the progress made has been less successful from practical and societal perspectives. Specifically, this concerns the ambient air in cities where over 70% of the population in the OECD countries and 50% of the world population lives. For a considerable number of cities a satisfactory level of urban air quality has not been attained and the requirements set by the air quality guidelines defined by the World Health Organization (WHO) (2006; 2010) are not met.

The management of the ambient air, be it urban or rural, has been suffering from the contradictions of the current societal model, where the vectors of economic growth supported by the industrial and the intensive agriculture production and its expressions in terms of urbanization and heavy traffic in cities seem to overwhelm the value of clean ambient/outdoor air for minimising exposures and therefore the associated health risks.

Given that the outdoor air may constantly be brought totally or partially inside the buildings by natural or mechanical forces/means, its quality is of paramount importance for controlling indoor air quality. The importance of the relationship between outdoor (ambient) and indoor air and their associated health impacts is reported in the scientific literature (Jantunen et al., 2011). Recent policy developments at European Commission (EC) level in co-operation with WHO, envisage building an environmental strategy in the European Union (EU) to tackle jointly the quality of outdoor and indoor air in the context of the European Union's 7th Environment Action Programme to 2020[47].

(II) The building as an air system

Buildings are overall shelters providing a barrier to the influences and impacts of the outdoor environment. They can also be organised spaces themselves with various indoor partitions, each one considered as a particular air system itself according to the differences in their uses and the corresponding specific requirements regarding the indoor air.

The indoor air quality of buildings is influenced through three different pathways:

a) *Location* - i.e. the building's location in relation to the quality of the ambient/outdoor air surrounding the building that may or may not respect the WHO air quality guidelines or the requirements set by the EU Ambient Air Quality Directive (such as in an urban area, city or metropolitan area in the proximity of a heavy traffic road or of an industrial area, or in a rural area far from the sources of pollution);

b) *Construction* - through the choice of construction materials and components (ordinary or labelled/certified materials and components with low pollutants emission), and by taking care of the quality of the construction itself (e.g. by avoiding discontinuities of the insulation or emergence of future cracks that may cause high levels of condensation or dampness and produce harmful biological contaminants (moulds and fungi) indoors; by reducing the penetration of ambient air pollutants through infiltration, etc.);

c) *Adequacy to the uses* - in terms of the ability of the building or specific indoor spaces of the building to adequately perform on the basis of a given human occupation density (expressed in meters square per person) and to control for the indoor activities (such as tobacco smoking, using printers/copying machines, etc.).

Buildings' construction is certainly one of the technologies closely linked to the location, geography, climate and available resources in terms of construction materials and components. The objective of the European Commission's Construction Products Regulation (CPR) (EC, 2011) is to facilitate cross-border trade of construction products and overcome trade barriers in EU and also to provide a common technical language in harmonised European product performance standards, for use by both manufacturers and regulators. CPR identifies seven essential requirements, which should be met by the construction products and one of them is on hygiene, health and environment. This recognises the importance that, besides mechanical resistance and stability that are basic requirements for any construction, also criteria such as health and energy

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[47] DECISION No 1386/2013/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 20 November 2013 on a General Union Environment Action Programme to 2020 'Living well, within the limits of our planet;

http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32013D1386&from=EN

performance should be equally considered. This is in line with the aforementioned holistic concept of building's sustainability.

Indoor air pollution in buildings tends to be higher than outdoors because of emissions from indoor sources, which increase the pollution load indoors that is due to the incoming outdoor air. The indoor sources can be of various origins including among others: construction and cladding materials, activities indoors such as cleaning, cooking, printing, combustion, smoking and human bio-effluents. They can also be the products of chemical reactions and transformations occurring indoors.

To assure healthy conditions for its occupants, all of the building's materials and equipment must be checked for their impact as emission sources of pollutants as early as the building's design stage. Nowadays, labelling systems have been put in place to evaluate the emissions from construction products in an increasing number of EU MS. Efforts have been undertaken to establish an EU harmonisation framework for existing systems which have been developed for the emission testing and the health based evaluation of indoor air relevant substances (ECA 27, 2012; ECA 29, 2013). These efforts are consistent with the well identified and widely recognised need to put emphasis on source control as the prime strategy to efficiently manage indoor air quality in buildings, as recommended by the EU funded EnVIE project (de Oliveira Fernandes et al., 2009).

(III) Ventilation System

The ventilation system is meant here as the mechanical ventilation which is intended to clean the incoming air whenever it is deemed necessary, and supply the air at rates according to health based requirements or other pre-established criteria. In terms of buildings' source control strategy, the contribution of mechanical ventilation therefore resides in ensuring that the incoming air is clean and in the necessary flow pattern to assure the acceptable level of exposure indoors. Concerning the operational performance and the quality of the ventilation system, it should be seen as an intrinsic service to be guaranteed by the system provider.

The ventilation system must be seen as a parallel option to the natural ventilation practice where outdoor air is transported indoors either automatically or manually by operable openings in the building envelope. As currently advocated, mechanical ventilation is increasingly becoming the preferred solution for cities with ambient air not respecting the WHO air quality guidelines or the pollution levels required by the EU Ambient Air Quality Directive. However, any approach that may support and promote the generalised use of mechanical ventilation in buildings must be first thoroughly scrutinised and evaluated before adoption. In this perspective, the conditions of the air pollution in a particular location of a city and time period, and the level and type of occupation of the building must be taken into account. New policies and trends on the urban transportation and mobility structures and practices in cities that might lead to a progressively cleaner urban air should be also considered in parallel as an essential strategy towards a sustainable, clean and healthy built environment for every European city.

In 2003, in Europe a number of strategies for achieving a good balance between good indoor air quality and the rational use of energy in buildings have been elaborated and published by the European Commission's Joint Research Centre (ECA report no. 23 (2003): *"Ventilation, Good Indoor Air Quality and Rational Use of Energy"*). In addition, information was also provided about available guidelines and assessment techniques on energy and IAQ as well as about significant trends for the future with implications for IAQ and the use of energy in buildings.

Later on and following the recommendations of the EnVIE project, the EU funded HEALTHVENT project (ECA no. 30, 2015) developed a framework for health based ventilation guidelines for public and residential buildings in Europe and assessed the consequences of implementing these guidelines, bearing in mind future trends in the built environment, including energy performance and environmental sustainability issues. The developed framework for health based ventilation guidelines requires the reduction of the health risks associated with air pollution exposure in buildings through proper source and exposure control. This control requires regulations to be developed and implemented in a co-ordinated framework where priority is given to source control measures and in second place to ventilation.

The guidelines are based on two fundamental prerequisites: (1) The air indoors must fulfil the requirements of the air quality (AQ) guidelines defined by the World Health Organization (WHO, 2010; WHO; 2005); and (2) The priority is given to source control as the strategy for controlling indoor air quality and reducing the health risks associated with indoor exposures. Ventilation is only used as a supplementary strategy to control exposure in support to the source control strategy.

In the context of HEALTHVENT a "*health based ventilation rate*" was defined for a specific building when exposures to pollutants meet the WHO air quality guideline values through a two-level sequential approach integrating at first source control measures and then defining appropriate ventilation rates for a specific building. Such defined health based ventilation requirements only refer to requirements pertaining to health effects related to air pollution and must not be confused with, and should be clearly separated from, ventilation requirements for heating and cooling related to comfort.

A decision diagram was developed as a procedural vademecum for determining the actual health based ventilation rate for a specific building (Figure 1.3). This diagram provides the possibility of exploring and implementing appropriate source control strategies during the building's design and operational stages (at the levels of the outdoor air, the ventilation system and the building itself and its components) and supplementing them by properly quantified health based ventilation rates to guarantee that the IAQ meets the WHO air quality guidelines.

The health based ventilation rate cannot be lower than the "base ventilation rate" set at 4 L/s per person taking into account the results of a review of epidemiological literature on ventilation and health and modelling of exposure to human bio-effluents using CO_2 and moisture levels as decision criteria. The base ventilation rate is intended to dilute and remove pollutants generated by occupants through the metabolic process (bio-effluents). This is a requirement that must always be satisfied. The base ventilation rate has been defined to create a true benchmark and reference point for defining ventilation rates based on health criteria advising that rates lower than the base ventilation rate are not allowed.

When the object of intervention is an existing building and/or if specific conditions have to be taken into consideration (e.g. the way the building is operated, the pollution load of the outdoor air, etc.), then appropriate ventilation levels have to be used to overcome the additional pollution load which may require higher health based ventilation rates than the 'base rate'.

The decision diagram starts with a first checkpoint to verify whether ambient air fulfils the WHO air quality guidelines. If this is not the case, measures to clean the air incoming to the building must then be taken, to avoid exposure to hazardous levels of air pollutants.

If the levels of the WHO ambient air quality guidelines are met then there is no need for special air cleaning systems and the air can be directly delivered into the building either by natural or mechanical ventilation if the latter proves to be better under the actual specific conditions. The adoption of measures that are disproportionate to the quality of ambient air should then be avoided.

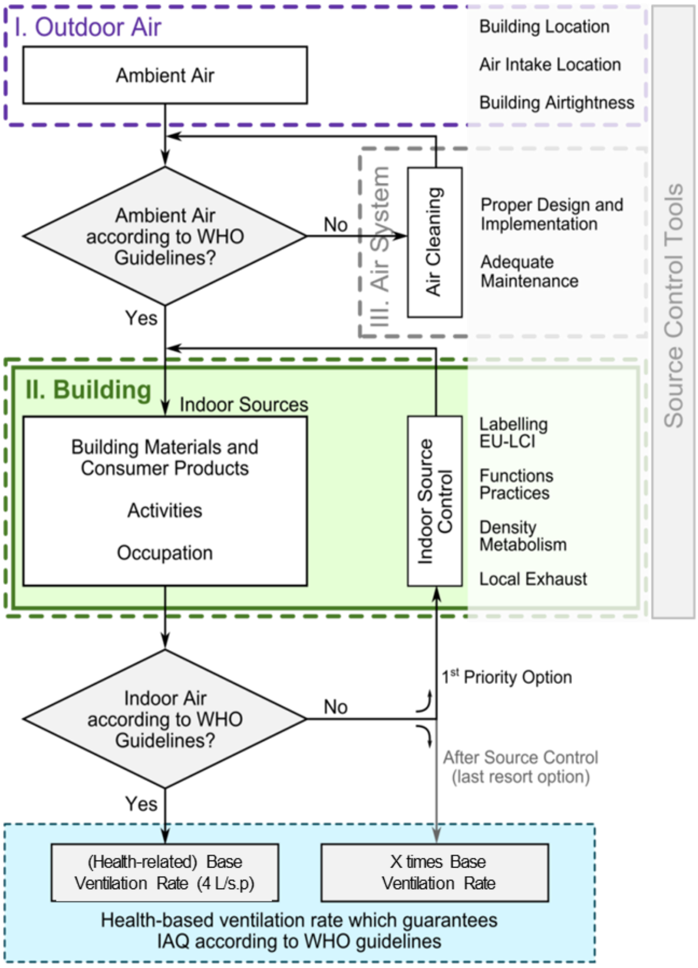

Figure 1.3 Decision diagram for deriving the adequate health based ventilation rate for a specific building (source: ECA report no. 30, 2015)

As outdoor air quality is particularly difficult to tackle at city level, the definition of the "health based ventilation rate" should be instrumental in stimulating the high priority that must be given to properly tackling air quality at city level. Consideration should still be given to aspects such as the building location (not near highways and roads with heavy traffic, industrial emissions, etc.), air intake location (e.g. adequately distanced from chimneys or air outlets), and even to building airtightness; they all affect the quality of the air indoors through the quality of the incoming outdoor air.

The next decision point is meeting the WHO air quality guidelines at the building level. The building must also be appropriately designed and built considering its specific functions and operation practices indoors (for example, the different demands and requirements for office and residential buildings). The source control and entrapment of pollution at source must be exercised at this stage.

As the design phase represents an exercise of anticipating the future building's operation and use, new ways of monitoring the building's design process must be explored (AIRLOG project). It will allow for the characterisation of the materials regarding their strength as emitting sources. This process should be informed by existing national labelling schemes for construction materials and products that are available in different EU countries as well as the recently developed harmonisation framework at EU level (ECA 27, 2012; ECA 29, 2013).

Occupant density (expressed in terms of square meters per person/ occupant) and typical metabolic rate of people in indoor environments (which is a function of the type of activity and of indoor environmental parameters - temperature and humidity) impose different requirements on the building and ventilation needs which must also be taken into account. The local removal of humidity and pollution from sources, such as showers or natural gas stoves, will limit the dispersion of pollutants into the indoor air and improve the indoor air quality without a need for an unnecessary increase of ventilation levels to meet health requirements.

Once these actions are undertaken, the health based ventilation can be determined as the ventilation rate needed to ensure that WHO air quality guidelines are met. If due respect is given to the source control requirements in the building, then it can be expected that the health based ventilation rate will not be higher than the "base ventilation rate", i.e. the rate needed to remove human bio-effluents when WHO air quality guidelines are met. Otherwise, the health based ventilation rate should be a multiple of the base ventilation rate. When the object of intervention is an existing building and/or if specific conditions have to be taken into consideration (e.g. the way the building is operated, the pollution load of the outdoor air, etc.), then appropriate ventilation levels have be used to overcome the additional pollution load which may also require health based ventilation rates that are higher than the 'base rate'.

If the use of a dedicated air system is justified, then care must also be taken for its proper design and implementation as well as its adequate operation and maintenance, and compliance with the health based ventilation requirements during its entire lifetime. This is the only way to avoid health risks due to improper use or inadequate maintenance of an air system in buildings; a situation that has been frequently encountered in the past and still continues to be often a problem nowadays.

Ventilation energy demand should be calculated and expressed in a transparent way according to health based ventilation requirements and should be clearly separated from the total heating and cooling demand.

Potential health implications of implementing the health based ventilation guidelines were estimated by assessing the expected health gains on the basis of current levels of exposure to air pollution indoors.

Source control of pollutants originating outdoors and indoors combined with the base ventilation rate was shown in simulations to halve the burden of disease caused by exposure to air pollutants indoors.

Potential energy implications of implementing the health based ventilation guidelines were estimated by simulating energy needs for heating and cooling in relation to the ventilation needs. A comprehensive set of scenarios was examined with different parameters representing different performance of the ventilation systems and climatic conditions (ECA no. 30, 2015; see also chapter 5 of the present report). Energy based simulations showed that substantial health benefits could be achieved if the health based ventilation guidelines would be integrated into energy efficient designs.

Proper implementation of the health based ventilation rate requires considering and implementing the aforementioned holistic approach of building's sustainability ensuring that both indoor and ambient air quality is adequately addressed in all relevant EU and MS policies and regulations.

3. Implementation status of EPBD in EU MS in relation to requirements and criteria for energy performance, IAQ, thermal comfort and ventilation

The EPBD provides a “whole building” approach towards efficient energy use in the buildings sector. The Directive aims at promoting cost-effective improvement of the energy performance of both residential and commercial buildings in the EU, by laying down minimum energy performance requirements.

The EPBD aims to promote the energy performance of buildings and building units, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness. Its provisions cover energy needs for the heating of premises, the production of hot water, cooling, ventilation and lighting for new and existing buildings (residential and non-residential).

The EPBD provisions concern:

1. The common methodological framework for calculating the integrated energy performance of buildings and building units (Art. 3)
2. Minimum requirements for the energy performance of new buildings and new building units (Arts. 4-6)
3. Minimum requirements for the energy performance of:
   i) Existing buildings, building units and building elements that are subject to major renovation (Art.7)
   ii) Building elements that form part of the building envelope and that have a significant impact on the energy performance of the building envelope when they are retrofitted or replaced (Art.7)
   iii) Technical building systems whenever they are installed, replaced or upgraded (Art.8)
4. National plans for increasing the number of nearly zero-energy buildings, including provision of appropriate financing instruments (Arts.9-10)
5. Mandatory energy performance certificates of buildings or building units (Arts.11-13)
6. Regular inspection of heating and air-conditioning systems in buildings (Arts.14-16) and
7. Independent control systems for energy performance certificates and inspection reports (Arts.17-18).

The requirements laid down in EPBD are minimum requirements and shall not prevent any MS from maintaining or introducing more stringent measures.

In order to further stimulate an increased number of highly energy performing buildings, the EPBD introduced the definition of nearly zero-energy buildings (NZEB) as buildings with very high energy performance where the very low amount of energy required should be extensively covered by renewable sources produced on-site or nearby. By 31 December 2020, all new buildings shall be NZEBs, while new buildings occupied and owned by public authorities shall comply with the same criteria by 31 December 2018.

This led to a progressive tightening of the energy performance requirements in the national building codes including those to ensure minimum levels of ventilation within buildings. Article 4 of the EPBD[48] clearly states that: *minimum energy performance requirements shall take account of general indoor climate conditions, in order to avoid possible negative effects such as inadequate ventilation (as well as local conditions and the designated function and the age of the building)*. Following the holistic concept and approach of building's sustainability that was introduced in chapter 2 of this report, ventilation is one of the main drivers for securing a good IAQ in buildings and therefore any minimum requirements should be set and implemented bearing in mind the health based ventilation concept and framework.

As far as the IAQ issue is concerned, recital 9 of the EPBD states that: *The energy performance of buildings should be calculated on the basis of a methodology, which may be differentiated at national and regional level. That includes, in addition to thermal characteristics, other factors that play an increasingly important role such as heating and air-conditioning installations, application of energy from renewable sources, passive heating and cooling elements, shading, indoor air quality, adequate natural light and design of the building. The methodology for calculating energy performance should be based not only on the season in which heating is required, but should cover the annual energy performance of a building. That methodology should take into account existing European standards.*

In terms of implementation, the aforementioned represented straightforwardly a challenging task that the EU MS were called upon to face in designing, revising and implementing their building codes in order to ensure meeting the minimum energy performance requirements and, in parallel, guaranteeing proper IAQ, thermal comfort, ventilation and daylight conditions for the buildings' occupants. It is essential that all of these aspects are given the same level of attention and importance and mutually and consistently reinforced in any plans and actions of EU MS concerning the renovation of the existing building stock in Europe.

In the rest of chapter 3 of the present report we will analyse recent evidence about how and to what extent the provisions and requirements of the EPBD were implemented in EU MS and whether the way and degree of implementation can ensure low health and comfort related risks of the buildings' occupants in highly energy performing buildings in EU over the entire buildings' lifespan. In line with the objectives of DG ENER – DG JRC Task 13.3 our focus will primarily be on requirements and criteria related to energy efficiency, indoor climate and quality, thermal comfort and ventilation.

To this purpose we will distil and make synthesis of the outcome of three relevant major EU based review activities/projects carried-out and published in the period 2012-2015 (i.e. HEALTHVENT WP5, Seppänen et al., 2012; CA EPBD 2015 and BPIE 2015) in order to capture the status of implementation after the EPBD came into force. This will allow understanding: (a) the steps taken by the EU MS for improving their related policy and regulatory frameworks to ensure that minimum energy performance requirements will be met and that NZEBs targets will be reached without compromising the conditions of health, comfort and performance of the buildings' occupants; (b) identify best practices examples of implementation in EU MS; and (c) summarising the evidence base for

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[48] Article 4 of the EPBD, 2010/31/EU. Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:EN:PDF

potential future improvements of policy instruments, regulations and standards at both EU and national levels.

HEALTHVENT WP 5 report (2012)

In the context of the HEALTHVENT project work package 5 (WP 5), existing requirements on ventilation and IAQ defined in building codes and European standards were reviewed and critically evaluated by Brelih and Seppänen (Brelih and Seppänen, 2011). Focus was put on ventilation rates, pollutants, acoustics, temperature and relative air movement in dwellings, offices, schools and kindergartens. Data in national legislation and building codes up to the end of 2011 were collected from 16 European countries (i.e. Bulgaria, Czech Republic, Finland, France, Germany, Greece, Hungary, Italy, Lithuania, Netherlands, Norway, Poland, Portugal, Romania, Slovenia and United Kingdom) via questionnaires that were sent to the HEALTHVENT project partners and trusted experts in EU MS. These countries represent a good geographic coverage of EU regions with different building practices, cultural peculiarities and climatic and economic conditions.

The main outcome of this review and comparisons made is summarised below.

Requirements and compliance for ventilation rates and other indoor air quality, comfort and health related parameters in European countries

Ventilation rates requirements

The requirements on ventilation rates were provided in different units (i.e. as flow rate 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) and consequently were not directly comparable. In the context of the HEALTHVENT WP 5 review test cases representing real-life design situations (i.e., two different dwellings, a kitchen, a toilet, a bathroom, a school classroom, a kindergarten playroom, and an office) were developed which allowed comparing the data on the basis of common metrics.

The comparison results showed that ventilation rates values provided in the national regulations were inconsistent with those specified in European Standards and very heterogeneous among the European countries (see Tables 2.1 and 2.2; Figures 2.1 to 2.8).

Table 2.1 Ventilation rates in European dwellings (source: HEALTHVENT WP 5 report).

Country and reference	Minimum air change rate for residencies	Exhaust air flow rates from kitchen	Exhaust air flow rates from toilette	Exhaust air flow rates from bathroom
Bulgaria Regulation 15/28.07.2005 except for min. air change rates for residences	*CEN/CR 1752: 4 l/s per person (lowest group C)*	5 ach continuous; 50 l/s for non-continuous operation	10 l/s continuous; 25 l/s for non-continuous operation	10 l/s continuous; 25 l/s non-continuous operation

Country and reference	**Minimum air change rate for residencies**	**Exhaust air flow rates from kitchen**	**Exhaust air flow rates from toilette**	**Exhaust air flow rates from bathroom**
Czech Republic *CSN EN 15665*	*0.3 ach*	*100 m^3/h*	*25 m^3/h*	*50 m^3/h*
Finland Building Regulations Part D2, Indoor climate and ventilation, 2010	0.5 ach and 6 l/s/p	8 l/s and boosted 25 l/s; 20 l/s continuous	10 l/s if can be boosted; 15 l/s continuous	7 l/s if can be boosted; 10 l/s continuous
France arrêté du 24 mars 1982, modified 28 October 1983	r = room 1 r: 35 m^3/h 2 r: 60 m^3/h 3 r: 75 m^3/h 4 r: 90 m^3/h 5 r: 105 m^3/h 6 r: 120 m^3/h 7+ r: 135 m^3/h	r = room 1 r: 20 m^3/h 2 r: 30 m^3/h 3+ r: 45 m^3/h	r = room 1-3 r: 15 m^3/h 4+ r: 30 m^3/h	r = room 1-2 r: 15 m^3/h 3+ r: 30 m^3/h
Germany DIN 1946-6:2008	*nominal ventilation:* *55 m^3/h (30 m^2)* *...* *215 m^3/h (210 m^2)*	*45 m^3/h (200 boosted)*	*25 m^3/h*	*45 m^3/h*
Greece (TOTEE)2425/86, 20701-4/2010, 20701-1/2010 (KENAK) Legislation 3661	0.7 ach	min 34 m^3/h recommended: 50 - 80 m^3/h	min 34 m^3/h recommended: 50 - 80 m^3/h	min 34 m^3/h recommended: 50 - 80 m^3/h
Hungary EN 15251, cat. II	0.42 $l/s/m^2$	20 l/s	10 l/s	15 l/s
Italy Dlgs 192/2005, Dlgs 311/2006, DPR 59/2009, DM 18/12/1975	0.3 ach	6 ach	6 ach	6 ach
Lithuania STR 2.09.02:2005; HN 42:2004	0.5 h^{-1}	72 m^3/h	36 m^3/h	54 m^3/h
Netherlands The Dutch Building Code 2012	total living area: 0.9 $l/s/m^2$ each room: 0.7 $l/s/m^2$	21 l/s	7 l/s	14 l/s
Norway Building Regulations Act, Technical regulations (TEK2010)	1.2 $m^3/h/m^2$ when occupied 0.7 $m^3/h/m^2$ when not used	36 m^3/h or 108 m^3/h forced	36 m^3/h	54 m^3/h or 108 m^3/h forced
Poland PN-83/B-03430Az3:2000	total airflow is sum of local extract airflows	all units: m^3/h WITH WINDOW: gas/coal stove: 70 el. stove: 30 (max 3 pers. in apartment) el. stove: 50 (>3 pers. in apartment) NO WINDOW: el. stove: 50 gas stove: 70	50 m^3/h	50 m^3/h

Country and reference	**Minimum air change rate for residencies**	**Exhaust air flow rates from kitchen**	**Exhaust air flow rates from toilette**	**Exhaust air flow rates from bathroom**
Portugal	*0.6 ach - practice*	*>5 ach - practice; for short periods*	*>5 ach - practice; for short periods*	*>5 ach - practice; for short periods*
Romania I5 normative	the procedure and requirements are the same as in France			
Slovenia ULRS 42/2002 SIST DIN 1946-6	0.5 h^{-1}	60 m^3/h	30 m^3/h	60 m^3/h
United Kingdom UK Building Regulations Part F (2010)	0.3 l/s/m^2 or 13 l/s - 1 bedroom 17 l/s - 2 bedrooms 21 l/s - 3 bedrooms whichever bigger	13 l/s	6 l/s	8 l/s

A wide range of ventilation rates and also of local exhaust rates was observed which suggests that a common background for the definition of ventilation metrics and criteria among the European countries does not exist. Almost all reviewed countries have requirements on a minimum ventilation rate for a dwelling as whole and separate requirements for local exhaust rates from spaces like kitchen, toilet, and bathroom. Moreover, many countries lack a clear link between local exhaust rates and a ventilation rate of the whole dwelling. That makes design and balancing of the system difficult in practice.

Table 2.2 Ventilation rates in European schools, kindergartens and offices (source: HEALTHVENT WP 5 report).

Country and reference	**Minimum ventilation rate for class rooms**	**Minimum ventilation rate for play rooms in kindergarten**	**Minimum ventilation rate in office rooms**
Bulgaria Regulation 15/28.07.2005 CEN/CR 1752:1988	2.4 l/s/m^2	2.8 l/s/m^2	0.8 l/s/m^2
Czech Republic Regulation 410/2005 Decree 361/2007	20 - 30 m^3/h/p	20 - 30 m^3/h/p	50 m^3/h/p
Finland Building Regulations Part D2, Indoor climate and ventilation, 2010	6 l/s/p + 3 l/s/m^2	6 l/s/p + 2.5 l/s/m^2	1.5 l/s/m^2
France arrêté du 24 mars 1982, modified 28 October 1983	15 - 18 m^3/h/p	15 - 18 m^3/h/p	25 m^3/h/p
Germany EN 15251, cat. II	_4.9 l/s/m^2_ _* for non-low polluting building materials_	_5.8 l/s/m^2_ _* for non-low polluting building materials_	_2.1 l/s/m^2_ _* for non-low polluting building materials_
Greece (TOTEE)2425/86	min 17 m^3/h/p recommended: 26 - 34 m3/h/p	min 17 m^3/h/p recommended: 26 - 34 m3/h/p	min 25.5 m^3/h/p recommended: 25.5 - 42.5 m3/h/p

Country and reference	**Minimum ventilation rate for class rooms**	**Minimum ventilation rate for play rooms in kindergarten**	**Minimum ventilation rate in office rooms**
Hungary EN 15251, cat. II	4.9 l/s/m^2 *for non-low polluting building materials	5.8 l/s/m^2 *for non-low polluting building materials	2.1 l/s/m^2 *for non-low polluting building materials
Italy DM 18/12/1975; UNI 10339	3.5 ach	*0.004 m^3/s/p*	*0.011 m^3/s/p*
Lithuania STR 2.09.02:2005; HN 42:2004	6 l/s/p	-	10 l/s/p
Netherlands The Dutch Building Code 2012	4.8 l/s/m^2 1 student occupies 1.3 – 3.3 m^2	2.4 l/s/m^2 (1 child 1.3-3.3 m^2); 6.4 l/s/m^2 (1 child <1.3 m^2)	1.0 l/s/m^2 (6 – 8 m^2 per p)
Norway Building Regulations Act, Technical regulations (TEK2010); Arbeidstilsynet 444	26 m^3/h/p; 2.5 m^3/h/m^2 used; 0.7 m^3/h/m^2 not used	7 l/s; 10 l/s high activity	26 m^3/h/p; 2.5 m^3/h/m^2 if used; 0.7 m^3/h/m^2 if not used; 3.6 m^3/h/m^2 for undocumented materials
Poland PN-83/B-03430Az3:2000	ventilation: 20 m^3/h AC: 30 m^3/h	ventilation: 20 m^3/h AC: 30 m^3/h	ventilation: 20 m^3/h AC: 30 m^3/h
Portugal Decree law 79/2006	30 m^3/h/p	30 m^3/h/p	30 m^3/h/p or 5 m^3/h/m^2; whichever is higher
Romania I5 normative	15 m^3/h/p	15 m^3/h/p	shared: 17 m^3/h/p individual: 25 m^3/h/p
Slovenia ULRS 42/2002	person: 7.2 m^3/h/m^2 building: 2.9 m^3/h/m^3	person: 8.7 m^3/h/m^2 building: 2.9 m^3/h/m^3	person: 1.5 m^3/h/m^2 building: 2.9 m^3/h/m^2
United Kingdom UK Building Regulations Part F (2010)	10 l/s/p	10 l/s/p	10 l/s/p

The collected ventilation rates were given in several different units, which did not allow making direct comparison. To make them comparable two cases of dwellings with the following attributes (Table 2.3) were used in HEALTHVENT WP 5:

Table 2.3 Properties of two test cases of dwellings (source: HEALTHVENT WP 5 report).

Properties	**Dwelling Case 1**	**Dwelling case 2**	**Kitchen**	**Toilet**	**Bathroom**
Area	50 m^2	90 m^2	10 m^2	2 m^2	5 m^2
Ceiling Height	2.5 m	2.5 m	2.5 m	2.5 m	2.5 m
Number of main rooms	2	4			
Number of kitchens	1	1			
Number of toilets	1	1			
Number of bathrooms	1	1			
Number of occupants	2	4			

On the basis of these attributes air change rates and exhaust ventilation rates were calculated and are shown in figures 2.1 to 2.5. The red dashed lines correspond to the air changes rates and ventilation rates proposed in in table B2.1.4-1 of prEN16798-1 for residential buildings corresponding to four categories of level of expectation (Cat I: High level of expectation; Cat II: normal level of expectation; Cat III: moderate level of expectation and Cat IV: low level of expectation).

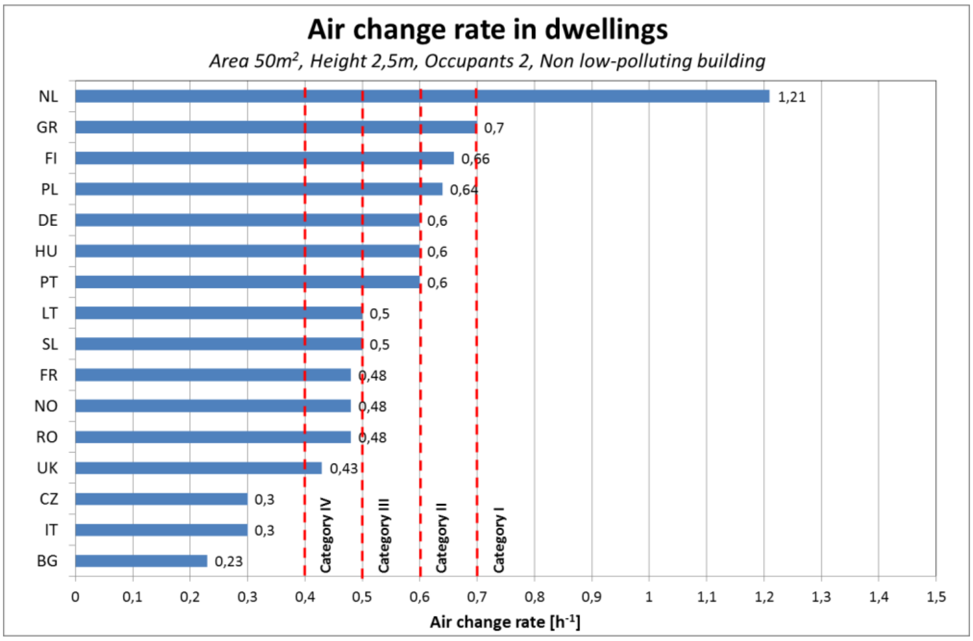

Figure 2.1 Air change rates in European countries for test dwelling case 1 – 50 m^2. Red dashed lines represent pre-defined ventilation rates proposed in pr16798-1 corresponding to four categories of level of expectation (Cat I: High level of expectation, Cat II: Normal level of expectation, Cat III: Moderate level of expectation, Cat IV: Low level of expectation).

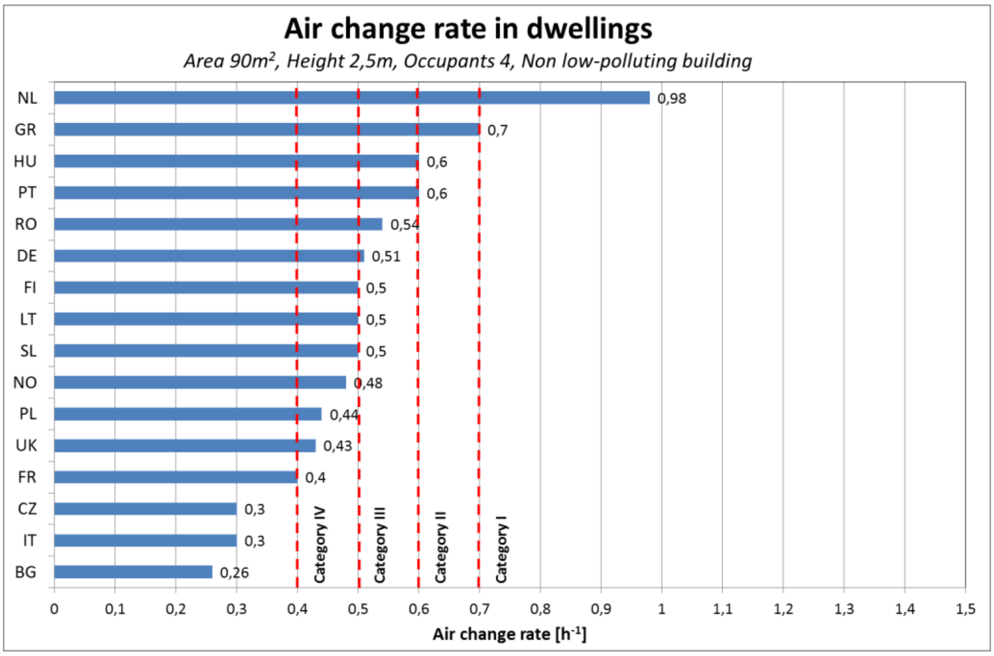

Figure 2.2 Air change rates in European countries for test dwelling case 2 – 90 m^2. Red dashed lines represent pre-defined ventilation rates proposed in pr16798-1 corresponding to four categories of level of expectation (Cat I: High level of expectation,

Cat II: Normal level of expectation, Cat III: Moderate level of expectation, Cat IV: Low level of expectation).

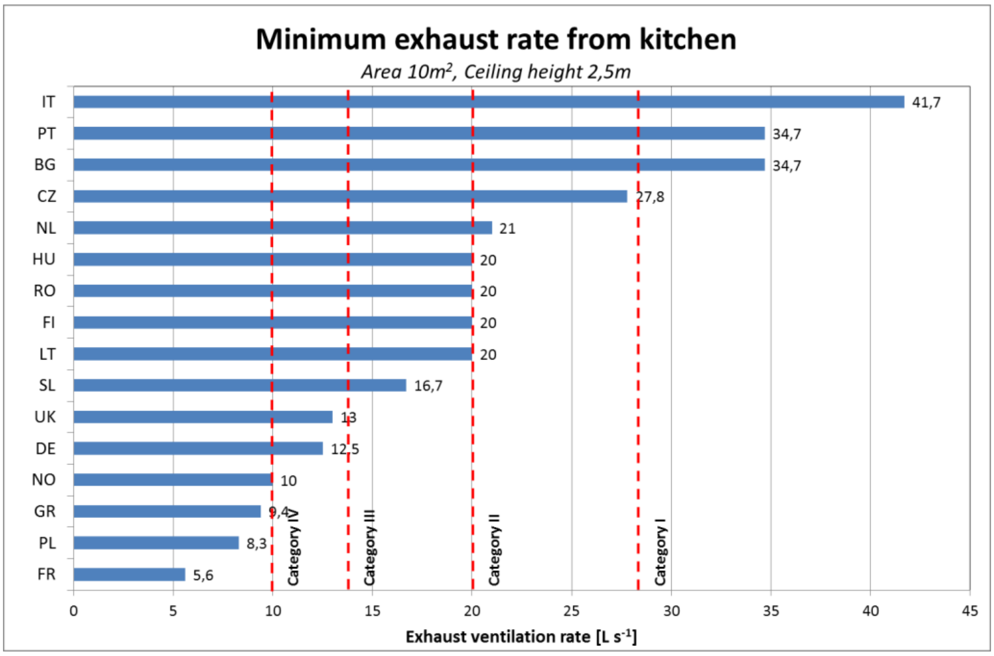

Figure 2.3 Exhaust ventilation rates in European countries for test case – kitchen 10 m^2. Red dashed lines represent pre-defined ventilation rates proposed in pr16798-1 corresponding to four categories of level of expectation (Cat I: High level of expectation, Cat II: Normal level of expectation, Cat III: Moderate level of expectation, Cat IV: Low level of expectation).

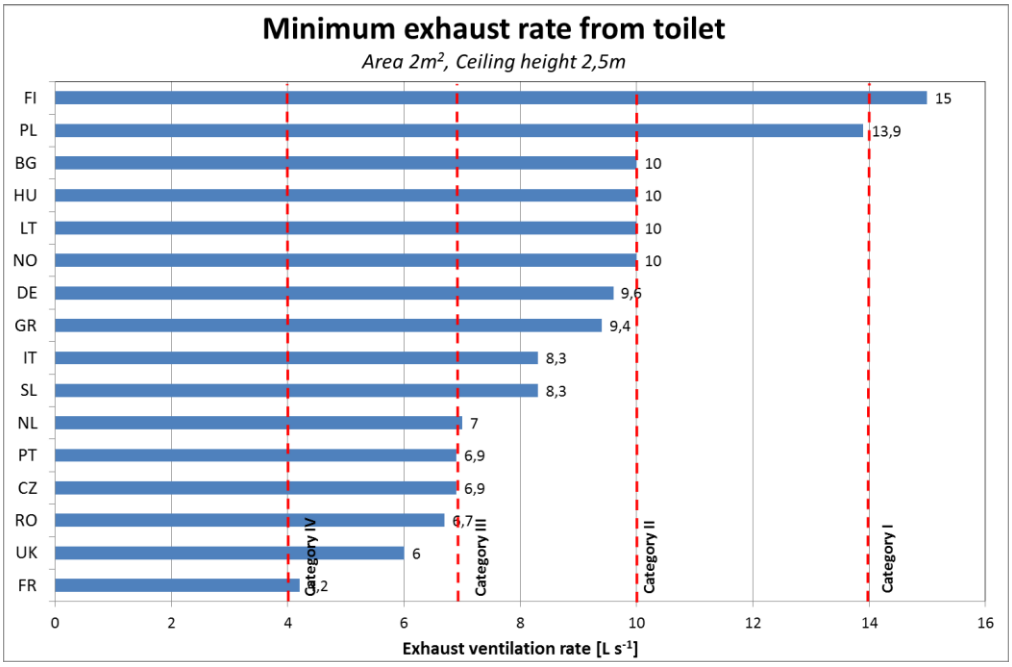

Figure 2.4 Exhaust ventilation rates in European countries for test toilet – kitchen 2 m^2. Red dashed lines represent pre-defined ventilation rates proposed in pr16798-1 corresponding to four categories of level of expectation (Cat I: High level of expectation, Cat II: Normal level of expectation, Cat III: Moderate level of expectation, Cat IV: Low level of expectation).

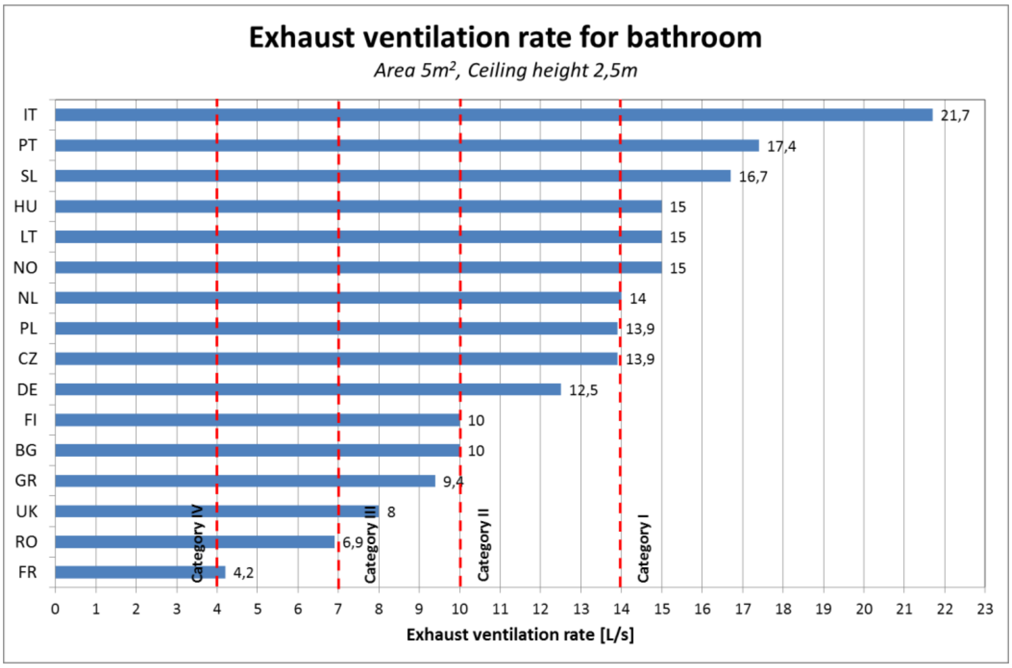

Figure 2.5 Exhaust ventilation rates in European countries for test case – bathroom 5 m^2. Red dashed lines represent pre-defined ventilation rates proposed in pr16798-1 corresponding to four categories of level of expectation (Cat I: High level of expectation, Cat II: Normal level of expectation, Cat III: Moderate level of expectation, Cat IV: Low level of expectation).

Figures 2.6 to 2.8 show the ventilation rates for school-classrooms, playrooms in kindergartens and offices as required in national regulations and standards in selected EU countries. As for residential buildings, also the data provided for schools, kindergartens and offices was not directly comparable. To make them comparable, cases for a school-classroom, a playroom in a kindergarten and an office were proposed (Table 2.4):

Table 2.4 Properties of the test classroom, playroom and office (source: HEALTHVENT WP 5 report).

Properties	**Classroom**	**Playroom**	**Office**
Area	50 m^2	50 m^2	12 m^2
Ceiling height	2.8 m	2.8 m	2.8 m
Number of occupants	25	25	1

The red dashed lines included in the figures correspond to the air changes rates and ventilation rates calculated for the four categories of acceptability (chapter 6.2.2.2 'Method based on perceived air quality') according to prEN16798-1 for non-low polluting non-residential buildings.

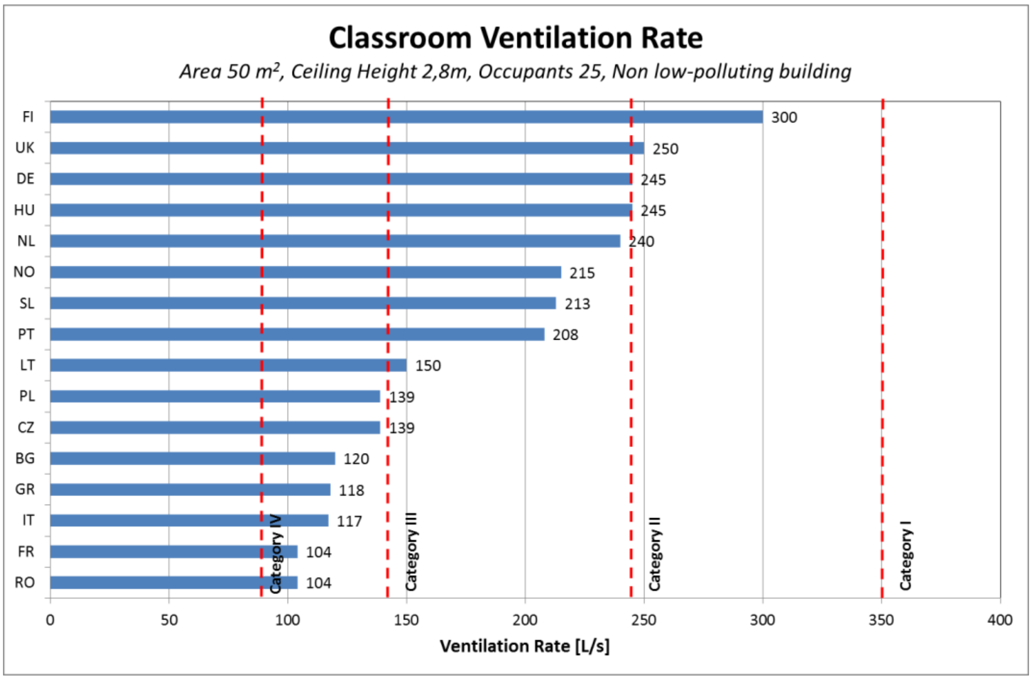

Figure 2.6 Ventilation rate in test case of a classroom. Red dashed lines represent the ventilation rates proposed in pr16798-1 for non-residential buildings and correspond to four categories of level of expectation. (Cat I: High level of expectation, Cat II: Normal level of expectation, Cat III: Moderate level of expectation, Cat IV: Low level of expectation).

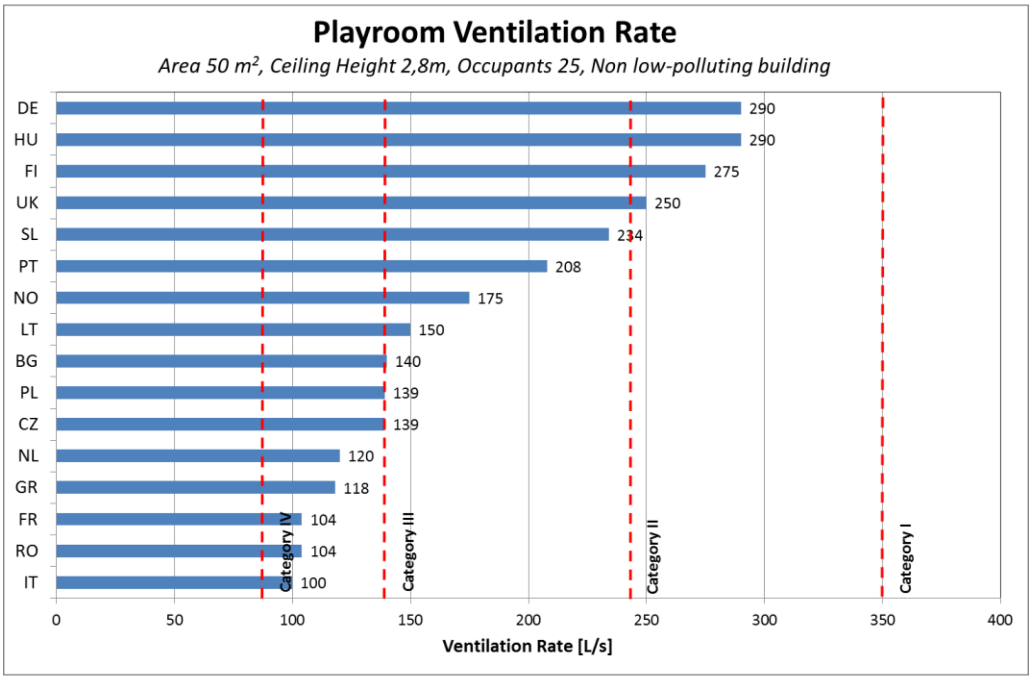

Figure 2.7 Ventilation rate in test case of a kindergarten playroom. Red dashed lines represent the ventilation rates proposed in pr16798-1 for non-residential buildings and correspond to four categories of level of expectation. (Cat I: High level of expectation, Cat II: Normal level of expectation, Cat III: Moderate level of expectation, Cat IV: Low level of expectation).

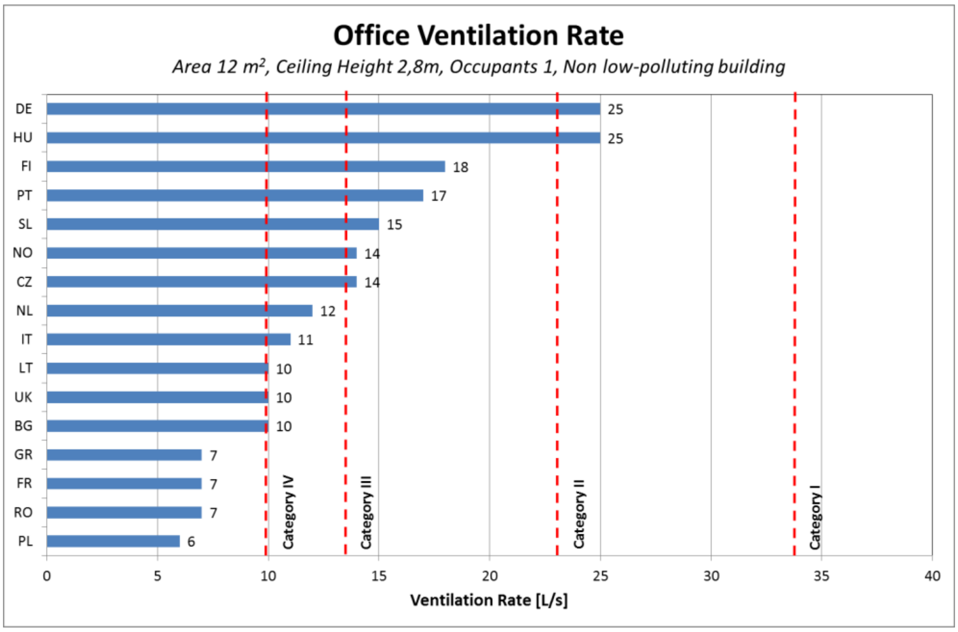

Figure 2.8 Ventilation rate in test case of an office. Red dashed lines represent the ventilation rates proposed in pr16798-1 for non-residential buildings and correspond to four categories of level of expectation. (Cat I: High level of expectation, Cat II: Normal level of expectation, Cat III: Moderate level of expectation, Cat IV: Low level of expectation).

Two clusters of ventilation rates were observed for classrooms and playrooms. One cluster around 10 l/s per person formed by Finland, Germany, Hungary, the Netherlands, Norway, Slovenia and UK and a second one around 4 l/s per person formed by Bulgaria, Czech Republic, France, Greece, Italy, Lithuania, Poland and Romania. Ventilation rates in offices were more scattered and in several countries less than 10 l/s per person.

Ventilation rates in Germany and Hungary are calculated according to the European Standard EN 15251. Some countries still have no legal values on ventilation rates and only use voluntary values from standards. Although members of the EU have accepted standards EN 15251 and EN 13779, which both define ventilation rates, values prescribed in their national regulations, are much diverging.

Approximately one third of countries have requirements for the ventilation of dwellings, which result in air change rate lower than 0.5 h^{-1}. This is in contrast with the health based recommendations of minimum air change rates of 0.5 h^{-1} (Sundell et al., 2011).

Mean ventilation rates in all studies on mechanically ventilated dwellings are lower than required and have large standard deviation. Results from countries where ventilation rates for dwellings are prescribed as air volume flow per floor area, show that ventilation rate for the whole dwelling may be sufficient, but at the same time ventilation rates in individual rooms may be too low. Definition of air change rate for the whole dwelling may not be appropriate due to poor balancing of systems.

Where air change rate of 0.5 is required, mean measured air change rates are as low as 0.3 ach. Values are higher in dwellings equipped with balanced mechanical ventilation system but the mean never exceeds 0.45 ach, with up to 76% of buildings not achieving required rates. Old dwellings, retrofitted with new windows achieve mean air change rate as low as 0.25 ach, with 50% of buildings having air change rate below 0.18 when unoccupied.

In France, only some 40% of local exhausts ventilation systems supplied the required ventilation rates in dwellings, with the situation being similar in the Netherlands.

In schools and kindergartens natural ventilation cannot provide required ventilation rates in all times of the year. Measured and estimated ventilation rates in existing schools are mostly insufficient when compared with regulatory requirements. Studies show that ventilation rates in mechanically ventilated schools are higher than in naturally ventilated and that maximum levels of CO_2 are not exceeded.

All mean measured ventilation rates in schools were below required values. Natural ventilation is not able to provide even as low required ventilation rates as low as 3 l/s per person. Lowest recorded average rates in naturally ventilated classrooms were 0.5 l/s per person. In up to 87% of cases, ventilation rates in naturally ventilated classrooms were too low. Mechanical ventilation systems are able to provide required ventilation rates. However in practice, some mechanical systems provide only one fifth of required ventilation rate.

Ventilation rates of naturally ventilated office buildings were found in the range of 4 l/s per person with a standard deviation of around 2 l/s per person. Ventilation rates in mechanically ventilated buildings were much higher, mean values ranging from 9 to 25 l/s per person, often exceeding minimum required rates.

Moreover, most of the countries do not allow or do not foresee the possibility of reducing ventilation rates if less polluting materials are used or if ventilation efficiency is improved and also do not foresee controlling ventilation rates based on the outdoor air quality. This is in contrast with the concept behind the health based ventilation guidelines framework proposed by HEALTHVENT (see chapter 2 of the present report) and the most recent review concerning the ventilation and health relationship in public and residential buildings (Carrer et al., 2015). The review performed in this latter paper, shows that there is a wide range of ventilation rates (from 6-7 L/s per person to 25 and even 40 L/s per person) over which different health outcomes decline in intensity and/or frequency. Based on the existing limited epidemiological evidence on the association between ventilation and health, this presumably depends on the strength of indoor and outdoor sources and therefore the exposure levels of building occupants. Although technically feasible, these ventilation rates are unjustifiable, on the grounds of energy usage and savings, and may not be feasible in the climates of some European regions. Additionally, increasing outdoor air supply rates can increase exposure to outdoor pollutants such as particles and ozone, especially in regions where the outdoor air is heavily polluted and high ventilation rates can then increase the risk of adverse health effects.

This highlights the need for harmonised ventilation regulations on European level which will provide a systematic and common approach for defining metrics and required levels of ventilation rates and ensuring that ventilation is designed and optimised on the basis of the exposures that are relevant for the specific outcome (health, comfort or cognitive performance), while taking into account local outdoor and indoor air quality sources as well as the condition (cleanliness) of the building's ventilation system (i.e. to avoid that this latter becoming an additional polluting source in buildings).

Indoor pollutants requirements

The EU has in place several directives on the quality of ambient air and occupational exposure limits of pollutants to protect the workers exposed to chemicals from industrial processes. Moreover, WHO has also produced guidelines for both ambient and indoor air pollutants (WHO 2006; 2010).

Some European countries included requirements on indoor air quality into their ventilation regulations for non-industrial buildings, either based on occupational limit values or national limit values (Table 2.5). Limit values and number of included pollutants included in regulations vary greatly from one country to another, which is due to a lack of a common guideline framework at EU level.

Limit levels of pollutants are often higher than those recommended by the WHO guidelines, and are not specified in the regulations of several countries.

In schools of the European countries reviewed (HEALTHVENT WP 5 report, 2012), the most commonly measured pollutant is CO_2. When windows cannot be kept open all the time natural ventilation is unable to provide sufficient low levels of CO_2. On the other hand, this is possible to achieve with mechanical ventilation systems. In none of the surveys formaldehyde levels in classrooms exceeded the maximum recommended values, despite the relatively low ventilation rates in both cases (i.e. naturally ventilated and mechanically ventilated schools). TVOC concentrations exceeded limit values in some individual cases due to very low ventilation rates (below 1 l/s per person).

Table 2.5 Maximum permissible levels of indoor pollutants in EU countries (Source: HEALTHVENT WP 5 report).

Country and reference	**Maximum values of indoor in non-industrial buildings**
WHO Guidelines	Annual average: Formaldehyde: 0.1 mg/m^3 Naphthalene: 0.01 mg/m^3 $N0_2$: 40 µg/m^3 PM_{10}: 20 µg/m^3
Bulgaria Regulation 15/28.07.2005	8 h OEL limit: Ammonia: 14 mg/m^3 Formaldehyde: 1 mg/m^3 CO: 40 mg/m^3 CO_2: 9000 mg/m^3
Czech Republic	8 h OEL: Ammonia: 14 mg/m^3 Formaldehyde: 0.5 mg/m^3 CO: 30 mg/m^3 CO_2: 9000 mg/m^3
Finland Building Regulations Part D2. Indoor climate and ventilation. 2010	Ammonium and amines: 20 µg/m^3 Asbestos: 0 fibres/cm Formaldehyde: 50 µg/m^3 CO: 8 mg/m^3 PM_{10}: 50 µg/m^3 Radon: 200 Bq/m^3 (annual average) Styrene: 1 µg/m^3 Carbon dioxide: 2160 mg/m^3 (1200 ppm)
France Target values	Asbestos: 5 fibres/dm^3 Formaldehyde: 10 µg/m^3 Benzene: 2 µg/m^3 Naphthalene: 10 µg/m^3 CO: 10 mg/m^3 (8 hour) Ozone: 0.2 mg/m^3 Trichloroethylene: 20 µg/m^3 Tetrachloroethylene: 250 µg/m^3

Country and reference	Maximum values of indoor in non-industrial buildings
Germany GefStoffV 2005 – AGW MAK 2000	8 h OEL: Ammonia: 14 mg/m^3 CO: 35 mg/m^3 CO_2: 9100 mg/m^3 Ozone: 0.2 mg/m^3 $N0_2$: 180 mg/m^3
Greece (TOTEE)2425/86. 20701-4/2010. 20701-1/2010	8 h OEL: Ammonium and amines: 0.35 mg/l Formaldehyde: 0.006 mg/l CO: 9 ppm PM_{10}: 50 mg/m^3 CO_2: 1000 ppm
Lithuania Regulation HN 35:2007 (for residential environment)	Ammonia: 0.04 mg/m^3 (daily) Asbestos: 0.1 mg/m^3 (instant) Formaldehyde: 0.01 mg/m^3 (daily) PM_{10}: 0.05 mg/m^3 (daily average) Ozone: 0.03 mg/m^3 (daily) Styrene: 0.002 mg/m^3 (daily)
Norway	Radon: should not exceed 100 Bq/m^3 VOC: not given. previously 400 µg/m^3 Formaldehyde: 100 µg/m^3 (30 min average) Asbestos: not exceeding 0.001 fibre/m MMMF: not exceeding 0.01 fibre/m CO: 10 mg/m^3 (8 hour average) CO_2: 1800 mg/m^3 NO_2: 100 µg/m^3 (1 hour average)
Portugal Decree law 79/2006	PM_{10}: 0.15 mg/m^3 CO_2 : 1800 mg/m^3 CO :12.5mg/m^3 O_3 : 0.2 mg/m^3 Formaldehyde: 0.1mg/m^3 VOC: 0.6 mg/m^3 Radon 400 Bq/m^3 Legionella : 100 UFC/l
Romania I5 normative	30 min avg: CO: 6 mg/m^3 Formaldehyde: 0.035 mg/m^3 annual avg: Radon: 140 Bq/m^3 instant max: CO_2: 1600 mg/m^3
Slovenia ULRS 42/2002	CO_2: 3000 mg/m^3 radon: 400 Bq/m^3 ammonia: 50 µg/m^3 formaldehyde: 100 µg/m^3 TVOC: 600 µg/m^3 CO: 10 mg/m^3 O_3: 100 µg/m^3 PM_{10}: 100 µg/m^3
United Kingdom UK Building Regulations Part F (2010) Appendix	NO_2: 40 µg/m^3 (annual average) CO (public): 10 mg/m^3 (8hr average) CO (occupational): 35 mg/m^2 (8hr average) TVOC: 300 µg/m^3 (8hr average) O_3: 100 µg/m^3 (8hr average)

In offices of the European countries, indoor levels of CO_2 were in all cases below the recommended value of 1000 ppm. This is expected due to the fact that buildings' occupants being the main source of CO_2 have more space available in office buildings than in schools or kindergartens.

Thermal comfort and noise requirements

Thermal comfort parameters among countries (Table 2.6) are inconsistent with temperature limits for summer varying from 28 to 25°C and for winter from 18 to 21°C. Minimum air temperature limits are prescribed more commonly than maximum air temperature limits.

Table 2.6 Thermal comfort requirements in European countries (Source: HEALTHVENT WP 5 report).

Country and legislative reference	**Temperature limits summer [°C]**	**Temperature limits winter [°C]**	**Maximum air velocity in residences and offices - summer**	**Maximum air velocity in residences and offices - winter**	**Limit value for humidity of indoor air (min winter/ max summer) [%rh]**
Bulgaria Regulation 15/28.07.2005 CEN/CR 1752:1988	office: 24.5±2.5 class: 24.5±2.5 kind.: 23.5±2.5	office: 22.0±3.0 class: 22.0±3.0 kind.: 20.0±3.0	office 0.25 m/s	office: 0.21 m/s	-
Czech Republic Regulation 410/2005 Decree 361/2007	office: 28 school: 26	office: 20 schools: 20	0.1 - 0.2 m/s	0.1 - 0.2 m/s	30 -70% RH
Finland Building Regulations Part D2, Indoor climate and ventilation, 2010	25	21	0.3 m/s	0.2 m/s	no humidification above 45% RH
France Code de la construction et de l'habitation	-	18	-	-	-
Germany EN 15251, cat. II	*26*	*20*	-	-	*max 12 g/kg*
Greece (TOTEE)2425/86	26	20	0.25 m/s	0.15 m/s	winter max: 40% RH summer max: 45% RH
Hungary EN 15251, cat. II	26	20	-	-	30 - 70%
Italy DM 18/12/1975; UNI 10339	-	20	-	-	*45-55%*
Lithuania HN 42:2004; HN 69:2003	24.5±1.5	22±2	0.3 m/s	0.2 m/s	max. 75% RH
Netherlands The Dutch Building Code 2012	-	-	0.2 m/s	0.2 m/s	-

Country and legislative reference	**Temperature limits summer [°C]**	**Temperature limits winter [°C]**	**Maximum air velocity in residences and offices - summer**	**Maximum air velocity in residences and offices - winter**	**Limit value for humidity of indoor air (min winter/ max summer) [%rh]**
Norway Building Regulations Act, Technical regulations (TEK2010); Arbeidstilsynet 444	work load: low. medium. heavy: 26	work load: low 19; medium 16; heavy 10	0.15 m/s	0.15 m/s	only recommendations to prevent dampness and mold growth
Portugal Decree law 79/2006	25	20	0.2 m/s in occupied areas	0.2 m/s in occupied areas	-
Romania I5 normative	residential: 25.5 - 27 offices: 25.5 - 27 kindergartens: 24.5 - 26	residential: 18 - 21 offices: 19 - 21 kindergartens: 15 - 17.5	20°C: 0.10 - 0.16 m/s 21°C: 0.10 - 0.17 m/s 22°C: 0.11 - 0.18 m/s 24°C: 0.13 - 0.21 m/s 26°C: 0.15 - 0.25 m/s		for 20 - 27°C RH = 30 - 70% upper max 12 g/kg
Slovakia Z.z. 259:2008	28	18	0.25 m/s	0.20 m/s	30 - 70% RH
Slovenia ULRS 42/2002	26	19	0.25 m/s	0.21 m/s	30 - 70% RH
United Kingdom UK Building Regulations Part F (2010)	28 for 1% annual occupied hours	19	0.15 m/s	0.15 m/s	-

Maximum air velocities vary from 0.15 to 0.30 m/s. The majority of regulations only prescribe maximum air velocities but not also the temperature of air at those velocities. Limits of air velocities are not prescribed as commonly as the temperature limits.

Limits of humidity levels are more consistent. Lower limits of relative humidity (RH) are constantly at 30% while higher limits are 70% in all cases except one which is 75%.

Noise levels are also inconsistent among European countries in terms of both units used (i.e. equivalent or instantaneous noise levels or noise rating curves) and limit values (Table 2.7). Noise in mechanical ventilation systems is a common problem and although these systems are in principle able of providing the required level of ventilation rate, the buildings' occupants often lower the fan speed setting because of disturbing noise levels.

Table 2.7 Requirements on limit indoor noise levels in European countries (Source: HEALTHVENT WP 5 report).

Country and legislative reference	**Limit values for ventilation noise in sleeping rooms of residencies**	**Limit values for ventilation noise in classrooms**	**Limit values for ventilation noise in playrooms**	**Limit values for ventilation noise in offices**
Bulgaria Regulation 15/28.07.2005 CEN/CR 1752:1988	-	40 dB(A)	40 dB(A)	45 dB(A)

Country and legislative reference	**Limit values for ventilation noise in sleeping rooms of residencies**	**Limit values for ventilation noise in classrooms**	**Limit values for ventilation noise in playrooms**	**Limit values for ventilation noise in offices**
Czech Republic Regulation 148/2006	40 dB(A)	45 dB(A)	45 dB(A)	50 dB(A)
Finland Building Regulations Part D2, Indoor climate and ventilation, 2010	28 dB(A) eq	33 dB(A) eq	28 dB(A) eq	33 dB(A) eq
France	30 dB(A)	38 dB(A)	38 dB(A)	-
Germany DIN 4109 VDI 2081	*35 dB(A)*	*40 dB(A)*	*40 dB(A)*	*40 dB(A)*
Greece (TOTEE)2425/86	NR 25	NR 35	NR 35	NR 35
Hungary EN 15251	26 dB(A)	35 dB(A)	40 dB(A)	35 dB(A)
Italy UNI 10339	*35 dB(A) eq*	*25 dB(A) eq*	*25 dB(A) eq*	*35 dB(A) eq*
Lithuania HN 33:2007	35 dB(A) eq 22-6h	40 dB(A)	40 dB(A) 6-18h	50 dB(A)
Netherlands The Dutch Building Code 2012	vent system: 30 dB(A)	vent system: 30 dB(A)	vent system: 30 dB(A)	vent system: 30 dB(A)
Norway NS 8175	35 dB(A)	35 dB(A)	35 dB(A)	35 dB(A)
Poland PN EN 15251	26 dB(A)	35 dB(A)	40 dB(A)	35 dB(A)
Portugal	-	-	-	-
Romania I5 normative EN 15251	20 - 35 dB	class rooms: 30 - 40 dB	30 - 45 dB	small: 30 - 40 dB landscape: 35 - 45 dB
Slovenia ULRS 14/1999 ULRS 07/2001	day/night: $L_{AF,max}$: 35/30 dB(A) L_{eq}: 40/35 dB(A)	day/night: $L_{AF,max}$: 40/40 dB(A) L_{eq}: 40/40 dB(A)	-	L_{eq}: 45 dB(A)
United Kingdom CIBSE recommended	*NR 25*	*NR 25-35*	-	*NR 35-45*

Ventilation systems and related problems

After the building regulations have become more stringent and in several cases cannot be fulfilled with natural or hybrid ventilation systems, the proportion of mechanically ventilated systems is gradually and rapidly increasing mostly in Northern European countries as opposed to natural ventilation which is the preferred option in Southern European countries. However, in countries with continental climate and relatively cold winters like Romania, the share of mechanical ventilation systems is low as well, which might suggest that the economic situation of a country also has an impact on the type of ventilation systems used.

Moreover, the natural ventilation systems are still widely used in some countries and in some building types where regulations require mechanical ventilation. This suggests compliance of regulations in practice is poor.

The review identified a number of technical features of ventilation systems which may become one of the pollution sources with negative effects on the health, comfort and performance of the buildings' occupants, namely:

- More than half of the countries do not have any requirements to prevent droplets from humidification to spread in systems and to prevent condensation on coils that can cause damage.
- Almost half of countries still do not have any requirements regarding the penetration/infiltration of outdoor air pollutants into the indoor environment.
- Requirements for cleanliness of system regarding dust, microbes and fibres for interior insulation are still not imposed in approximately one third of countries, while regulatory requirements for ozone and other chemicals are almost non-existent.
- More than a third of participating countries do not have any requirement for air filtering. Out of those that have requirements for air filtering, more than half have no requirements for regular filter replacements.
- Approximately one third of countries still do not require operating instructions for the ventilation systems.
- More than half of countries do not have requirements for cleaning the ventilation systems during their lifetime.
- In more than half of cases, countries have no requirements on qualifications of operation and maintenance personnel of ventilation systems.
- Re-circulation of air is allowed in most countries but recommended only in one fifth.
- Countries use two different types of regulations of ventilation systems: prescriptive based and performance based. Countries with performance-based regulations allow all types of ventilation systems as long as they are able to provide required air change or airflow rates and fulfil the requirements of energy regulations.
- The vast majority of countries have no regulatory limitation regarding the location of ventilation systems in relation to outdoor pollution sources like heavy congested roads, industry areas etc., which can all greatly influence the quality of indoor air.
- Balancing of ventilation systems is required in 14 out of 16 countries but it is controlled in only 6 out of 14 countries.
- Three quarters of countries have no requirements regarding the pressure differences between rooms and/or between rooms and outdoor air.
- Out of 16 countries 11 have no requirements on follow-up measurements of ventilation rates, IAQ etc. during the lifetime of buildings.
- Again 11 of 16 countries have no requirements regarding the leakage of extract air to supply air in heat recovery exchangers.
- A half of responding countries have requirements regarding regular inspections of ventilation systems.

Review of ventilation standards related to IAQ

The review within the HEALTHVENT WP 5 of European standards on ventilation related to IAQ (i.e. standards that directly addressing functional properties of ventilation systems or equipment which influence indoor air quality) has revealed that (until recently) none of them was truly health based (Table 2.8). Standards which can be used for determination of ventilation rates (e.g. EN 15251:2007[49] and EN 13779:2007[50]) are based on different categories of comfort criteria following EN ISO 7730 and CR 1752. The general principle applied to these documents is that a better indoor air quality requires higher ventilation rates. Indoor air quality in EN standards is not well defined. Only some general guidance on air quality and values for CO_2 concentration and humidity levels is provided, whereas there are no other generally accepted criteria and measuring methods for other pollutants relevant to IAQ and health.

Table 2.8 Ventilation standards according to their purpose and building type (Source: HEALTHVENT WP 5 report).

<table>
<tr><th rowspan="2">Purpose of EN standard</th><th colspan="2">Building type</th></tr>
<tr><th>Residential</th><th>Non residential</th></tr>
<tr><td>Criteria for indoor environment</td><td colspan="2">EN 15251:2007</td></tr>
<tr><td>Design and dimensioning of ventilation systems</td><td>CEN/TR 14788:2006</td><td>EN 13779:2007</td></tr>
<tr><td>Determining performance criteria of residential ventilation systems</td><td>EN 15665:2009</td><td></td></tr>
<tr><td rowspan="2">Calculation of ventilation rates</td><td colspan="2">EN 15242:2007</td></tr>
<tr><td>EN 13465:2004</td><td></td></tr>
<tr><td>Calculation of ventilation energy</td><td colspan="2">EN 15241:2007</td></tr>
<tr><td>Rating and performance characteristics</td><td>prEN 13142 Rev V7
on components/products for residential ventilation</td><td>EN 13052:2006
on air handling units</td></tr>
<tr><td>Performance testing of components and products</td><td>EN 13141-1 /air transfer devices
EN 13141-2 /exh. & supply air terminal devices
EN 13141-4 /fans
EN 13141-5 /cowls and roof outlets
EN 13141-6 /exh. ventilation system packages
EN 13141-7 /mech. supply & exh. units + HR for dwellings
EN 13141-8 /mech. supply & exh. units + HR for rooms
EN 13141-9 /ext. mounted RV-controlled air transf. device
EN 13141-10 /hum. controlled extract air terminal device</td><td>EN 1886:2007 /Mech. performance air handling units
ISO 5801:1997 /Industrial fans performance testing
ISO 12248 /Ind. fans tolerances & conversion methods
ISO 5221 /Acoustics, in duct radiated sound power level
ISO 5213 /Acoustics, casing radiated sound power level
EN 1751 /Aerodynamic testing of dampers & valves
EN 1216 /Performance testing heating/cooling coils
EN 779 /Determination of filtration performance
EN 308 / Performance testing air-to-air HR-devices</td></tr>
</table>

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[49] Available at:
http://standards.cen.eu/dyn/www/f?p=204:110:0::::FSP_PROJECT,FSP_ORG_ID:24552,6138&cs=1AAF5A672C76C7DC4F78CCAAE6304DE5D

[50] Available at:
http://standards.cen.eu/dyn/www/f?p=204:110:0::::FSP_PROJECT,FSP_ORG_ID:24553,6138&cs=12A085D540F27A006B62E32D4714C4E9A

The two ventilation standards mostly related to IAQ (i.e. EN 15251 on "Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics" and EN 13799 on "Ventilation for non-residential buildings") are under revision. The revised draft standards include criteria and in several cases default values for a number of technical issues related to buildings and buildings' systems including heat recovery (air tightness, demand control ventilation, specific fan power, filtration and air cleaning, revised target values of pollutants, lighting, noise, occupants' schedules for energy calculations, etc.).

The proposed revised version of EN 15251 (EN 15251 rev 2015; prEN 16798-1) (CEN, 2015) includes default criteria for 3-4 categories for indoor environmental parameters which account for the contribution of the building's occupants and building materials to the overall indoor air pollution. These criteria do not depend on the type of the system (i.e. mechanical or non-mechanical) used for conditioning the space. The criteria for thermal environment (i.e. for both mechanical and non-mechanical heated, cooled and ventilation buildings) are identical to the existing standard. Personalised systems have been newly introduced but without any default criteria. In addition to the revised standard, a technical report (16798-2) is also developed to support and explain the standard in more details. Default values for technical criteria are included in the informative Annexes of the standard, however EU MS may select other values but following the concept of how the default values are expressed and applied.

Concerning the aspect of IAQ, the revised version of the standard includes some new features and the design parameters for IAQ shall be derived using one or more of the following three methods:

- Method based on perceived air quality
- Method using criteria for pollutant concentration
- Methods based on pre-defined ventilation air flow rates.

Within each method, the designer should choose among different categories of IAQ and define which building category to use.

If the method based on perceived air quality is chosen a total ventilation rate for the breathing zone is calculated by combining the ventilation rate for occupancy per person (in l/s per person) and the ventilation rate for emissions from the building materials (in l/s per m^2). The perceived air quality levels are set for non-adapted persons and in special cases also for adapted persons. In this method, the newly introduced criterion is that the total ventilation rate must never be lower than 4 l/s per person. This corresponds to the minimum health based ventilation rate of 4 l/s per person defined in HEALTHVENT, however, it should be stressed that in the latter case this base rate accounts only for emissions from the human bio-effluents and no other pollution sources (i.e., stemming from building materials or from the outdoor air). Moreover, in the revised version of EN 15251, there are situations where the calculated ventilation rate is lower than the base (health based) value of 4 l/s per person.

If the method based on pollutant concentration is used, the ventilation rate required is that calculated to dilute the pollution load due to the most critical or relevant pollutants. When this method is used it is required to use CO_2 as one of the pollutants as it represents the pollutant emissions from human bio-effluents. Threshold values for other pollutants are those in the WHO guidelines (WHO, 2010; WHO, 2006). Emission rates and outdoor concentrations for the gases considered should be defined based on material testing or certification and local ambient (outdoor) air quality values.

A method is also provided to determine pre-defined minimum ventilation air flow rates meeting the requirements for both perceived air quality and health criteria in the occupied zone. For residential buildings, pre-defined ventilation rates can be given on the national level based on one or more of the following criteria: total air change rate for the dwelling, supply air flows for specific rooms, exhaust air flows from specific rooms. Default values for these three criteria are provided in the revised draft of EN 15251 (prEN 16798-1).

Requirements are set also for: filtration and air cleaning in line with prEN 16798-3 (revised version of standard EN 13779) and the draft Technical Report TR 16798-2; lighting including a table with default values for day-lighting in Annex B4 of prEN 16798-1; noise in line with the guidance for noise evaluation at the design stage according to EN 12354-5 including default values for various building typologies and type of spaces and three categories of equivalent continuous sound levels in Annex B5 of prEN 16798-1.

The standard prEN 16798-1 in its Annex B7 also lists a number of recommended occupant schedules to use in energy calculations for different types of building spaces (e.g. residential, offices, schools, restaurants, meeting rooms, department stores, etc.). These schedules include criteria for the indoor environment based on default values, time and level of occupancy and internal loads from other equipment. The criteria used for room temperatures, ventilation and humidity are based in Category II (i.e. normal level of expectation) and very low-polluted building.

As far as the revised version of standard EN 13799 on “Ventilation for non-residential buildings” is concerned, it specifies common understanding of ventilation systems in Europe and provides a classification system for key performance data. This standard was renumbered to EN 16798-3 (its normative part) and supported by a Technical Report (CEN/TR 16798-4) containing all informative annexes following the similar logic of the prEN 16798-1 and 16798-2.

All indoor air quality related aspects in EN 16798-3 have been deleted or moved to EN 16798-1. All aspects of non-residential ventilation are kept in EN 16798-3 (i.e. outdoor air quality, supply air quality, system performance and system design).

In the process of the system design consideration is given to the quality of the outdoor air around the building or proposed location of the building with three levels of classification (ODA) (subdivided into categories one for gaseous pollutants ODA (G) and another one for particles (ODA (P)) which are applied according to the level of compliance of the quality of the outdoor air against WHO 2005 guideline values or national air quality standards and regulations (i.e. ODA 1, fulfilled; ODA 2, outdoor air pollutants levels exceeding WHO 2005 guidelines or national air quality standards and regulations by a factor up to 1.5; ODA 3, outdoor air pollutants levels exceeding WHO 2005 guidelines or national air quality standards and regulations by a factor greater than 1.5).

The corresponding classification levels for the supply air (SUP) are when the supply air fulfils the WHO 2005 guidelines limit values and any national air quality standards limit values or regulations with a factor x 0.25 (SUP1), factor x 0.5 (SUP2), factor x 0.75 (SUP3) and fully (SUP4).

Concerning filtration, depending on the outdoor particle pollution level (ODA(P) and desired supply air quality (SUP) different levels of filtration are required. In cases where supply air level of SUP1 or 2 is required and where the outdoor air quality based on gaseous pollutants is of level ODA(G) 2 or OD(G) 3 the particle filtration should be optionally complemented with suitable gas phase filtration to reduce harmful levels of gaseous components like CO, NO_x, SO_x, VOC and O_3.

Beyond the aforementioned air quality aspects, standard EN 16798-3 deals with the calculation of the specific fan power (SFP) and air handling units (AHU) related SFP values, the ventilation systems and heat recovery related leakages as well as aspects of energy rating of ventilation systems and primary energy use of ventilation.

In conclusion, in the revised version of standard EN 15251 the IAQ and health related aspects in the ventilation rates design and criteria are more strengthened compared to the existing version of the standard but still do not match the health based ventilation concept and approach proposed by HEALTHVENT although they come a step closer.

Moreover, there are still a number of open and at the same time practical issues to consider and solve when estimating the required minimum ventilation rate for real-life building scenarios especially for existing buildings. These are mostly relating to the way requirements for acceptable levels of IAQ based on health, comfort and performance criteria and emission rates from all building related pollution sources can be taken on board when calculating ventilation rates.

According to the health based ventilation concept of HEALTHVENT (see chapter 2 of the present report), when determining the minimum ventilation rate the pollution sources related to both occupant's activities (including their bio-effluents) and the building itself and its systems (e.g., construction materials, HVAC systems, furniture, etc.) as well as the outdoor air should all be taken into account. When calculating the ventilation rate the open and practical issues inter alia concern: (a) in practice, the ventilation rates are based on full mixed airflows and ventilation effectiveness is rarely taken into account; but even when ventilation effectiveness is taken into account some systems may present a different ventilation effectiveness in winter than in summer; (b) when air cleaning devices are used (for reducing the amount of outdoor pollution penetrating indoors, saving energy and still guaranteeing acceptable levels of IAQ) the testing methods employed focus on some types of pollutants for which they work well (e.g. for VOCs emitted from construction materials) and not for others (e.g. the occupants' bio-effluents affecting odour or perceived air quality); (c) a common methodology at EU level for establishing criteria and estimating the pollution load in new buildings or assessing it in existing buildings and then associating it with the building pollution typologies defined in prEN 16798-1 (i.e. very low, low and non-low polluting buildings) does not yet exist; this concerns also number, type and associated health based thresholds of prioritised pollutants to consider as mostly relevant to IAQ and health (given that different pollutants may impact different health endpoints) which might suggest changes in the criteria specified in Annex B3 of prEN 16798-1; (d) usually neither the number of building's occupants nor the pollution load from buildings' materials at the building's design stage can be anticipated and precisely estimated in terms of their correspondence also at the building's operation stage (i.e. the ventilation design is completed before the construction and surface materials are selected, and there is no possibility to control the impact of the additional emissions due to 'add on' products and materials such as furniture, the occupants' activities and any potential renovations that may occur during the lifetime of the building's ventilation system).

HEALTHVENT prescriptive guidelines part based on real-world indoor air quality and ventilation problems

HEALTHVENT proposed contents of prescriptive guidelines covering 21 elements that have an impact on the performance of ventilation. Guidelines were grouped into three categories dealing with: (A) actions to avoid specific sources of pollution related to ventilation system; (B) actions to reduce exposure to pollutants associated with ventilation systems; and (C) actions to achieve compliance of regulations regarding operation and maintenance.

Each of the 21 items in the prescriptive guidelines was checked for occurrence in existing CEN documents, which included European Standards (EN), draft European Standards (prEN), and CEN technical reports (TR). The review showed that European Standards, if properly applied, should ensure avoidance to a large extent of problems related to ventilation systems as they already cover a significant part of the elements which are included in the HEALTHVENT prescriptive guidelines. Standards are, however, not used or implemented in practice as they are not mandatory unless they are referred to in national or EU regulations. National building regulations regarding ventilation, on the other hand, include only a few of the elements of the proposed prescriptive health based guidelines. The HEALTHVENT prescriptive guidelines, if adopted and implemented, would reduce exposures and health and performance related risks to buildings' occupants associated with improperly operated and maintained ventilation systems. Harmonized regulations would benefit also industry by reducing the construction cost of ventilation systems.

HEALTHVENT WP 5 based conclusions and recommendations

- The HEALTHVENT WP 5 review showed that considerable discrepancies do exist among measured and required values of ventilation rates, indoor environmental parameters and noise. Guidance at EU level is needed to provide instructions on proper design, construction, maintenance and inspections of ventilation systems. For better effect, inspection of ventilation systems could be merged with inspections of air-conditioning systems and energy auditing. More effort should be put into education of all parties, which are involved in design, construction and operation of ventilation systems.
- Overall, considerable differences were found among ventilation systems, regulations and compliance practices in the European countries that have been investigated.
- Requirements for indoor air quality should be included in national building related regulations of all European countries (including a minimum number of pollutants and associated limit levels according to the WHO IAQ guidelines).
- Common European regulatory values are needed for minimum temperature during the heating season and maximum temperature during the cooling season and adjusted by accounting for the specific climatic conditions across Europe. The same applies for maximum air velocities, which should also be based on the temperature of moving air.
- The reviews of national regulations in European countries on ventilation rates, indoor pollutants, and indoor environment criteria revealed inconsistencies among

countries and between countries and European Standards. Although, the majority of regulated parameters are already defined in European Standards, which were accepted in CEN voting process by national bodies, the values found in standards and those in national regulations are in several cases inconsistent and not harmonized. The observed inconsistencies between criteria and values in EN standards and regulations at national level and among countries at European level, cause problems to designers and industry, and increase construction costs. Besides that, current practice is in contrast to the efforts of unification and standardization of European common market.

BPIE 2015 report

The most recent review of national regulations related to indoor air quality, thermal comfort and daylight for both new and existing residential buildings was performed by BPIE but it was limited to eight EU countries and regions (i.e. Denmark, France, Sweden, Germany, Italy, Poland, UK and Brussels-Capital Region of Belgium) (BPIE, 2015).

Requirements for ventilation rates and other indoor air quality, comfort and health related parameters in European countries

IAQ and its potential impact for the comfort and health conditions of the buildings' occupants is recognised as an important aspect to consider and include in national building codes by all EU MS surveyed.

IAQ related requirements (such as minimum ventilation rates, airtightness, limitation of pollutants, etc.) in terms of mandatory or recommended values are largely differentiated among the EU MS surveyed for new buildings whereas they can hardly be found in the analysed building codes for existing residential buildings. For this latter category of buildings only recommendations on IAQ aspects are included in most of national building codes, however, energy performance related improvements do often apply without any mandatory requirements for a posteriori checking and assessing how these improvements have influenced the IAQ of the buildings. Given the current trend in renovation measures resulting in more airtight buildings, such missing mandatory provisions explain the reported levels of air change rates below the required levels in many situations. This represents a serious shortcoming in building codes which should be addressed in a future revision of EPBD and related legislation and regulatory framework for renovation.

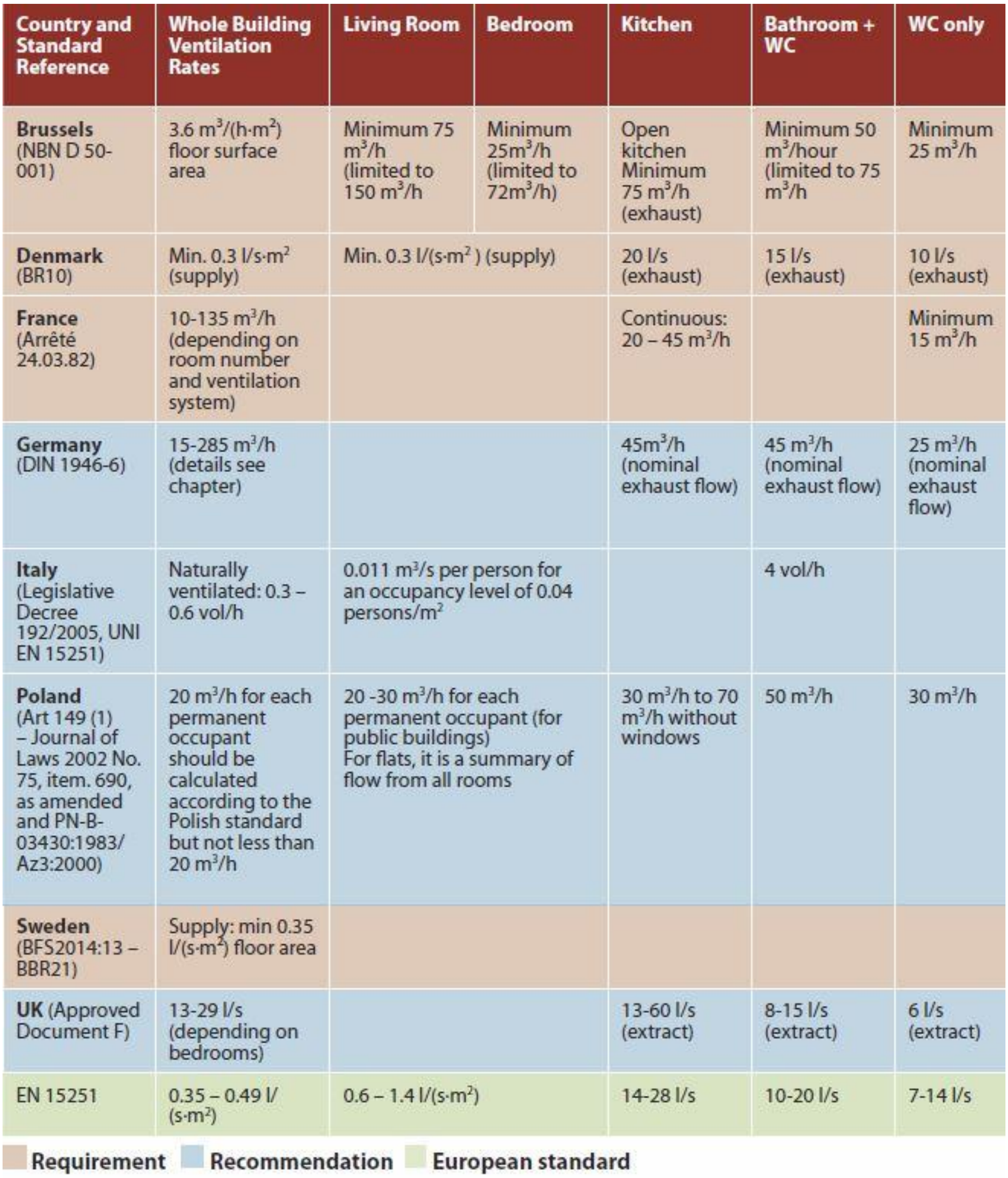
Ventilation requirements

Ventilation is included in all surveyed MS building regulations but minimum requirements are set only for half of the countries (Denmark, France, Sweden and Brussels-Capital Region (BE)), while for the other half (Germany, Italy, Poland and the UK) there are only recommended minimum ventilation rates (Table 2.8).

For new residential buildings, the metrics used for minimum ventilation rates vary from one country to another and are generally different from those specified in EU standards (e.g. EN 15251 and 13779) (Table 2.9).

The most commonly used units are litres per second (l/s) and cubic meters per hour (m^3/h) while the air exchange rate is regulated based on the assumed number of occupants, on the type of the room (e.g. bedroom, kitchen, bathroom, WC, etc.), or on the floor area. This identifies a clear need for further harmonisation at EU level which could facilitate a proper comparison and an easier transfer of knowledge and practices among European countries.

Table 2.9 Ventilation standards for new dwellings in eight EU MS (Source: BPIE 2015 report based on feedback from country experts)



Country and Standard Reference	Whole Building Ventilation Rates	Living Room	Bedroom	Kitchen	Bathroom + WC	WC only
Brussels (NBN D 50-001)	3.6 $m^3/(h{\cdot}m^2)$ floor surface area	Minimum 75 m^3/h (limited to 150 m^3/h	Minimum 25m^3/h (limited to 72m^3/h)	Open kitchen Minimum 75 m^3/h (exhaust)	Minimum 50 $m^3/hour$ (limited to 75 m^3/h	Minimum 25 m^3/h
Denmark (BR10)	Min. 0.3 $l/s{\cdot}m^2$ (supply)	Min. 0.3 $l/(s{\cdot}m^2)$ (supply)		20 l/s (exhaust)	15 l/s (exhaust)	10 l/s (exhaust)
France (Arrêté 24.03.82)	10-135 m^3/h (depending on room number and ventilation system)			Continuous: 20 – 45 m^3/h		Minimum 15 m^3/h
Germany (DIN 1946-6)	15-285 m^3/h (details see chapter)			45m^3/h (nominal exhaust flow)	45 m^3/h (nominal exhaust flow)	25 m^3/h (nominal exhaust flow)
Italy (Legislative Decree 192/2005, UNI EN 15251)	Naturally ventilated: 0.3 – 0.6 vol/h	0.011 m^3/s per person for an occupancy level of 0.04 persons/m^2			4 vol/h	
Poland (Art 149 (1) – Journal of Laws 2002 No. 75, item. 690, as amended and PN-B-03430:1983/Az3:2000)	20 m^3/h for each permanent occupant should be calculated according to the Polish standard but not less than 20 m^3/h	20 -30 m^3/h for each permanent occupant (for public buildings) For flats, it is a summary of flow from all rooms		30 m^3/h to 70 m^3/h without windows	50 m^3/h	30 m^3/h
Sweden (BFS2014:13 – BBR21)	Supply: min 0.35 $l/(s{\cdot}m^2)$ floor area					
UK (Approved Document F)	13-29 l/s (depending on bedrooms)			13-60 l/s (extract)	8-15 l/s (extract)	6 l/s (extract)
EN 15251	0.35 – 0.49 $l/(s{\cdot}m^2)$	0.6 – 1.4 $l/(s{\cdot}m^2)$		14-28 l/s	10-20 l/s	7-14 l/s

🟫 **Requirement** 🟦 **Recommendation** 🟩 **European standard**

Concerning types of ventilation systems to use, mandatory mechanical ventilation is required in some countries (e.g. for multi-family in Denmark and high-rise buildings in

Poland) and recommended in others (e.g. Br-Region in Belgium and Germany), while in Southern European countries, that are featuring warmer climates, natural ventilation is more encouraged (e.g. in Italy).

Last but not least, it seems that most of the surveyed countries have to further improve their calculation tools to adequately address hybrid and demand-controlled ventilation in order to have comprehensive calculation methods to ensure that the ventilation needs are met.

Comparing the reviews performed on ventilation rates in European dwellings in the context of HEALTHVENT WP 5 (Table 2.1) and BPIE 2015 (Table 2.8), it can be readily seen that the required or recommended values and the metrics used for ventilation rates in the EU MS were not changed in the period 2012-2015. Some discrepancies observed in the values or range of values of ventilation rates reported by the two review studies is due to the different level of detail extracted and reported from national regulations. For example, the different range of values reported for the whole building ventilation rates for Germany that was surveyed in both review studies is simply due to the fact that HEALTHVENT WP 5 reported only the range corresponding to nominal ventilation (Level 3 category of DIN 1946-6) while BPIE 2015 reported the range of all values (Level 1 to Level 4 categories of DIN 1946-6).

Similarly, the different lower limit of exhaust flow rate for kitchens reported in BPIE 2015 in the case of Poland compared to that reported by HEALTHVENT WP 5 is due to the fact that in the former case the reported flow rate was for a kitchen in an apartment with less than 3 people (i.e. 30 m^3/h) while in the latter it was a flow rate for a kitchen in an apartment for more than 3 people (i.e. 50 m^3/h).

Heat recovery requirements

Requirements for *heat recovery systems* are rarely found in national building codes for dwellings.

Minimum performance requirements for heat recovery systems are in place in some countries (Sweden, Poland, Italy) when new mechanical ventilation systems are installed.

Airtightness requirements

Building *airtightness* requirements differ largely across the EU. Six of the surveyed MS already have precise requirements in place (Belgium, Denmark, France, Germany, Sweden and the United Kingdom). Likewise for ventilation, indicators for airtightness requirements vary throughout Europe (e.g. volume per hour, litres per second per m^2).

Default values for building airtightness differ from country to country, which reflects differences in building traditions and construction types. In some countries, a better airtightness than the default value can only be taken into account if proven by measurements (blower door test), whereas other countries also allow the use of quality management approaches (e.g. France).

There are countries with minimum requirements (e.g. Denmark and UK) and others with guidelines for maximum envelope leakage (e.g. Germany).

Random airtightness tests are required in Denmark and France (random check of minimum 5%, all from 2015), but are voluntary in the other surveyed countries and are usually required only for applications to receive financial subsidies, or energy certification in the high classes.

Due to different calculation methods in EU MS, measured airtightness data are not fully comparable.

Regulations for heat recovery and airtightness, mainly introduced for energy efficiency reasons, have to be complemented by relevant ventilation requirements in order to secure proper indoor living conditions.

Indoor pollutants requirements

EU MS and the World Health Organisation (WHO) have defined their own inhomogeneous set of benchmarks for indoor pollutants and other IAQ related indicators.

The national implementation of the EU Construction Products Regulation and further national standards address the emissions of a number of unhealthy chemicals, however, this legislation was not considered in the BPIE 2015 review.

Thermal comfort and daylight requirements

Aspects of thermal comfort related to low temperatures or draught are often improved through measures primarily addressed at improving the energy performance of a building. However, there is an increasing risk of overheating to be addressed. Therefore, thermal comfort should be acknowledged in building regulations and the use of simple and efficient measures, e.g. solar shading, solar protective glazing and ventilative cooling, should be encouraged.

In all countries surveyed, for new dwellings, there are minimum requirements in place for the *thermal transmittance* of external building elements, but only a few of them (i.e. Denmark, Sweden) underline the co-benefits of thermal comfort.

When major renovation is undertaken, the most common requirement across surveyed countries concerns the thermal transmittance of building elements (U-Values), as required by the EPBD.

Indoor air temperature is the most used indicator of thermal comfort in all countries surveyed and there are requirements and recommendations in place for lower and upper limits during winter and summer respectively for both new and existing dwellings. In a few countries such as France and the UK, operative temperature is also used to assess thermal comfort. Five out of eight countries require minimal temperatures in dwellings in winter (i.e. France, Germany, Poland, Sweden and the UK). Only Italy demands a lower limit in summer (max. cooling) and an upper limit in winter (max. heating).

Five countries within this survey (Br-Region/Belgium, Denmark, France, Germany and the UK) have *overheating limitations* (either mandatory or recommended), where overheating indicators differ by temperature and time limit. The extremes are found in the Brussels-Capital Region (> 25°C for 5%/yr) and the UK (> 28°C for 1%/yr), but only as recommendations in the latter case. Passive systems to avoid overheating are common in southern climates (Italy and France), but minimum requirements are mainly limited to solar shades while others such as ventilative cooling, use of building mass, natural ventilation, night time ventilation etc. are rarely considered. France and Italy include shading requirements also in cases of refurbishment.

In Sweden, the building codes explicitly ask for the consideration of some passive solutions. The new Brussels-Capital Region regulations, which will came in force from 2015, require a minimum share of 50% for passive systems. Leading examples in Europe are the French indicator "TIC" (Indoor Conventional Temperature) and the German "Sonneneintragskennwert" (Solar Transmittance Value), which takes several (passive) aspects into account.

Maximum *relative air velocity limits* are inconsistent in Europe; they range from 0.15 to 0.40 m/s (in summer) and from 0.15 to 0.25 m/s (in winter). In most countries, the relative air velocity does not depend on the air temperature.

Maximum values for air velocity in order to avoid draughts are required in Sweden and recommended in Denmark, Italy, Poland, the UK and Brussels (from 2015).

Recommendations concerning the *humidity* (in order to avoid water condensation or an air too dry) are given in Germany, Poland, Italy, Sweden and the UK.

Energy Balance requirements that include solar gains when assessing the energy performance of windows are included in the Danish and British building regulations. Considering solar gains together with the heat loss of a window provides a more comprehensive assessment of its energy performance.

Increased thermal comfort is often considered as a main driver for the decision of an owner-occupier to invest in renovation. However, thermal comfort results from improved energy performance are rarely captured by national and/or European legislation.

The use of *daylight* is an important element to achieve a good indoor environment in buildings, with a major impact on the health of inhabitants. Moreover, maximising the use of daylight in buildings offsets electric lighting and has a consistent energy saving potential. Acknowledging the importance of daylight use in buildings, all surveyed countries include at least a basic reference to it in their building codes. For new residential buildings, daylight requirements or recommendations in MS legislations mainly specify a minimum share of window/glazing area per floor area, indicate minimum levels for daylight or simply stipulate the need for sunlight access in buildings and a view to the outside.

As good practice, Danish building codes are the only ones requiring minimal solar gains in winter while the Swedish regulations recommend the use of daylight management systems for permanently installed luminaries. Only some building codes within the ones surveyed (i.e. Brussels-Capital Region, Denmark, Germany) highlight the importance of having a view to the outside as part of visual comfort.

Introducing requirements for daylight use in existing buildings can be more challenging, as possible interventions to further increase daylight availability may be limited due to structural aesthetic reasons.

The Danish regulations stipulate requirements for a minimal solar gain in winter when replacing windows. No requirements have been identified across the surveyed building codes stipulating minimal daylight preservation when renovating a building, except in the UK where the regulation Right to Light is in place. This regulation secures that changes to neighbouring buildings must not reduce daylight availability in existing buildings.

BPIE 2015 recommendations

- Indoor related health and comfort aspects should be considered to a greater extent in European building codes than it is current practice. When planning new NZEBs or NZEB refurbishments, requirements for a healthy and pleasant indoor environment should be included. While indoor climate is mentioned in the EPBD, strengthening the importance of indoor air quality, thermal comfort and daylight needs to be considered in the review of the EPBD. Such requirements should also be considered in national renovation strategies as developed under Articles 4 of the Energy Efficiency Directive.
- In EU and national legislation, stricter energy performance requirements should be completed with appropriate requirements and recommendations to secure proper indoor air quality, daylight and thermal comfort. For instance, requirements for stricter insulation and airtightness should be complemented by appropriate minimum requirements for indoor air exchange and ventilation. As there are several ways to obtain significant savings in energy consumption in buildings while at the same time improving the indoor climate, clear legislative provisions for conflicting situations will create certainty for planners and architects. At the same time legislation should be technology-neutral.
- Unused potentials for energy savings should be further exploited in European and national legislation taking a system-approach to the building. This means that the building's envelope and its insulation, use of daylight, demand-controlled ventilation, heat recovery through mechanical ventilation systems, installations to avoid overheating such as ventilative cooling and solar shading (e.g. by overhangs, louvers and awnings) should be analysed and optimised in a systematic way in order to achieve the highest energy saving possible.
- One option to consider as part of the revision of national or EU legislation on buildings is the integration of indoor air quality, thermal comfort and daylight indicators in Energy Performance Certification as relevant information regarding the actual living conditions in the building.
- The development of a proper cost indicator and calculation formula to estimate the benefits of a healthy indoor environment should be considered and further integrated in the European methodology to calculate cost-optimal levels at macroeconomic level.
- Co-benefits of a healthy indoor environment should be taken into account when assessing the macroeconomic impact of energy renovation measures (e.g. reduction of health service costs).
- Windows are elements of the building envelope and play an important role in the overall energy performance of the building. Therefore, thermal transmittance, daylight usage and solar gains should be considered in the overall energy performance of buildings, both for new and existing buildings undergoing energy renovation. Requirements for ventilation and to prevent overheating should be taken into account in the same context.
- Passive systems to avoid overheating are common in southern climates, but minimum requirements are mainly limited to solar shades. Additional measures, such as the management of glazing areas of the building envelope, dynamic external shading, consideration of solar gains and the use of building mass, natural

and night time ventilation strategies, etc. have to be further covered within national and European legislation.

- The mandatory compliance tools to evaluate energy performance according to national EPBD transposition should to a larger extent reward and facilitate the use of energy efficient ventilation solutions and measures to prevent overheating.

Examples of national building related regulations giving prominence to IAQ issues in relation to energy performance of buildings

- The *Swedish Building and Planning Regulation* stresses the potential conflicts between energy saving requirements and good indoor air quality in existing buildings with priority given to this latter. The modification of a building must not lead to lower energy performance unless there are exceptional circumstances (e.g. when other requirements have to be fulfilled such as providing good indoor comfort and air quality conditions). To fulfil these latter conditions, if necessary, might be adopted alternative solutions not complying with the new building requirements provided that that these alternative solutions can prove that they will effectively fulfil the conditions of good comfort and indoor air quality. During renovation of buildings also the building materials negatively affecting the indoor environment quality should be removed or their impact be reduced[51].
- The *Danish Buildings Regulation (BR10)*[52] addresses the importance of IAQ and ventilation by stating in Article 6.1(1) that: "Buildings must be constructed such that, under their intended operational conditions, a healthy, safe and comfortable indoor climate can be maintained in rooms occupied by any number of people for an extended period". Building materials must not emit gases, vapours, particles or ionising radiation that can result in an unhealthy indoor climate, yet materials with the lowest possible emissions of pollutants to the indoor climate should always be used according to the Danish Indoor Climate Labelling scheme.

  Moreover, ventilation systems must be designed, built, operated and maintained so to achieve their intended performance while in use throughout the building's lifetime. To guarantee this, BR10 specifically asks ventilation systems to be easy to maintain even by the inhabitants. Maintenance of ventilation systems should be done systematically via an easy and affordable procedure. Additionally, ventilation installations and ventilation openings leading directly to the external air must not transfer substances to the ventilated rooms, including microorganisms, which render the indoor climate unhealthy.
- In *Germany*, for refurbishments, besides the specific provisions of the German Technical Standard DIN 1946-6 on ventilation rates, there is also the general

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[51] BFS 2014:3 - BBR 21, 9:91. Planning and Building Regulation 2011-338 (chapter 3, paragraph 14) specifies also that both low energy consumption and satisfactory thermal comfort have to be guaranteed.

BFS 2014:3 - BBR 21, 6:9241. Air quality requirements may also demand a different approach for existing buildings according to the general advice in section 6:924.

BFS 2014:3 - BBR 21, 6:911. Materials in case of alteration of buildings, unless there are exceptional reasons to keep them.

[52] http://w2l.dk/file/155699/BR10_ENGLISH.pdf

requirement to provide a healthy indoor air climate. However, the responsibility for issuing the right recommendation on whether a (mandatory) energy saving measure requires additional changes in order to protect the building and the occupants’ health stays with the building planner and architect.

4. Compliance and Quality Control audits for energy efficiency and IAQ requirements in existing and new buildings

A critical factor for effective implementation of building energy codes is compliance checking and enforcement. EU MS need to check compliance and enforce their building energy codes to ensure that regulations on paper translate into action on the ground.

In principle and ideally, compliance should be assessed regularly during the design, construction stages, prior to the occupancy of the building and when the building is occupied for both new buildings and existing buildings being renovated or extended by using the indicators and methodology defined at the planning phase (IEA/UNDP, 2013).

Checking compliance in each of these four stages serves a different purpose and consequently has its own value.

Checking compliance *at the design stage* serves to see whether the project complies with building energy code requirements and also if the plans and materials submitted for construction permits comply with the requirements of the building energy code.

Checking compliance *at the construction stage* is needed to check whether the building was built according to the plans and the building code requirements. A number of inspections may be required during the construction phase and upon completion including reviewing of potential materials substitution compared to what was initially planned and of the test reports indicating the approval of the changes.

Check compliance *prior to the occupancy* of the building is needed before issuing occupancy permits to locate and fix potential leaks in the building envelope and test and check each building system.

Check compliance *after the building is occupied* is essential for at least a minimum number of years after the building's occupancy to check energy consumption and IAQ patterns also in relation to usage patterns so as to guide an informed potential adjustment of heating, cooling, ventilation and lighting patterns.

Compliance procedures for both new and existing residential buildings are mainly focusing on the structural analysis and energy performance aspects during the design and construction of new buildings such as U-Values, the right installation of heating equipment, airtightness, availability of EPCs, etc. Compliance with indoor air quality or thermal comfort standards is rarely checked by the designated control bodies and, if so, mainly at the design stage rather than by performing onsite measurements (BPIE, 2015). For existing buildings, compliance checks are only done on structural analysis and energy performance aspects, while no indoor air quality or thermal comfort verification procedures have been identified.

Concerning the compliance-checking procedures in place in the EU MS, Sweden represents one example of good practice, the salient features of which are summarised below with the aim to provide an insight of compliance control elements and steps that might be considered by other EU MS (within the boundaries of their national specificities, namely cultural, climatic, technological and economical) that either do not have their own procedures or they are going to revise the ones that are in place. Sweden has in place a compliance-checking procedure illustrating how to implement compliance checking that can be conducted during the operational phase of a building (Swedish National Board of Housing, Building and Planning, 2014).

The Swedish compliance-checking procedures include checking compliance two years after the building is occupied. For each new construction project, a meeting is held between the developer and the building board of the municipality to decide the compliance-checking procedure to consider. Three options are possible. The first option consists of compliance checking based on an estimate of the energy performance of the building. The second option consists of compliance checking of the measured energy consumption of the building two years after it is occupied. The third option is a combination of options one and two. For the first two years, the building board of the municipality gives the developer an interim permit of use. In case of non-compliance, the developer must stop using the building until corrections have been made. Developers usually pay a fine in the event of non-compliance. In addition to compliance checking after the building is occupied, an energy label (EPC) based on measured energy consumption is required two years after the occupancy of new buildings.

Besides Sweden, compliance and control checks in a few other EU MS (i.e. Belgium (Brussels Capital Region), Denmark, France, Germany, Italy, Poland and the UK (England and Wales)) are summarised in the BPIE report (BPIE, 2015).

It would be extremely useful and mutually beneficial to the EU MS to create at EU level a pool of best practice examples in the EU MS to show buildings' compliance and certification performance for energy-efficiency and IAQ together and associated costs within an economy of scale perspective while considering and reflecting national/local climatic conditions and other relevant specificities (e.g. cultural, technological and economical).

The EPBD obliges MS to avoid possible negative effects such as inadequate ventilation when setting requirements in line with Article 4. As such, the EPBD does not explicitly impose EU MS to set requirements regarding the indoor air quality in buildings. Several EU MS have started setting such requirements outside the context of the EPBD, while others are integrating IAQ requirements into those foreseen by the national legislation implementing the EPBD.

In Portugal, the National System for Energy and Indoor Air Quality Certification of Buildings (SCE) is based on a central registry and database. EPCs in public buildings are updated every six years. The IAQ part is updated depending on the building typology, varying from two years for critical typologies (e.g. schools, hospitals and nursing homes), to six years for other typologies. The Indoor Air Quality (IAQ) is a complementary issue in the Portuguese EPCs. For new buildings, legislation was based on a prescribed method to establish the ventilation requirements for indoor compartments, in terms of airflow rate per person and per unit of floor area. In the revised building codes, this aspect will be fine-tuned to ensure a good balance between IAQ and energy efficiency. For existing buildings, the requirements are based on maximum indoor air pollutant concentrations. In the new legislation, a two stage approach will be established: a first diagnosis based only on CO_2 and particles levels, followed by a full IAQ audit of a full set of pollutants if a certain threshold, of either CO_2 or particles, is exceeded. The inspection of boilers as well as air-conditioning (AC) systems is however still a challenging issue due to the specific climate characteristics of the country. In residential buildings the boilers and air-conditioners only operate for relatively short periods of time during the year, the real energy consumption is very low, and this hardly makes regular inspections a cost effective strategy (CA EPBD, 2012).

Nordic countries, having already included IAQ and ventilation requirements in building codes in the last decades, represent countries where EPBD requirements complement existing IAQ requirements. In those countries building codes include commissioning requirements and the IAQ compliance is approved via the ventilation flow rate measurement protocols when a new building or a major renovation of a building is handed over (Cao et al., 2012).

In France, there are no mandatory controls of IAQ in highly energy performing buildings. Nevertheless, the French IAQ observatory (OQAI) coordinated by the Scientific and Technical Centre for Building (CSTB) was mandated in 2011 to assess IAQ and comfort in new or refurbished highly energy performing buildings (Derbez et al., 2014). A permanent system of data collection was set up with the objective to produce an annual state of the knowledge on IAQ and comfort in these buildings.

The EU funded QUALICHeCK project (Maivel et al., 2015) has collected information on 4 technology areas (transmission characteristics, ventilation and air tightness, sustainable summer comfort technologies, renewables in multi-energy systems) from several field studies in nine EU MS (Austria, Belgium, Cyprus, Estonia, France, Greece, Romania, Spain, and Sweden). The analysis of the evidence collected show poor results in terms of compliance of the Energy Performance Certificates. In particular, these studies have reported significant and frequent discrepancies between declared and "determined as-per-the-rules" building characteristics in Energy Performance Certificates (EPC).

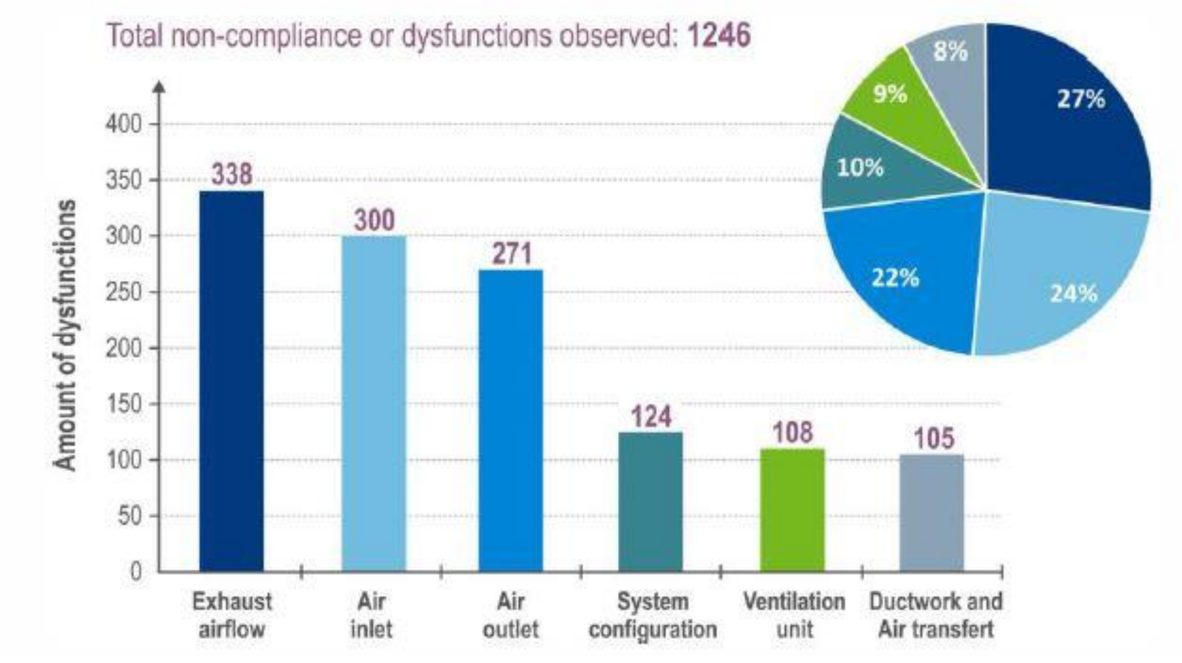

Figure 3.1 Number and type of residential ventilation related systems in France (Source: Jobert and Guyot (2011))

These observations confirm that the introduction of articles 18 and 27 as well as Annex II in the EPBD (concerning measures to be implemented such as independent control systems and penalties) has not been effective in setting boundary conditions in EU MS to secure consistency between what is effectively done and what is declared. Because energy performance regulations have become extremely strong market drivers, this leads to competition distortion and can discourage building professionals to deliver compliant buildings.

Regarding the quality of the works, there are also a number of studies showing evidence of poor workmanship, whereby several studies are related to HVAC systems. This can very severely affect the performance of Nearly Zero-Energy Buildings, not only in terms of energy performance but, even more important, also in terms of indoor climate.

In the frame of the French construction technical regulation observatory (ORTEC), the performances of 1246 residential ventilation systems in France were evaluated (Jobert and Guyot, 2011), Figure 3.1. A large number of non-compliances or dysfunctions were observed (non-compliance for 44% of the multi-family dwellings and 68% for the single-family dwellings).

The problem of often poor-performing ventilation installations is well known in a growing number of countries. The challenge is to take measures to substantially improve the current situation. An interesting case concerns the Netherlands. The Netherlands has experience with ventilation standards since the seventies and wide scale application of ventilation systems for many decades. Nevertheless, problems are often observed. In 2012 the conclusions of the major stakeholders concerned were that 50% of new residential ventilation systems do not perform well. It is in this context that the major stakeholders together with the Dutch government signed in 2012 a declaration by which the objective was to have in 2015 correctly working ventilation systems in the Dutch territory.

Facilitating enforcement and compliance

Based on the analysis of field studies and existing approaches performed within QUALICHeCK, to improve enforcement and compliance several aspects are considered relevant, including:

- At national or local level, frameworks for the compliance and quality of the works should clarify and efficiently implement three fundamental aspects:
    - *The procedures to achieve compliant buildings and prove compliance*
        - In the case of IAQ related systems, it means that there should be clear procedures for what has to be done in order to meet the specifications (e.g. the conditions under which the appropriate ventilation air flow rates have to be reached).
    - *The legal framework to check compliance*
        - In case compliance checks are done, it is important that the rules for such checks including their enforcement and related sanctions (penalties) in case of non-compliance should be clear and well documented.
    - *The enforcement in practice*
        - It is important to provide the necessary resources (both financial and technical) and ensure the political will to carry out appropriate control and enforcement procedures. Strong support of major stakeholders is crucial.

Experience shows that in many EU MS, one or several of these aspects are neglected and/or not efficiently implemented, often resulting in poor performances.

- Checking EPCs after completion of the works (as for instance in Austria, Belgium or France) has proved to be effective for resolving recurrent problems due to changes between the design and execution phases. This is valid for EPC related aspects in general, but also for HVAC and IAQ aspects.
- Standard formats to document the input data used to issue the EPCs and to report the results of energy calculations and ventilation performances make the EPC input data and the results documentation transparent (such as in Estonia).
- Automatic checks in the calculation software and/or during upload into the EPC database (Austria, Belgium).
- Databases of product data and catalogues of construction methods help ensuring that correct product data is used (such in Belgium and France).
- Dedicated responsibilities for testing, controls and reporting by qualified personnel and or certified bodies (e.g. voluntary certification schemes for construction workers and/or companies such in Belgium, France, or Romania). The importance of a 3rd party control is emphasised.
- Voluntary building certification schemes that require measurements and tests (e.g. in Austria and Spain) and mandatory inspection of the building service systems (e.g. in Cyprus, or Sweden).

In addition, although strict compliance frameworks can be very cost-effective and governmental measures can stimulate innovation (e.g. the Swedish example regarding ductwork airtightness), the overall support to such frameworks may strongly reduce if there is no appropriate framework for integrating innovative concepts (i.e. those not covered by standard procedures).

In March 2015, a 2-days workshop was organised by the QUALICHeCK project in Lund (Sweden) to discuss voluntary and regulatory frameworks to improve quality and compliance in EU MS. All presentations made during this event are available at the following website:
http://qualicheck-platform.eu/2015/06/workshop-lund-quality-and-compliance-of-ventilation-and-airtightness-files/.

Specific sessions were dedicated to the approaches of quality check and compliance in Belgium, France and Sweden.

The Swedish experiences in particular illustrate that it is possible to reach on a wide scale cost effective procedures for well-functioning ventilation systems. Of course, it is important to take the national/local context into account. A very important element is the societal support for imposing quality checks.

In the context of the QUALICHeCK project a source book on "Guidelines for better enforcement of EPC compliance" is under preparation (expected in March 2017) which will: (a) provide thorough analysis of the reasons for good/poor EPC compliance; (b) document a set of 'best practices' for easy access to compliant EPC input data as well as for better compliance and effective penalties. This is expected to provide guidance on how to tackle quality and compliance issues to help the effective implementation of the EPBD.

Extending compliance and quality control audits for Energy to include IAQ requirements for existing and new buildings

Bearing in mind that the ultimate objective of all building related policies should be to achieve sustainable buildings that are safe, healthy, energy-saving, and environmentally friendly, an extension of compliance and quality control audits for energy to include IAQ requirements is a foreseeable option ahead to be evaluated.

In this perspective, to ensure healthy built environments for their occupants, a high indoor environment quality (IEQ) has to be prepared during the design phase and to be maintained during the whole life of the building. Indoor air quality (IAQ) requirements are considered as a subset of the overall IEQ requirements and are progressively considered in various national monitoring programs in EU and 'green' building certifications worldwide.

Although the general/conceptual definition of 'green' buildings (also known as 'sustainable' buildings) (US EPA, 2014) does not offer a threshold distinction from conventional buildings (which often makes hard the task of distinguishing real green buildings from those employing "green" merely as a marketing tool), in the following we will briefly refer to them with a three-fold objective. First, to show the progressive consideration of IAQ pollutants indicators in various Green Building Certifications and the percentage these indicators are covering in each of the systems compared to the non-chemical based indicators (whereas a few years ago most performance indicators in these certifications were exclusively environmental based ones). Secondly, to see which are the most commonly considered IAQ priority pollutants in comparison with those in the WHO ambient and IAQ guidelines and other national related guidelines in Europe. Thirdly, to understand how and to what extent the three main pathways for IAQ management in buildings (i.e. emission source control, ventilation, and indoor air measurements) as promoted by the HEALTHVENT project (see Chapter 2 of the present report) were considered and implemented in green building schemes worldwide.

This analysis will indicate to what extent there exists common understanding and ground about IAQ management practices in buildings and consequently identify a minimum common set of indoor air chemical pollutants to consider as a starting point for a potential extension of existing energy auditing procedures to include IAQ monitoring auditing.

Wei et al. (2015) analysed how and to what extent indoor air quality (IAQ), as a subset of IEQ, is taken into account in existing green building certifications worldwide. IAQ requirements were reviewed in 31 green building certifications from 30 countries worldwide. These certification programs include 13 countries in Asia, 9 in Europe, 5 in Americas, 2 in Oceania, and 1 in Africa. Fifty-five green building schemes were selected from among the 31 certifications programs. Rating systems were found to be commonly used in green building schemes to evaluate the capability and level of a building to achieve life-cycle sustainability.

The average contribution of IAQ to green building schemes worldwide was found to be 7.5%. Volatile organic compounds (VOCs), formaldehyde, and carbon dioxide (CO_2) were the indoor air pollutants most frequently considered.

VOCs are taken into account in 26 (84%) of the green building certifications. In 21 certifications, VOCs are used to represent indoor chemical pollutants in general, and no specific compounds are identified in the category. In 5 certifications, VOC species are listed in detail, including compounds such as benzene and toluene. CO_2 is considered an indoor pollutant in 65% of the certifications. Asbestos pollution is taken into account in 45% of the certifications, not only for existing buildings but also for new construction. Microbes, such as fungi and bacteria, are considered in 32% of the certifications. The control of indoor airborne particle (PM_{10} or $PM_{2.5}$) concentrations is proposed in 16% of the certifications.

Ozone (O_3) and semi-volatile organic compounds (SVOCs) were mentioned in less than 6.7% of the certification schemes worldwide although deserve to be considered in a larger number of certifications due to their known negative health effects.

Emission source control, ventilation, and indoor air measurements were the three main pathways used in green building schemes for IAQ management.

All of the certifications included ventilation (by mechanical or natural means) as a way to manage IAQ but detailed requirements for ventilation vary greatly among different schemes. 39% of the green building certifications examined preferentially use the ASHRAE 62.1 standard to specify minimum ventilation rates whereas a total of 23% of the green building certifications, mostly in European countries, rely on EN 15251 and EN 13779 standards.

Emission source control was included in 77% of the certifications and is mainly targeted at building material emissions. However, emission source control pathways should be more widely considered, such as the reduction of emissions due to cleaning products and cleaning practices. Very few schemes consider this issue, possibly due to the lack of existing tools, standards and labels to characterize the VOC emissions from these products. Recently, such efforts were undertaken in Europe in the context of the DG SANCO funded EPHECT project (Emissions, Exposure Patterns and Health Effects of Consumer Products in the EU) (EPHECT, 2013).

Indoor air measurements were included in 65% of the certification schemes but may be optional. Indoor air measurement can take place before or during indoor occupancy, depending on the certification. There are 20 green building certifications comprising 25 schemes that propose indoor air measurements. In 21 schemes indoor air measurements are mandatory while in 4 others only optional. In the schemes that propose indoor air measurement, the thresholds of IAQ pollutants vary depending on the level of certification. Five pollutants of concern are indicated on every continent: CO_2, formaldehyde, TVOCs, CO, and PM_{10}. On average, three parameters are measured in each certification.

This study concluded that IAQ is taken into account in all the green building certifications considered, and equal emphasis is placed on the two major ways to improve IAQ: emission source control and ventilation. Nevertheless progress still needs to be made to harmonize the different approaches used worldwide including the indoor air sampling strategies, the standards and analytical methods used to perform the measurements, and the concentration thresholds (i.e. IAQ guidelines) used to qualify the monitoring results.

Although green buildings have the potential to promote more favourable indoor air quality, however "green" does not necessarily guarantee good indoor air quality (Steinemann et al., 2016). Certification schemes may provide inadequate incentive in the credit system for improving indoor air quality. Also, certain green practices and green products could actually impair indoor air quality. The focus on ventilation as a primary method for IAQ control overlooks opportunities for source control and exposure reduction.

Comparing the indoor air pollutants that are taken into account in WHO ambient and indoor air guidelines (WHO, 2010; WHO, 2014) (SO_2, airborne particles, NO_x, CO, CO_2, water vapour, mould spores, radon, pollen, lead, manganese, cadmium, mercury, arsenic, asbestos, ammonia, ozone, nicotine, acrolein, allergens, viable organisms, VOCs, polycyclic aromatic hydrocarbons (PAHs), formaldehyde, benzene, naphthalene, trichloroethylene, and tetrachloroethylene) it can be readily seen that the pollutants in the WHO guidelines that are also considered in green building certifications include: SO_2, NO_x, CO, CO_2, radon, asbestos, ammonia, ozone, nicotine, VOCs, formaldehyde, benzene, and particulate matter.

From the above, it can be therefore concluded, that there is a common basis for a potential extension of existing energy auditing procedures to include IAQ monitoring auditing. A number of the priority compounds linked to building related health and comfort concerns are commonly considered in both green building certifications and WHO ambient and IAQ guidelines and therefore this can form a common starting point for future building of IAQ monitoring auditing procedures and certificates.

The potential extension of energy control and compliance procedures and certificates to include IAQ auditing requirements can therefore be supported from the state-of-the-art scientific/technical knowledge, however, the challenging issue is how this can be done in a resource-efficient way especially when applied across the entire building stock (existing and new buildings) in EU. Bearing in mind that energy consumption in buildings accounts for a large share of the overall building operation budget and its reduction and control are desirable goals to achieve with high priority, therefore, any associated complex and/or frequent indoor air quality audits could be difficult to accept if not fully justified and economically afforded.

In this context, the potential extension of energy control and compliance procedures and certificates to include IAQ auditing requirements should be evaluated in strict connection with the buildings' IAQ management. Indoor air quality (IAQ) management can be made difficult not only by the large number and the diversity of indoor use spaces in a given building, but also due to the complex relationship of indoor air quality with the building's design, materials, behaviour of the building's occupants as well the buildings' systems operation and maintenance practices including ventilation.

Currently, none of the EU building related directives explicitly requires a monitoring and reporting plan for IAQ parameters. Consequently, no European wide systematic indoor air monitoring system is actually running following a harmonized process. Nevertheless, several indoor air monitoring studies in the EU have been performed in the framework of EU funded research projects (e.g. IAQ audit, EXPOLIS, PEOPLE, THADE, AIRMEX, SINPHONIE, OFFICAIR, etc.) or in the context of national monitoring programs in the EU MS (e.g. the German Environmental Survey (GerES), French Indoor Air Quality Observatory (Observatoire de la qualité de l'air intérieur), the FLIES study in Belgium (Flanders Indoor Air Exposure Survey), etc.). Standardised procedures and assessment protocols for IAQ have been described and adopted at national level in Portugal (integrated in the legislation on Building Performance Certification since 2006) and in Spain but not yet implemented on a systematic and European wide basis.

In the context of the DG SANCO funded and JRC co-ordinated PILOT INDOOR AIR MONIT project (Kephalopoulos et al., 2013) a harmonised framework was developed which consists of criteria, analytical methods and protocols for indoor air monitoring and investigation purposes for a number of priority chemicals in the EU. This framework differentiates among five main categories of indoor air monitoring objectives and tailors the criteria, analytical methods and investigation protocols according to the specific requirements of each objective and two levels of buildings' investigation (i.e. Level 1 corresponding to an ad hoc investigation of indoor air quality in one or a few particular buildings to meet a specific indoor air monitoring objective; Level 2 corresponding to a general investigation to characterise the IAQ for building stock that is relevant for population exposure within a large area, a country or multiple urban areas and countries).

The 5 main IAQ monitoring objectives considered in the PILOT INDOOR AIR MONIT project are the following:

- *Guidelines compliance*: IAQ monitoring to verify the (non-) compliance of a building or part of it with specific IAQ targets as those specified in national and international IAQ guidelines/regulations.
- *Health complaints*: IAQ monitoring in response to the emergency of symptom/health complaints in specific buildings.
- *Remediation effectiveness*: IAQ monitoring to evaluate the effectiveness of remedial actions in specific buildings.
- *Source attribution*: IAQ monitoring to enable the attribution of the indoor air contaminants to outdoor and indoor sources and to the activities of the building's occupants.
- *Surveys*: general investigation to characterize the IAQ situation for a limited but representative number of buildings pertaining to a given building typology via a number of selected IAQ parameters with the aim of establishing a baseline database concerning the specific IAQ situation. This baseline database can then be used to support follow-up studies within the same buildings' typologies also in relation to potential health effects of the building's occupants (e.g. schools, offices, etc.)

The IAQ auditing process is complex, quite often dealing with low concentrations which are moderated/influenced by the buildings' design, systems, location, potential pollution sources and operational and maintenance conditions. This implies the need for a clear definition of the objectives and proper characterization of the mandate and boundaries of the IAQ auditing process while guaranteeing the quality and comparability of the results at both EU and national levels.

In this perspective, each of the aforementioned objectives requires to be preceded by a tailored design and operational strategy that includes a proper selection of the various parameters including pollutants to be measured, standardized analytical techniques to be employed, survey designs (including standardised questionnaires), target locations for measuring exposure (e.g. schools, offices, private dwellings, day care centres, hospitals, transportation means), periods and frequencies of measurements, range and distributions of concentrations, target population groups (general public, susceptible groups, etc.), statistical tools for data evaluation and reporting accustomed across different categories of stakeholders (e.g. policy makers, scientific community, general public, etc.). Figure 3.2 graphically represents the types of building's indoor air quality monitoring objectives and the associated procedural steps to follow in designing and conducting an indoor air monitoring study for each IAQ audit typology according to PILOT INDOOR AIR MONIT project.

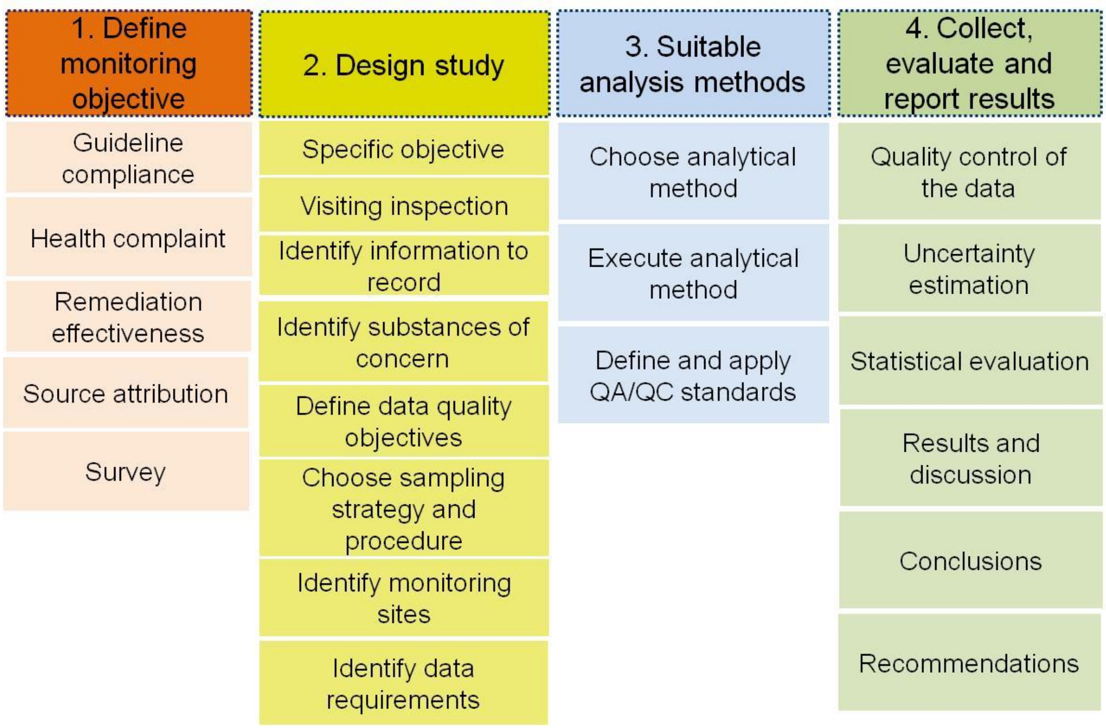

Figure 3.2 Schematic IAQ monitoring approach according to the PILOT INDOOR AIR MONIT project

In practice and in the perspective of a joint energy and IAQ audit process, the IAQ audit typologies which can be mostly considered are those corresponding to the PILOT INDOOR AIR MONIT objectives 1 ('Guidelines compliance') and 5 ('Surveys') which combined with a radical 'source control' approach (e.g. choosing low emission construction materials as recommended by the HEALTHVENT project) should be addressed and implemented since the early stage of the building's project phase.

The 'Guideline compliance' and 'Surveys' criteria and parameters should be tailored differently for new and existing buildings and be operated in a resource-efficient and rational way so that the audit and compliance control process can be successfully and efficiently implemented at affordable cost (e.g. over a statistically representative fraction of the overall building stock for a specific building typology; number of evaluations during the building's design and operational phases; the periodicity of the control checks, for example, every five years for buildings without complaints or every two years for buildings where complaints have been already registered as part of a surveillance procedure; the minimum number of IAQ parameters to monitor depending on the sources and activities performed inside the building, whether complaints have been already registered in case of existing buildings and whether in the buildings are living or working vulnerable population groups).

Buildings that have been included in surveys or other IAQ related projects/studies at EU or national levels, could be exempted from undergoing the periodic audits during that period, if no specific problems were detected provided that the survey data of these studies are streamlined and made available via the recently developed/planned European Commission's relevant data portals and knowledge systems (i.e. DG ENV's IPCHEM module 4 on 'Products and Indoor Air Monitoring' data (https://ipchem.jrc.ec.europa.eu/RDSIdiscovery/ipchem/index.html) and the DG JRC's European Energy Efficiency Platform Portal – E^{3}P (http://e3p-beta.jrc.nl/).

IPCHEM is an initiative by the European Commission (DG ENV) in close co-operation with the European Environment Agency and the European Food Safety Authority and technically supported and coordinated by the European Commission's Joint Research Centre. IPCHEM offers a single access point for locating and retrieving chemical occurrence data across all media (environment, humans, food/feed, indoor air and products) in the European Union and its ultimate objective is to improve the quality and comparability of chemical monitoring data. It will enable better risk assessment of chemicals and chemical mixtures and greater linking of chemical monitoring data with the understanding of their effects on human health and the environment. It will also facilitate harmonisation and standardisation practices across its modules (human bio-monitoring data, environmental data, food and feed data, indoor air monitoring and products data).

The DG JRC's E^{3}P portal will provide scientific support to the current and future EU energy efficiency policies, to the 2020 strategy and the forthcoming 2030 climate and energy strategy. This initiative will reinforce cooperation among and provide a unified point of reference for relevant stakeholders. It will rely on a constantly updated and integrated repository of projects, data outcomes and competences throughout EU. Moreover, through an integrated approach, based on different thematic areas and selected flagship initiatives (one of them being on Buildings), the EU decision-making dealing with buildings' energy performance will be supported.

When combining energy performance compliance with IAQ audits this should be done in line with the criteria and parameters specified in the revised standard prEN 16798-1 (CEN, 2015). This pre-standard is a revision of EN 15251-2007 which specifies indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. The revised standard specifies how design criteria shall be established and used for dimensioning of systems, heating, cooling, ventilation and lighting systems. It defines how to establish and define the main parameters to be used as input for building energy calculation and short- and long-term evaluation of the indoor environment. Finally this standard will identify parameters to be used for monitoring and displaying of the indoor environment as recommended in the EPBD.

Different categories of criteria may be used depending on the type of building, type of occupants, type of climate and national conditions. This standard specifies several different categories of indoor environment, which could be selected for the space to be conditioned. These different categories can be used for design and may also be used to give an overall, yearly evaluation of the indoor environment by evaluating the percentage of time in each category. These criteria are, however, mainly for dimensioning of building, heating, cooling and ventilation systems. They may not be used directly for energy calculations and year-round evaluation of the indoor thermal environment. Studies have shown that occupant expectations in naturally ventilated buildings may differ from conditioned buildings, which will be part of this standard. However, it's up to national regulations or individual project specifications to define the exact criteria to be used.

Criteria specified in national building codes for design and dimensioning of systems must be used. The standard prEN 16798-1 gives, in informative annexes, recommended input values for use in cases where no national regulations are available.

According to prEN 16798-1, IAQ shall be controlled by one or more of the following means: source control, ventilation, filtration, air cleaning. Source control shall be the primary strategy for controlling the level of air pollutants (which is in line with the HEALTHVENT project's approach and recommendations). The design requirements for the ventilation air flow rates shall take into account the pollutant emissions rates left after source control. For diluting pollutant emissions from buildings, the total ventilation rate must never be lower than 4 l/s per person, which corresponds to the base health based ventilation rate proposed by HEALTHVENT (that accounts for the dilution of the bio-effluent emissions of the building's occupants). However, it should be stressed that in the latter case this base rate accounts only for emissions from the human bio-effluents and no other pollution sources (i.e. stemming from building materials or from the outdoor air). Ventilation air flow rates in naturally ventilated buildings shall be calculated based on building layout, location and weather conditions according to EN 15242 or with dynamic thermal simulation tools. In Annex A6 of the prEN 16798-1, WHO guidelines values for indoor and outdoor pollutants are recommended.

5. Data collection initiatives in EU MS on IAQ, thermal comfort and health in highly energy performing buildings

The importance of Indoor Air Quality (IAQ) for the health, thermal comfort and productivity of the building's occupants and the way to consider it within the holistic concept of buildings sustainability was framed and explained in Chapter 2 of the present report. The interplay among IAQ sources, ventilation practices and systems, building characteristics and operational conditions (while accounting for regional climate differences) is crucial for the EU MS to properly consider and efficiently implement in practice via appropriate plans and building codes and thereby adequately and successfully address the challenge of meeting the EPBD energy performance requirements, while in parallel ensuring good IAQ, comfort and health conditions for the buildings' occupants.

Buildings are progressively built in EU with much higher airtightness requirements in order to prevent uncontrolled ventilation heat losses. In order to satisfy energy performance and ventilation requirements, the mechanical ventilation systems are increasingly used. Moving from buildings with infiltration rate by air leakage to airtight buildings mainly mechanically ventilated is a large step change in terms of culture and needs to be implemented with caution and only if justified and necessary bearing in mind differences in climatic zones and also cultural, social, technological and economical peculiarities at national and local levels.

There are increasing concerns regarding the impact of the airtight construction on health and well-being of the occupants such as the possible degradation of the indoor environment quality (IEQ), the effectiveness of the mechanical ventilation system in maintaining healthy indoor environment and the potential impact of occupants behaviour on the operation of the buildings' equipment (ventilation, heating, cooling, etc.).

Improving energy performance in buildings generally improves the indoor environment; however, if energy performance measures are implemented incorrectly, they can have negative impacts on IAQ and thus on health and well-being. The risks can, and should, be carefully managed. Implementing a holistic approach to building's sustainability interventions can avoid the potential energy performance and health related pitfalls (see Chapter 2).

Evidence on the impacts on IAQ, comfort and health of highly energy performing buildings is rather limited compared to conventional buildings that have received substantially more attention. In Europe, data collection initiatives and projects (e.g. national monitoring surveys) on IAQ, thermal comfort and health in highly energy performing buildings involving EU MS and other relevant stakeholders have been undertaken progressively in the recent years but are still limited in number and not performed in a co-ordinated way at EU level. In the first part of chapter 5 the main outcomes of the most relevant projects and initiatives in EU (as well as in North America) will be reported and analysed to demonstrate the potential impact (improvement or deterioration) on IAQ, thermal comfort and health conditions in newly constructed or renovated buildings in the EU as result of the interplay of the aforementioned factors. Studies conducted in other regions were not included, although they may have added to the general evidence base for Europe if the impact of construction type, climate and cultural differences could be distinguished.

Modelling efforts suggest that both improved energy performance and good IAQ and thermal comfort conditions can be achieved (see examples in the last sections of Chapter 5 of the present report), however, only limited data are available on whether this is truly achieved in practice and even less for highly energy performing buildings, such as deep energy retrofit or net zero-energy buildings (Bone et al., 2010; Howieson et al, 2014; Lubeck et al., 2010; Crump et al., 2009; Hemsath et al., 2012). Several studies have explored the relationship between energy performing homes and occupant health. Most of the studies reviewed in the context of Task 13.3 report health benefits in highly energy performing homes (Breysse, et al., 2015; Breysse et al., 2011; Colton et al., 2014; Garland et al., 2013; Howden- Chapman et al., 2011; Jacobs et al., 2015; Jacobs et al., 2014; Leech et al., 2004), although Sharpe et al. report higher physician-diagnosed adult asthma cases among those living in energy performing dwellings in UK (Sharpe et al., 2015). A recent meta-analysis by Maidment et al. found a small, but statistically significant improvement in health associated with energy performing housing, but also acknowledged the need for additional research in this area (Maidment et al., 2014). Recipients on low incomes saw greater improvements in health following energy performance interventions, supporting the inclusion of energy performance measures in strategies to tackle social issues like fuel poverty and health inequity. Vardoulakis et al. (2015) reviewed the possible impact of climate change in terms of direct and indirect adverse health effects in the indoor environment in UK, focussing on building overheating, indoor air pollution and biological contamination.

Regarding IAQ, there is a dearth of information relating to highly performing structures as pointed out by the extensive literature review (over 100 references and publications) on indoor air quality (IAQ) in highly energy performing houses world-wide (Crump et al, 2009). In the same review it is noted that is difficult to extrapolate the results of studies of the construction of airtight buildings in colder climates (Canada, Central Europe and Northern America) to other countries because of differences in climate, construction practices, specify of indoor sources in buildings as well as the social and economic conditions of the buildings' occupants.

Finally, a small number of studies in Europe have investigated indicators of IAQ, but none has conducted an IAQ longitudinal survey and compared their results with those of standard buildings except the case of the recently established French national data collection system on IAQ and comfort in highly energy performing buildings (Derbez et al., 2014). The evidence and analysis provided in Chapter 5 of the present report should be therefore strictly seen in the context of the aforementioned limited evidence and difficulties to extrapolate the results of the surveys from one European region to another and from one continent to another.

European studies

In Europe, the French system was put in place in the context of the mandate given to the French IAQ observatory (OQAI) which is coordinated by the Scientific and Technical Building Centre (CSTB) to assess indoor air quality (IAQ) and comfort in French highly energy performing buildings. A permanent system of data collection was set up with the development of a common standardised set of protocols and a national database. This system is a unique tool that will make it possible to follow the deployment of low-energy buildings in real-time regarding indoor air quality and comfort. The indoor environment quality of new and renovated buildings is being evaluated and compared with existing housing stock. The outcome of the investigations provides informed advice for better design, implementation and management of the French building stock. The national data collection system targets all new buildings built after January 1st 2013 in compliance with the French 2012 Thermal Regulation (RT2012). Refurbished buildings with the French energy performance label (Effinergie-Rénovation) or equivalent are also included. Residential and non-residential highly energy performing buildings are targeted. To date, two types of non-residential buildings (educational and offices) are included. In the future, other types of buildings will be investigated like retirement homes, commercial buildings, hospitals, etc.

Over the year 2013, more than 100 buildings (mainly residential buildings) were investigated in association with the PREBAT (program for research and experimentation on energy conservation in buildings) in different regions of France. From mid-2014, OQAI will analyse periodically the collected data and publish reports on key performance indicators regarding IAQ and comfort in low-energy buildings. The results for new and renovated residential buildings will be compared with the IAQ in standard French dwellings.

In a field survey that was carried out by Derbez et al. (2014a) in seven newly built highly energy performing houses in France several indoor air quality indicators (total volatile organic compounds, volatile organic compounds, aldehydes, carbon monoxide, particulate matter less than 2.5 µm in diameter ($PM_{2.5}$) and radon) and other thermal comfort and indoor environmental parameters (CO_2, temperature, relative humidity and noise) were measured before and during the houses' first year of occupancy. The air exchange per hour (ACH) and air exhaust rate were measured simultaneously, and the perceptions of the occupants were evaluated via a questionnaire. The air changes per hour (ACH) for mechanical ventilation with heat recovery (MVHR) homes were measured and compared to those of standard French homes. The air-exhaust rates were compared to the French standards for minimal airflow for dwellings according to the number of habitable rooms.

The results showed that the levels of aromatic hydrocarbons, terpenes, alkanes and aldehydes were higher before occupancy than during occupancy, whereas the opposite trend was observed for $PM_{2.5}$. During occupation, the concentrations of acetaldehyde, alpha-pinene, ethylbenzene, limonene, styrene, toluene and xylenes decreased, most likely because of the decrease in emissions sources from the houses. At the same time, the levels of benzene, formaldehyde, hexaldehyde, n-decane and n-undecane temporarily increased because of human activities. The $PM_{2.5}$ levels showed seasonal variation. Compared to the IAQ of standard French houses, the median concentrations of benzene, ethylbenzene, m- and p-xylenes, $PM_{2.5}$ and radon were lower in the houses studied, whereas the CO_2 and formaldehyde levels were not significantly different. In contrast, the levels of acetaldehyde, hexaldehyde, n-decane, n-undecane, o-xylene and styrene were higher in these new homes, possibly because of the emissions from products and materials. The levels of indoor pollutants in the study houses were within the guideline values for indoor air quality used in France, but the $PM_{2.5}$ level exceeded the levels set by WHO recommendations.

MVHR systems exhibited commonly reported shortcomings but provided sufficient ACH (0.5 h^{-1} or higher), making the air drier. The systems proved to be difficult to use, and high noise levels were produced at the highest fan speed. It was found that in airtight buildings the mechanical ventilation systems need to operate constantly because if they shut down without ventilation through open windows indoor air quality becomes poor and presents a potential risk to human health.

In order to improve the knowledge of the indoor environment quality of highly energy performing buildings, Derbez et al. (2014b) conducted a 3-year follow-up study in two wooden-framed low-energy single-family houses in France. In this study several indoor air indicators and indoor environmental parameters were measured during seven weeks in total from the pre-occupancy stage up to three years of occupancy. Questionnaires were used for each investigation to record the family activities and perceived comfort of occupants. The ventilation systems presented some shortcomings, including the failure to reach the designed exhaust air flow rate and induced occupant dissatisfaction. Regarding the measured pollutants, both houses did not present any specific indoor air pollution. The variability of IAQ over time was explained by the high emissions from the new building materials, products, and paints during the first months after completion and then more episodically by human activities during occupancy. Regarding the thermal comfort, even if occupants were globally satisfied, overheating and under-heating conditions were observed. The authors concluded that in order to guarantee the health and the well-being of occupants in these buildings, it would be useful to integrate solar shadings at the very first stage of the building design, to design more quiet, user-friendly and robust ventilation systems and to implement mandatory inspection as well as frequent maintenance by professionals and finally to promote the labelling of low-emitting construction and decoration products, furniture and consumer products. No direct relationship between IAQ and energy performance has been observed in this study.

Within the MERMAID study (Verriele et al., 2015) indoor air quality was characterised in 10 recently built highly energy performing French schools during two periods (occupied and unoccupied conditions) of 4.5 days. The objectives of this study were to determine the respective contributions to indoor air pollutants of the building itself, of outdoor air intake, and of the impact of occupants' presence and activities but also to check for possible differences with conventional buildings, based on previously published data. The study did not reveal any significant differences in the chemical footprints between recently built, highly energy performing school buildings and conventional buildings, but highlighted the main sources of pollution and the key role of ventilation in these new buildings. Average measurements permitted identification of high contributions from human and activity sources.

The INSULAtE project, which is co-financed by EU Life+ programme and Finnish Energy Industries, focuses on assessment of national policies developed in order to fulfil the EPBD aiming to maximise energy performance for new and renovated buildings. The project aims to develop a comprehensive protocol for assessment of the impacts of energy efficiency on IEQ and health. Two north-east European countries are involved (Finland and Lithuania). So far, measurement data on IEQ parameters (PM, CO, CO_2, VOCs, formaldehyde, NO_2, radon, T and RH) and questionnaire data from occupants were collected from 16 multifamily buildings (94 apartments) in Finland and 20 (96 apartments) in Lithuania before renovation (Du et al., 2015). Post-renovation measurement data has not yet been published.

Kauneliene et al. investigated the indoor environment of 11 newly built low-energy residential buildings in Lithuania (Kauneliene et al., 2016). Temperature, relative humidity, the concentrations of CO_2, NO_2, formaldehyde, volatile organic compounds (VOC), and semi-volatile organic compounds (SVOC, i.e. PAHs, PCBs, HCB) were measured. Despite of the low air exchange rate in most buildings (0.08-0.69 h^{-1}), CO_2 and many monitored VOC and SVOC concentrations were at typical indoor levels, while the concentration of formaldehyde (3.3-52.3 μg/m^3) was elevated above the Lithuanian limit value. In several buildings, extremely high concentrations of VOCs were observed where the installation of interior surfaces and furnishing were done shortly prior the measurement campaign. Decrease of benzene, toluene, ethylbenzene and xylene (BTEX) sum concentrations was rapid and fell below Lithuanian limit values in one month. This study demonstrates the importance of checking indoor air quality before occupancy and avoiding moving into buildings before the complete installation of the interior. Selection of low-emitting building and finishing materials, furniture, cleaning products and ensuring effective work of mechanical ventilation will contribute to good indoor air quality in low-energy buildings.

In a recently built 'Passive House' in the UK solely ventilated with trickle ventilators (Howieson et al., 2014) measured CO_2 concentrations (as proxy indicator of IAQ) in occupied bedrooms (with bedroom-doors closed) that were found to be unacceptably elevated (occupied mean peak of 2317 ppm and a time weighted average of 1834 ppm, range 480–4800 ppm). The authors concluded that dwellings (which have been built to the prescribed standards for air tightness - 5m^3/m^2/h@50 Pa) with only trickle ventilators as the 'planned' ventilation strategy do not meet the standards demanded by the Building Regulations due to under-ventilation. This clearly calls for an implementation of post occupancy evaluation of the dwellings. Moreover, the authors of the study recommended that reliance on trickle ventilators to provide background ventilation in airtight buildings should be reconsidered, with a greater emphasis placed on the planning and prediction of overall house ventilation strategies, taking into account, either solely or in combination, cross, stack, permanent, displacement and mechanical ventilation.

Ghita and Catalina aimed at jointly investigating the indoor environmental quality (IEQ) (i.e. thermal comfort, IAQ, lighting and acoustics conditions) in Romanian countryside schools with high energy performance (Ghita and Catalina, 2015). They investigated three different types of rural schools (old, new, and renovated) located for comparison purposes within a radius of 2.5 km from each other. In terms of indoor air quality all three buildings performed poorly, registering average CO_2 concentrations in excess of 2000–3000 ppm and even approaching the health hazard level of 5000 ppm. Based on these concentrations, the corresponding ventilation rates were calculated being 2.4 L/s/person (renovated school), 2.25 L/s/person (new school) and 0.7 L/s/person (old school). The IEQ index was calculated using the experimental data allowing the three analysed schools to be better rated. The new and renovated buildings rank class C on the IEQ index scale and class A from an energy consumption standpoint, whereas the old building is rated D class (IEQ) and C class (energy performance). The authors concluded that high energy consumption, as was the case for the old school, does not necessarily result in better comfort conditions despite their inverse correlation in this case. They also concluded that relying solely on natural ventilation is insufficient to meet the norms on IAQ.

Langer et al. investigated IAQ in passive and conventional new houses in Sweden (Langer et al., 2015). The indoor environment was evaluated in 20 new passive houses and 21 new conventionally built houses during the 2012/2013 and 2013/2014 heating seasons. Temperature, relative humidity (RH), the concentrations of NO_2, ozone, formaldehyde, volatile organic compounds (VOC) and viable microbiological flora were measured. Air exchange rates (AER) were estimated from the CO_2 concentrations measured in the bedrooms. The median AER was slightly higher in the passive houses than in the conventional ones (0.68 h^{-1} vs. 0.60 h^{-1}).

The authors concluded that the quality of the indoor environment in the newly built passive dwellings was comparable to, or better than in, the conventionally built new houses and the Swedish housing stock. Significantly lower relative humidity was found in the passive houses compared to the conventionally built houses. Formaldehyde concentrations were significantly lower in the passive houses than in the conventional ones and in the housing stock. TVOC concentrations were significantly higher than in the conventional houses, but were not significantly different from the housing stock. The concentrations of NO_2 were similar in the two building types, although they were higher in both compared to the housing stock. The high indoor-to outdoor ratios of NO_2 indicated the presence of indoor combustion sources. The good IAQ in the investigated new buildings can be explained by the relatively high air exchange rates achieved by mechanical ventilation, which was used in all of the buildings. The absence of microbiological flora related to mould growth or water-damage in the passive houses, as opposed to several of the newly built conventional houses, further indicates that comfortable and healthy passive houses are attainable. The authors underline that the results of this study should however not be generalized for all newly built passive and conventional residential buildings.

Holopainen et al. conducted a study in which they determined how occupants perceived indoor environment quality in five low-energy and five conventional houses in Finland (Holopainen et al., 2015). The assessment was done by filling questionnaires.

Occupants perceived indoor environment quality as slightly better in the low-energy houses than in the conventional houses. The occupants of the conventional houses more often complained about draught, high or varying room temperature, stuffy and dry air, insufficient ventilation, unpleasant odours, or dim light in the winter than the occupants of the low-energy houses. However, too high and varying room temperatures were the most commonly reported unsatisfactory indoor environment factors in both the low-energy and conventional houses in the winter and summer. Therefore, correct room temperature was an important factor for primary energy use and perceived indoor environment quality in the houses. The measured air change rate did not fulfil the given minimum value in four of the low-energy houses and four of the conventional houses. The differences between the perceived environment quality of the low energy and conventional houses were higher in the winter than in the summer.

Wallner et al. conducted a large-scale study in Austria on Indoor Environmental Quality in mechanically ventilated with heat recovery systems in highly energy performing buildings vs. conventional buildings. Both types of houses investigated (highly energy performing with mechanical ventilation vs. conventional) were built at almost the same time (Wallner et al, 2015). After 3 months of occupation, they were investigated living and bedrooms in 123 buildings (62 highly energy performing and 61 conventional buildings) built in the years 2010 to 2012 in Austria (mainly Vienna and Lower Austria). Measurements of indoor parameters (CO_2 as ventilation parameter, temperature, humidity, chemical pollutants, biological contaminants, radon, air flow rates and noise) were conducted twice. In total, more than 3000 measurements were performed. This study shows that IAQ in highly energy performing new houses (private homes, with mechanical ventilation) was higher than in conventional new buildings. This was true for almost all investigated parameters like, inter alia, TVOC, aldehydes, CO_2, radon, and mould spores. The authors recommended investigating the mechanically ventilated properties again, in e.g. 5 years, to see whether the maintenance regimes concerning the air ducts have an influence on IAQ.

A study by Coutalides et al. in Austria showed significant differences between quality-assured and not quality-assured buildings, in terms of total VOC concentrations in properties in which measurements were made between 30 and 100 days after building completion, albeit before anyone moved in and before the installation of furniture (Coutalides et al., 2014). In properties where building was carried out with construction supervision, a median value TVOC of 480 µg/m^3 was found, for properties without construction supervision it was 1100 µg/m^3.

Peper et al. monitored a Passive House school and day-care centre over more than two and a half years in Frankfurt a.M. (Germany) (Peper et al., 2008). Results of this study showed comfortable indoor climate and good air quality. The space heat consumption was low and showed savings of approximately 90 % as compared to average existing schools. Excellent performance was also achieved in terms of primary energy.

Milner et al. (Milner et al., 2014) investigated the effect of reducing home ventilation as part of household energy efficiency measures on deaths from radon related lung cancer. The study entailed two main components: building physics modelling of current and future radon levels in the housing stock of England, and a health impact model for lung cancer mortality based on a life table method. Results showed that increasing the air tightness of dwellings (without compensatory purpose-provided ventilation) increased mean indoor radon concentrations by an estimated 56.6%, from 21.2 becquerels per cubic metre (Bq/m^3) to 33.2 Bq/m^3. The increases in radon levels for the millions of homes that would contribute most of the additional burden proved to be below the threshold at which radon remediation measures are cost effective. Fitting extraction fans and trickle ventilators to restore ventilation would help offset the additional burden but only if the ventilation related energy efficiency gains are lost. Mechanical ventilation systems with heat recovery would lower radon levels and the risk of cancer while maintaining the advantage of energy performance for the most airtight dwellings, however there is potential for a major adverse impact on health if such systems fail.

Published in January 2012, Zero Carbon Hub's report on 'Mechanical ventilation with heat recovery in new homes' (Zero Carbon Hub, 2012) summarises the main outcomes of a study in which the Ventilation and Indoor Air Quality Task Group has been reviewing the health implications that can be associated with poor indoor air quality, against a background of new homes becoming much more airtight. Specifically it reviewed current practice in relation to mechanical ventilation with heat recovery and evidence from homes in which it has been installed. The study reports failures in design, installation and commissioning. In particular, the report identifies problems with the design and provision of controls to enable the system to be operated correctly and with the location of MVHR units, particularly in roof spaces, where access for user-maintenance is restricted. The Task Group's interim report recommends that MVHR practice must change substantially to ensure that systems are designed, installed and commissioned correctly. It also points to the importance of fully taking into account the needs of the consumer in good system design, providing appropriate controls and making sure that there are proper arrangements for on-going maintenance.

The NHBC Foundation published a report in 2013 (Report NF52) (Dengel and Swainson, 2013) that presents the findings from a two-year research project carried out by BRE entailing assessment and monitoring of 10 zero carbon Code for Sustainable Homes

Code (CSH) Level 6 homes at Scottish and Southern Energy's (SSE's) Greenwatt Way development at Chalvey, near Slough, Berkshire. The project was conceived in response to concerns highlighted through the review paper on indoor air quality in highly energy performing homes regarding the possible adverse consequences of increased airtightness in highly energy performing homes on the quality of the indoor environment (Crump et al., 2009).

These homes studied during construction and then monitored for a period of almost two years post-occupancy provided a perfect test bed for the detailed evaluation of MVHR systems in practice. In addition to continuous monitoring of temperature, humidity and power consumption by the mechanical ventilation and heat recovery (MVHR) systems, periodic testing of indoor air quality and airtightness was carried out. This project also allowed obtaining occupant feedback and to gauge perceptions of living in the zero carbon homes by use of questionnaires, walk-through interviews and focus groups. It largely involved assessment and evaluation of MVHR systems, taking in design, procurement, installation, commissioning, performance, maintenance and occupant perceptions. After approximately one year of occupation, nine of the MVHR fan units were re-commissioned and changes made to room inlet air valves and air filters. In one home the MVHR fan unit was replaced and changes were made to sections of ductwork and its insulation. As a result of pre- and post-monitoring these interventions provided more insights into operation of MVHR systems in airtight homes.

The main findings in connection with MVHR systems were the following: It is critical that the overall ventilation strategy is taken into consideration during the design stage when intending to use MVHR systems in homes. During the procurement process it is important to seek technical input from the supplier and installer of MVHR systems. MVHR systems should be installed by trained and experienced installers. Commissioning of MVHR systems must be fit for purpose. Factors likely to adversely affect the power consumption by MVHR fan units during operation and the thermal performance of MVHR systems in operation must be considered. Successful measures may be taken to increase the performance of MVHR systems and to reduce noise levels associated with their operation.

Occupant feedback regarding living in the homes and general comfort was mainly positive, with levels of satisfaction tending to increase over time as the homes and their MVHR systems became more familiar. Much of the negative feedback associated with ventilation, thermal comfort and internal noise could be attributed to MVHR systems, including issues with perceived lack of control, temperature differences between storeys, experiences of draughts from cool air dumping and levels of mechanical noise.

Measurements made across the post-occupancy period showed the air quality in the homes to be generally acceptable. This was borne out in the occupant feedback, which indicated good air quality and highlighted only sporadic cases of perceived 'stuffiness', which appeared to be due to issues associated with the MVHR system at certain times of year. Elevated levels of VOCs and formaldehyde persisted for up to six months after completion of construction but generally decreased with time. As expected, as the occupancy phase proceeded the main VOCs found in the air were those associated with occupant activities and use of consumer products. Cooking tests suggested that source control and ability to achieve purge ventilation, particularly in cases where the MVHR system is not in operation or fails, are important in order to maintain good IAQ.

One of the first detailed and prolonged monitoring studies into the performance of correctly fitted ventilation systems in terms of indoor air quality and related energy performance was carried out in the period 2012-2015 in the context of the MONICAIR[53] project (Van Holsteijn et al., 2015). MONICAIR is a precompetitive field research project of a broad consortium of Dutch ventilation unit manufacturers and research institutes, supported by the Dutch government. The aim was to investigate in real-life conditions the performance in terms of indoor air quality (IAQ) and energy consumption of ten different mechanical ventilation solutions in dwellings that meet strict air-tightness standards and comply with current building regulations.

Over a whole year the habitable individual rooms of 62 residential dwellings were monitored every five minutes via sensors in terms of occupancy, CO_2 concentrations (as indicator of the IAQ performance), relative humidity and air temperature. The study also continuously measured mechanical airflow rates and the real-life energy consumption of the mechanical ventilation units.

One of the main conclusions of this project was that the implicit assumption that all code compliant ventilation systems perform comparably in terms of IAQ could not be substantiated. Significant differences related to the IAQ performances were identified which the existing legal framework currently does not assess. Only the energy performance of ventilation systems is assessed. Moreover it was showed that the real-life energy related performance of ventilation systems can differ with the results of the methodologies applied to calculate the energy performance of buildings, in particular how the characteristics of the ventilation systems are taken into account. Because low ventilation rates reduce the energy needs for heating and cooling, the energy performance and the IAQ of buildings can be seen as conflicting targets. Therefore, a true representation of the ventilation systems can only be given with a proper assessment of both IAQ and energy performances.

Maidment et al. systematically reviewed studies investigating the impact of household energy performance interventions (e.g. the installation of double-glazing) on the physical health (e.g. respiratory health) and mental wellbeing of building occupants (Maidment et al., 2014). To this end thirty-six primary research studies with a combined sample of over thirty thousand participants were meta-analysed. A small, but significant and positive, effect of household energy performance interventions on health was found. Significant health benefits were identified for children in particular and for people with poor health and vulnerable groups in general, supporting the continued use of household energy performance improvements to tackle fuel poverty and reduce health inequalities, rather than purely as a tool for carbon reduction.

A paper published by Gilbertson et al. (Gilbertson et al., 2006) reports the results of research carried out as part of the national health impact evaluation of the Warm Front Scheme, a government initiative aimed at alleviating fuel poverty in England. Semi-structured interviews were carried out in a purposive sample of 29 households, which received home energy improvements. Each household had received installation, replacement or refurbishment of the heating system and, in some cases, also insulation of the cavity wall or loft or both, and draught-proofing measures. Most householders reported improved and more controllable warmth and hot water. Many also reported perceptions of improved physical health and comfort, especially of mental health and

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[53] MONICAIR (MONItoring & Control of Air quality in Individual Rooms) project: http://www.monicair.nl/en/index.html

emotional well-being and, in several cases, the easing of symptoms of chronic illness. The authors concluded that results obtained provided evidence that Warm Front home energy improvements were accompanied by appreciable benefits in terms of use of living space, comfort and quality of life, physical and mental well-being, although there was only limited evidence of change in health behaviour.

Sharpe et al. assessed whether improvements to energy performance increase the risk of adult asthma, determined if mould contamination increases the risk of current adult asthma, and whether energy performance modifies the likelihood of mould contamination (Sharpe et al., 2015). Their study focussed on a population residing in social housing in Cornwall (UK). The target population resided in properties owned and managed by a medium-sized Social Housing Association. Study participants were recruited from 3867 postal questionnaires. Questions covered age, sex, height, weight, smoking status, employment, cleaning regimes, number of rooms carpeted, pets, health data on asthma, allergy and chronic bronchitis or emphysema, heating/ventilation regimes and whether participants thought damp/mould impacted their family's health. Questionnaire data was merged with property records from the Social Housing Association's asset management and stock condition data using a household identifier. Energy performance ratings were calculated according to the Government's Standard Assessment Procedure (SAP). The study concluded that, in contrast to previous studies, residing in highly energy performing homes might increase the risk of adult asthma. The authors reported that mould contamination increased the risk of asthma, which was in agreement with existing knowledge. Exposure to mould contamination could not fully explain the association between increased energy performance and asthma.

A study conducted by Sameni et al. (2015), considered the overheating risk during the cooling season in 25 social housing flats built to the Passivhaus standard in the UK. Overheating assessment based on Passivhaus criteria, using a fixed benchmark, suggested there is a significant risk of summer overheating with more than two-thirds of flats, which exceeded the benchmark. While the level of overheating in different flats varied considerably, detailed analysis indicated that this was more related to occupant behaviour than construction. They applied also an alternative approach to evaluate the overheating risk: the adaptive thermal comfort model, which takes into account occupant vulnerability and actual outdoor temperature. Use of the adaptive benchmark suggested this overheating risk is lower for normal occupants; but higher for vulnerable occupants.

Building overheating, indoor air pollution and biological contamination have been addressed in the study of Vardoulakis et al. (2015) that reviewed the possible impact of climate change in terms of direct and indirect adverse health effects in the indoor environment in UK. The authors concluded that joined-up climate change mitigation and adaptation measures in the residential building sector involving improved building design and ventilation, passive cooling, and energy efficiency measures can result in benefits to health, if well designed and successfully implemented. Moreover, new buildings should be designed to address the health effects of climate change in the indoor environment, but also to minimise the impact of the built environment on the climate by reducing fossil fuel use and making more use of low carbon energy sources. Practical health impact assessment methodologies, accounting for the combined direct and indirect effects (including health equity) of climate change in the indoor environment, should be developed.

Shrubsole et al. (2016) modelled the impacts of energy efficiency retrofitting measures on indoor $PM_{2.5}$ concentrations in domestic properties across different income groups in UK both above and below the low-income threshold (LIT). Simulations using EnergyPlus and its integrated Generic Contaminant model were employed to predict indoor $PM_{2.5}$ exposures from both indoor and outdoor sources in building archetypes representative of (i) the existing housing stock and (ii) a retrofitted English housing stock. Results indicate that all low-income households below the LIT experience greater indoor $PM_{2.5}$ concentrations than those above, suggesting possible social inequalities driven by housing, leading to consequences for health. Whilst tightening the building envelope to save energy and assist with climate change mitigation objectives is necessary, it is also essential that adequate fit for purpose ventilation be provided to avoid the negative health impacts.

North American Studies

Garland et al. (Garland et al., 2013) investigated the respiratory health effects of residents moving into a LEED Platinum certified affordable residential building in New York (5-floor, 63-unit building constructed in 2009). Certified building attributes included formaldehyde-free and low volatile organic compound building materials, compartmentalised ventilation systems with trickle vents, high-efficiency particulate arresting, filtration of public areas, and no-combustion venting appliances. Participants completed a home-based respiratory health questionnaire before moving into the green housing. Follow-up occurred at 6, 12, and 18 months post-move. In the participants' previous thirteen households (pre-move), nine households (69%) did not have a kitchen exhaust to the outside and eight households (62%) did not have a bathroom exhaust to the outside. Furthermore, ten (83%) households had a gas stove. Six (46%) households had mould in the past month and six households had cockroaches in the past month. Clinically relevant outcomes of this study included fewer days with asthma symptoms; asthma episodes; days of work, school, or day-care missed; and emergency department visits.

Jacobs et al. compared health before and after families moved into new green healthy housing (325 apartments in Chicago, USA) with a control group in traditional repaired housing (Jacobs et al., 2015). Housing conditions and self-reported physical and mental health improved significantly in the green healthy housing study group compared with both the control group and the dilapidated public housing from which the residents moved, as did hay fever, headaches, sinusitis, angina, and respiratory allergy. Asthma severity measured by self-reported lost school/work days, disturbed sleep, and symptoms improved significantly, as did sadness, nervousness, restlessness, and child behaviour.

Colton et al. in two successive years conducted environmental sampling, home inspections in Boston (USA), and health questionnaires with families in green and conventional (control) apartments in two public housing developments (Colton et al., 2014). A subset of participants was followed as they moved from conventional to green or conventional to conventional housing. They measured particulate matter less than 2.5 µm aerodynamic diameter ($PM_{2.5}$), formaldehyde, nitrogen dioxide (NO_2), nicotine, carbon dioxide (CO_2), and air exchange rate (AER) over a seven-day sampling period. In multivariate models, they observed 57%, 65%, and 93% lower concentrations of $PM_{2.5}$, NO_2, and nicotine (respectively) in green vs control homes, as well as fewer reports of mould, pests, inadequate ventilation, and stuffiness. Differences in formaldehyde and

CO_2 were not statistically significant. AER was marginally lower in green buildings. Participants in green homes experienced 47% fewer building related health, comfort and performance related symptoms. Conclusively the authors observed statistically significant reductions in multiple indoor exposures and improved health outcomes among participants who moved into green housing, suggesting multilevel housing interventions have the potential to improve long-term resident health.

Breysse et al. conducted a study the aim of which was to determine whether renovating low-income housing using "green" and healthy principles improved resident health and building performance (Breysse et al., 2011). To this end they investigated resident health and building performance outcomes at baseline and one year after the rehabilitation of low-income housing in Minnesota (USA) using Enterprise Green Communities green specifications, which improve ventilation; reduce moisture, mould, pests, and radon; and use sustainable building products and other healthy housing features. They assessed participant health via questionnaire, provided Healthy Homes training to all participants, and measured ventilation, carbon dioxide, and radon. Adults reported statistically significant improvements in overall health, asthma, and non-asthma respiratory problems. Adults also reported that their children's overall health improved, with significant improvements in non-asthma respiratory problems. Post-renovation building performance testing indicated that the building envelope was tightened and local exhaust fans performed well. New mechanical ventilation was installed (compared with no ventilation previously), with fresh air being supplied at 70% of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers standard. Radon was <2 picocuries per litre of air following mitigation, and the annual average indoor carbon dioxide level was 982 parts per million. Energy use was reduced by 45% over the one-year post-renovation period. In conclusion, the authors found significant health improvements following low-income housing renovation that complied with green standards.

Breysse et al. (Breysse et al., 2015) conducted a second study in which they investigated the impact of green low-income housing renovation in a 101-unit building (Minnesota, USA) not just on physical safety but also on the physical and mental health of primarily elder residents, evaluating whether self-reported physical and mental health of study residents changed from baseline to 1-year post renovation and whether these changes differed from changes in a comparable Minnesota population over the same time period. The renovation included building envelope restoration; new heating, electrical, and ventilation systems; air sealing; new insulation and exterior cladding; window replacement; Energy-Star fixtures and appliances; asbestos and mould abatement; apartment gut retrofits; low volatile organic chemical and moisture-resistant materials; exercise enhancements; and indoor no-smoking. The authors concluded that Green healthy housing renovation may result in improved mental and general physical health, prevented falls, and reduced exposure to tobacco smoke.

A prospective telephone-administered questionnaire study conducted by Leech et al. (2004) in new home occupants compared general and respiratory health at occupancy and 1 year later in two groups. The test group or cases, was 52 R-2000TM homes (128 occupants) in New Brunswick and Nova Scotia, Canada, built to preset and certified criteria for energy efficient ventilation and construction practices. The control group were 53 new homes (149 occupants) built in the same year in the same geographic area and price range. One of the principal outcomes of this study was that in comparison with control homes, occupants of case homes reported more improvement in throat irritation, cough, fatigue and irritability.

Frey et al. (2015) measured IAQ before, during, and after energy performance renovations in approximately 50 senior housings in Arizona (USA). They found significant decreases in formaldehyde, but not in the concentrations of particulates and other aldehydes. The significant decrease in formaldehyde levels was attributed primarily to the replacement of building materials and furnishings during the retrofit. Changes in ventilation would have affected all aldehydes in the same way.

Wells et al. (2015) conducted a longitudinal study in USA to compare IAQ and occupant comfort in 12 low income single-family homes renovated to a deep energy retrofits (DER) or energy star (ES) standard. They conducted quarterly visits for a median of 18 months post-renovation; IAQ was assessed in 4 rooms per visit for a total of 237 measurements. Multivariable regression models accounted for repeated measurements and controlled for house- and family-related covariates. In fully adjusted models, average difference (95% confidence interval) in IAQ parameters in DER homes versus ES homes were: temperature: -0.3 °C (-1.2, 0.6); relative humidity: 0.4% (-1.1, 1.8); CO_2: 43.7 ppm (-18.8, 106.2); and TVOC (total volatile organic compounds): 198 ppb (-224, 620).

Although on average parameters met generally accepted standards for indoor air quality, a few measurements of elevated TVOCs were observed. Some individual measurements of TVOCs were substantially higher than the median value; this frequently correlated with some activity (such as use of air fresheners immediately prior to the study visit) that could result in the introduction of VOCs into the home. This trend is similar to the one observed in one of the French studies reported above that has also reported elevated concentrations of some VOCs following renovations for energy performance (Derbez et al., 2014). Residents in DER homes were significantly less likely to report their homes were comfortable, most likely due to initial difficulties with new heating system technology. They found no statistically significant differences in IAQ between DER and ES homes; however education was strongly recommended when incorporating new technology into residences for achieving the energy savings and IAQ goals.

Mechanical ventilation systems in highly energy performing buildings if properly operated and maintained generally lead to an increased removal of pollutants, and thus to an overall improvement of the IAQ and reduction of reported comfort and health related problems (Leech et al, 2004; Eick and Richardson, 2011; Hutter et al., 2015; Passive-House project, 2015). However, there are a number of concerns about potential risks associated with these systems which could nullify the advantage they are providing. The most frequently mentioned concerns are excess noise, increased draughts, the hygiene of the air duct system (Rohracher et al., 2015) and low humidity indoors due to an elevated volume of outdoor air especially during winter (IPHA, 2015).

Table 4.1 summarises the objectives, the buildings' typologies, the evaluated parameters and the principal outcomes of the listed studies.

Table 4.1 Summary of studies reviewed in terms of objectives, buildings' typologies, evaluated parameters and principal outcomes

Study	Country	Objective of study	Description of dwellings	Evaluated parameters	Outcome
Breysse et al., 2011	USA	Determine whether renovating low-income housing using "green" and healthy principles improved resident health and building performance.	A three-building, 60-unit apartment complex which underwent substantial green renovation.	Radon, CO_2, ventilation, health interview to assess self-reported health status of participating adults and children.	Significant health improvements following low-income housing renovation that complied with green standards.
Breysse et al., 2015	USA	Investigate the impact of green low-income housing renovation on physical safety and on the physical and mental health of primarily elder residents.	7-story low-income public housing building built in the early 1970s in Mankato, Minnesota, with 101 units arranged in a rectangular block around an open atrium.	Self-reported health status.	Green renovation proved to have a positive effect on self-reported mental and physical health.
Colton et al., 2014	USA	Compare the indoor exposure profiles of conventional and newly constructed green, low-income public housing to understand how comprehensive improvements in development-level policies, building-level structures, and participant-level behaviours affect indoor air quality.	18 green apartments 6 control apartments. Green apartments certified Leadership in Energy and Environmental Design (LEED).	$PM_{2.5}$, NO_2, HCHO, nicotine, CO_2, AER.	Significant decreases in multiple indoor exposures and improved health outcomes for public housing residents moving from conventional housing into housing that was green renovated.
Dengel and Swainson, 2013	UK	Detailed evaluation of MVHR systems in practice in	10 zero carbon Code for Sustainable Homes Code (CSH) Level 6	It was carried out continuous monitoring of temperature, humidity and	Elevated levels of VOCs and formaldehyde persisted for up to six months

		homes that were studied during construction and then monitored for a period of almost two years post-occupancy (taking in design, procurement, installation, commissioning, performance, maintenance and occupant perceptions).	homes.	power consumption by the mechanical ventilation and heat recovery (MVHR) systems as well as periodic testing of indoor air quality and airtightness. Occupant feedback on living in the zero carbon homes was also obtained by use of questionnaires, walkthrough interviews and focus groups.	after completion of construction but generally decreased with time. It is critical that the overall ventilation strategy is taken into consideration during the design stage when intending to use MVHR systems in homes.
Study	**Country**	**Objective of study**	**Description of dwellings**	**Evaluated parameters**	**Outcome**
Derbez et al., 2014a	France	Evaluation of IAQ and occupants' comfort in 7 low-energy newly-built houses. The survey was conducted during the pre-occupancy stage and during occupancy in summer and winter.	7 Newly built highly energy performing houses.	TVOC, VOC, Aldehydes, CO PM$_{2.5}$, Radon CO$_2$, Temperature, relative humidity, noise, perceived comfort (questionnaire).	The levels of indoor pollutants in the study houses were within the guideline values for indoor air quality used in France, but the PM2.5 level exceeded the levels set by WHO recommendations. The MVHR systems exhibited commonly reported shortcomings but provided sufficient ACH (0.5 h^{-1}).
Derbez et al, 2014b	France	Follow-up study of Derbez et al, 2014a. → assessment 3 years after occupancy - Description of time-trends in indoor concentration	2 wooden-framed low-energy single-family houses.	TVOC, VOC, Aldehydes, CO PM$_{2,5}$, Radon CO$_2$, Temperature, relative humidity, noise, perceived comfort (questionnaire).	IEQ and comfort conditions in these houses were generally acceptable over time despite some specific problems. Regarding IAQ, the comparison with literature data did not show any

		s over a long period - Description of thermal comfort during repeated seasons.			specificity regarding measured indoor air pollutants.
Study	**Country**	**Objective of study**	**Description of dwellings**	**Evaluated parameters**	**Outcome**
Dutton and Fisk, 2014	USA	Based on modelling, this work evaluated the energy and IAQ implications of various fixed fixed minimum VRs, with results presented first from models for buildings that include include economizers and then from models for buildings without economizers.	Model.	Model.	Raising future minimum VRs in California offices is unlikely to significantly improve time-averaged IAQ in buildings with economizers. Lowering future minimum VRs would be unlikely to deliver substantive energy savings.
Frey et al., 2015	USA	Evaluation on how retrofit affects the indoor air quality both immediate post-renovation and 1 years following renovation.	Local apartment complex (116 units) for seniors who qualify for subsidized rent.	PM, volatile carbonyls.	Initially, formaldehyde exposure was quite high for all study participants, but an overall decrease was measured a year after the construction was completed. Particulate matter, however, was largely impacted by resident behaviour (such as smoking), and a long-term decrease was only observed when combined with particular subpopulations.
Garland et al., 2013	USA, New York	Investigate the respiratory health effects	LEED Platinum-certified residential	Home-based respiratory health questionnaire.	Fewer days with asthma symptoms; asthma

		of residents moving into a LEED Platinum certified affordable residential building in New York.	housing in New York State, 5-floor, 63-unit building constructed in 2009 in the South Bronx.		episodes; days of work, school, or day-care missed; and emergency department visits.
Study	**Country**	**Objective of study**	**Description of dwellings**	**Evaluated parameters**	**Outcome**
Ghita and Catalina, 2015	Romania	Couple indoor environmental quality (IEQ) in countryside schools with energy performance.	3 different types of rural schools (old, new and renovated) 10 classrooms All schools are naturally ventilated.	CO_2 IEQ-Index Relative humidity Temperature.	High energy consumption, as is the case for the old school, does not necessarily result in better comfort conditions despite their inverse correlation.
Gilbertson et al., 2006	UK	Quantify the impact of the Warm Front Scheme (a government initiative aimed at alleviating fuel poverty in England) on homes, and householders' mental and physical health and quality of life.	A purposive sample of 50 of the 3000 study dwellings stratified by area, household type and period since intervention (recent installation or installation in the preceding Winter) was randomly selected on a first come basis.	Semi-structured interviews were conducted by four experienced Interviewers using a topic guide. The guide covered conditions in the home before, during and after Warm Front intervention, and probed issues around how lifestyle and health were affected.	Warm Front home energy improvements are accompanied by appreciable benefits in terms of use of living space, comfort and quality of life, physical and mental well-being, although there is only limited evidence of change in health behaviour.
Holopainen et al., 2015	Finland	- Compare calculated primary energy demand and the purchased primary energy use in five Finnish low-energy houses and 5 conventional houses - Determine how occupants perceived	5 recently (2009-2012)built low-energy houses 5 older conventional houses Mechanical ventilation in low-energy houses.	Perceived environment quality (questionnaire) e.g. dry air, noise, unpleasant odours, odour of mould, insufficient ventilation, room temperature.	The occupants in the low-energy houses perceived indoor environment quality as slightly better than the occupants in the conventional houses

		indoor environment quality in the studied low-energy and conventional houses.			
Study	**Country**	**Objective of study**	**Description of dwellings**	**Evaluated parameters**	**Outcome**
Howieson et al., 2014	UK	- Determination of CO_2-concentrations in airtight dwellings ventilated with trickle ventilation.	1 Passive House 20 new-build houses Air tightness: 2.9-6.1 $m^3/m^2/h@50Pa$ Ventilation only with trickle ventilators.	Carbon dioxide, temperature and relative humidity in kitchen, bedroom and living room.	-CO_2-concentrations were high - trickle ventilation insufficient.
Jacobs et al., 2015	USA	Compare health before and after families moved into new green healthy housing with a control group in traditionally repaired housing.	Public housing and low-income subsidized households (n = 325 apartments with 803 individuals).	Health status (self-reported).	Housing conditions and self-reported physical and mental health improved significantly in the green healthy housing study group compared with both the control group and the dilapidated public housing from which the residents moved, as did hay fever, headaches, sinusitis, angina, and respiratory allergy.
Kauneliene et al., 2016	Lithuania	Compare IAQ parameters in low energy residential buildings in relation to ventilation systems and air exchange rates.	11 newly built low energy residential buildings.	Temperature, relative humidity, CO_2, NO_2, formaldehyde, VOCs, SVOCs.	VOC and SVOC levels in the investigated buildings were at typical indoor levels despite the low exchange rate in most buildings. Formaldehyde concentrations were above the Lithuanian limit value. This study

Study	Country	Objective of study	Description of dwellings	Evaluated parameters	Outcome
					demonstrates the importance of checking indoor air quality before occupancy and avoiding moving into buildings before the complete installation of the interior. Selection of low-emitting building and finishing materials, furniture, cleaning products and ensuring effective work of mechanical ventilation will contribute to good indoor air quality in low energy buildings.
Langer et al., 2015	Sweden	- seasonal variation of indoor environmental parameters in five passive houses - comparison of indoor climate parameters and pollutant concentrations between passive and conventional houses - comparison of the new passive and conventional houses with the Swedish housing stock.	20 new passive houses and 21 new conventionally built houses All built since 2010 Mechanical ventilation in all buildings.	Temperature Relative humidity NO_2 O_3 HCHO VOC Viable microbiological flora.	The quality of the indoor environment in the newly built passive dwellings was comparable to or better than in the conventional houses and the Swedish housing stock.
Leech et al., 2004	Canada	Examine reported changes in health status by questionnaire in occupants	52 R-2000 homes Control group: 53 new homes.	Questionnaires (cough, throat irritation, fatigue, irritability).	In comparison with control homes, occupants of case homes reported more improvement in

		of case homes at about 1 year after occupancy in comparison with health status in the year before occupancy and to control new home occupants reported health changes over the same period of time.			health symptoms.
Study	**Country**	**Objective of study**	**Description of dwellings**	**Evaluated parameters**	**Outcome**
Maidment et al., 2014	UK	Investigating the impact of household energy performance interventions on the physical health and mental wellbeing of building occupants.	Thirty-six primary research studies with a combined sample of over thirty thousand participants were meta-analysed.		A small, but significant and positive, effect of household energy performance interventions on health was found.
Milner et al., 2014	UK	Investigate the effect of reducing home ventilation as part of household energy efficiency measures on deaths from radon related lung cancer.	Modelling study.	Modelling study. Indoor radon levels for the present day and for four future scenarios representing a variety of plausible retrofitting strategies, which could be applied to the existing stock to help achieve reduction targets for carbon dioxide emissions.	Increasing the air tightness of dwellings (without compensatory purpose-provided ventilation) increased mean indoor radon concentrations by an estimated 56.6%.
Peper et al., 2008	Germany	Two and a half years monitoring of a passive house school and day-care centre.	Passive house school and day-care centre.	CO_2, temperature, relative humidity.	Comfortable indoor climate and good air quality (CO_2) was measured
Sameni et al., 2015	UK	Investigation of the	25 social housing flats	Temperature	Significant risk of summer

		overheating risk during the cooling season in 25 social housing flats built to the Passivhaus standard in the UK.	built to the Passivhaus standard in the UK.		overheating with more than two-thirds of flats which exceeded the benchmark.
Study	**Country**	**Objective of study**	**Description of dwellings**	**Evaluated parameters**	**Outcome**
Sharpe et al., 2015	UK	Assess the impact of household energy performance (using the UK Government's Standard Assessment Procedure) on asthma outcomes in an adult population residing in social housing.	Postal questionnaires were sent to 3867 social housing properties to collect demographic, health and environnemental information on all occupants.	Questionnaires covered age, sex, height, weight, smoking status, employment, cleaning regimes, number of rooms carpeted, pets, health data on asthma, allergy and chronic bronchitis or emphysema, heating/ventilation regimes and whether participants thought damp/mould impacted their family's health.	Residing in highly energy performing homes may increase the risk of adult asthma.
Shrubsole et al., 2016	UK	Model the impacts of energy efficiency retrofitting measures on indoor PM$_{2.5}$ concentrations in domestic properties across different income groups in UK both above and below the low-income threshold (LIT).	Existing and retrofitted English housing stock.	Simulations using EnergyPlus and its integrated Generic Contaminant model were employed to predict indoor PM$_{2.5}$ exposures from both indoor and outdoor sources in building archetypes representative of the existing and retrofitted English housing stock.	Results indicate that all low-income households below the LIT experience greater indoor PM$_{2.5}$ concentrations than those above, suggesting possible social inequalities driven by housing, leading to consequences for health.
Vardoulakis et al., 2015	UK	This study reviewed the possible impact of climate change in	UK housing sector.	Reviewed the factors associated to existing risks related to heat exposure,	It was concluded that joined-up climate change mitigation and adaptation measures in the

		terms of direct and indirect adverse health effects in the indoor environment in UK, focussing on building overheating, indoor air pollution and biological contamination.		flooding, and chemical and biological contamination in buildings.	residential building sector involving improved building design and ventilation, passive cooling, and energy efficiency measures can result in benefits to health, if well designed and successfully implemented.
Study	**Country**	**Objective of study**	**Description of dwellings**	**Evaluated parameters**	**Outcome**
Van Holsteijn et al., 2015 (MONICAIR project funded by the Dutch Government)	The Netherlands.	The aim was to investigate in real life conditions the performance in terms of indoor air quality (IAQ) and energy consumption of ten different mechanical ventilation solutions in dwellings that meet strict air-tightness standards and comply with current building regulations.	62 residential dwellings.	For a whole year, the dwellings were monitored every five minutes via sensors in terms of occupancy, CO_2 concentrations (as indicator of the IAQ performance), relative humidity and air temperature. The study also continuously measured mechanical airflow rates and the real-life energy consumption of the mechanical ventilation units.	The MONICAIR project's outcome shows that the implicit assumption that all code compliant ventilation systems perform comparably in terms of IAQ could not be substantiated. Significant differences related to the IAQ performances were identified which the existing legal framework currently does not assess. Only the energy performance of ventilation systems is assessed. Moreover it was showed that the real-life energy related performance of ventilation systems is not in line with the results of the EPBD assessment methods. Therefore, the current legal framework and assessment

					tools give an incorrect representation and ranking of code compliant ventilation systems and only with a proper assessment of both IAQ and energy performances a true representation of the ventilation systems can be given.
Study	**Country**	**Objective of study**	**Description of dwellings**	**Evaluated parameters**	**Outcome**
Verriele et al., 2015	France	Studying the comfort and air quality in 10 recently constructed, highly energy performing schools.	Ten low-energy consumption education facilities (engineering school, junior high schools, primary schools) were selected in northern and eastern France.	In each building, IAQ (VOCs, T, rH, CO_2) and comfort parameters were monitored during 4.5 days. Two periods were investigated: school term (occupied conditions) and school holiday (unoccupied conditions).	This study does not reveal any significant differences in the chemical footprints between recently built, highly energy performing school buildings and conventional buildings.
Wallner, et al., 2015	Austria	Compare very highly energy performing houses with ventilation system to conventional houses.	New houses (62) built according to very low energy or passive house standards with controlled ventilation systems with heat recovery systems. Houses which corresponded to the normal building standards without mechanical ventilation systems formed the control group (61). Built 2010-2012.	Fist measurement three months after resident moved into buildings. Follow-up 1 year later. VOCs, aldehydes, mould spores, dust mite allergens, radon	Almost all indoor air quality and room climate parameters showed significantly better results in mechanically ventilated homes.

Wells et al., 2015	USA	Compare IAQ and occupant comfort for one year among low-income homes renovated using Energy Star (ES) and Deep Energy Retrofits (DER) renovation methods.	12 low income single-family homes renovated to a 'Deep energy retrofits' or 'energy star' standard.	Temperature, relative humidity, CO_2, TVOC, occupant confort (questionnaire).	No differences in indoor air quality between DER and ES homes.

Linking health, IAQ, ventilation and energy

Concerning the linkages between health, IAQ, ventilation and energy, in the remaining sections of Chapter 5, evidence from measured data is further supported by example calculations: (a) demonstrating the impact of the triangulation among exposure, indoor/outdoor sources, energy efficiency and ventilation; (b) of physical models showing that IAQ and energy are linked in many ways, but when proper measures are applied energy performance improvements may result in IAQ and thermal comfort improvements, i.e. energy performance and IAQ and comfort can be tackled upon and optimised concurrently.

Inadequate indoor air quality, caused by indoor sources and polluted outdoor air, is estimated to lead to an annual loss of two million healthy life years in Europe (Jantunen et al., 2011).

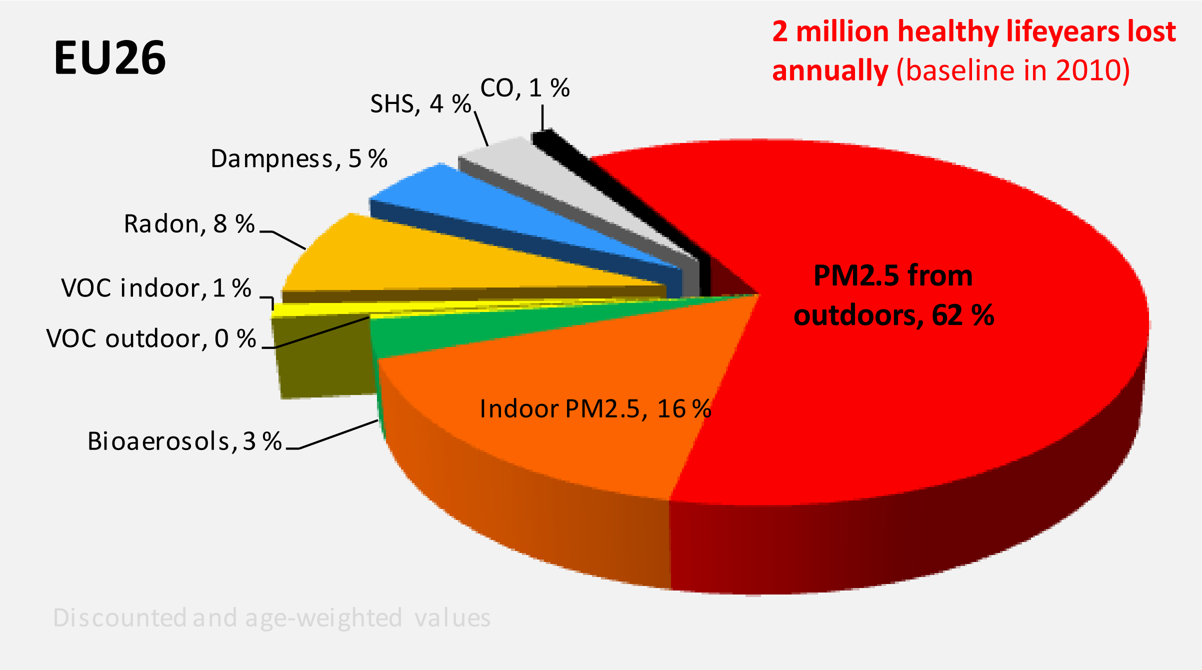

Figure 4.1 The European Commission's DG SANCO funded IAIAQ project estimated that 2 million healthy life years (DALY) are lost annually in EU26 due to indoor exposures to air pollution (baseline year 2010) (Jantunen et al., 2011).

Ambient air quality is a major threat to human health also in Europe. EEA estimates that 91-93 % of Europeans live in areas where the WHO Guideline for $PM_{2.5}$, the most significant indicator of air pollution, is not met (EEA, 2014).

In the European Commission's DG SANCO funded HEALTHVENT project it was estimated that half of the burden of disease caused by indoor exposures could be reduced, if the health based ventilation guidelines were fully adopted (ECA report 30, 2015).

Buildings partly protect the occupants from outdoor air pollution, but until now not very efficiently. The outdoor pollutants still clearly dominate the burden of disease attributed to indoor exposures (Figure 4.2). Gaseous pollutants enter indoor spaces efficiently, and even particles are able to infiltrate building envelopes to large extent. This is the case also in modern houses with mechanical ventilation and efficient filtration of the air ventilated through the mechanical system. Even in such buildings the $PM_{2.5}$ infiltration factor is in the order of magnitude of 50% (Hänninen et al., 2004, 2011, 2013). Tightening of the building envelopes will reduce this and create substantial co-benefits for energy use, exposures and health (Hänninen et al. 2015).

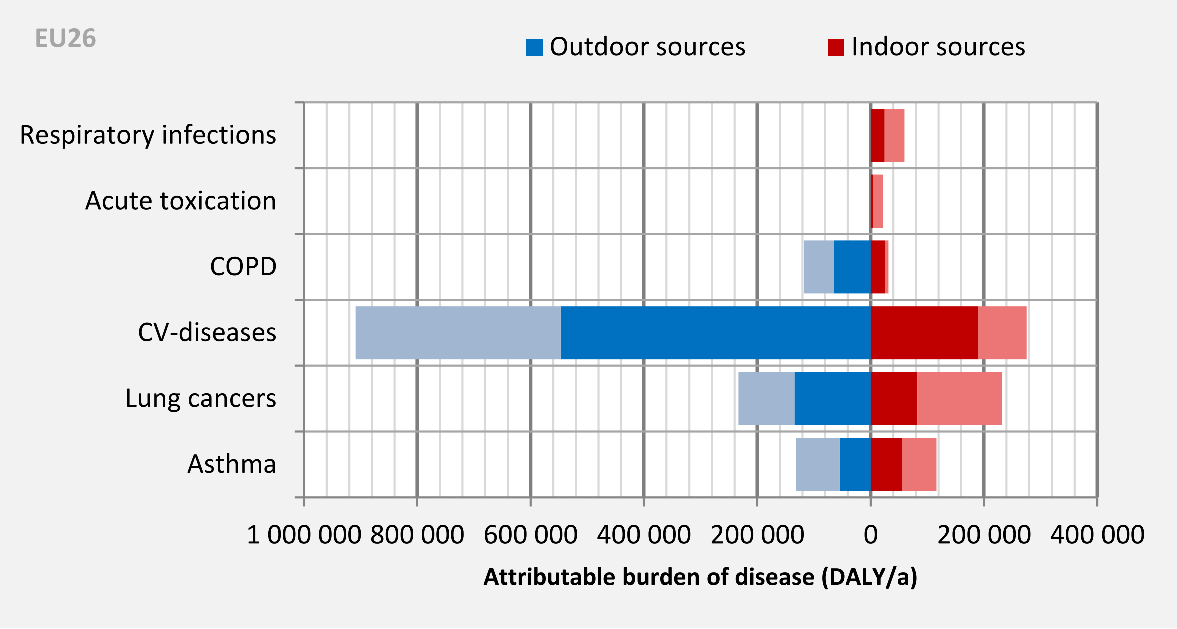

Figure 4.2 The health losses due to inadequate IAQ are dominated by diseases in the cardiovascular and respiratory systems. Substantial fraction of this burden is associated with outdoor air pollution brought indoors via infiltration and ventilation. (Hänninen & Asikainen, 2013)

When tightening of the building envelopes attention should be made that ventilation rates respect the health based ventilation concept and implementation framework of the HEALTHVENT project.

Simulations made to estimate the size of the European population that is exposed in buildings in which ventilation rates do not meet the required levels, and thus to estimate the associated health risk thereof (Asikainen et al., 2016) showed that for 26 EU countries (EU26), on average, about 33% of dwellings are expected to have ventilation rates less than 0.5 h^{-1}, i.e. less than about 10 L/s per person; 0.5 h^{-1} is the minimum air exchange rate recommended by the standard EN 15251 (2007) for residential buildings with mechanical ventilation.

Ventilation and infiltration of air in the current European building stock consumes over 25% of the residential energy use (Figure 4.3). Increasing insulation will substantially reduce the conductive heat losses. Energy losses due to air exchange can be reduced by optimising ventilation rates and using heat exchangers in mechanical ventilation systems.

Physical models show that IAQ and energy are linked in many ways; especially ventilation has a strong effect on IAQ as diluting pollutants and resulting in ventilation heat loss at the same time, if effective heat recovery is not applied. There exists both measured and simulated evidence showing that if proper measures are applied energy performance improvements may result in IAQ and thermal comfort improvements, i.e. energy and IAQ problems can be solved concurrently.

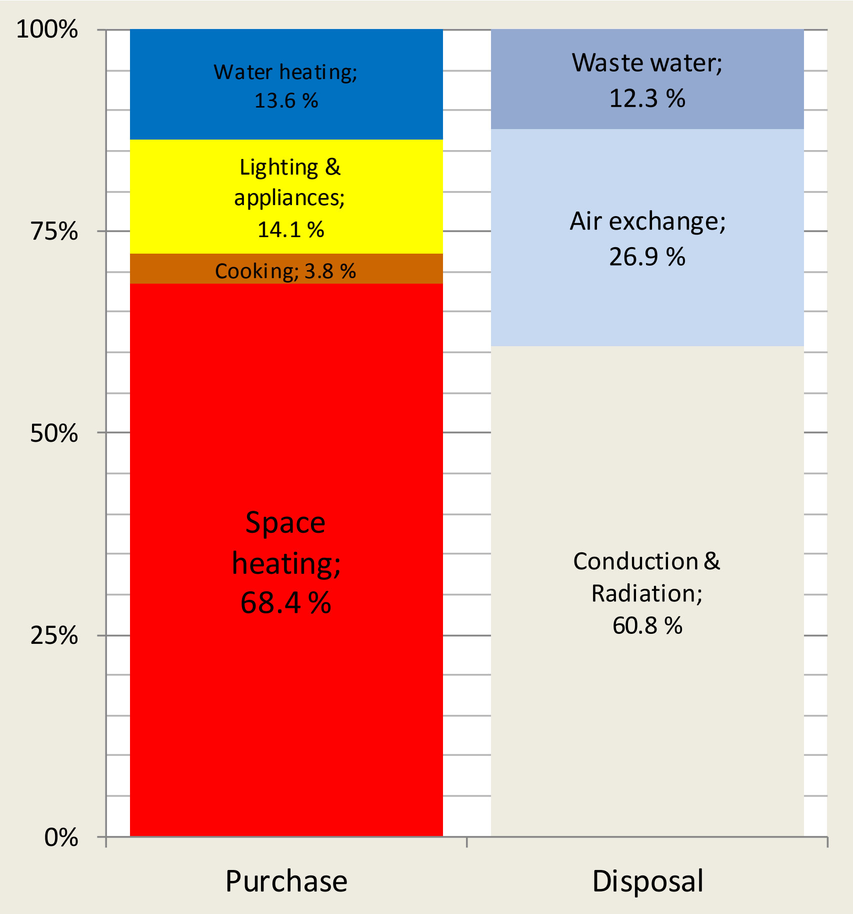

Figure 4.3 Air exchange represents a quarter of residential energy use in Europe (Hänninen & Asikainen, 2013).

IAQ problems have been very severe in renovated apartment buildings where replacement of windows, additional insulation and generally sealing the envelope to be air tight in order to save energy has stopped natural ventilation that has previously happened mainly as a buoyancy (stack effect) driven air change through leaky windows. Such evidence has been reported from Estonia, from apartments that undergone major renovation, which have been the subject of renovation grants, i.e. governmental financial support. Measurements from 20 renovated apartment buildings show almost missing or very low ventilation rates in buildings, which remained with natural stack ventilation. In a small minority of buildings, which installed new heat recovery ventilation systems, measured ventilation rates were much better, close to recommended values (Maivel et. al QUALICHeCK report 2015, pp. 44-45), Figure 4.4.

Ventilation almost stopped in the majority of naturally ventilated buildings. With mechanical supply and exhaust heat recovery ventilation one apartment building reached indoor climate category II value and others were reasonably close to that.

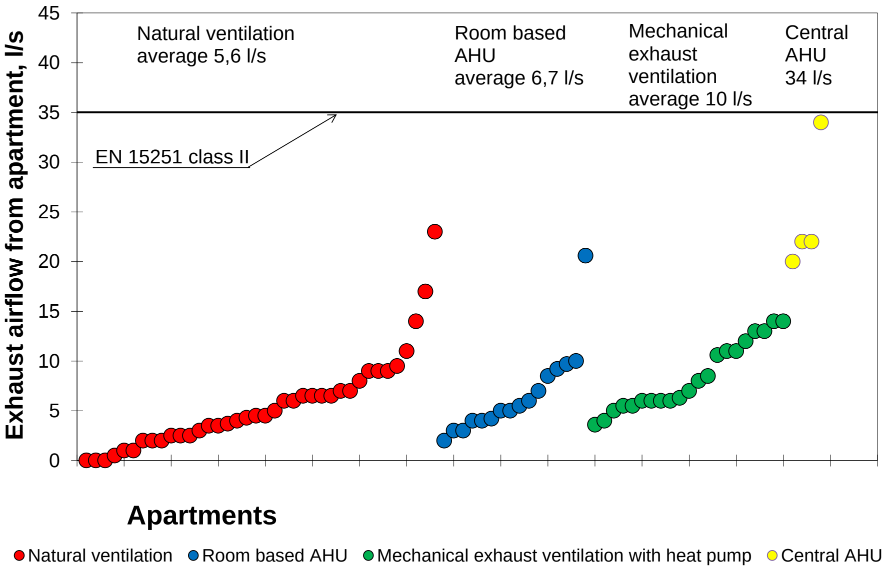

Figure 4.4 Ventilation rates in deeply renovated apartment buildings (Maivel et. al. QUALICHeCK report 2015, pp 44-45).

It is concluded that inadequate ventilation in the majority of apartment buildings renovated via the renovation grant scheme was likely a result of too general technical requirements of renovation grant applications. The outcome of this study resulted in Estonia introducing strict ventilation requirements specification for renovation grants, which are specified as L/s values for supply and exhaust air following the indoor climate category II requirements of European standard EN 15251:2007. With the category II values (being reached also in one measured building with heat recovery ventilation) an energy modelling study was done by Kurnitski et al. (2014). This study modelled energy use of reference buildings (existing buildings and different renovation options) with two ventilation rates:

- Standard ventilation rate equal to minimum requirements resulting in higher energy use;
- Ventilation rate of 30% of minimum requirements resulting in statistical average energy use.

The energy use calculated with lower ventilation rates describes the situation in existing building stock with poor indoor climate. This value is relevant for the assessment of average energy use in the building stock, which is needed for scenario calculations, because any scenario should be compared with the existing situation. For the integrated renovation variants assessment the higher energy use value with ventilation rate equal to minimum requirements was used. The higher value corresponds to the situation, where ventilation will be improved with available means (including window opening) in order to fulfill the requirements and to continue the building's operation, which could be a typical situation especially in school and office buildings. In residential buildings this option was considered also as a relevant baseline, because otherwise a deteriorated indoor climate could cause major public health expenses, which are to be quantified as one cost component of energy savings.

An example of energy modelling for dwellings is shown Figure 4.5. Simulated energy uses are shown with both ventilation rates and occupancy considerations for the existing situation. The difference was highest in old detached houses, where in the case of DH-Old, delivered heating increased from the average of existing stock 201 kWh/m^2 (low ventilation rate, not all rooms occupied/heated) to 398 kWh/m^2 with standard ventilation rate and full occupancy. Correspondingly, delivered electricity increased from 30 to 142 kWh/m^2 with full occupancy, because of the mix of electric and stove heating in the existing situation. The next points of the curves correspond to renovation variants, from which the two last ones are with ground source heat pumps (delivered heat 0 kWh/m^2 and electricity use increased). In the case of DH-New (relatively new dwellings from 1990), the differences between average and standard energy use of the existing situation are smaller. The difference of first renovation variants were caused by replacement of a gas boiler to pellet boiler which increased delivered heat from 150 to 159 kWh/m^2, but resulted in a better EPC category, because of lower primary energy factor. Three last variants were with ground source heat pump which explains delivered heat of 0 kWh/m^2.

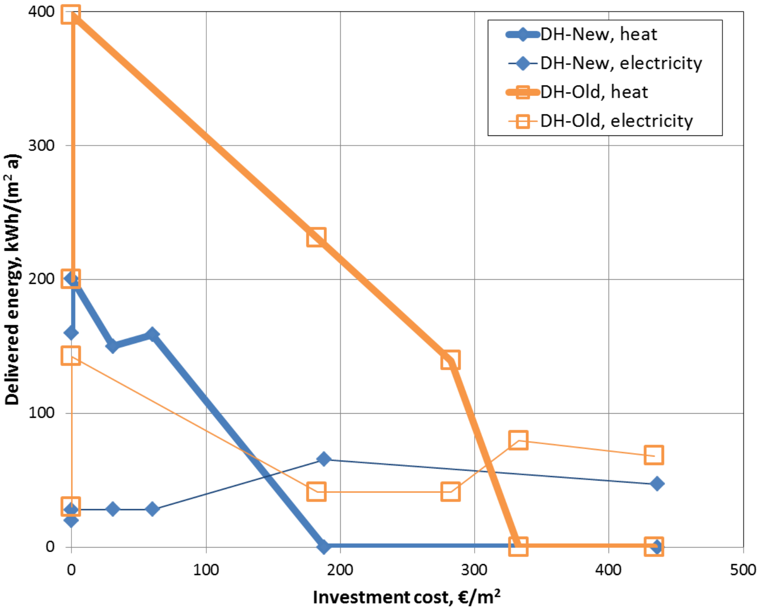

Figure 4.5 Integrated renovation variants energy and cost modelling in reference detached houses; Kurnitski et al. (2014). First points from the left (investment cost 0 €/m^2) correspond to average statistical energy use (lower delivered energy value) and to existing situation with full occupancy and standard ventilation (higher delivered energy value). Next points correspond to renovation variants which improve energy performance to Estonian energy performance certificate class E, D, C (requirement for new buildings) and B (low energy) respectively.

The second last points from the right represent renovation variants corresponding to energy performance requirements of new buildings, and the last points represent even better energy performance than required for new buildings (Estonian low energy class). These results reveal that dramatic energy savings are possible with category II ventilation, and therefore, without any compromises in indoor climate. Vice versa, deep renovation with additional insulation and dedicated ventilation installation will improve thermal comfort because it eliminates cold draughts from leaky windows and poorly insulated structures and results in uniform thermal environment as well as by ventilation controlled IAQ.

Similar evidence as from residential buildings can be found from school buildings. In the MERMAID project, Verriele et al. studied the comfort and air quality in ten recently constructed, highly energy performing schools in France (Verriele et al., 2015). It was demonstrated that the comfort parameters were most of the time within the ASHRAE recommended values and that the CO_2 level was acceptable when the ventilation was operational and adapted to occupancy. A time schedule slightly larger than the occupancy period was the best compromise for air quality and energy consumption in these buildings. The MERMAID project measured extensively VOCs by detecting over 150 VOCs. It was concluded that pollutant concentrations in these low-energy public buildings were similar to or lower than the levels reported in standard buildings, and no clear difference was observed between the pollution patterns in low-energy and conventional buildings.

From the above, it therefore becomes evident that addressing the issue of ventilation, by tackling both health and energy concerns simultaneously represents a challenging and important task for further investigation. By characterizing comprehensively how the energy use of buildings varies with the ventilation rate would provide important information for estimating the impacts of hypothetical changes in ventilation rates to cope with IAQ and health related requirements in existing and new highly energy performing buildings.

The relation between ventilation of buildings and their energy use is a multi-variable issue. It depends on a large number of variables (regarding the building type, location/climate, building airtightness, use of heat recovery, use of air-flow control, heating and cooling set-points and humidity control) the influence of which has been mostly explored on an individual basis (e.g. airflow control, heat-recovery, building airtightness and humidity control). A systematic study was performed by Santos and Leal in the context of the HEALTHVENT project (Santos, H. and Leal, V., 2012) based on a multi-variable approach. They calculated the annual energy needs through detailed building simulations on the basis of a set of scenarios covering a large part of the possible combinations of variables that can be found in Europe (and by extrapolation in other parts of the world). The analysis concerned a comprehensive characterization of the relation between energy use and ventilation rates in both residential and services buildings across different European climates. A sensitivity analysis was performed considering:

- Four building types (detached house, apartment, office and school);
- Three climates/locations (Helsinki, Paris and Lisbon);
- Three heating and cooling set-points settings (standard (20–25°C), stricter (21–27°C) and more flexible (18–27°C));

- Four air-flow control strategies (no control, demand control (D. C.), free-cooling (F.-C.) and both D.C.+F.-C.);
- Usage of heat recovery (not used or used (with efficiency of 80%)) coupled with
- Four different building airtightness conditions (very high airtightness (0.1 h^{-1}), high airtightness (0.3 h^{-1}), low airtightness (0.6 h^{-1}) and very low airtightness (1.2 h^{-1})), and
- Three ranges of humidity control (none, medium control (25–75%) and stricter control (40–60%).

A schematic view of variables addressed in the study is shown in Figure 4.6.

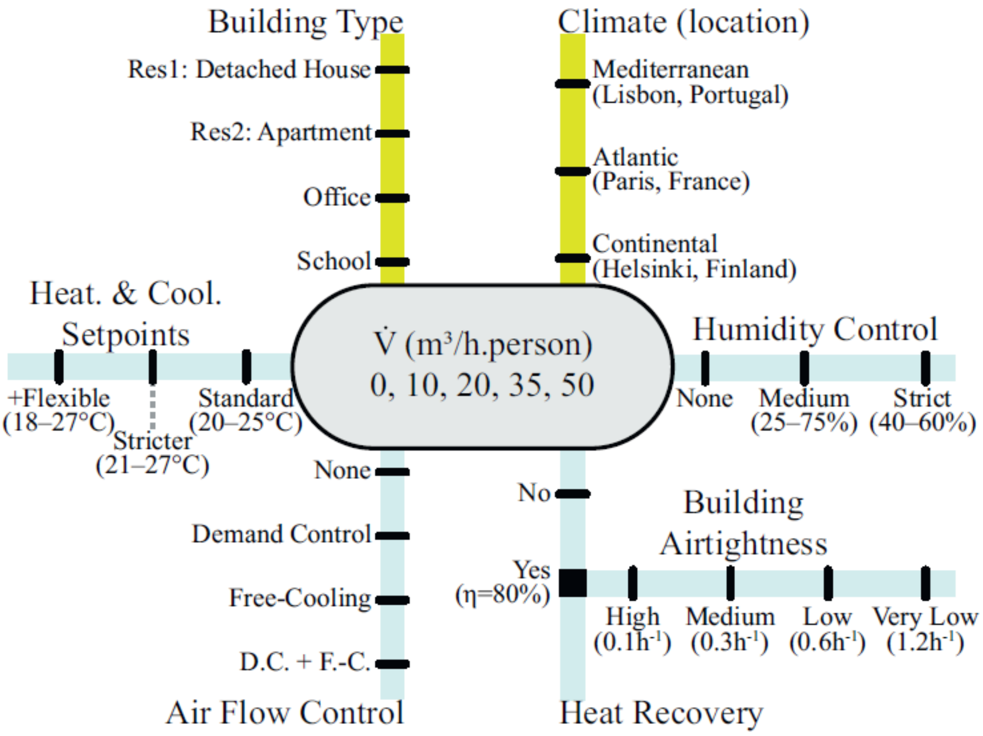

Figure 4.6 A schematic view of variables addressed in the study (Source: Santos, H. and Leal, V., 2012; HEALTHVENT WP 6 final report, 2012)

The impacts of changing ventilation rate (ICV) were determined for each case in terms of the slope of the energy needs as function of the ventilation rate, in the range of 0–50 $m^3/(h \cdot person)$. The energy results, assessed through dynamic building simulations, show that changing ventilation by 1 $m^3/(h \cdot person)$ with current practice systems has an impact in total HVAC-related final energy demand between 0.3 and 0.6 $kWh/(m^2 \cdot year)$ depending on building type and location. However, with advanced systems the ICV values could become close to 0.1 $[kWh/(m^2 \cdot year)]/[m^3/(h \cdot person)]$ in most cases analysed. These results could be used to assess the energy impacts of IAQ policies, including hypothetical trade-offs between health and energy or different degrees of use of the precautionary principle.

It was concluded that the impact of ventilation on the energy use of buildings could be significant. In the climatic context analysed, supposed to be representative of most of the European diversity, increasing ventilation rates leads to increased yearly heating needs and lower yearly cooling needs, but since heating is predominant in the residential buildings and some services buildings, the general trend is for increased energy use with higher ventilation rates. The electricity needed to move the air becomes very significant at higher ventilation rates, becoming in some cases the main factor of increase of the final energy demand.

The sensitivity analysis performed showed that there is significant variability across building types and across European locations/climates. Some buildings tend to need more heating than cooling (mostly in the residential sector) while others tend to need more cooling than heating (usually services buildings). Climate differences are very significant in the European context and between the three locations assessed. These differences, however, tend to be reduced by local building and ventilation practices and systems. For instance, while the weather is warmer in Lisbon when compared to Paris, the fact that thermal insulation levels are significantly higher and heat recovery is a standard feature in the latter case result in similar nominal heating and cooling needs in the residential buildings in these two locations. When the differences in construction are small, as happens to be the case between Paris and Helsinki, which in current new buildings tend to have similar thermal insulation levels and ventilation systems, then climate differences become the main drivers on heating and cooling needs.

When the advanced technical options are combined (heat recovery, very high building airtightness, demand control and free-cooling) both total final energy use as well as the impact of changing ventilation rate are significantly reduced. The reduction is more pronounced in the residential buildings than in the services ones because the former typically make use of more basic systems, hence the potential for technical improvement tends to be larger in those cases. With advanced systems, the sensitivity to ventilation rate change on total delivered energy for heating, cooling and moving the air would be of about 0.1 [kWh/(m^2.year)]/[m^3/(h·person)] in the residential and office buildings (more than 50% improvement over the current practice systems), and about 0.2 to 0.3 [kWh/(m^2· year)]/[m^3/(h· person)] in the school building. In practical terms, this improvement means that, if accompanied by an upgrade of the systems "current practice" to "advanced", ventilation rates could be increased from, for example, 20 m^3/(h· person) to 30 m^3/(h· person) without causing any increase in total energy needs in all but one of the cases here studied (office building in Lisbon).

From all the variables accounted for in this work, the one that more consistently provides a larger reduction on the total energy needs was demand control. It not only reduces heating needs in a very significant way but also decreases electricity needed for moving the ventilation fans (at the expense of only a slight increase in cooling needs).

Heat recovery is the other most significant contributor technology to decrease the impact of the ventilation rate in buildings, as it tends to decrease the slope of energy needs as a function of ventilation rate in a proportional way to its efficiency. That is, a system that makes use of a heat recovery element with 80% efficiency tends to have a decreased sensitivity to ventilation rate, by about four fifths compared to similar systems without heat recovery. However, in scenarios of low building airtightness, the increased electricity needs for the ventilation fans (due to increased pressure drop on the ventilation ducts) may be enough to offset the benefits coming from the use of heat recovery. Therefore, to be effective heat recovery requires airtight buildings, which may be a technical and especially a cultural challenge for some regions of Europe where there is a tradition of strong linkage between the building's indoor and outdoor environments via preferred natural ventilation practices and their buildings mostly featuring low airtightness.

Figure 4.7 shows a direct comparison when increasing ventilation rate by 10 m³/(h.person) from a base value of 20 m³/(h.person) with either the current practice system or an advanced system. It shows that making an 50% increase of the ventilation rate with the current systems, represented by the darker bars, will usually result in about 20 to 30% more or less total electricity consumption while doing it with an advanced system will have a much smaller impact, in many cases around 10% but reaching almost 20% in the worst case scenarios. The reduction is more dramatic in the residential buildings, mainly because the use of demand control decreases effective ventilation rate significantly. The services buildings, since they already feature a ventilation system operating only during working hours get a lower benefit from demand control. In a certain way, it could be said that demand control is already partially implemented in the current systems. Also, the gains from moving to an advanced system would be the highest in the case of Lisbon's house and apartment models, since these are distinguished from all the other cases for not using heat recovery as standard practice.

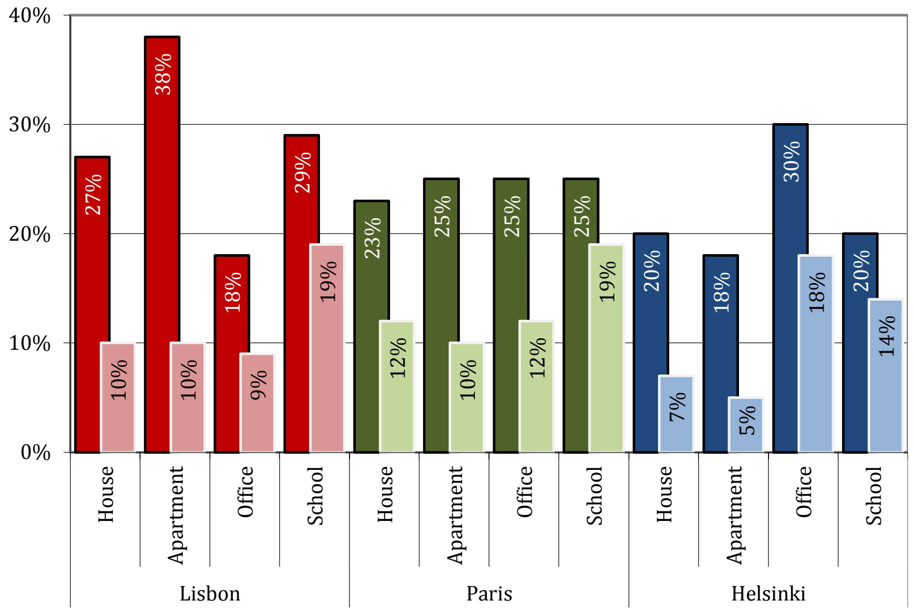

Figure 4.7 Change in total electricity consumption when ventilation increases by 10 m³/(h.person) from a base value of 20 m³/(h.person), with a current practice system (darker bars with white labels) or with an advanced system (lighter bars with black labels). (Source: Santos, H. and Leal, V., 2012; HEALTHVENT WP 6 final report, 2012).

In fact, the gains from installing a system with advanced features such as heat recovery and, most significantly, demand control, is high enough to allow the intensification of ventilation from 20 m³/(h.person) in the current practice system to 30 m³/(h.person) with an advanced one without incurring any increase in total electricity consumption. This can be seen more clearly in Figure 4.8, which shows that in all but two cases that change would result in an effective reduction on electricity consumption. Besides Europe, similar studies on the interplay among energy consumption, IAQ and ventilation have been undertaken also in other places of the globe.

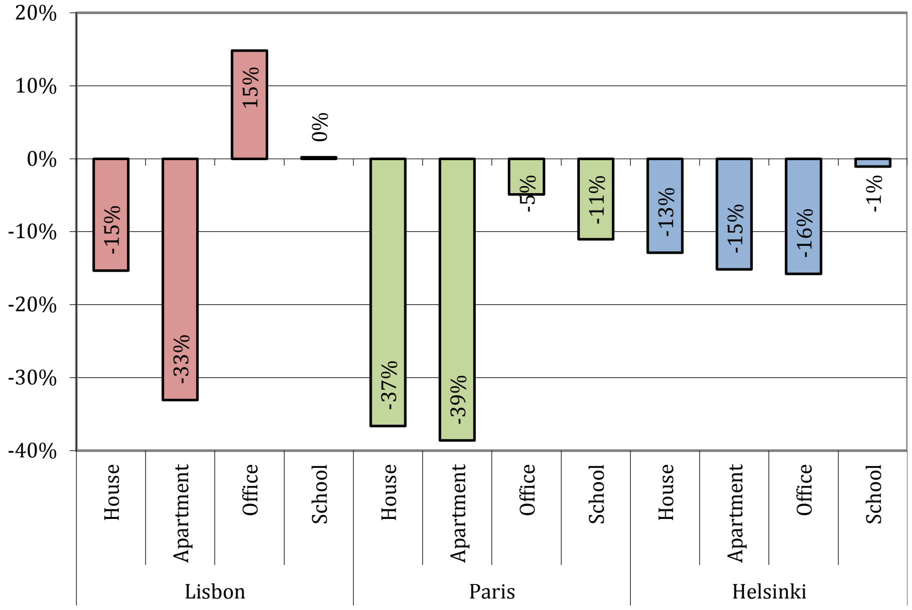

Figure 4.8 Difference in total electricity consumption when going from 20 m³/(h.person) with a current practice system to 30 m³/(h.person) with an advanced system. (Source: Santos, H. and Leal, V., 2012; HEALTHVENT WP 6 final report, 2012).

Besides natural and mechanical ventilation, there is another type of ventilation, known as hybrid ventilation or mixed-mode ventilation. This type is a combination of mechanical and natural ventilation. Utilising hybrid ventilation in buildings integrated with suitable control strategies, to adjust between mechanical and natural ventilation, leads to considerable energy savings while an appropriate IAQ is maintained. This was pointed out by Chenari et al. who reviewed existing literature in energy-efficient ventilation methods, the influence of occupants' behaviour on ventilation and energy consumption and the relation of ventilation with health and productivity (Chenari et al., 2016).

Based on this review, it was found that, despite considerable advances in the field in the last two decades, there remain open questions which are pertinent to the wider acceptance and implementation of novel hybrid ventilation strategies. One fundamental question that remains open relates to what extent today's state-of-the-art rule based control strategies can be improved upon for hybrid ventilation systems, and whether a different approach to control could introduce substantial improvements in a real use situation. In particular, there is no study in the existing literature, addressing intelligent window-based hybrid ventilation strategies for maintaining the IAQ and reducing the energy consumption at the same time. On the other hand, many researchers have reported on various approaches to controlling ventilation with various degrees of performance in terms of energy savings and occupants' satisfaction. It is pertinent, nevertheless, to think in terms of a lower bound for the energy requirements in order to provide a comfortable and healthy indoor environment for people, and it does not make sense to reduce energy consumption further if it affects negatively people's comfort and health (Chenari et al., 2016).

With the introduction of more and more NZEBs in the coming decades, the energy consumption in buildings paradigm will shift from a long timescale (yearly) assessment metric to a short time scale (daily) quest for a balance between local production, demand and storage capacity. In this new paradigm, it is envisaged that dynamic, predictive control of the building systems, including hybrid ventilation, can become a much more effective strategy to condition the indoor climate, not necessarily because energy consumption is reduced, but because the available renewable energy resources are used most efficiently (Chenari et al., 2016).

Beyond Europe, in USA, Dutton and Fisk estimated the energy and IAQ implications of varying prescribed minimum outdoor air ventilation rates (VRs) in California office buildings using the EnergyPlus building simulation software tool. Weighting factors were used to scale these model predictions to state wide estimates (Dutton and Fisk, 2014). Energy use predictions were then verified using surveyed California building energy end use data.

Models predicted state-wide office electricity use that was within 15% of reported electricity consumption from power utilities. The HVAC energy penalty of providing the current Title-24 VRs (California Energy Commission, 2013) was approximately 6%, of the total HVAC energy use. Having economizers installed reduced average indoor formaldehyde exposure by 38% and lowered HVAC EUI by 20%. For California offices with economizers, 50% and 100% increases in Title-24 prescribed minimum VRs increased heating, ventilating, and air conditioning (HVAC) modelled energy use by 7.6% and 21.6%, respectively, while decreasing the annual average workplace formaldehyde exposure by 8.6% and 14.4%, respectively. Economizers increased VRs above the minimum 79% of the time lowering annual average concentrations of formaldehyde. Decreasing minimum VRs below the Title-24 rate would have smaller predicted effects on energy use and comparatively larger effects on formaldehyde concentrations. In buildings without economizers in many climate zones, increasing VRs up to 150% of the current Title-24 minimum would save HVAC energy and significantly reduce formaldehyde.

The predicted energy impacts of minimum VRs varied substantially with both climate and building size. Raising the minimum VR had the largest effects on energy use in climates with higher heating demand and in smaller offices. Climate affects how minimum VRs influence energy use more than climate affects how minimum VRs affect IAQ. Consequently, the benefit-to-cost ratio of increased minimum VRs will also vary with climate and building size.

A key conclusion of this study was that raising future minimum ventilation rates in California offices is unlikely to significantly improve time-averaged IAQ in buildings with economizers. Lowering future minimum ventilation rates would be unlikely to deliver substantive energy savings. When simulations were repeated assuming no installed economizers, the results indicate that there would be both overall energy and IAQ benefits to higher minimum VRs for buildings without economizers. In theory, one potential mechanism for realizing these dual benefits would be prescriptions for different minimum VRs depending on whether or not a building has an economizer.

Despite the modest impacts of minimum VRs on predicted indoor formaldehyde concentrations, experimental data (Fisk et al., 2012) indicate that VRs in offices have small but economically significant effects on work performance and substantially affect rates of health, comfort and performance related symptoms experienced at work. An analysis of these effects in the entire stock of U.S. offices indicates that the economic benefits of improved health and performance when minimum VRs are increased far outweigh the increases in energy costs (Fisk et al., 2012).

6. Boosting a Flexible and Comparative Methodology Framework for Energy Performance and IAQ in EU MS

Provisions about IAQ in EPBD Comparative Methodology Framework and associated acts

In recital 9 of the EPBD it is required that: *the energy performance of buildings should be calculated on the basis of a methodology, which may be differentiated at national and regional level. That includes, in addition to thermal characteristics, other factors that play an increasingly important role such as heating and air-conditioning installations, application of energy from renewable sources, passive heating and cooling elements, shading, indoor air quality, adequate natural light and design of the building. The methodology for calculating energy performance should be based not only on the season in which heating is required, but should cover the annual energy performance of a building. That methodology should take into account existing European standards***.**

Moreover, article 5 of the EPBD requires that: *the Commission shall establish by means of delegated acts in accordance with Articles 23, 24 and 25 by 30 June 2011 a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements. The comparative methodology framework shall be established in accordance with Annex III and shall differentiate between new and existing buildings and between different categories of buildings.*

In January 2012 a Commission Delegated Regulation (EU) No 244/2012 (EC, 2012b) came into force for supplementing the EPBD by establishing a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements (hereinafter 'the Regulation')[54].

The methodology specifies how to compare energy efficiency measures, measures incorporating renewable energy sources and packages of such measures in relation to their energy performance and the cost attributed to their implementation and how to apply these to selected reference buildings with the aim of identifying cost-optimal levels of minimum energy performance requirements.

In paragraph 6 of Annex I (2) to the Regulation it is stated that: *The selected energy efficiency measures and measures based on renewable energy sources, and packages/variants, shall be compatible with the basic requirements for construction works as listed in Annex I to Regulation (EU) No 305/2011 and specified by Member States. They shall also be compatible with air quality and indoor comfort levels according to CEN standard 15251 on indoor air quality or equivalent national standards. In cases where measures produce different comfort levels, this shall be made transparent in the calculations.*

Annex III of the EPBD requires the Commission to: *provide guidelines to accompany the comparative methodology framework with the aim of enabling the Member States to take the necessary steps.* These guidelines were subsequently provided on 19 April 2014 (2012/C 115/01)[55].

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[54] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:081:0018:0036:en:PDF

[55] http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52012XC0419%2802%29&from=EN

While these guidelines are not legally binding, they provide relevant additional information to EU MS and reflect accepted principles for the cost calculations required in the context of the Regulation. As such, the guidelines are intended for facilitating the application of the Regulation. It is the text of the Regulation which is legally binding and which is directly applicable in the EU MS.

For ease of use by the EU MS, this document closely follows the structure of the methodology framework as laid down in Annex I to the Regulation. The guidelines will – unlike the Regulation itself – be reviewed periodically as experience is gained with the application of the methodology framework, both by the Member States and by the European Commission.

Section 4.3 of the guidelines text is dedicated to indoor air quality and other comfort-related issues. In this section, are mentioned the following:

- As stipulated in paragraph 6 of Annex I (2) to the Regulation, the measures used for the calculation exercise must meet the basic requirements for Construction Products Regulation ((EU) No 305/2011) and for indoor air comfort in line with existing EU and national requirements.
- The cost-optimal calculation exercise has to be designed in such a way that differences in air quality and comfort are made transparent. In case of a serious violation of indoor air quality or other aspects, a measure might also be excluded from the national calculation exercise and requirement setting.
- Concerning indoor air quality, a minimum air exchange rate is usually set. The rate of ventilation set can depend on, and vary with, the type of ventilation (natural extraction or balanced ventilation).
- Regarding the level of summer comfort it might be advisable, in particular for a southern climate, to deliberately take into account passive cooling that can be obtained by a proper building design. The calculation methodology would then be designed in such a way that it includes for every measure/package/ variant the risk of overheating and of a need for an active cooling system.

In the Commission Delegated Regulation (EU) No 244/2012 (EC, 2012b) and accompanying guidelines, it is therefore emphasised the need that indoor air quality and comfort related requirements not only should be taken on board in the application of the cost-optimal methodology framework but should also be aligned to related requirements specified in other European regulations and standards. However, no clear provisions are set that ventilation rates should be health based which as shown in previous chapters of the present report represent an essential prerequisite to guaranteeing the required level of conditions for the health, comfort and productivity of buildings' occupants.

The six influential factors impacting building energy use and IAQ

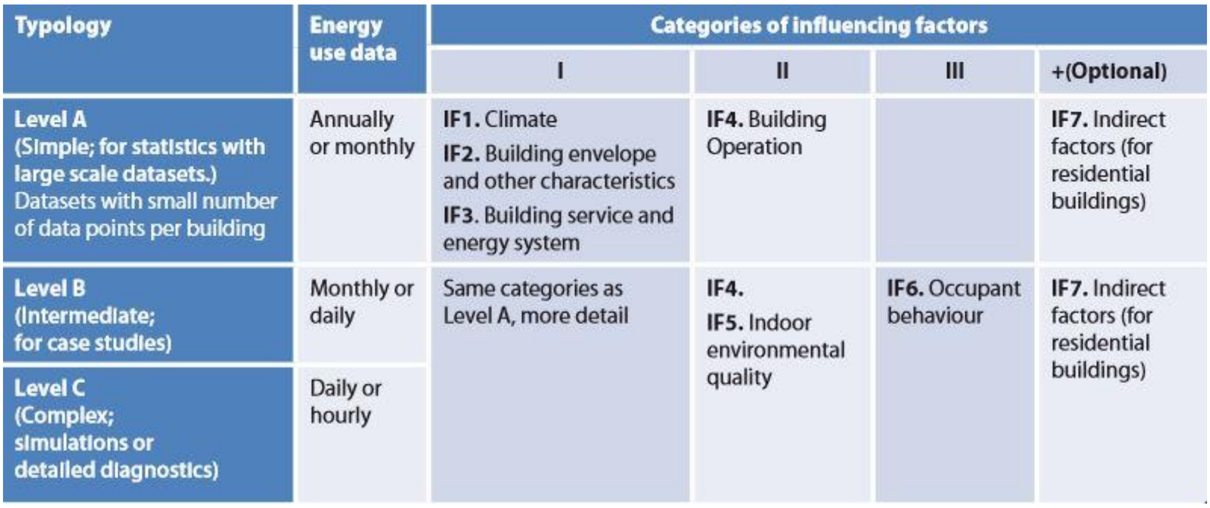
The calculation methodology on energy performance as required in recital 9 of the EPBD mainly focus on the following three factors: climate, building envelope and building services and energy systems. These factors have a direct impact on building energy use while the impact of building operation and maintenance, occupants' activities and behaviour on energy use are also important to consider and take on board in the calculations. Occupants' activities and behaviour influence the indoor air quality (IAQ) of buildings and this impact should also be considered and taken on board in line with the holistic concept and approach of building's sustainability (chapter 2 of the present report).

Detailed comparative analysis of building energy consumption and IAQ data, accounting for the interactions between all the aforementioned six factors, would provide essential guidance to identify opportunities to save energy while safeguarding the occupant's health, comfort and productivity conditions.

Understanding of the interplay among the six factors and their impact on energy use in buildings have been investigated in the period 2009-2014 in the context of the IEA EBC (International Energy Agency's Programme on Energy in Buildings and Communities) project of "Annex 53: Total Energy Use in Buildings – Analysis and Evaluation Methods" (IEA EBC, 2014). An approach and a model to describe quantitatively the occupant behaviour were developed and tested in 24 case studies (12 office buildings and 12 residential buildings) which were used to collect and analyse data on total energy consumption driven by the aforementioned six factors and their interactions.

To take on board the six influencing factors three-level typology definitions have been developed by IEA EBC as shown in Table 5.1. The level of complexity and detail increases in terms of typology definitions, energy use data and categories of influencing factors (and the number and specificity of their qualitative and quantitative parameters) when moving from Level A to level B and then level C.

Table 5.1 Three-level typology definitions for residential and office buildings (Source: IEA EBC, 2014)



Typology	Energy use data	Categories of influencing factors			
		I	II	III	+(Optional)
Level A (Simple; for statistics with large scale datasets.) Datasets with small number of data points per building	Annually or monthly	**IF1.** Climate **IF2.** Building envelope and other characteristics **IF3.** Building service and energy system	**IF4.** Building Operation		**IF7.** Indirect factors (for residential buildings)
Level B (Intermediate; for case studies)	Monthly or daily	Same categories as Level A, more detail	**IF4.** **IF5.** Indoor environmental quality	**IF6.** Occupant behaviour	**IF7.** Indirect factors (for residential buildings)
Level C (Complex; simulations or detailed diagnostics)	Daily or hourly				

Note: Levels B and C include six categories of influencing factors, besides the optional indirect factors, while more extensive set of definitions are covered in Level C.

Influencing factor 5 on indoor environmental quality (IF5) and factor 6 on occupant behaviour (IF6) are included only in levels B and C as they require substantial data and complex simulations that can only be afforded for a small sample of buildings and not for large statistically based datasets on energy use data when simulating the entire building stock in a region or a country.

The occupants' behaviour may be triggered by various driving forces classified as internal and external driving forces (IEA EBC, 2013; Fabi et al., 2011; Fabi et al., 2015).

Internal driving forces are of biological type (e.g. age, gender, health conditions, activity level, hunger, thirst and behavioural thermoregulation aspects), psychological type (e.g. habits, lifestyle, perceptions, emotions, financial and environmental concerns, etc.) and the influence of the social and cultural context. External driving forces are those related to the building, the building equipment properties (such as insulation level of buildings, orientation of facades, the HVAC system type, etc.), the building's environment (e.g. temperature, humidity, air velocity, noise, illumination, indoor air quality) and time (i.e. season of the year, week or weekend day, time of the day).

Energy consumption and IAQ are largely influenced by the occupants' activities and consumer products use and their control actions related to the operation of windows, heating, cooling and ventilation devices, blinds, electrical appliances, lighting, domestic hot water, cooking etc., driven by the indoor and outdoor environmental conditions the so-called environment-related actions (Figure 5.1).

These control actions are usually driven by some environmental stimuli that depart from the comfort zone based on the transient demand of people. Through actions, people are enabled to adjust the indoor environment conditions to satisfy their thermal, visual, acoustic, olfactory comfort, and indoor air quality needs.

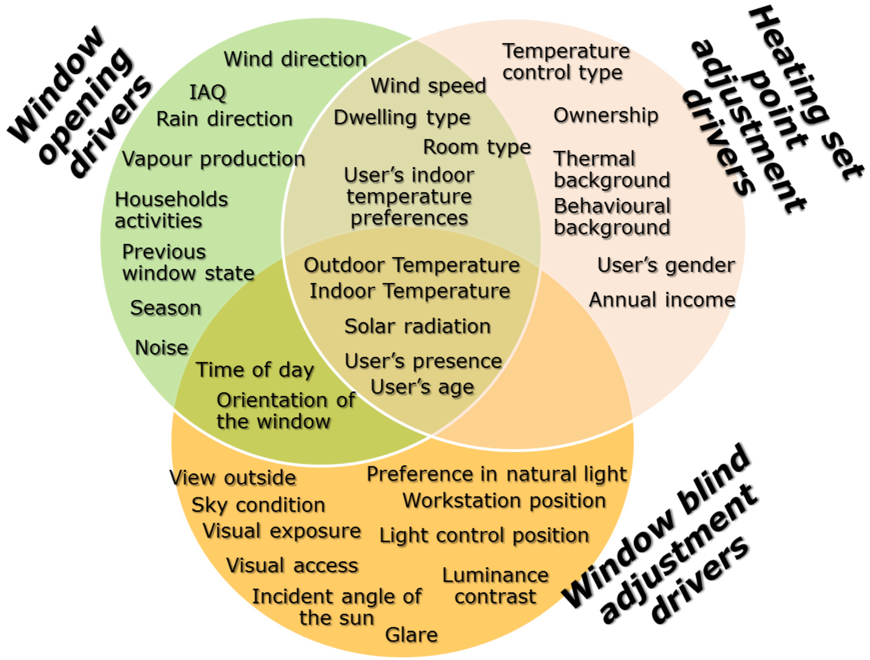


Figure 5.1 Predominant occupants' behavioural drivers influencing energy consumption and IAQ in buildings (Source: Fabi V. et al., 2011)

Building users adapt their energy-related behaviour to changes in their local building environment including changes in building technologies. Based on collected field data from longitudinal studies, energy use models can be built representing the adaptation of occupants at different stages to changes in building services and building quality resulting from thermal renovations. This behaviour may also be referred to as "learning behaviour". This clearly suggests the need for a paradigm shift in the occupant's role in buildings. The buildings' occupants should not be any more considered as "passive recipients" of pre-determined comfort conditions but as "active users" playing an important role in the performance and maintenance of a building.

Information on the combined impact of energy and IAQ related occupant behaviour is limited. More studies are needed to understand this impact especially in real-life scenarios as occupant behaviour represents a complex phenomenon that is very different from the way it is currently implemented into most energy performance simulations (IEA EBC, 2013). This should be taken into consideration during the design phase of a new building in such a way as to maximise the chances that the building system is operated as designed.

Together with the occupants' behaviour and activities, the building's equipment performance and quality of the building's envelope represent the three main drivers for energy consumption and IAQ in buildings during the building's operational phase. Buildings and their technical systems, without appropriate operation and maintenance, will not only gradually consume more energy, but they will also deliver a lower indoor environment quality (i.e., thermal comfort, indoor air quality, acoustical and lighting conditions).

Continuous monitoring and benchmarking is a support tool for a high quality operation and maintenance programme. It can help to easily identify energy conservation opportunities while not compromising the indoor environment quality. According to the iSERVcmb project the average annual energy savings of the order of 9-15% can be achieved just from monitoring and benchmarking and not at the expense of indoor environmental quality (iSERVcmb, 2014). Building automation and control systems are being increasingly developed and they promise to ensure energy use optimisation (energy is used only when and where necessary) and at the same time high indoor environment quality. Moreover, they may offer straightforward ways to control at a glance the status of all the technical building systems and the means to control their operation, as well as to provide tailor made information about both energy use and indoor environment quality and the means to take informed actions.

Automatic control systems are therefore very promising for reducing energy use in buildings. However, possible discomfort experienced by occupants due to the lack of control in the case of automatic control systems may result in unforeseen reactions of occupants leading to improper use of installations and an increase in energy use. This should be investigated further, and should be considered during the design and operation of new buildings and installations and their control systems (IEA EBC, 2013).

Boosting a Comparative and Flexible Methodology Framework for energy performance and IAQ in EU

The existing Comparative Methodology Framework requires the EU MS to:

- Define reference buildings that are characteristic and representative of their functionality and climate conditions. The reference buildings must cover residential and non-residential buildings, both new and existing ones.
- Define the energy efficiency measures that are assessed for the reference buildings. These may be measures for buildings as a whole, for building elements, or for combination of building elements.

- Assess the final and primary energy need of the reference buildings, as well as that of the reference buildings with their defined energy efficiency measures applied.
- Calculate the costs of the energy efficiency measures during the expected economic life cycle applied to the reference buildings, taking into account investment costs, maintenance and operating costs, as well as earnings from the energy produced.

The EU MS may decide whether the national benchmark used as the final outcome of the cost-optimal calculations is the one calculated with a macroeconomic perspective (looking at the costs and benefits of energy performance investments for the society as a whole), or from a strictly financial viewpoint (looking only at the investment seen from an investor’s perspective). The EU MS must make the calculations under both these perspectives, and choose the perspective on which they shall base their energy performance requirements.

From the above, it becomes evident that a Comparative Methodology Framework should be flexible to consider national peculiarities (i.e. national building typologies and their historic evolution, cultural traditions, climatic conditions and economic possibilities) and to allow choosing among different calculation perspectives. Such a framework would represent a powerful tool to guide EU MS in the process of checking the level of their minimum energy performance requirements and to improve the energy performance of their building stock.

From the review of evidence presented and discussed in this and previous chapters of the present report, it has been shown that there is a need to extend and boost the existing Comparative Methodology Framework for Energy Efficiency in EU MS by integrating IAQ aspects and assessing associated costs and benefits.

An increasing number of studies show substantial health benefits if good IAQ can be ensured in energy performance renovation of buildings or new highly energy performing buildings. In the beginning of chapter 2 of the present report, the reported figures show that benefits in terms of improved life quality, less public health spending, less absenteeism and improved productivity at work and performance at school have been quantified in various studies in Europe and beyond but not systematically under a common framework. The estimated cost due to the health based benefits could be of the same order of magnitude with that estimated when considering the energy savings alone.

Therefore it is highly recommended to establish key performance indicators for energy use and IEQ in buildings that are integrated with a proper cost indicator for estimating the co-benefits of energy efficiency measures, health and comfort in indoor environments in the context of cost-optimal calculations at macroeconomic level, especially in the case of renovation measures related to the existing EU building stock (i.e. gains from energy savings, less health care costs, less absenteeism rates from work, increased productivity).

7. Highly Energy performing, safe, healthy and sustainable buildings – a challenging cross-road for EU policies, standards and regulations

The holistic concept of Building's sustainability presented in chapter 2 reflects the multifaceted dimension of buildings in terms of socioeconomic, energy, health, safety of constructions and sustainability aspects which should all be accounted for in the conception and implementation of building related policies. In terms of implementation this requires going beyond building-specific energy considerations and shifting to a new paradigm of concisely implementing all aforementioned aspects in an integrated and efficient manner.

When designing building energy codes this implies considering the broader policy landscape that concerns a number of building related instruments (policies, standards and regulations) that are cross cutting with respect to energy performance, safety, health and sustainability and their synergistic implementation and alignment. This calls for the need to support the existing overarching EU energy policy framework to buildings' sustainability (that includes in addition to building energy performance codes also energy labelling and renewable energy policies) with a comprehensive, integrated and flexibly implemented approach with consistent standards and regulations at both EU and national levels.

The energy performance requirements included in building energy performance codes need to be aligned with those considered in land-use policies, labelling policies (both those for buildings and those for appliances and equipment) and renewable energy policies.

Land-use policies have a long-term effect on building energy needs and are central to energy sufficiency measures. Effective land-use policies allow for the efficient use of natural sources such as natural shading, daylight and sunshine to reduce heating, cooling and lighting demand (OECD, 2010). Building energy performance codes should consider the requirements of land-use policies to calculate the amount of shading needed and the position of the shade and its effects at different periods of the year when setting minimum energy performance requirements. Greater attention should be given to heat waves, especially in hot climates.

The EPBD calls MS to apply minimum requirements for the energy performance of new and existing buildings. In addition to the EPBD, the EC regulates the energy consumption of appliances and equipment by setting minimum performance requirements for energy-using products, as specified in the Eco-design Directive (2009/125/EC)[56]. The EC also requires that industry provide consumers with information on the energy performance of energy-using products by affixing a label on each product, as specified in the Energy Labelling Directive (2010/30/EU)[57]. The Energy Efficiency Directive[58] calls MS to put in place long-term building renovation strategies targeting especially poorly energy performing buildings. According to the EPBD, all new buildings shall be NZEBs by 31

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[56] http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0125&from=EN

[57] http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010L0030&from=EN

[58] http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012L0027&from=EN

December 2020, and 2 years earlier for buildings occupied and owned by public authorities. 'NZEB' means a building that has a very high-energy performance. The nearly zero or very low amount of energy required should be covered to a significant extent by energy from renewable sources, including energy produced on site or nearby. The use of energy from renewable sources in Europe is promoted by the RES Directive (2009/28/EC)[59].

Concerning the environmental performance of buildings, existing EU policy initiatives in this area have mainly targeted energy performance, which represents one of the dimensions pertaining to the holistic concept of buildings' sustainability.

Considering the 'sustainability' dimension of the holistic concept of buildings' sustainability, the main focus for sustainable buildings is the reduction of the environmental impact of resources such as materials (including waste), water and embodied energy, throughout the life cycle of buildings, from the extraction of building materials to demolition and the recycling of materials. The revised Waste Framework Directive (2008/98/EC)[60] with its objective to reach 70% of preparation for re-use, recycling and others forms for material recovery (excluding energy recovery) represents the main European policy driver towards better recycling of construction and demolition waste in the coming years. So far, only a limited number of MS initiatives have addressed resource use beyond energy performance in the building sector. A few of those are, in different ways, regulating the calculations of the environmental impacts of buildings and/or construction products. However, though aiming at tackling more or less the same issues, national initiatives partly differ in scope and methods.

In this context, the development of a common EU framework for building environmental performance indicators to drive improvements in both new and refurbished buildings was recently launched by the European Commission (DG ENV, DG GROW and DG JRC)[61]. This development responds to the need identified in the Communication 'Resource Efficiency Opportunities in the Building Sector' (COM (2014)445)[62] for a common European approach to assess the environmental performance of buildings throughout their lifecycle, taking into account the use of resources such as energy, materials and water. The common EU framework for building environmental performance indicators will be used in assessment and certification schemes to ensure that their criteria reflect priority areas of focus for resource efficiency at a European level and to assure comparability of data and results. Indoor air quality (IAQ) is among the building environmental performance indicators considered in this initial stage of the process.

In order to avoid 'conflicting overlaps' in terms of environmental and health impacts and costs and a potential fragmentation of the European market, it is of utmost importance to ensure consistency in the criteria and coherence of objectives among the various EU policy and regulatory instruments addressing the energy, environmental and IAQ related performances of products and buildings with particular attention given to sector-specific regulatory instruments (e.g. the Construction Products Regulation[63] (EU 305/2011), the

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[59] http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0028&from=EN

[60] http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0098&from=EN

[61] http://ec.europa.eu/environment/eussd/buildings.htm

[62] http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014DC0445&from=EN

[63] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:088:0005:0043:EN:PDF

EPBD, the Eco-design Directive, the Energy Labelling Directive), voluntary standards and instruments (e.g. the Ecolabel, the Green Public Procurement[64], CEN TC 350 'sustainability of construction works' related standards), other framework Directives (e.g. the Waste Framework Directive 2008/98/EC, the Ambient Air Quality Directive 2008/50/EC[65]) and international guidelines (WHO, 2010; WHO, 2006).

Ensuring consistency and coherence in the criteria used and objectives set in the building related policies and regulatory instruments at EU level is essential to help industries and SMEs producing construction products complying with several different regulations and policies for the same product(s) with reduced burdensome conditions and at affordable costs (e.g. the CE-marking and labeling of windows according to the requirements of the Construction Products Regulation, the Eco-design, the Green Public Procurement and Energy Labeling Directives).

On a European level significant efforts are taken in the direction of progressively ensuring coherence and consistency in criteria and objectives among building related policies, regulations and standards pertaining to the implementation of the holistic concept of buildings' sustainability.

The implementation of the EPBD in the EU MS is supported by a set of European standards. The extended requirements for the energy performance assessment introduced by the EPBD including the introduction of the NZEB target by 2020 gave rise to the development of a 2nd generation of standards under the mandate M/480 of the European Commission to CEN, CENELEC and ETSI. The aim of M/480 is to work out in one assessment structure a common calculation methodology for the integrated energy performance of buildings. The overarching CEN standard concerning the energy performance of buildings is EN 15603 that connects, via a modular structure, all other individual standards dealing with the thermal performance of buildings and building components, ventilation, daylight and artificial lighting, heating systems, building automation, controls and building management.

This common methodology is flexible to allow EU MS to take into account national, regional or local specificities and setting-up their level of requirements according to their priorities. The flexibility is enabled by the possibility given to EU MS to use either their own input data for the calculations following the templates provided in the normative Annex A of each individual standard or to use the default choices and values of the informative Annex B. This way the transposition of the requirements at EU level into national legal requirements can be done straightforwardly and made available as a National Annex or as separate (e.g. legal) document.

The 2nd generation of EPBD related standards will increase the accessibility, transparency, comparability and objectivity of the energy performance assessment in the EU MS, as mentioned in the EPBD.

Construction products affect the performance of buildings with respect to safety, health, environment, energy and sustainability. Construction products are covered under the Construction Product Regulation (CPR, EU 305/2011) which lays down harmonised conditions for the marketing of construction products in order to remove barriers to trade that might otherwise be created by specific national legal requirements. CPR aims

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[64] http://ec.europa.eu/environment/gpp/index_en.htm

[65] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:152:0001:0044:en:PDF

to provide information on product performance by converting performance requirements of buildings, so called basic working requirements, into product performance and technical standards which are prepared to provide a common measuring and reporting format. The seven basic working requirements of CPR are: 1. Mechanical resistance and stability; 2. Safety in case of fire; 3. Hygiene, health and the environment; 4. Safety and accessibility in use; 5. Protection against noise; 6. Energy economy and heat retention; 7. Sustainable use of natural resource.

IAQ and health related issues are linked to emissions from construction products into indoor air and pertain to the 3rd basic working requirement on 'hygiene, health and environment'. A new horizontal testing method for emissions from construction products was published in October 2013 as CEN/TS 16516 (CEN/TS 16516, 2013). CEN/TC 351/WG 2 undertook the process of transforming the CEN/TS 16516 into a European Standard with final voting scheduled during 2016. The evaluation of the emissions from a health standpoint is facilitated and served by the EU-LCI harmonisation framework developed by JRC (ECA report 29, 2013). Since 2015, the EU-LCI work continues under the umbrella of the CPR. CEN/TS 16516 will be referenced in updated harmonised product performance standards (hEN) that are used for CE marking. Furthermore, it is expected that the new testing standard will become the key benchmark also for voluntary low VOC emissions specifications, such as Ecolabels and programs for sustainable buildings in Europe.

For the construction and building products and systems of relevance to EPBD (e.g. HVAC products), as well as the coverage under the CPR harmonised product standards, the requirements of the Eco-design and the Energy-Efficiency Labelling Directives could improve the coherent assessment of the overall performance of these products and systems while reducing the administrative burden and costs associated with their certification and type approval across Europe.

It should be underlined that CPR targets the performance of construction products and not buildings. There is a need for further work to provide guidance at EU level on how to effectively implement the requirement under paragraph 6 of Annex I (2) of the Commission Delegated Regulation (EU) No 244/2012 (EC, 2012b) (associated to EPBD implementation) concerning the compatibility of the energy efficiency related measures and requirements with the basic requirements for construction works as listed in Annex I to CPR.

IAQ and other health based criteria, requirements and indicators are progressively penetrating into and/or given more emphasis in a number of building related policy and legislative instruments (e.g. EPBD, CPR, Ecolabel and GPP technical criteria for office buildings, furniture, etc.), European standards (e.g. prEN 16798-1 and CEN/TS 16516) and national regulations. These processes are informed by and are highly benefiting from the outcome of a number of European Commission and WHO initiatives and EU funded projects: (a) harmonisation frameworks for construction products labelling and health based evaluation of the products' chemical emissions (ECA report 27 and 29); (b) tools and protocols for the monitoring and auditing of indoor air quality in European buildings (PILOT INDOOR AIR MONIT and AIRLOG projects); (c) the holistic approach consisting of pollution source based strategies and ventilation practices (HEALTHVENT project) and (d) guidelines for indoor and outdoor air pollution (WHO).

However, still lacking is a co-ordinated and coherent implementation of IAQ related requirements in building related policies in EU as from a regulatory point of view this remains under the competencies and responsibilities of the EU MS with no binding requirements at EU level. This creates obstacles for the implementation of an integrated performance-based approach for buildings' related energy and IAQ issues in Europe.

Consequently, within the holistic concept and approach of buildings' sustainability, the definition of the boundaries and implementation of the requirements of each of the building related sectorial policies, regulations and standards should be co-ordinated and optimised via an overarching and balanced approach at EU level. Such an approach should fully consider energy, environmental, health and resource efficiency aspects and national characteristics and constraints (economic, social, cultural, climatic). The efficient implementation of such an approach requires rapid and efficient exchange and sharing of relevant information and data concerning the cross-cutting issues of the holistic approach for buildings' sustainability. This could be supported by the standardised infrastructure and common interface for geographical information exchange offered by the INSPIRE Directive and the tools and data hubs recently developed by the European Commission relevant to the buildings' energy performance and IAQ (i.e. the European Observatory of the buildings stock, the E^3P portal and the IPCHEM module 4 'products and indoor air monitoring').

In the aforementioned context and perspective, the most feasible, technically robust, flexible and cost-optimised solutions satisfying minimum mandatory requirements across the issues of safety, health, energy, and sustainability in the EU MS should be pursued and investigated. This could be enabled by developing a "head standard" for each of the seven Essential Requirements of CPR to: (i) provide the basic principles; (ii) set the framework for the performance assessment methodology; (iii) set mandatory minimum performance requirements and (iv) define performance classes. This development should be synergistically performed and aligned with the principles and requirements of the overarching European standard on energy performance of buildings (EN 15603) and with the recently launched (by the European Commission) development of a common EU framework for building environmental performance indicators to drive improvements in both new and refurbished buildings.

Provided that this challenging task is successfully undertaken and implemented, it will pave the ground for the development of a common building's sustainability metrics and labelling system at EU level to rate buildings for their performance jointly in terms of energy efficiency, IAQ and thermal comfort, structural and fire safety and sustainability (see also recommendation R4.6 of the present report). However, this common framework should provide additional information and not duplicate or contradict information already included in EPCs.

The aforementioned delineates a potential path to follow for the envisaged conception and implementation of an integrated performance-based approach to the overall buildings' sustainability concept[66]. It would address, conceptualise and implement a coherent set of definitions and requirements of building related policies, regulations and standards (at both EU and national levels) that are featuring cross-cutting criteria and requirements in a resource-efficient and flexible way.

Such development would also reinforce the position of the European construction industry in the global market, by providing a new and wider family of innovative standards related to the holistic buildings' sustainability concept and approach.

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[66] https://ec.europa.eu/assets/jrc/events/20131129-eeb-roundtable/20131129-eeb-roundtable-report.pdf

Last but not least, the greater integration of IAQ aspects and procedures into EPBD and other building related policies would also translate into maximised health-benefits in terms of DALYs gained per year in the EU as already demonstrated and quantified by the IAIAQ project (Jantunen et al., 2011) (Figure 6.1).

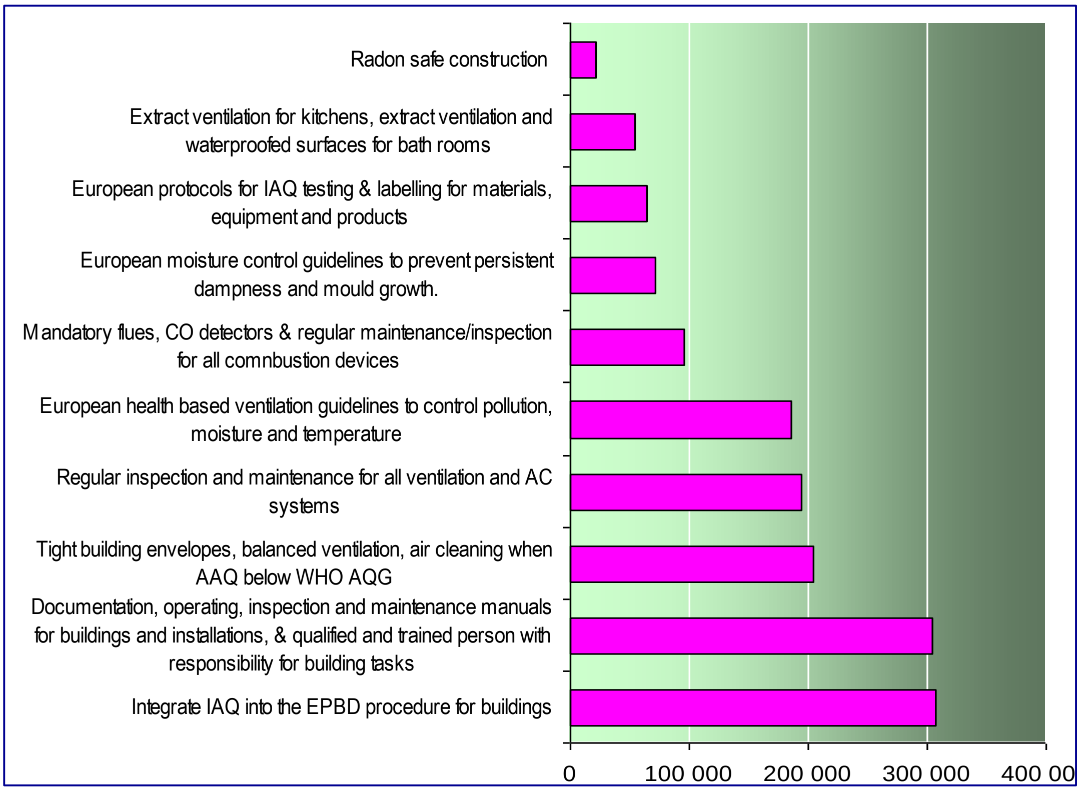

Figure 6.1 Health benefits (DALYs/yr) in EU-26 in the 10th year of implementation of ten policies

8. Conclusions and recommendations

EU MS have been developing policies and measures to generally reduce the actual energy use of their buildings.

Energy consumption in buildings shall be primarily meant to guarantee conditions of well-being, comfort and health for the buildings' occupants. This creates the need and challenging endeavour to reconcile energy savings ambitions with the obligation to guarantee the conditions of growing-up, living working and learning in healthy indoor environments.

A number of challenges need to be addressed in terms of the impact of high-energy performance on the quality of the indoor environment of buildings without compromising the comfort, health and productivity of their occupants. EU MS are called to properly implement and enforce the EPBD.

This chapter includes the conclusions drawn from the review performed in the context of Task 13.3 and the recommendations made to help promote and enable the effective implementation of healthy and highly energy performing buildings in EU.

The conclusions on the implementation status in the EU MS of the EPBD provisions relating to ventilation, indoor air quality and energy efficiency criteria and requirements are reported separately from those drawn from the review of data monitoring surveys and modelling simulations at EU and national levels on IEQ, energy efficiency and comfort and health conditions in highly energy performing buildings. This will help the reader to distinguish these two distinct categories of conclusions.

The recommendations are reported separately according to their affinity and content (i.e. more policy, legislative, regulatory oriented or more research, technical, implementation oriented).

Conclusions on the implementation status in the EU MS of the EPBD relating to ventilation, indoor air quality and energy performance criteria and requirements

- Most EU MS have introduced minimum ventilation requirements but these are in most cases based on comfort criteria and use health based criteria[67] to a lesser extent. In some cases the minimum ventilation requirements are below the generally accepted levels for comfort. In some cases no legally binding requirements exist at all.

- Other than minimum ventilation rates, IAQ related requirements in EU MS, such as acceptable exposure levels of pollutants (according to national or international IAQ guidelines) and building airtightness, are largely differentiated in terms of

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[67] The health based ventilation criteria are defined in the context of the health based guidelines framework that was developed within the EU funded HEALTHVENT project (ECA report, 2015). The "health based ventilation rate" for a specific building is defined when the WHO air quality guidelines are met through an integrated approach following the principles of primary prevention, which combines source control measures and health based ventilation practices that guarantee the protection of health. Both indoor and outdoor air pollution sources should be tackled through coordinated actions and treated as equally important for human health.

mandatory or recommended values for new and existing residential buildings. In several cases, there is a mismatch of the IAQ related requirements that are set for new and existing buildings.

- As energy efficiency related measures are often applied without any mandatory requirements for a subsequent assessment of their impact on the levels of ventilation and other IEQ related parameters such as thermal comfort, lighting (including day lighting), noise and indoor air pollution levels, in several cases values for these parameters are reported to be below the required or recommended levels by national regulations and international standards. This situation could further deteriorate given the current trend in energy efficiency related renovation measures resulting in more airtight building envelopes.
- Several European countries do not allow or do not recognise the possibility of reducing ventilation rates when less polluting materials are used or when ventilation efficiency is improved. Also they do not provide the possibility of controlling ventilation rates based on the outdoor air quality (with the exception of those EU MS that have adopted and currently apply the EN 15251:2007[68] and EN 13779:2007[69] standards in their national regulations).
- In the on-going revision of standard EN 15251:2007 (prEN 16798-1)[70] the IAQ and health aspects related to the design and criteria of ventilation rates have a greater emphasis in the former version of the standard but the concepts, targets, tools and methods proposed do not yet fully match the framework of the health based ventilation guidelines that was developed within the EU funded HEALTHVENT project[71].
- Compliance check procedures in EU MS currently focus mainly on structural analysis, safety and energy performance aspects during the buildings' design stage. During the construction of new or renovated buildings compliance procedures are limited to aspects such as thermal transmittance of building elements (U-values), installation of heating and air conditioning equipment (but not their operation nor any guarantee of the quality of the supplied air), airtightness, availability of Energy Performance Certificates (EPCs), etc.
- Compliance with building and installation aspects related to indoor air quality (e.g. ventilation and Heating, Ventilating and Air Conditioning - HVAC systems) or thermal comfort (in particular risk of overheating) is rarely checked by the designated control bodies and if so, mainly at the design stage based on calculations rather than by performing onsite controls. During the operation phase of existing buildings, compliance checks are only carried out for aspects

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[68] EN 15251:2007. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. European Committee for Standardization (CEN), 2007.

[69] EN 13779:2007. Ventilation for non-residential buildings - Performance requirements for ventilation and room-conditioning systems. European Committee for Standardization (CEN), 2007.

[70] CEN. European Committee for Standardization, prEN 16798-1 "Energy performance of buildings – Part 1: Indoor environmental input parameters for design and assessment of the energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics (EN 15251 rev: 2015). CEN/TC 156 WG19-N68, May 2015.

[71] ECA (European Collaborative Action "Urban Air, Indoor Environment and Human Exposure"). Report no. 30. Framework for health based ventilation guidelines in Europe. European Commission. Joint Research Centre. EUR 27640 EN (2015).

such as energy performance, safety (e.g. resistance to fire, structure defects such as cracks, etc.) and occupational health and safety, while systematic indoor air quality or thermal comfort verification procedures have been rarely identified and even less practiced.

Conclusions from data monitoring surveys and modelling simulations at EU and national levels on indoor environment quality, comfort and health conditions in highly energy performing buildings

- To date, only a very limited number of studies investigating IAQ, health and comfort in low-energy buildings have been conducted in the EU and other parts of the globe. The outcomes of these studies contribute to the knowledge about IEQ and occupants' comfort and health in energy performing buildings. However, due to the limited sample size of buildings and occupants included in the investigations and also considering the diversity of climate conditions, cultures and economic status, caution must be applied when assessing outcomes and the findings should not be generalised.

- The reviewed studies show limited evidence about the impact of energy efficiency strategy and retrofits on IEQ, comfort and health in Europe and beyond. The initial work underway in some EU MS to understand and quantify this impact is promising but still limited. There is a need to investigate further and produce more data to fully understand the implications of highly energy performing buildings on the relationships between energy efficiency measures, IEQ and comfort conditions, ventilation and health in Europe.

- A number of studies have explored occupants' health in energy performing homes. The majority of these studies report that highly energy performing homes are associated with health benefits although there have also been reports of an increase in health problems in some cases for this type of buildings. Recipients on low incomes experience greater improvements in health following energy efficiency interventions, supporting the inclusion of energy efficiency measures in strategies to tackle social issues like fuel poverty and health inequity.

- The studies that were reviewed in this report show that improving buildings' energy performance generally improves the indoor environment and IAQ. However, if energy sufficiency and energy efficiency measures[72] are implemented incorrectly then the health based ventilation conditions may not be fulfilled. If the building itself and its systems and components are not adequately designed, installed and maintained, negative impacts on IAQ and consequently on the occupants' health, comfort and performance might be expected. Several studies have shown that a substantial performance gap is emerging between the design expectations and the measured performance in terms of energy consumption and

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[72] Energy sufficiency, energy efficiency and supply from renewable sources are key drivers in the transition to a sustainable, cost-effective, secure and contributing to the planet as a low-carbon energy system (IEA/UNDP, 2013).

IAQ in both new and refurbished buildings, reflecting the related lack of proper design and commissioning procedures.

- The reviewed studies show that mechanical ventilation systems in highly energy performing buildings, if properly operated and maintained, lead to an increased removal of pollutants, and thus to an overall improvement of the IAQ and reduction of reported comfort and health related problems. In the case of poor design, operation and/or maintenance, there are a number of concerns about potential failures associated with these systems. The most frequently mentioned concerns are: wrong airflow rates, excess noise, draughts, poor hygiene of the air handling system and low humidity indoors due to elevated outdoor air rates (especially during winter when the outdoor humidity is low). In practice, design, installation and operation of mechanical ventilation systems is not an equally preferred solution across the entire building stock of the EU MS due to climatic, cultural and social characteristics and economic possibilities (e.g. different practices observed among Northern and Southern European countries).
- Demand controlled ventilation can significantly decrease the energy needs for heating and cooling in buildings by fine-tuning ventilation rates to the strict needs. Additionally, when applicable, heat recovery can further reduce those energy needs by lowering the energy impact associated with ventilation. In cases where higher ventilation rates are required, modelling simulations show that the use of any or both of these strategies enables meeting health based ventilation needs without necessarily having a negative impact on the energy consumption. However, the benefits from the use of heat recovery may be offset in scenarios of low building airtightness which might be a technical and especially a cultural challenge in countries in which natural ventilation practices prevail and buildings mostly have low airtightness (e.g. Southern European countries).
- With the increasing demand for minimising energy consumption in residential buildings, the relationship between building characteristics and operation, occupant behaviour and the quality of the indoor environment in low-energy and high-energy performing dwellings requires further attention.
- Detailed comparative analysis of building energy consumption data and IEQ data accounting for the interactions between six factors (i.e., climate; building envelope; building services and energy systems; building operation; building maintenance; occupants’ activities and behaviour) would provide essential guidance to identifying opportunities for energy saving while safeguarding the occupant’s health, comfort and productivity conditions.
- Building occupants’ behaviour, equipment performance and quality of the building envelope during the building operation phase are essential drivers for energy consumption and indoor environment quality (IEQ) (i.e., thermal comfort, IAQ, acoustical and lighting conditions) in buildings. Therefore, the building’s design, commissioning and operational phases including maintenance aspects should be given the same level of prominence in the evolution of existing building codes and related standards and regulations in the EU and Member States.
- Studies showed that the use of low-emitting construction and decoration products, furniture and consumer products would help limit the episodic indoor air pollution events observed in buildings and therefore reduce the exposure to pollutants linked to human activities. This is an important consideration that could

significantly reduce some of the health based ventilation demand in highly energy performing buildings. In some European countries building materials labelling has been systematically used over many years (e.g. in Finland since 1995 with over 3000 labelled construction materials) which has incentivised the process of producing and progressively using low-emitting materials throughout EU.

- Many of the reviewed studies focussed primarily on measuring CO_2 concentration (as a 'proxy' of IAQ) and general comfort parameters (i.e. relative humidity and temperature). Only a few studies have also included measurements of IAQ parameters known to be associated to health risks (i.e. physical, chemical and biological pollutants, including those with WHO guidelines).

Recommendations to help promoting and enabling the effective implementation of healthy and highly energy performing in the EU

The conclusions of this report suggest that in order to guarantee that highly energy performing buildings in the EU will also be healthy for their occupants, a number of indoor environment quality related issues should be considered as part of the review of the EPBD. These should be implemented in the EU MS within a holistic approach to building's sustainability, which should consider optimising buildings' energy performance and associated costs without compromising the implementation and enforcement of the health based ventilation concept in EU buildings.

It should be noted that the EPBD already provides a "whole building" approach by promoting the improvement of the energy performance (i.e. energy efficiency and renewable energy use) of buildings, taking into account both outdoor climatic and indoor climate requirements and cost-effectiveness. In addition, according to the EPBD the energy performance of buildings should be calculated on the basis of a methodology that includes, in addition to thermal characteristics, other factors that play an increasingly important role including indoor air-quality.

To this purpose the following specific policy/legislative/regulatory and research/technical/implementation oriented recommendations are made.

Policy/ legislative/ regulatory oriented recommendations

- Careful policy design, combined with adequate regulation and enforcement regimes, can strike a balance between good IEQ and the rational use of energy in buildings, while also avoiding the potential pitfalls of introducing energy efficiency measures into the complex system that buildings represent.

  In such context and perspective, the existing overarching EU policy framework to buildings' energy performance needs to be supported by a comprehensive, integrated and flexibly implemented approach of consistent standards and regulations at both EU and national levels.

- The conception, integration and efficient implementation of building related policies, regulations and standards in EU should be performed considering the multi-dimensional concept of buildings' sustainability which encompasses socioeconomic, energy, health, safety of constructions and sustainability aspects.

- The best approach for designing effective building codes from an energy point of view and for successfully reducing building related energy consumption patterns in the long term is by properly combining energy sufficiency, energy efficiency and supply from renewable energy sources.
- IEQ and health aspects should be considered to a greater extent in European building codes than in the current practice. While indoor climate is mentioned in the EPBD the importance of indoor air quality, thermal comfort, daylight and noise has to be strengthened. Inclusion of requirements for indoor air quality in the national regulations of all European countries should be reinforced, including specific pollutants to be measured and their associated limit levels in line with the WHO guidelines (or EU or other international standards).
- A co-ordinated and coherent implementation of IEQ related requirements in building related policies in EU is still missing as from a regulatory point of view this remains under the competencies and responsibilities of the EU MS with no binding requirements at EU level. This creates obstacles for the implementation of an integrated performance-based approach for buildings' related energy and IEQ issues in Europe.

  Consequently, within the holistic view and approach of buildings' sustainability, it is recommended that the definition of the boundaries and implementation of the requirements of each of the building related sectorial policies, regulations and standards should be co-ordinated and optimised via an overarching and balanced approach at EU level which fully considers energy, environmental, health and resource efficiency aspects as well as national characteristics and constraints (economic, social, cultural and climatic).

  Such an approach would help avoid 'conflicting overlaps' in terms of environmental and health impacts and costs, as well as the potential fragmentation of the European market by ensuring consistency in criteria and coherence of objectives among the various EU policy and regulatory instruments addressing the energy, environmental and IEQ related performances of products and buildings. It would also help industries and SMEs producing construction products complying with the requirements of several different regulations and policies for the same product(s) by reduced burdensome conditions and more affordable costs.
- The most feasible, technically robust, flexible and cost-optimised solutions satisfying minimum mandatory requirements across the issues of safety, health, energy, and sustainability in the EU MS should be pursued and investigated. This could be enabled by developing a "head standard" and setting mandatory minimum performance requirements for each of the seven Essential Requirements of the Construction Products Regulation (CPR)[73] which should be aligned with: (a) the principles and requirements of the overarching European standard on energy performance of buildings (EN 15603)[74]; (b) with the recently launched (by the European Commission) development of a common EU

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[73] EC. (2011). Construction Products Regulation. Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC; 2011

[74] prEN 15603:2013 standard. Energy performance of buildings - Overarching standard EPBD and related technical reports (TR 2013, prEN 15603, May 2013).

framework for building environmental performance indicators to drive improvements in both new and refurbished buildings.

Provided that this could be successfully undertaken and implemented it would then pave the way for the development of a *common set of building‘s sustainability metrics* and *labelling system* at EU level to use for rating buildings for their performance jointly in terms of energy performance, IEQ, structural and fire safety and sustainability.

- The common building‘s sustainability metrics and labelling system could be accompanied by a *building passport* to follow a building for its entire life cycle. Building passports, on a voluntary basis, include tailor-made information to building owners on long term investments and financing mechanisms in renovation measures over the lifetime of the building and could also include relevant information about ventilation systems characteristics and IEQ related aspects and traceability of expected cost and benefits in terms of improved energy savings, IEQ, comfort and health conditions. Building passports should not replace the role of existing EPC schemes across MS.
- The progression towards meeting the targets for Nearly Zero-Energy Buildings (NZEB) by 2020 has involved a stepwise tightening of minimum energy performance requirements in EU MS. To avoid this resulting in deterioration of IEQ and health conditions in the European building stock, measures related to energy sufficiency/efficiency and renewable energy supply should be implemented in an integrated fashion together with appropriate strategies dealing with indoor and outdoor pollution sources, ventilation, thermal comfort, acoustics and lighting.

  In this respect, it is recommended that the health based guidelines framework that was developed within the EU funded HEALTHVENT project be consulted and properly implemented in building related policies, regulations and standards at both EU and EU MS levels.

  According to the HEALTHVENT health based ventilation guidelines concept, to ensure that energy efficiency measures are properly combined with health based ventilation it is necessary to consider controlling the outdoor and indoor pollution sources, reduce the emissions from the materials used, and take account of the type and level of occupancy and the activities taking place in buildings during their lifetime (including changes in use) when health based ventilation rates are defined and calculated.

  All relevant key stakeholders (EU MS, policy makers, building designers and constructors to building managers and users) should ensure that in the entire building stock (existing buildings and new highly energy performing buildings) the buildings’ design, maintenance and operation respect the HEALTHVENT framework's concept and other relevant EU policies, standards and WHO guidelines.

  In this context, there is a need to provide *common health based ventilation guidance in Europe* that will reinforce the definition and setting of ventilation requirements and metrics based on health criteria to be applied after all possible control strategies of indoor and outdoor pollution sources have been exploited.

Harmonisation of *ventilation metrics* and *calculation practices* among countries is also recommended. The guidance should focus on methods covering aspects such as controlled ventilation (accounting for occupancy, activities, and outdoor and indoor air quality), improved ventilation efficiency, localised ventilation, air cleaning, adjusting the ventilation rates according to the indoor and outdoor air pollution conditions, use of clean HVAC components, balancing the ventilation based on the actual use of the building, selection of low pressure drop equipment to reduce electricity use, heat recovery, etc. The guidelines should also cover the quality of the air handling system as described in the HEALTHVENT WP 5 report. These issues are partly dealt with in the standard prEN 16798-3[75] but not exhaustively.

- EU and national policies are recommended to promote sustainable buildings that can adapt to variations in outdoor and indoor pollution sources as well as featuring passive/active control for moisture/dampness and avoidance of particles. The IEQ issues (IAQ, thermal comfort, noise, daylight, etc.) should be given more emphasis in the labelling criteria of sustainable buildings.
- The Construction Products Regulation (CPR) targets the performance of construction products and not buildings. Further work is required to provide guidance at EU level on how to effectively implement the requirement under paragraph 6 of Annex I (2) of the Commission Delegated Regulation (EU) No. 244/2012[76] (associated to EPBD implementation) concerning the compatibility of the energy efficiency related measures and requirements with the basic requirements for construction works as listed in Annex I to CPR.
- With the increasing energy performance requirements towards NZEBs, the compliance checking of the energy performance of new buildings becomes increasingly important and should be seen within the holistic concept and implementation perspective of building's sustainability (i.e. exploring the potential of energy performance in relation to the climate conditions and performance requirements, optimising over energy performance and costs without compromising the enforcement of the health based ventilation concept).
- There is a need to provide guidance at EU level on proper design, construction, installation, maintenance and inspections of ventilation systems. Inspection and compliance checks of ventilation systems are recommended to become part of energy and IAQ auditing under the EPBD.

  The review of the EPBD and of national ventilation regulations could consider including requirements for IEQ inspection and audit in the operational phase of buildings to monitor and ensure that the IEQ related requirements are met. This can be based on the outcomes and experience gained in the development of the harmonisation framework for indoor air monitoring by the European Commission

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[75] EN 16798-3:2014. Energy performance of buildings Part 3: Ventilation for non-residential buildings - Performance requirements for ventilation and room-conditioning systems. European Committee for Standardization (CEN), 2014.

[76] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:081:0018:0036:en:PDF

(DG SANCO and DG JRC) in the context of the PILOT INDOOR AIR MONIT[77] project (2010-2012).

- Clear provisions and criteria in the buildings' energy performance calculation methodology (including cost-optimality calculations) should be introduced so that the simulated scenarios for various buildings' typologies and climates and the subsequent energy efficiency measures shall guarantee good indoor air quality and comfort conditions for the buildings' occupants at the design and operation phases of new and renovated buildings during their entire lifespan while also optimising energy savings and costs. This will help achieving better acceptance of energy related measures and labelling systems among the public and all other relevant stakeholders.
- It is also recommended to model and systematically assess the total buildings' performance at the EU level (i.e. energy performance, adequate ventilation, IEQ, occupants' health, comfort and performance) and the associated socio-economic implications under various scenarios representing different climatic zones, building typologies and operation practices and regimes of various building systems (e.g. HVAC systems), quality of building products (e.g. low-emitting construction materials) and occupants behaviour in EU MS. In addition to considering and including the construction and operational cost of buildings, this would also allow provision of consolidated figures to compare the economic benefits from improved health, comfort and performance against those from energy-efficiency saving measures alone.

  In this context and perspective, the EPBD Comparative Methodology Framework could incorporate *key performance indicators* for *energy use, health, comfort and IEQ* in buildings. These would need to be integrated with a proper cost indicator for estimating the co-benefits of energy-efficiency measures, health and comfort in indoor environments in the context of cost-optimal calculations at the macroeconomic level especially in the case of renovation measures related to the existing EU building stock (i.e. gains from energy savings, less health care costs, less absenteeism rates from work, increased productivity).
- It is recommended to create an information resource at EU level with best practice examples in the EU MS, contextualised in their respective climate, cultural tradition and values, technological and economic contexts, to show buildings' compliance and certification performance rates jointly for energy use and performance levels, IEQ and associated costs within a perspective of economy of scale.
- It is recommended to establish rewarding mechanisms for best performing EU MS as to the degree of compliance and performance of their building stock jointly in terms of energy performance (in its broader sense), IAQ, thermal comfort and ventilation. This would create incentives for better performance at the EU MS level, which could extend also to building owners (e.g. reduction of their annual taxes, exception of the EPC issuing fee, etc.) when they manage to improve the energy performance and IEQ of their buildings either through major renovation

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[77] PILOT INDOOR AIR MONIT project's final report (2013). Administrative arrangement between DG SANCO and DG JRC (contract no. SI 2582843) (Kephalopoulos et al., 2013).

and/or applying the EPC recommendations. Conversely, in case of non-compliance penalties should be activated.

Research/Technical/implementation oriented recommendations

- A key issue is to progressively start building up a consolidated picture of energy-efficiency measures, IAQ, thermal comfort, ventilation and health via co-ordinated, systematic and centralised large scale longitudinal studies with data collection and reporting mechanism at the EU level.

  Population representative measurement campaigns should be planned and carried out on indoor exposures for various typologies of buildings to fill the gaps in knowledge about the effects of ventilation and indoor air exposures on health. These measurement campaigns should include a much better characterisation of exposures and ventilation than has been previously done. They should also investigate in detail the role and impact of indoor and outdoor sources on chronic diseases. Particular emphasis should be given to vulnerable groups such as children, elderly and patients with allergies and chronic respiratory diseases.

  In such context and perspective, it is recommended to set up monitoring campaigns to collect information and data in EU MS on the performances of ventilation systems and the IEQ levels achieved in relation to indoor and outdoor pollution sources, energy sufficiency and energy efficiency measures in the EU building stock. The information and data should be streamlined and made available via the European Commission's relevant data portals and knowledge systems (i.e. the DG JRC's European Energy Efficiency Platform Portal and the DG ENV's IPCHEM[78] module 4 on 'Products and Indoor air Monitoring' data).
- IEQ and comfort parameters should become an integral part of all building related performance standards and regularly monitored after building completion and during building use (i.e. at both building commissioning and occupation phases).
- Ventilation energy demand should be calculated and expressed in a transparent way according to health based ventilation requirements and should be clearly separated from the total heating and cooling demand.
- Ventilation systems should undergo mandatory and periodic inspection by qualified professionals and be subject to periodic maintenance as per the related technical prescriptions. When seen and implemented according to the health based ventilation concept and approach, this will increase the chances of achieving the designed ventilation rates and encourage maintenance of proper health based ventilation conditions in relation to real pollution sources load and changes occurring during building occupancy for the entire building life cycle.
- Harmonized criteria for construction products' labelling are recommended to be used as a part of the design specification of ventilation requirements and be aligned with the principles and requirements of the Construction Products Regulation. This can take advantage of the two harmonisation frameworks for indoor products labelling and health based evaluation of product emissions which

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[78] https://ipchem.jrc.ec.europa.eu/

were developed by the European Commission (DG GROW and DG JRC) (ECA Reports n°27[79], 2012 and n°29[80], 2013 respectively).

- It is recommended to develop a common, flexible and comparative framework methodology in the EU that includes guidelines for compliance checks related to energy efficiency energy sufficiency and IEQ. Such compliance checks should ensure proper levels of IAQ and adaptive comfort behaviour to avoid health risks of the buildings' occupants while optimising actual energy expenditures. The methodology should be developed and implemented via a comprehensive and holistic approach which properly considers pollution source based strategies and lighting, HVAC and ventilation practices (such as those proposed by the HEALTHVENT and AIRLESS[81] projects), in line with the criteria and parameters specified in relevant CEN standards, and considering integration of various IAQ monitoring typologies (e.g. such as those elaborated by the EC's PILOT INDOOR AIR MONIT[82] and AIRLOG[83] projects). Moreover, it is recommended to preferably cover all stages of compliance checking and quality control during the building's design and construction phases and, ultimately, prior to and also during the building's occupation and operation.
- One possible option for consideration would be extending the EPC to include ventilation systems characteristics (where applicable) and IEQ related aspects related to occupants. Such an extended EPC could also include recommendations (as foreseen by the EPBD) about the overall building's improvement potential. For issuing such an extended certificate and enable monitoring of the implementation of the recommendations via proper auditing procedures at an affordable cost, it is important to find a trade-off between standard recommendations generally applicable to the entire building stock and tailor-made recommendations that may be more effective for specific buildings.

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[79] ECA (European Collaborative Action "Urban Air, Indoor Environment and Human Exposure"). Report no. 27. Harmonisation Framework for Indoor Products Labelling Systems in EU. European Commission. Joint Research Centre. EUR 25276 EN (2012).

[80] ECA (European Collaborative Action "Urban Air, Indoor Environment and Human Exposure"). Report no. 29. Harmonisation framework for health based evaluation of indoor emissions from construction products in the European Union using the EU-LCI concept. European Commission. Joint Research Centre. EUR 26168 EN (2013).

[81] AIRLESS: A European project to optimise Indoor Air Quality and Energy consumption of HVAC-systems (Bluyssen et al., 2003).

[82] PILOT INDOOR AIR MONIT project's final report (2013). Administrative arrangement between DG SANCO and DG JRC (contract no. SI 2582843) (Kephalopoulos et al., 2013).

[83] HEALTHY INDOOR LIFE - Integrated platform for intelligent indoor air quality audit management (http://www.iaq-airlog.eu/)

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Definitions

'Indoor environment quality (IEQ)' means a set of factors used to describe healthy and comfortable general indoor climate conditions in buildings, which should cover at least indoor air quality, thermal comfort, ventilation, noise and lighting.

'Indoor air quality (IAQ)' means the level of potentially harmful substances in the indoor air, including, organic and inorganic gases, vapours, particles and microbes.

'Thermal comfort' means thermal conditions indoors like temperature, air velocity and air humidity.

'Health based ventilation' means that ventilation rates are defined and calculated only after considering and controlling the indoor and outdoor pollution sources, reduction of emissions from the materials used, the type and level of occupancy and activities taking place in buildings during their lifetime (including changes in use).

List of abbreviations and acronyms

ACH	Air Changes per Hour
AER	Air Exchange Rate
AQ	Air Quality
ASHRAE	American Standard for Heating, Refrigeration and Air-conditioning Engineers
BoD	Burden of Disease
BPIE	Buildings Performance Institute Europe
CEN	Comité Européen de Normalisation
COST	European Cooperation in Science and Technology
CPR	Construction Products Regulation
CSTB	Scientific and Technical Centre for Building
DALY	Disability Adjusted Life Years
DER	Deep Energy Retrofit
DG ENER	Directorate-General for Energy
DG GROW	Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs
EAHC	Executive Agency for Health and Consumers
ECA	European Collaborative Action
EEA	European Environment Agency
EED	Energy Efficiency Directive
EPA	Environmental Protection Agency
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificates
ES	Energy Star
EU	European Union
EU MS	European Union Member States
GDP	Gross Domestic Product
GHG	Greenhouse Gases
HVAC	Heating, Ventilating, and Air Conditioning
IAQ	Indoor Air Quality
ICV	Impacts of Changing Ventilation Rate
IEA	International Energy Agency
IEQ	Indoor Environment Quality
JRC	Joint Research Centre
KCEE	Knowledge Centre on Energy Efficiency
LCA	Life Cycle Assessment
LEED	Leadership in Energy and Environmental Design
MS	Member States
MVHR	Mechanical Ventilation with Heat Recovery
NZEB	Nearly Zero-Energy Buildings
OECD	Organisation for Economic Co-operation and Development
OQAI	Observatoire de la qualité de l'air intérieur

PAH	Polycyclic Aromatic Hydrocarbons
PM	Particulate Matter
R&D	Research and Development
REHVA	Federation of European Heating, Ventilation and Air Conditioning Associations
SAP	Standard Assessment Procedure
SVOC	Semi-volatile Organic Compounds
TVOC	Total Volatile Organic Compounds
UNDP	United Nations Development Programme
VOC	Volatile Organic Compounds
VR	Ventilation Rate
WHO	World Health Organization

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As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

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