EXPLORING INNOVATIVE INDICATORS FOR THE NEXT-GENERATION ENERGY PERFORMANCE CERTIFICATES FEATURES - OUTDOOR AIR POLLUTION

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EXECUTIVE SUMMARY

Energy performance certificate (EPC) schemes have not evolved much since their first introduction in the Member States to meet the mandatory requirements of the Energy Performance of Buildings Directive (EPBD). Stakeholders have questioned their reliability but at the same time, they have been useful for the real estate industry. All the Member States have legislation in place and existing infrastructure or systems to run EPC schemes. These schemes require evolution with the changing needs of the built environment and requirements to look beyond the energy consumption of buildings to take in elements such as better indoor comfort, reducing air pollution and others. Public authorities view them as potential instruments to improve the performance of the existing and new building stock. Extending the functionalities of existing systems will create several pathways to update and manage next-generation EPCs.

This report presents the preliminary scoping and analysis of the five technical features related to developing innovative EPC indicators proposed within X-tendo[1]: (i) smart readiness, (ii) comfort, (iii) outdoor air pollution, (iv) real energy consumption, and (v) district energy. The outcome of this report is an initial mapping and selection of the suitable options of methods for developing indicators for these five features. The follow-up activities in the project will take forward this work to elaborate and provide technical specifications of the methodologies and concepts for the five features.

This report presents an overview of existing assessment approaches and methodologies for each feature that could be adopted in the indicator development for the EPCs. Details are provided of the most suitable existing methods that can be applied in the assessment of five technical indicators when integrated with EPCs. Their suitability and applicability to EPCs is analysed in a broader context, including building typologies and ranking/scoring techniques.

The report also evaluates existing links between these methods and the energy performance of a building/EPCs to determine how these can be integrated in the feature development. Since most of the assessment methods require some type of data related to end-users, therefore, their legal boundaries are also studied. Within the scoping and analysis, a ranking and SWOT analysis of several methods is presented to assess their suitability and feasibility of application in the development of the new features. Finally, a conceptual approach is proposed for the development of each of the five features. Findings are presented, highlighting the barriers, challenges and limitations of the assessment methods for the five features.

[1] In addition to these five features, X-tendo will also provide a set of five features dealing with innovative handling of EPC data.

Across all features, the following conclusions are made:

Indicators

- 'Smart readiness' approach presents a potential method for assessing the smartness of buildings with nine domains (e.g. lighting, ventilation, envelope, monitoring and control etc.)
- 'Comfort' approach incorporates four key indicators – thermal, visual and acoustic comfort and indoor air quality – to be assessed through checklists, on-site measurements and surveys
- 'Outdoor air pollution' approach addresses a building's impact on air by two methods: an outdoor air pollution contribution index and indoor air purity index
- 'Real energy consumption' approach outlines an assessment method based on operational ratings, with options for normalisation to allow for better inter-building comparison
- 'District energy' approach focuses on predicting the potential for future development for buildings via two methods: expected future performance of district heating and heat distribution and transfer system

Cross-cutting issues

- Technical challenges that constrain the application of existing methods such as assessment time, accuracy, normalisation process, variable definitions and emission factors could be overcome by certain modifications in approach
- Features should be aligned financially to increase market acceptance and cost-effective assessments during the development
- Legal and governance issues should be addressed by dealing with challenges such as development of universal methodologies, presence of multiple standards at Member State level, control of citizen data and privacy, and acceptance of future estimations by public authorities
- From a social perspective, user acceptance and public understating of the features are key issues and should be considered in feature development
- If these indicators are well integrated within EPCs, significant environmental benefits are anticipated
- Future implementation of indicators can be strengthened by addressing lack of industry readiness, understanding of anticipated benefits and enforcement issues

Certain limitations need to be overcome to implement these innovative indicators, such as variable levels of implementation in the Member States due to different local requirements and regulations. Some indicators require extensive monitoring and measurements, and a lack or absence of data is a barrier in the development and acceptance of these features within EPC schemes.

A concise overview of all the features is given in Figure 1. Overall, a promising picture is visible with the proposed conceptual approaches for features combining new ideas with existing methods to work towards developing innovative indicators that could be tested and integrated into the EPC schemes of the implementing countries within the X-tendo project.

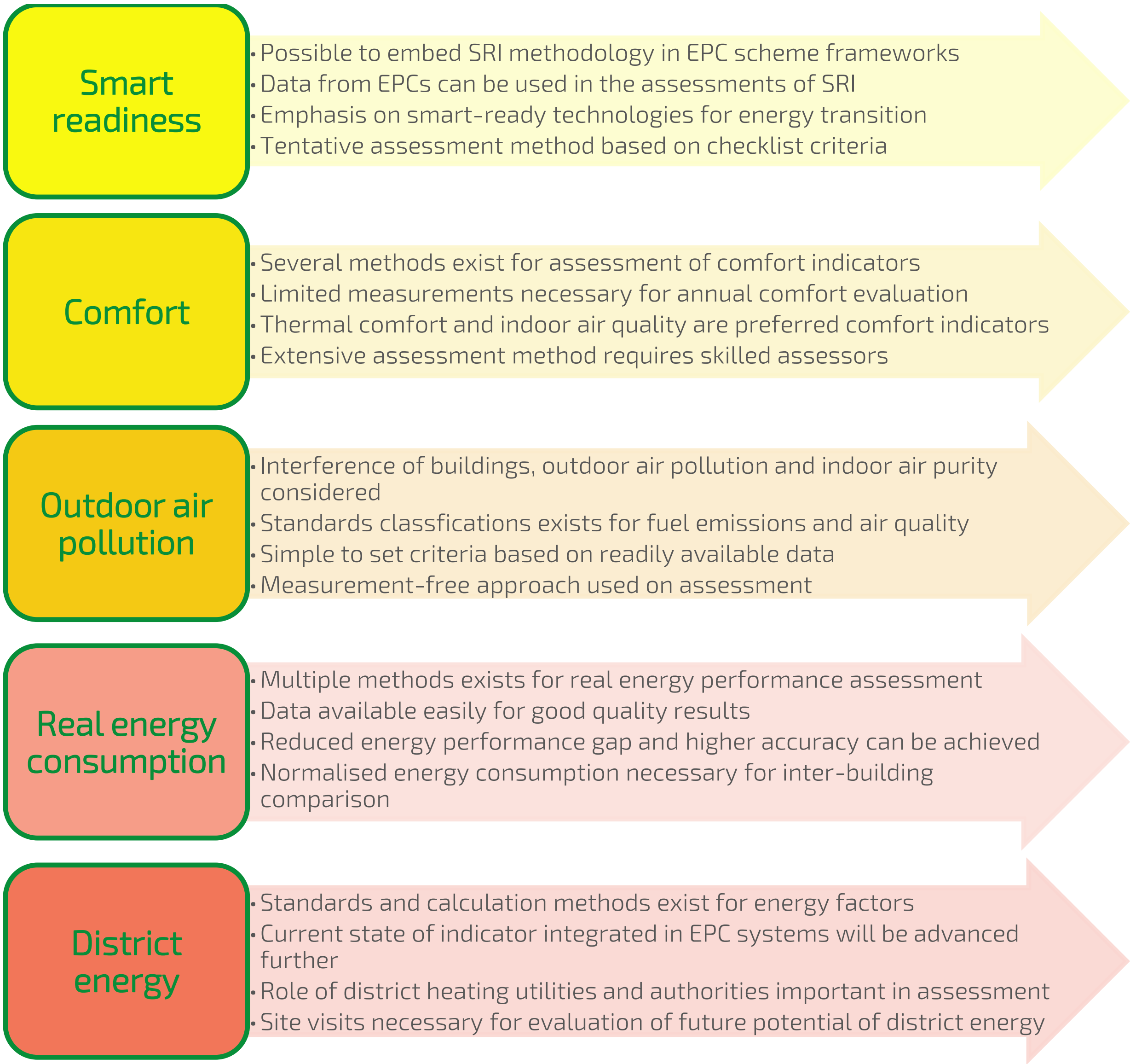

Figure 1: Overview of the five features

1 EXTENDING THE FUNCTIONALITIES OF EPCs WITH INNOVATIVE INDICATORS: SCOPING AND ANALYSIS

Energy performance certificates (EPCs) are the key source of information on the energy performance of the building stock [1]. Their role for the end-user and the real estate sector has mainly been limited to indicating and comparing the energy class of the building, helping to regulate property transaction prices and rents. They have also been attractive for end-users and builders in gaining access to funds and incentives to conduct energy efficiency improvements. EPCs have also been seen as an unreliable source of information by stakeholders in some Member States [2]. Weak enforcement, low public acceptance and awareness, quality of audits, qualifications of the auditors and widely varying certificate costs all influence the role of EPCs and how they can affect the real estate market.

Many Member States stepped up efforts in the last decade to improve their EPC frameworks after the introduction of the requirement of energy performance and assessment systems under the EPBD (2002/91/EC) and EPBD recast (2010/31/EU). The recent amendments in the EPBD (2018/844) further strengthened the existing provisions by setting out that Member States should provide information to owners and tenants on the purpose and objectives of EPCs, energy efficiency measures, and supporting financial instruments through accessible and transparent advisory tools such as direct advice and one-stop-shops.

In the current scenario, EPCs are viewed as instruments that can bring additional benefits to the end-user (e.g. property seller, buyer, or tenant) by being a vehicle for additional information other than energy efficiency.

1.1 Aim of the X-tendo project

The X-tendo project is developing a framework of 10 “next-generation EPC features”, aiming to improve compliance, usability, and reliability of the EPC. The X-tendo partners cover 10 countries or regions – Austria, Belgium (Flanders) Denmark, Estonia, Greece, Italy, Poland, Portugal, Romania, and the UK (Scotland) as displayed in Figure 2.

Figure 2: X-tendo consortium and target countries

The X-tendo project approaches next-generation EPCs by exploring 10 new features in addition to their existing functionalities (see Figure 3). The features that will be explored in the project fall into two broad categories:

- New technical features used within EPC assessment processes and enabling the inclusion of new indicators in EPCs
  1) Smart readiness
  2) Comfort
  3) Outdoor air pollution
  4) Real energy consumption
  5) District energy
- Innovative approaches to handle EPC data and maximise its value for building owners and other end-users.
  6) EPC databases
  7) Building logbook
  8) Tailored recommendations
  9) Financing options
  10) One-stop-shops

Figure 3: The X-tendo toolbox representing both innovative EPC indicators and novel ways of handling EPC data

Existing EPC schemes lack focussed vision. In order to become a catalyst for energy renovations, the next-generation EPC must provide an improved and more reliable service to the end-users. The key output of the project will be the X-tendo toolbox, a freely available online knowledge hub that will be continued beyond the project duration. For each feature, the toolbox would include (i) solution concepts and good practice examples, (ii) descriptions of methodological approaches, (iii) calculation tools, and (iv) implementation guidelines and recommendations.

1.2 Scope and objective of this report

The purpose of this report is to identify suitable methods and approaches to assess the five features (i) smart readiness, (ii) comfort, (iii) outdoor air pollution, (iv) real energy consumption, (v) district energy. Before developing individual methods for their assessment, a detailed review of the existing assessment and calculation methods is presented for developing the indicators for all the five features in this report. Although the goal of the next-generation EPC will be more holistic, the relation with energy performance remains a key boundary condition for the selected approaches presented in this report.

The identification of the suitable methods will consider the objective of the modular toolbox being developed specifically for EPC assessments. The results of the report will be an initial selection of options for methods and indicators for features 1-5. Findings of the scoping and analysis are gathered in this report for these indicators.

Table 1 lists the five innovative EPC indicators that could make EPCs more than just an informative tool. It also indicates the feature leads (VITO, BPIE, NAPE and e-think) who will develop the innovative indicators and organisations (EASt, DEA, TREA, CRES, ENEA, NAPE, ADENE, AAECR and EST) from implementing/expert partner countries that would support them in the development and testing of the indicators on several test projects.

Table 1: Innovative EPC indicators

	 Smart readiness	 Comfort	 Outdoor air pollution	 Real energy consumption	 District energy
Feature lead	*VITO*	*BPIE*	*NAPE*	*VITO*	*e-think*
EASt (Austria/Styria)	Implementer	Implementer		Implementer	
DEA (Denmark)	Implementer	Implementer			Expert
TREA (Estonia)	Implementer/ Expert			Implementer	
CRES (Greece)	Implementer	Implementer			
ENEA (Italy)				Implementer	Implementer
NAPE (Poland)			Implementer/ Expert		Implementer
ADENE (Portugal)		Implementer			
AAECR (Romania)	Implementer	Implementer		Implementer/ Expert	Implementer
EST (UK)				Implementer	

The EPCs can become much more useful for the end-users, public authorities and policymakers by providing more detailed information on the existing building stock and its performance. Next-generation EPCs can support the transition to a low-carbon building sector, provided they are revised considering new indicators, with effective mechanisms to ensure compliance and high quality, reliable certifications.

2 FEATURE 3: OUTDOOR AIR POLLUTION

2.1 Air pollution levels across the EU

Air pollution is perceived as the second biggest environmental concern for Europeans, after climate change [83]. Indoor and ambient air pollution in 2018 were recognised as one of the risk factors for non-communicable diseases [84]. The data gathered by the WHO from 4,300 cities shows that the annual level of pollutants within the air can lead to health conditions such as asthma, lung cancer and heart disease. It is estimated that 90% of the population worldwide are breathing highly polluted air, while in the EU, 80% of monitored cities exceed the threshold levels recommended by the WHO [85]. Based on the EU air quality report [86] the concentration of particulate matter (PM) in large parts of Europe exceeded the EU limit values and the WHO air quality guideline. In 2017, 17% of the EU-28 urban population was exposed to PM10 (particulate matter 10mm) levels above the daily limit, and 8% for PM2.5 (particulate matter 2.5 mm) It was even worst when the stricter WHO guidelines were taken as a limit level value: for PM10 it was 44% and for PM2.5 it was 77% of urban population.

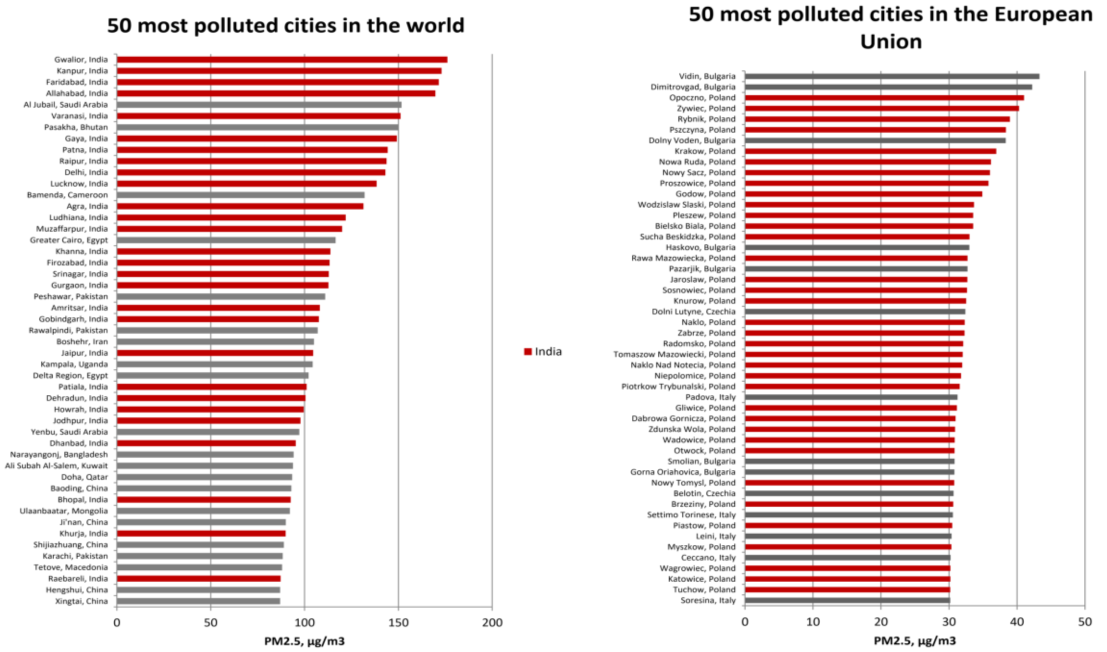

Figure 4: The 50 most polluted cities in the world and in the European Union [85]

The most visible symptom of air pollution is smog. Smog is an atmospheric phenomenon resulting from the mixing of fog with smoke and exhaust fumes. It is caused by the release of harmful chemical compounds into the atmosphere, such as sulphur oxides and nitric oxide, and solid substances, i.e. particulate matter, as well as carcinogenic polycyclic aromatic hydrocarbons. Two distinct types of smog are recognised: sulphurous smog and photochemical smog. Sulphurous smog, which is also called "London smog", results from a high concentration of sulphur oxides in the air and is caused by the use of sulphur-bearing fossil fuels, particularly coal. This type of smog is aggravated by dampness and a high concentration of suspended particulate matter in the air [87]. Photochemical smog, which is also known as "Los Angeles smog", occurs most prominently in urban areas that have large numbers of automobiles. It requires neither smoke nor fog. This type of smog has its origin in the nitrogen oxides and hydrocarbon vapours emitted by automobiles and other sources, which then undergo photochemical reactions in the lower atmosphere [87].

The main contributors in PM10, PM2.5 and CO (carbon monoxide) emission are the commercial, institutional and household sectors. The SO_x (sulphur oxides) emission is mainly related with the energy production and distribution sector and NO_x (nitrogen oxides) with the road transport sector [86]. Twelve supreme audit institutions (SAIs) identified transport and/or industry as the sources with the biggest impact on air quality in their countries. In Eastern Europe, seven SAIs specified 'low emission' as the main source of air pollution in their country [84]. Low emission is related to fossil fuel combustion in individual heating sources, which causes locally emitted pollutants.

2.2 Overview of the methods for assessing the impact of buildings on outdoor air and indoor air

Buildings affect both the quality of the outside air (pollutant emissions) and the purity of the indoor air (air filtration). The impacts of atmospheric air pollution can, therefore, be included in EPCs in two different ways:

- First, the local air pollution contributor index will be used to assess a building's effect on outside air quality. To determine this index a calculation of pollutants emitted by local energy sources will be calculated. The emissions will be compared with reference values. A weighting will be integrated to reflect the impact of each pollutant on air pollution (e.g. smog development). The local air pollution contributor index will be estimated based on the amount and type of fuels used in the building for the purposes of heating, cooling, hot water preparation and potentially electricity needs (e.g. a combined heat and power (CHP) system).
- Second, the indoor air purity index will be used to assess the ability of a building's ventilation system to purify outdoor air. This assessment will, for example, consider the type of filters used in the mechanical ventilation systems (if present), including their replacement and cleaning. Also, the historical measured data on outdoor air pollution (particulates, ozone, nitrogen oxides, etc.) from the surrounding monitoring stations will be taken into consideration.

2.2.1 Impact of buildings on ambient air pollution

In the EPC calculation methodology, both building energy performance and installation characteristics are available. The main influencing parameter of the local ambient air pollution is the low emission from the production of energy in the buildings. The energy can be delivered to the buildings through different energy vectors:

- Heating, cooling, and electricity from district network (city) (e.g. heat from district heating substation)

- On-site production of heating, cooling and electricity using renewable energy sources (RES) but without fuel combustion (e.g. biomass or biogas)
- On-site production of heating, cooling, and electricity by fuel combustion.

As the main focus of the feature is on the indicators for individual buildings and not on energy plants, district energy networks will be excluded from consideration of a building's impact on local air pollution. Only buildings with local heat and energy production by fuel combustion will be considered.

The energy sources can be sub-divided considering the general size (thermal capacity) and the combustion techniques applied. For residential purposes, heating sources like fireplaces, stoves and small boilers (<50 kW) can be used. In institutional/commercial/agricultural/other sectors heating sources like boilers, space heaters (>50 kW) and smaller-scale CHP generation are used [88]. Small combustion installations are characterised by their quantities, type of combustion techniques, fuels used and range of efficiencies. The plants and equipment in some buildings can be outdated and are polluting and inefficient. The emissions from such installations are significant.

Standards and regulations

The simplest way of estimating pollutant emissions from an energy source is to use a method based on regulations and mandatory standards. The heating sources must fulfil the requirements of pollutant emission rate limits for exhaust gases that are described in EU standards or other regulation, such as EU directives. There are many standards that cover requirements for solid fuel heating appliances, including EN 16510-1:2018 (appliances fired by solid fuel); EN 14785:2006 (residential space heaters fired by wood pellets), EN 15250:2007 (slow heat release appliances fired by solid fuel), EN 303-5:2012 (heating boilers for solid fuels) or EN 303-7:2006 (gas-fired central heating boilers). The pollutant emission rate limits for new appliances intended for sale must also meet the requirements of the Eco-design Directive [89]. For example, from September 2015, non-condensing gas boilers with an open combustion chamber cannot be sold in Europe.

The pollutant emission rate limits can be estimated based on heating source type and emission class. However, to calculate the quantity of pollutant emitted in a specific period of time, exhaust gas flow must be measured. In addition, such a calculation does not enable an estimate of the influence of the total pollutant emissions on local smog development or outside air quality.

Emission rates

The production of heat and energy from fossil fuels is related to the combustion process. Using the thermodynamic description of combustion processes (e.g. chemical reaction of fuel and oxidant such as atmospheric oxygen), emission rates of pollutants can be estimated per fuel unit (weight in Mg, volume in m^3 or energy of used fuel in GJ). The emission rates consider the quality of the fuel, so its characteristic like sulphur or ash content must be known. In this method the following types of pollutants are considered:

- Sulphur oxides (SO_x)
- Nitrogen oxides (NO_x)
- Carbon monoxide (CO)
- Total suspended particulates
- Benzo(a)pyrene.

In this method a pollutant emission reduction device efficiency can also be included. The pollutant emissions can be estimated based on the quantity of fuel used and the calculated emission rate. This method allows values to be estimated for each pollutant emission in a given period. However, it does not enable an estimate of the influence of the total pollutant emissions on local smog development or outside air quality.

Air quality index (AQI)

To estimate the local air pollution contributor index, the calculated values of pollutant emissions must be compared with reference values and weighted. The methodology used for the AQI can be used for this purpose. AQI is used by government agencies internationally to communicate current and future air pollution estimates to the public. Different countries have their own quality indices like the Air Quality Health Index (Canada), the Air Pollution Index (Malaysia), and the Pollutant Standards Index (Singapore)[2].

In Europe, the Common Air Quality Index (CAQI) was used from 2006. In 2017, this was changed by the European Environment Agency (EEA) to the European Air Quality Index (EAQI). The EAQI is based on concentration values for five key pollutants:

- Particulate matter (PM10)
- Fine particulate matter (PM2.5)
- Ozone (O_3)
- Nitrogen dioxide (NO_2)
- Sulphur dioxide (SO_2)

It reflects the potential impact of air quality on health. The AQI is determined by the pollutant for which concentrations have the highest impact on human health. EU legislation sets air quality standards for both short-term (hourly or daily) and long-term (annual) air quality levels. Standards for long-term levels are stricter than for short-term levels since serious health effects may occur from long-term exposure to pollutants.

The AQI relies on the measured hourly data and corresponds to the poorest level for any of five pollutants. Although it does not correspond directly to the pollutant emissions from buildings, the methodology used in determining the AQI can be used to estimate the local air pollution contributor index.

[2] https://en.wikipedia.org/wiki/Air_quality_index

2.2.2 Impact of outdoor air pollution on indoor air purity

The building performance in the EPC scheme depends on characteristics of building installations like ventilation systems. Fresh air can be delivered into buildings by natural or mechanical ventilation systems. The concentration of pollutants in indoor air is a function of outdoor air quality and the ability of the ventilation system to purify the incoming air.

There are different methods to assess indoor air purity in rating systems that assess filtration system efficiency. These assessments also consider the level of outdoor air pollution.

- WELL Building Standard

The American WELL Building Standard [52] is a performance-based system based on the interactions between humans and the built environment. Air filtration is one of the categories included because of its impact on human health, including the cardiovascular, immune and nervous systems. In order to assess the air filtration system within a building, three criteria are considered: filter accommodation (free space for additional filters), particle filtration (minimum filter class in terms of filtration efficiency or low polluted ambient outdoor air) and air filtration maintenance (verification with manufacturer's recommendations). A building can achieve a higher rating when air filtration is optimised by, for example, an advanced air purification system that includes carbon filters and/or air sanitisation, properly maintained.

- LEED

The American LEED (Leadership in Energy and Environmental Design) includes indoor air purity in its rating system [50] for sustainable buildings. It includes basic requirements (in accordance with ASHRAE Standard 62.1-2010 [90] or CEN Standard EN 15251-2007 [55] and EN 13779-2007 [91]) and some additional requirements, including details of higher class filters. Buildings collect points for fulfilling these additional requirements, and for innovation within indoor air purity.

- BREEAM

The British BREEAM (Building Research Establishment Environmental Assessment Method) rating system [92] requires buildings to fulfil national standards to provide outdoor air into the building, including EN 13779-2007 [55] for the location of the building's air intakes and exhausts and filter class level. This system considers the use of specific filters depending on the expected purity of the indoor air and evaluated pollution of the ambient outdoor air (level of pollution is assessed on the basis of comparison between measured data and data from appropriate guidelines).

2.3 Description of assessment methods

2.3.1 Ambient air pollution

- Emission rates

In this method, the emission of pollutants is calculated based on the fuel used and standard emission rates estimated at local/country level. Emission rates for different fuels depend on certain parameters:

- Hard coal [g/Mg], fuel quality (sulphur and ash content [%]) is considered to determine the emission rates of sulphur oxides and particulates
- Wood [g/Mg], fuel quality (ash content [%]) is considered to determine the emission rate of particulates
- Heating oil, [g/Mg], fuel quality (sulphur content [%]) is considered to determine the emission rate of sulphur oxides
- Natural gas, [g/m^3], fuel quality (sulphur content [mg/m^3]) is considered to determine the emission rate of sulphur oxides
- Propane, [g/GJ], standard fuel quality was adopted.

The emission rates of different fuels type can be found in national documents; an example of the emission rates for coal is given in Table 2 .

Table 2: Emission rates of coal [93]

<table>
<tr><th rowspan="4">Pollutant</th><th rowspan="4">Unit</th><th colspan="4">Fixed grade</th><th>Mechanical grade</th></tr>
<tr><th colspan="5">Nominal heat output of the boiler [MW]</th></tr>
<tr><th>≤ 0.5</th><th>> 0.5 - 5 ≤</th><th>≤ 0.5</th><th>> 0.5 - 5 ≤</th><th rowspan="2">> 0.5 - 5 ≤</th></tr>
<tr><th colspan="2">Natural draught burner</th><th colspan="2">Forced draught burner</th></tr>
<tr><td>Sulphur oxides</td><td rowspan="6">g/Mg</td><td colspan="5">16,000 x s</td></tr>
<tr><td>Nitrogen oxides</td><td>2,200</td><td>1,000</td><td>2,000</td><td>3,000</td><td>3,200</td></tr>
<tr><td>Carbon monoxide</td><td colspan="2">45,000</td><td>70,000</td><td>20,000</td><td>10,000</td></tr>
<tr><td>Carbon dioxide</td><td>1,850,000</td><td>2,000,000</td><td>1,850,000</td><td>2,000,000</td><td>2,130,000</td></tr>
<tr><td>Total suspended particulates</td><td>1 000 x A^r</td><td colspan="3">1 500 x A^r</td><td>2 000 x A^r</td></tr>
<tr><td>Benzo(a)pyrene</td><td colspan="4">14</td><td>3.2</td></tr>
<tr><td colspan="7">s - total sulphur content expressed as a percentage [%]
A^r - ash content expressed as a percentage [%]</td></tr>
</table>

This methodology allows consideration of the efficiency of emission reduction devices. To calculate the total pollutant emission over a given period (e.g. one year) the formulae (1) and (2) can be used. In equation (1) the emissions are calculated on the basis of emission rates and annual fuel demand. Equation (2) allows the efficiency of pollution reduction equipment to be included.

$$E = B \times W \left[\frac{g}{a}\right] \quad (1)$$

where

- B fuel consumption [Mg/a], [m^3/a], [GJ/a]
- W emission rate [g/Mg], [g/m^3], [g/GJ]

$$E' = E \times \frac{(100-\eta)}{100} \left[\frac{g}{a}\right] \quad (2)$$

where

- E' emissions with the emission reduction device
- E emissions calculated in (1) [g/a]
- η emission reduction device efficiency [%]

Figure 5 presents the emissions rate per MWh of energy used for four pollutants that are the main components of smog. Four types of fuels were considered: coal, wood, natural gas, and heating oil. The calculations were based on the method presented above.

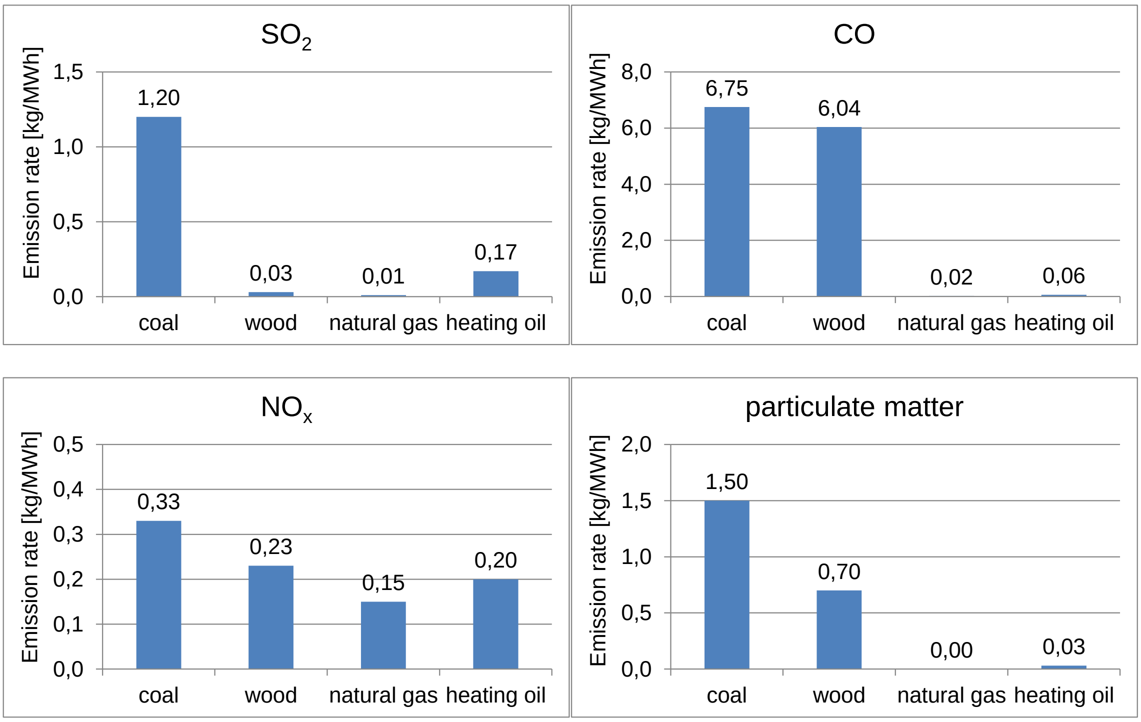

Figure 5: Emissions of pollutants generated during combustion of different types of fuel in boiler with heat output ≤ 0.5 MW. Source: Own calculations based on [93]

Air quality index (AQI)

The AQI is expressed using six grades: good, fair, moderate, poor, very poor and extremely poor. Despite the use of several scales for different national air quality indexes, the index bands are in most cases similar. In Table 3, the index bands are complemented by health-related recommendations for both the general population and sensitive populations.

Table 3: The index bands with health-related messages [94]

AQ index	General population	Sensitive populations
Good	The air quality is good. Enjoy your usual outdoor activities.	The air quality is good. Enjoy your usual outdoor activities.
Fair	Enjoy your usual outdoor activities	Enjoy your usual outdoor activities
Moderate	Enjoy your usual outdoor activities	Consider reducing intense outdoor activities if you experience symptoms
Poor	Consider reducing intense activities outdoors, if you experience symptoms such as sore eyes, a cough or sore throat	Consider reducing physical activities, particularly outdoors, especially if you experience symptoms
Very poor	Consider reducing intense activities outdoors, if you experience symptoms such as sore eyes, a cough or sore throat	Reduce physical activities, particularly outdoors, especially if you experience symptoms
Extremely poor	Reduce physical activities outdoors	Avoid physical activities outdoors

To estimate AQI, measured pollutant concentrations are compared with the limit values. Five pollutants are taken into consideration: PM2.5, PM10, NO_2, O_3, SO_2. For each of pollutant, the index levels are based on assigned pollutant concentration limits. In the Table 4, the example ranges of pollutant concentration limits for the EU CAQI (Common Air Quality Index) are presented.

Table 4: Index levels of the EU CAQI [94]

Pollutant	Index level (based on pollutant concentrations in μg/m^3)					
	Good	Fair	Moderate	Poor	Very poor	Extremely poor
Particles less than 2.5 μm (PM2.5)	0-10	10-20	20-25	25-50	50-75	75-800
Particles less than 10 μm (PM10)	0-20	20-40	40-50	50-100	100-150	150-1200
Nitrogen dioxide (NO_2)	0-40	40-90	90-120	120-230	230-340	340-1000
Ozone (O_3)	0-50	50-100	100-130	130-240	240-380	380-800
Sulphur dioxide (SO_2)	0-100	100-200	200-350	350-500	500-750	750-1250

The final result, representing the assessment of the air quality, is based on the poorest level of any individual pollutant component. The same methodology is used for all different air quality indexes. This method requires the measurement of the pollutant concentration of outdoor air, and the result cannot be directly linked with emissions from buildings. However, the idea of index levels can be used to estimate a local air pollution contributor index.

2.3.2 Indoor air purity

WELL Building Standard

The WELL Building Standard [52] method demands fulfilment of the following requirements:

- Recirculated air in the main air ducts, connected directly to the air handling unit:
  - rack space is available and rack location identified for future implementation of carbon filters or combination particle/carbon filters
  - there is a possibility to accommodate the additional filters
- Particle filtration:
  - outdoor air filters' class is minimum MERV 13 (ASHRAE Standards [90]) or F7 (CEN Standard EN 779-2002 [95])
    or
  - according to the building project for 95% of all hours in a calendar year, ambient outdoor PM10 and PM2.5 levels measured within 1.6 km of the building are below the limits set in the WELL Air Quality Standards feature
- Air filtration maintenance:
  - projects must annually provide International WELL Building Institute with records of air filtration maintenance, including evidence that filters have been properly maintained as per the manufacturer's recommendations

Filter class and space for additional filters are checked in the construction project and/or through on-site inspection. Correct cleaning/replacement of exploited filters are shown in annual reports. Additionally, the building ranking recognises optimisations concerning advanced air purification.

LEED

The LEED v4 [50] method connected with air filtration is an element of Enhanced Indoor Air Quality Strategies. After meeting the minimum requirements for 'minimum indoor air quality performance' and 'environmental tobacco smoke control' (contained in relevant ASHRAE Standards), the building can achieve points for indoor air purity improvements, including air filtration. Mechanically ventilated spaces should be equipped with appropriate entryway systems, interior cross-contamination prevention, and filtration. Spaces with natural ventilation should have entryway systems and natural ventilation design calculations. Spaces with mixed-mode systems should meet requirements for all items above and mixed-mode design calculations.

The LEED v4 describes detailed requirements for entryway systems in the main direction of travel to capture particulates entering the building at regularly used exterior entrances and their weekly maintenance. It contains details of design calculations based on Chartered Institution of Building Services Engineers (CIBSE) Applications Manual (AM10/2005, AM 13/2000).

For filtration systems, each ventilation system that provides outdoor air to occupied spaces must be equipped with particle filters or air-cleaning devices. The devices' class is minimum MERV13 (in accordance with ASHRAE Standard) or F7 (CEN Standard EN 779–2002). All air filtration media should be replacement after completion of construction and before occupancy.

- BREEAM

The method in BREEAM [92] requires the ventilation system to meet the national best practice standard in terms of providing fresh air into the building. Next, in mechanically ventilated and mixed-mode spaces the location of the building's air intakes and exhausts, in relation to each other and external sources of pollution, should be designed in accordance with EN 13779-2007 (Annex A2). This document includes information about the location of air intakes and adjacent spaces like garbage collection sites, car parks, access roads, loading zones, sewage gas outlets, chimney outlets, cooling towers, busy streets. Requirements for exhaust locations and distance between intakes and exhausts are also described. Where EN 13779-2007 is not followed, the building's air intakes and exhausts must be over 10m of horizontal distance apart and intakes over 10m of horizontal distance from sources of external pollution. In naturally ventilated spaces, openable windows or ventilators must be at least 10m of horizontal distance from sources of external pollution (including the location of any building-related air exhausts).

The filtration system is designed also in accordance with EN 13779-2007 (Annex A3). First, the quality of ambient outdoor air is classified based on the level of main pollutants (SO_2, O_3, NO_2, PM10). Measured values (from the European Topic Centre on Air and Climate Change data) are compared with values according to the guidelines: 1999/30/EC[3] (only for PM10) and WHO 1999 [96] (the rest of pollutants). Outdoor air is classified in three categories: clear, dusty and very high dust or gas concentration. The standard assigns an appropriate filter class (between F5 to F9 and carbon filter) depending on the expected quality of indoor air (high, medium, moderate, low). The standard EN 13779-2007 among others recommends appropriate periods for filter replacement (one year or 2000 working hours for first stage filters, and two years or 4000 working hours for second stage filters, with some exceptions).

2.4 Application of assessment methods for the indicator

2.4.1 Voluntary or mandatory methods for EPCs

Methods listed in Section 2.2 are not mandatory for EPCs. Requirements regarding CO_2 emissions exist in some EU member states, including Austria, France, Ireland, Portugal, Romania, Spain and the UK (England and Scotland). In others, the value of the CO_2 emissions is given in the EPC but without fulfilling the requirements (e.g. Croatia, Italy,

[3] 1999/30/EC: Council Directive 1999/30/EC of 22 April 1999 relating to limit values for sulphur dioxide, nitrogen dioxide and oxides of nitrogen, particulate matter and lead in ambient air

Lithuania, Poland and Slovakia) [97]. However calculated emissions correspond to local and centralised energy sources (district heating networks or electricity plants) and consider only carbon dioxide emissions. In none of the EU-28 countries are other pollutants considered.

There are no requirements in EPCs regarding indoor air purity, although Belgium and Portugal require appropriate ventilation rates [97]. In no European country is the ability of the ventilation system to purify inlet air is assessed.

As air quality is a critical issue both the local air pollution contributor index and the indoor air purity index should be integrated into EPCs. The air pollution contributor index will provide information about the environmental quality of the energy source of the building, and so increase environmental awareness among building owners. The indoor air purity index offers information about the ability of ventilation systems to purify intake air, driving action to modernise systems with the use of filters.

2.4.2 Applicability of methods to different building typologies

Both local air pollution contributor index and indoor air purity index assessment methods apply to existing and new buildings. In terms of indoor air purity index methods, the WELL Building Standard and the LEED are applicable to existing and new buildings, and for core and shell buildings. The BREEAM concerns new buildings, core and shell buildings (with some restrictions), and also small buildings (floor area up to 1000 m^2) where at least half of the assessed floor area of the building is new, and the rest is modernised. For larger buildings, this assessment can be more challenging.

The presented methods for calculation of the local air pollution contributor index apply to all building types (residential and non-residential), as building functions are irrelevant in methodology. The first two methods (standard and regulation, and emission rates) take into consideration the type of energy source in the building. There are no restrictions to using any of the energy sources in specific building types. The third method (AQI) is also not related to any type of building as it takes into consideration the concentration of pollutants in outdoor air.

In terms of indoor air purity index methods, the WELL Building Standard v1 concerns commercial and institutional buildings, but ongoing pilot programmes are connected to other building sectors including multifamily residences, educational facilities, retail, restaurants and commercial kitchens. The LEED v4 is recommended for new buildings, schools, retail, data centres, warehouses and distribution centres, hospitality and healthcare. The BREEAM New Construction 2016 includes the assessment of residential, commercial (offices, industrial, retail), educational, hotels and bespoke non-standard building types (e.g. cinema, sports facility).

2.4.3 Presentation of the indicator

- **Emission rates**

  This covers all the main pollutants causing smog. The method is used for quantitative calculations. It does not include a qualitative assessment of heat sources. For boilers with the lowest power, the result depends on the quality of the fuel. With solid fuels, the result also depends on the combustion air supply (natural draught, mechanical). This method allows a calculation of the quantity of pollution related to the use of energy sources but does not rank them.

- **Air Quality Index**

  The scoring is related to the chosen index scheme. For example in the UK the Daily Air Quality Index has the values from 1 up to 10, the EU CAIQ has a scale from 0 up to 100, the US AQI from 0 to 500, and in Poland (PL IJP) from 0 to 10 [98]. Figure 6 gives a comparison of scales for EU CAIQ, US AQI and PL IJP for PM2.5.

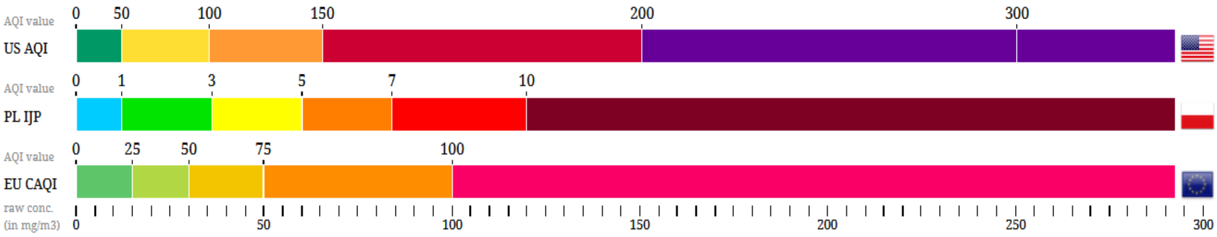

Figure 6: Comparison of scales for EU CAIQ, US AQI and PL IJP for PM2.5 [99]

Although the scale is different for different indexes, the bands are the same.

In the local air pollution contributor index assessment method, the calculated building emissions will be compared with reference emissions, and an index level assigned for each pollutant. The scale of the index levels will be very low, low, moderate, high, very high, hazardous. The very low index means that pollutant emissions from the assessed building is much lower than for the reference building, and thus the contribution of the building to local smog development is very low. The indexes will be assigned for each pollutant and the final index for the building will be determined by the poorest score out of the individual pollutants assessed.

- **Indoor air purity methods**

The WELL Building Standard is a scoring method where points are achieved for each requirement fulfilled. Additional optimisations also taken into account, with the score calculated as the share of optimisations conducted divided by the total possible optimisations in the WELL Building Standard, multiplied by five. The total score is the sum of the above values, according to the equation:

Total score = 5 + (Optimisations achieved / Total optimisations) x 5

Depending on the number of points the building is rated silver, gold or platinum. This enables comparison between buildings.

The method from the WELL Building Standard v1 demands fulfilment of requirements in three areas: free space for filters, appropriate level of filter class (or appropriate level of outdoor air polluted by PM) and proper air filtration maintenance. Filter class and space for additional filters are checked in the construction project and on-site inspections. Correct cleaning/replacement of used filters is shown in annual reports. EPCs in Poland do not include exploitation tracking of filters. Parameters for air filtration systems are presented in EPCs in descriptive format with the ventilation system and are not separately evaluated (but some requirements must be met in accordance to national requirements to obtain a building permit). Thus, in Polish EPCs there is no additional benefit from equipping the ventilation system with a higher filter class than obligatory under national law.

The method from the LEED v4 demands requirements are met and uses a scoring system. After fulfilment of obligatory requirements (that are not scored), the building can get 1-2 additional points for meeting demands related to, among others, filter class, entryway systems, interior cross-contamination prevention, and ventilation design calculations. The points system enables comparison between buildings of the same type.

The method from the BREEAM New Construction 2016 also demands requirements are met and uses a scoring system. After fulfilment of obligatory requirements (which are not scored), the building can get points, which are shown as a percentage share of all possible points. In addition, 1% can be added to the final BREEAM score for each 'innovation credit' achieved. There are five levels of ratings from pass (standard good practice, which is achieved by more buildings) and outstanding (innovator, the best of buildings). Such a division enables comparison between buildings of the same type.

2.5 Linking the assessment methods to energy performance and EPCs

For assessing the energy performance of the building, the consumption of chemical energy in fuel must be determined. On this basis, the impact of emissions from fuel combustion on smog development can be assessed. The type of fuel and the type of boiler should be considered.

Methods from Section 2.2 require, among others, appropriate filter class. A new proposed method also focuses on indoor air purity provided by sufficient filtration system efficiency. In most cases, higher-efficiency filters consume more energy (but there are some exceptions).

In EPC systems, energy is calculated and compared with reference values (on a scale or using classes). This means data on building fuel consumption (divided into energy sources) and reference values of energy are already available. With the known emission rates for a given pollutant and type of fossil fuel, the total or specific CO_2 emissions can be easily calculated.

The EPC contains information on ventilation systems and can include information about air filter efficiency. There is no direct information about indoor air purity. These demands should be met by requirements under national regulations related to building installations. EPCs assess the energy consumption resulting from the function and standard of the building and characteristics of its installation. In the first case it is difficult to assess objectively the use of the building by its users. Therefore, for example, an increase in energy consumption due to an incorrectly maintained air filtration system is not included in the certificate. There is also no information on annual filter maintenance.

The proposed new method requires information about the filter class to be included in EPC methodologies and assessment approaches. Currently, this is described additionally, and is not assessed (except in meeting the basic requirements to obtain a building permit). Application of Eurovent classification in terms of annual energy consumption (A-G classes) can negatively influence the energy consumption – in most cases, higher efficiency filters consume more energy, but there are exceptions.

2.6 Legal boundaries or requirements of assessment methods

The first two methods of air pollution assessment based on standards and regulations and emission rates require information on the energy characteristics of a building, including data on building energy (fuel) consumption for each type of energy source. This can be measured or calculated, depending on the country's EPC system. Reference values of energy consumption are also needed. These values can be calculated for reference buildings, or reference energy indicators are given, again depending on the EPC system. The emission rates for each pollutant must be estimated for each country. The presented method for calculating the local air pollution contributor index is a framework that can be adapted to include specific country data.

The AQI method has been presented as a way to weight the emission indicator for each pollutant. This method cannot be directly applied in the estimation of the energy source influence on outdoor air pollution (smog effect) as it is based on pollutant concentration measurements. However, the index scale can be used as basis in developing a ranking for this X-tendo feature.

The method from the WELL Building Standard requires information on characteristics of the ventilation system (or alternatively ambient outdoor levels of PM), together with annual reports on maintenance of the air filters. The LEED and BREEAM methods also demand parameters of ventilation systems. Data on ventilation systems for new buildings is available in the approved construction project plan. Ventilation systems and reports about maintenance of air filters in existing buildings can be assessed with the permission of the owner. The proposed method also requires information about building location to define levels of outdoor air pollution.

2.7 Ranking of assessment methods to evaluate their feasibility for the feature

The methods for assessing the impact of buildings on outdoor and indoor air are assessed for their feasibility in Table 5 and Table 6. The ranking of the methods is presented based on expert judgements.

Table 5: Feasibility of outdoor air pollution methods for EPCs

Method	Ranking	Comment on feasibility/ Explanation
The influence of emissions from fuel combustion on smog formation		
Standards and regulations	**	To assess the impact, it is sufficient to know the type of fuel and boiler design/class. Data on emission rates is general. Not all pollutant data is available. To estimate total pollution emissions the amount of exhaust gas must be measured. This method cannot be directly used for the X-tendo feature as it is used for classification of heating sources.
Emission rates	***	The method requires information on energy consumption and type of energy source (used fuel). The emission rates can be determined for each country, using internal regulation. If no standard values are defined, the method considers all main pollutants related to smog development. This method can be used to calculate pollutant emissions but cannot be directly used for the X-tendo feature as it does not give a local air pollution contributor index value.
Air Quality Index	***	The method cannot be directly used for the new feature. However, the index scale used in the AQI method can be used as a basis in developing a ranking for the X-tendo feature.
Likert scale used for suitability: not at all (*), slightly (**), moderately (***), very (****), extremely (*****)		

A new method is needed to measure the X-tendo feature on outdoor air pollution (influence of emissions from fuel combustion on smog formation). The proposed approach is presented in later sections.

Table 6: Feasibility of indoor air purity methods for EPCs

Method	Ranking	Comment on feasibility/ Explanation
Indoor air purity		
WELL Building Standard	***	Requires information about space for additional filters, filter class (and ambient outdoor air pollution) and annual maintenance
LEED	**	Requires information about filter class (also entryway system, interior cross-contamination prevention, ventilation design calculation)
BREEAM	****	Requires information about filter class, indoor air quality plan, etc. and ambient outdoor air pollution
Likert scale used for suitability: not at all (*), slightly (**), moderately (***), very (****), extremely (*****)		

2.8 SWOT analysis of the assessment methods

To assess the usefulness of the described methods, a SWOT analysis is given in Table 7 and Table 8. In the analysis, only methods being used in the development of the feature indexes are presented. For the local air pollution contributor index, methods based on emission rates and AQI were considered.

Table 7: SWOT analysis of the outdoor air pollution methods for EPCs

Strengths	Weaknesses
Simple to set criteria	More qualitative than quantitative assessment – data on emissions cannot be verified through measurement
Readily available data	Based on concentration of pollutant in air and not amount of emission
Based on existing scale	
Opportunities	**Threats**
Increased user awareness of their impact on their immediate surroundings	People performing energy performance certification may have insufficient knowledge about heat sources and emissions (templates application instead of informed assessment)
Willingness to undertake actions regarding the building and/or energy source modernisation	

For the indoor air purity index all three presented methods (WELL, LEED and BREEAM) were considered.

Table 8: SWOT analysis of the indoor air purity methods for EPCs

Strengths	Weaknesses
Indexes for outside air pollution assessment generally available	Monitoring of system maintenance frequency (according to correct air filtration system exploitation)
Common European classification of air filters	In the WELL Standard: measurement of the pollution level within 1.6 km of the building
LEED gives points for maintenance of filters during construction and pre-occupancy	In BREEAM: impact evaluation of the adjacent environment, but e.g. distances between intakes and air pollution sources are regardless of the filter class
BREEAM requires appropriate air intake locations to ensure they are not located near external air pollution sources	
BREEAM: impact evaluation of the adjacent environment	
Opportunities	**Threats**
Improving indoor air purity is highly in the interest of end-users (promotes occupant comfort, well-being and productivity)	Negative impact on energy consumption with high class filters

2.9 Proposed approach to develop the feature

- Method of local air pollution contributor index assessment

The proposed method considers fuel combustion in the building for the purpose of heat and electricity generation for the functions included in the national EPC system. The procedure for estimating the local air pollution contributor index is presented in Figure 7 below.

In the local air pollution contributor index assessment method, the calculated building emissions will be compared with reference emissions and for each pollutant an index level will be assigned. Using the value of building energy consumption and the type of energy source (type of fuel) the building emission indicators (PM10, PM2.5, NO_x, SO_x, CO) are calculated. Next, the reference emission indicators are calculated using reference energy consumption and reference energy source. The reference values will be estimated based on national regulations. Using calculated values, the ratio of building to reference emission indicators will be estimated (ratio of emission indicator). The ratio of each pollutant will be assessed using a scale (very low, low, moderate, high, very high, hazardous). The indexes (index of emission indicator) show the impact of a given pollutant on outdoor air pollution in comparison with reference values. A very low index means that pollutant emissions from the assessed building are much lower than for the reference building, meaning the contribution of the building to local smog development is very low. In the last step, the pollutant indexes are weighted to get one value for the local air pollution contributor index.

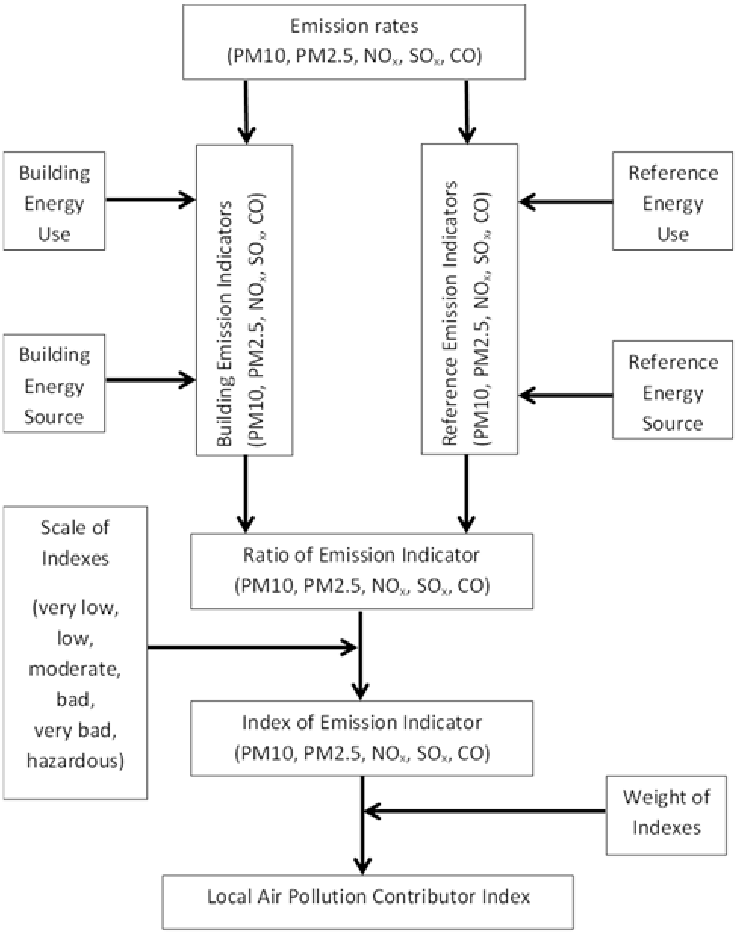

Figure 7: Scheme of local air pollution contributor index estimation procedure

Input data/information needed: building energy consumption, type of energy source (type of fuel used).

The emission rates, reference values, scale of indexes and weights of indexes will be specific for each country and will be included in the methodology as constants.

Method of indoor air purity index assessment

The proposed method considers outside air quality and indoor air purity in the building with a ventilation system equipped with an air filter. It is in the form of a point scale. Buildings get points according to outside air pollution in their location, with less pollution meaing fewer points. Simultaneously, the air filtration system in the building is assessed. Points are assigned for the air filtration system efficiency – higher efficiency, more points. These points are subtracted from the outdoor air pollution value. The indoor air purity index estimation procedure is presented in Figure 8 below.

This method indicates that buildings located in areas with high outdoor air pollution require higher air filtration system efficiency to get the same air purity inside the building as locations with low outdoor air pollution.

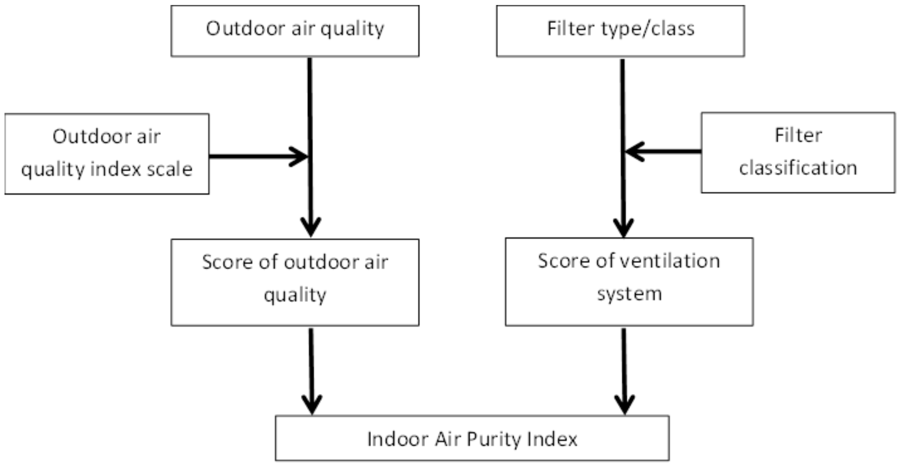

Figure 8: Scheme for indoor air purity index estimation procedure

Input data/information needed: Outdoor air quality, ventilation system characteristic.

The outdoor air quality index scale and filter classification can be specific for a given country and will be included in the methodology as constants.

3 FINDINGS

This section presents a summary of key findings (Table 9) related to the indicators that will be developed for the five innovative features in the X-tendo toolbox. This summary will be a precursor for further work in WP3. The findings have been categorised into key barriers, challenges, limitations, delivery actors, presentation, target audience and link with energy performance.

Table 9: Key findings of the scoping and analysis of all features

	Feature 1: smart readiness	Feature 2: comfort	Feature 3: outdoor air pollution	Feature 4: real energy consumption	Feature 5: district energy
Key barriers					
Technical/ methodological	Dealing with differences in building services (heating, EV presence, etc.) and characteristics (age, type or geographical location) Weighted measures and theoretical building maximums need to be developed	Assessment methodology for different building typologies	Proper definition of outdoor air quality	Length of the monitoring duration	Implementation of a certification scheme for calculating future PEF, REF and CEF could be a major barrier for some countries
Financial /economic	Existence of several schemes (market saturation)	-	-	Normalisation for user behaviour financially	-
Legislative/ governance	Differences across MS in smart readiness levels	Various standards at MS level	-	Enforcement frame Accounting for bulked quantities	-
Social	Novelty of the indicator requires the presence of useful information	Benefits are not well understood by public	-	Landlord/tenant split	-

	for the majority of the public				
Environmental	ICT technology might have a significant environmenta l impact	-	-	Monitoring infrastructure cost in relation to benefits	Additional efforts and committing to values stated in EPCs might be a reason for district heating utilities to oppose these indicators
Industry	Potential lack of readiness of the industry to satisfy the demand of new ICT	Application of industry-based solutions in building sector	-	Strict enforcement is difficult or even not feasible	Implementati on of a certification scheme for calculating future PEF, REF and CEF could be a major barrier for some countries
Key challenges					
Technical/ methodological	Quick assessment -> Method A is created to reduce assessment time	Provision of single rank/score Accuracy of methods with or without measuremen ts	Estimation of filter classificatio n for each county Proper definition of reference values of emission rates Scale of indexes and weights for each country	Development of suitable models for missing data (e.g. DHW energy consumption) Differentiation of method for various functions (especially non-residential) Normalisation versus maintaining the link with actual measured energy consumption Normalisation for indoor environmental	Variable definitions of PEF, REF and CEF

				quality and service provision	
Financial/ economic	Low cost and easy-to-use option	Developing cost-effective assessment criteria	-	Cost/accuracy or effectiveness balance	Estimation of data for future years for a district heating system (mainly plant capacities and full load hours)
Legislative/ governance	Universal methodology applicable to all MS (in contrast to EPC)	No reference for EPCs available from MS	Multiple standards and regulations in different MS	Minimising fraud GDPR (especially in the case of individual dwellings or buildings with low number of users) Citizen security and data privacy	Estimation of data for future years for the public electricity grid so that it is accepted by the district heating utilities and authorities
Social	Acceptability and appropriation	-	-	User acceptance; maintaining the link with energy billing/metering information	Method for verification between roadmap of district heating utility and estimated data
Environmental	Benefits vs. costs understudied	Integration in decision-making for renovation measures	Integration of variable sources of emissions in different MS	Positive balance of environmental benefits of EPC method effectiveness improvement versus environmental impact	-
Industry	Demand satisfaction	Quantified benefits not well integrated in assessments	-	-	-

Limitations	Might work at the level of some MS but not all Higher smartness levels should reflect better quality of life for occupants and building performance	Reduction of measurements for cost-effectiveness Limited complexity to simplify training of experts	AQI data is required	For the design, calculation is still required; duration of measurement period (relevant for new/renovated buildings) Monitoring infrastructure roll-out may not be supported in all MS	-
Presentation	Well-developed presentation approach	Few examples of presentation available	Existing colourful scale exists	As part of EPC, printed, digital, as part of building logbook, complementary to current EPC information or replacing it.	-
Delivery actors	EPC assessors, qualified experts but also owners (self-assessment)	EPC assessors, qualified building professionals	EPC assessors, energy auditors	EPC assessors, qualified building professionals/ experts Depending on data availability, potentially fully automated	EPC assessors, district heating utilities
Target audience	Whole building ecosystem: property owners, buyers, renters, tenants, facility managers, public authorities	Property owners, buyers, renters, tenants, facility managers	End-users, owners, occupants	Same as current EPC target audience, although focus is more user-oriented.	Property owners, buyers, renters, tenants, facility managers, research, public authorities responsible for planning heating and cooling
Link with energy performance	Monitoring and operation at the building level and	Thermal comfort and indoor air quality have a	Pollutant emission and indoor air purity	Real energy consumption directly links with energy	All indicators have a strong link to the energy

	improved interoperability with the grid	strong link with energy performance	have a strong link with building thermal and installation characteristics	performance and additional operational (energy) performance Potentially contributes to mitigation of energy performance gap	performance of the building

4 CONCLUSIONS

This report provides useful and crucial insights into working out the indicators for the five features during the X-tendo project. For all features, we have outlined details of the existing assessment/calculation methods in the context of EPCs. Their application domain, legal boundaries, and links with energy consumption and EPCs were also studied and evaluated. A SWOT analysis and ranking of methods were presented highlighting the best fits for each of the indicators. However, further work and adjustments to these methods would be required to make them available for real testing. A proposed approach for the development of each feature based on a preliminary concept for the indicator is also presented. Finally, across all features, key findings have been presented, leading to the following conclusions in two groups:

Indicators

- 'Smart readiness' approach presents a potential method for assessing the smartness of buildings with nine domains (e.g. lighting, ventilation, envelope, monitoring and control etc.)
- 'Comfort' approach incorporates four key indicators – thermal, visual and acoustic comfort and indoor air quality – to be assessed through checklists, on-site measurements and surveys
- 'Outdoor air pollution' approach addresses a building's impact on air by two methods: an outdoor air pollution contribution index and indoor air purity index
- 'Real energy consumption' approach outlines an assessment method based on operational ratings, with options for normalisation to allow for better inter-building comparison
- 'District energy' approach focuses on predicting the potential for future development for buildings via two methods: expected future performance of district heating and heat distribution and transfer system

Cross-cutting issues

- Technical challenges that constrain the application of existing methods such as assessment time, accuracy, normalisation process, variable definitions and emission factors could be overcome by certain modifications in approach
- Features should be aligned financially to increase market acceptance and cost-effective assessments during the development
- Legal and governance issues should be addressed by dealing with challenges such as development of universal methodologies, presence of multiple standards at Member

State level, control of citizen data and privacy, and acceptance of future estimations by public authorities
- From a social perspective, user acceptance and public understating of the features are key issues and should be considered in feature development
- If these indicators are well integrated within EPCs, significant environmental benefits are anticipated
- Future implementation of indicators can be strengthened by addressing lack of industry readiness, understanding of anticipated benefits and enforcement issues

Certain limitations need to be overcome to implement these innovative indicators, such as variable levels of implementation in the Member States due to different local requirements and regulations. Some indicators require extensive monitoring and measurements, and a lack or absence of data is a barrier in the development and acceptance of these features within EPC schemes.

A range of delivery actors was identified for all the features, including EPC assessors, qualified experts, building professionals, and auditors. It is especially important to focus on them while developing the features as they will directly affect the outcomes of the assessments. While developing the features, links with energy performance are being explored and studied with reference to interoperability with the grid, energy consumption, and operational energy performance. To successfully develop the indicators and their implementation in the EPC schemes of the Member States, the features should ensure compliance with the requirements of the target audience and the framework principles of the cross-cutting criteria in X-tendo.

GLOSSARY OF TERMS

Term/words	Meaning/definition
Air Quality Index (AQI)	Index used by government agencies to communicate to the public how polluted the air currently is or how polluted it is forecast to become
Building smartness	A building's capacity to communicate with its occupants and the grid and to monitor and regulate efficiently the use of energy and other resources. It exemplifies the ability of the building to adapt to internal and external situations, relies on information and connectivity, and requires an appropriate level of cybersecurity.
Carbon emission factor (CEF)	A coefficient which allows conversion of activity data (process/processes) into CO_2 emissions
Emission rate	The emission intensity of a given pollutant relative to the intensity of a specific activity, or an industrial production process; for example grams of carbon dioxide released per megajoule of energy produced, or the ratio of greenhouse gas emissions produced to gross domestic product (GDP)
Energy Performance of Buildings Directive (EPBD)	The EPBD covers a broad range of policies and supportive measures that will help national EU governments boost energy performance of buildings and improve the existing building stock
Expectable return temperature (ERT)	Average temperature to be expected in the return of a building's heat distribution system
Filtration	A physical, biological or chemical operation that separates solid matter and fluid from a mixture with a filter medium that has a complex structure through which only the fluid can pass
Final energy consumption	Final energy consumption is the total energy consumed by end users, such as households, industry and agriculture. It is the energy which reaches the final consumer's door and excludes that which is used by the energy sector itself.
Indoor environmental quality (IEQ)	IEQ encompasses the conditions inside a building – air quality, lighting, thermal comfort, acoustic conditions, ergonomics – and their effects on occupants or residents
Information and communication technologies (ICT)	Infrastructure and components that enable modern computing
Internet of Things (IoT)	Enabling of everyday devices to send and receive data through the internet

Low emission	Emission of combustion products of solid, liquid and gaseous fuels to the atmosphere from emission sources (emitters) located at a height of not more than 40 m
Nearly zero energy building (nZEB)	nZEBs have very high energy performance, and the low amount of energy they require comes mostly from renewable sources
Necessary supply line temperature (NST)	Maximum temperature that is necessary to be supplied to a building's heat distribution system in order to ensure that the heat load can be supplied to each part of the building on the coldest day of the year
Overheating risk	Situations where the indoor temperature of a home becomes uncomfortably or excessively warm
PM2.5/PM10	Particles with an aerodynamic diameter smaller than respectively 2.5 and 10 µm
Pollutant	A substance or energy introduced into the environment that has undesired effects, or adversely affects the usefulness of a resource
Primary energy factor (PEF)	A PEF connects primary and final energy by indicating how much primary energy is used to generate a unit of electricity or a unit of useable thermal energy
Primary energy consumption	Primary energy consumption measures the total energy demand of a country. It covers consumption of the energy sector itself, losses during transformation (for example, from oil or gas into electricity) and distribution of energy, and the final consumption by end users. It excludes energy carriers used for non-energy purposes (such as petroleum not used not for combustion but for producing plastics).
Primary resource factor (PRF)	The ratio between fossil energy supply and energy used in a building
Renewable energy factor (REF)	The share of renewable energy in the heat supplied by the district heating system
Sick building syndrome (SBS)	A condition affecting office workers, typically marked by headaches and respiratory problems, attributed to unhealthy or stressful factors in the working environment such as poor ventilation
Smart readiness indicator (SRI)	Measure of the capability of buildings to adapt their operation to the needs of the occupant, optimising energy efficiency and overall performance, and to adapt their operation in reaction to signals from the grid (energy flexibility)
Smog	An atmospheric phenomenon resulting from the mixing of fog with smoke and exhaust fumes

Volatile organic compounds (VOCs)	Organic chemicals that readily produce vapours at ambient temperatures and are therefore emitted as gases from certain solids or liquids. All organic compounds contain carbon, and organic chemicals are the basic chemicals found in all living things.

REFERENCES

[1] Buildings Performance Institute Europe (BPIE), *Europe's Buildings Under The Microscope*. 2011.

[2] Buildings Performance Institute Europe (BPIE), *Energy Performance Certificates Across the EU. A mapping of National Approaches*. 2014.

[3] B. L. Risteska Stojkoska and K. V. Trivodaliev, "A review of Internet of Things for smart home: Challenges and solutions," *Journal of Cleaner Production*. 2017.

[4] I. Alam, S. Khusro, and M. Naeem, "A review of smart homes: Past, present, and future," *ICOSST 2017 - 2017 Int. Conf. Open Source Syst. Technol. Proc.*, 2018 (6), pp. 35–41, 2018.

[5] A. H. Buckman, M. Mayfield, and S. B. M. Beck, "What is a smart building?," *Smart Sustain. Built Environ.*, 3(2), pp. 92–109, 2014.

[6] D. Arditi, G. Mangano, and A. De Marco, "Assessing the smartness of buildings," *Facilities*, 33(9–10), pp. 553–572, 2015.

[7] X. Lu, D. Clements-Croome, and M. Viljanen, "Past, present and future mathematical models for buildings," *Intell. Build. Int.*, 2009.

[8] J. Yang and H. Peng, "Decision support to the application of intelligent building technologies," *Renew. energy*, 2001.

[9] A. B. R. González, J. J. V. Díaz, A. J. Caamaño, and M. R. Wilby, "Towards a universal energy efficiency index for buildings," *Energy Build.*, 2011.

[10] D. Katz and J. Skopek, "The CABA building intelligence quotient programme," *Intell. Build. Int.*, 1(4), pp. 277–295, 2009.

[11] W. L. Lee and J. Burnett, "Benchmarking energy use assessment of HK-BEAM, BREEAM and LEED," *Build. Environ.*, 2008.

[12] P. Mathew, D. Sartor, W. Lintner, and P. Wirdzek, "Labs21 Environmental Performance Criteria : Toward ' LEED TM for Labs ,'" December, pp. 1–10, 2001.

[13] W. To, L. Lai, K. Lam, and A. Chung, "Perceived Importance of Smart and Sustainable Building Features from the Users' Perspective," *Smart Cities* 1(1), pp. 163–175, 2018.

[14] N. Dodd, M. Cordella, M. Traverso, and S. Donatello, *Level(s)-A common EU framework of core sustainability indicators for office and residential buildings Part 3: How to make performance assessments using Level(s) (Draft Beta v1.0)*, August 2017.

[15] DGNB, "New DGNB 'Climate Positive' award for buildings that make an active contribution to climate protection," 2019. [Online]. Available: www.dgnb.de/de/aktuell/pressemitteilungen/2019/new-dgnb-climate-positive-award.

[16] Y. M. Stijn Verbeke, D. Aerts, G. Rynders, "Interim report July 2019 of the 2th technical support study on the Smart Readiness Indicator for Buildings," *VITO Rep.*, July, p. 281,

2019.

[17] A. Romero, P. De Agustin, and T. Tsitsanis, "Integration of Real-Intelligence in Energy Management Systems to Enable Holistic Demand Response Optimization in Buildings and Districts," in *Proceedings - 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2018*, 2018, no. 768614.

[18] S. Verbeke, D. Aerts, G. Rynders, and Y. Ma, "3rd Interim report of the 2nd technical support study on the Smart Readiness Indicator for buildings," Brussels, 2020.

[19] S. Kephalopoulos, O. Geiss, J. Barrero-Moreno, D. D'agostino, and D. Paci, "Promoting healthy and energy efficient buildings in the European Union," European Commission, Luxembourg, 2016.

[20] Y. Al horr, M. Arif, M. Katafygiotou, A. Mazroei, A. Kaushik, and E. Elsarrag, "Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature," *Int. J. Sustain. Built Environ.*, 5(1), pp. 1–11, 2016.

[21] R. Antikainen, S. Lappalainen, A. Lönnqvist, K. Maksimainen, K. Reijula, and E. Uusi-Rauva, "Exploring the relationship between indoor air and productivity," *Scand. J. Work. Environ. Heal. Suppl.*, 4, pp. 79–82, 2008.

[22] C. Dai, L. Lan, and Z. Lian, "Method for the determination of optimal work environment in office buildings considering energy consumption and human performance," *Energy Build.*, 76, pp. 278–283, 2014.

[23] DOE, "International Performance Measurement & Verification Protocol: Concepts and Practices for Improved Indoor Environmental Quality," National Renewable Energy Laboratory, Oak Ridge, 2001.

[24] EU, *Directive 2010/31/EU of the European Parliament and the Council of 19 May 2010 on the energy perfromance of buildings (recast)*. 2010, pp. 13–35.

[25] EU, *Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency*, October. 2012, pp. 1–56.

[26] EC, *Energy Efficient Buildings: Multi-annual roadmap for the contractual PPP under Horizon 2020*. Publications Office of the European Union, 2013.

[27] E. C. You, D. Dunt, and C. Doyle, "Influences on Case-Managed Community Aged Care Practice.," *Qual. Health Res.*, 2015.

[28] I. Sarbu and C. Sebarchievici, "Aspects of indoor environmental quality assessment in buildings," *Energy Build.* 60, pp. 410–419, 2013.

[29] ASHRAE, "ANSI/ASHRAE 55:2013 Thermal Environmental Conditions for Human Occupancy," American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, 2013.

[30] ISO, "ISO 7730 Ergonomics of the Thermal Environment: Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria," International Organization for Standardization, 2006.

[31] P. Wargocki, D. P. Wyon, J. Sundell, G. Clausen, and P. O. Fanger, "The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity.," *Indoor Air*, 10(4), pp. 222–236, 2000.

[32] S. R. Jurado, A. D. P. Bankoff, and A. Sanchez, "Indoor air quality in Brazilian universities," *Int. J. Environ. Res. Public Health*, 11(7), pp. 7081–7093, 2014.

[33] M. Di Giulio, R. Grande, E. Di Campli, S. Di Bartolomeo, and L. Cellini, "Indoor air quality in university environments," *Environ. Monit. Assess.*, 170(1–4), pp. 509–517, 2010.

[34] T. Godish and J. D. Spengler, "Relationships Between Ventilation and Indoor Air Quality: A Review," *Indoor Air*, 6(2), pp. 135–145, 1996.

[35] WHO, "WHO guidelines for indoor air quality: Selected Pollutants," World Health Organisation, Copenhagen, 2010.

[36] CEN, "EN 12665:2011- Light and lighting- Basic terms and criteria for specifying lighting requirements," European Commitee for Standardization, Brussels, 2012.

[37] D. K. Serghides, C. K. Chatzinikola, and M. C. Katafygiotou, "Comparative studies of the occupants' behaviour in a university building during winter and summer time," *Int. J. Sustain. Energy*, 34(8), pp. 528–551, 2015.

[38] M. Frontczak and P. Wargocki, "Literature survey on how different factors influence human comfort in indoor environments," *Build. Environ.* 46(4), pp. 922–937, 2011.

[39] I. A. Sakellaris *et al.*, "Perceived Indoor Environment and Occupants' Comfort in European 'Modern' Office Buildings: The OFFICAIR Study," *Int. J. Environ. Res. Public Health*, 13(5), 2016.

[40] S. Kang, D. Ou, and C. M. Mak, "The impact of indoor environmental quality on work productivity in university open-plan research offices," *Build. Environ.*, 124, pp. 78–89, 2017.

[41] P. Ricciardi and C. Buratti, "Environmental quality of university classrooms: Subjective and objective evaluation of the thermal, acoustic, and lighting comfort conditions," *Build. Environ.*, 127(August), pp. 23–36, 2018.

[42] K. L. Jensen, E. Arens and L. Zagreus, "Acoustical Quality in Office Workstations, as Assessed By Occupant Surveys," in *Indoor Air: 10th international conference on indoor air quality and climate*, 2005, pp. 2401–2405.

[43] ISO, "ISO 16283-1:2014 Acoustics- Field measurments of sound insulation in buildings and of building elements- Part 1: Airborne sound insulation," International Organization for Standardization, 2014.

[44] BREEAM, "BREEAM International Non-Domestic Refurbishment 2015-Technical Manual SD225 1.4," 2015.

[45] BREEAM, "BREEAM Refurbishment Domestic Buildings 2015-Technical Manual SD5077 2.2," 2015.

[46] DGNB, "DGNB- Sociocultural and functional quality- SOC1.1/Thermal Comfort," 2018.

[47] DGNB, "DGNB- Sociocultural and functional quality- SOC1.2/Indoor Air Quality," 2018.

[48] DGNB, "DGNB- Sociocultural and functional quality- SOC1.3/Acoustic Comfort," 2018.

[49] DGNB, "DGNB- Sociocultural and functional quality- SOC1.4/Visual Comfort," 2018.

[50] USGBC, "LEED v4.1 Operations and Maintenance - Getting started guide for beta participants," 2018.

[51] IGBC, "Home Performance Index," 2019.

[52] WELL, "The WELL Building Standard v1," 2019.

[53] P. Fanger, *Thermal comfort: analysis and application in environmental engineering*. Danish Technical Press, 1970.

[54] N. Djongyang, R. Tchinda and D. Njomo, "Thermal comfort: A review paper," *Renew. Sustain. Energy Rev.*, 14(9), pp. 2626–2640, 2010.

[55] CEN, *EN-15251: Indoor environemntal input parameters for design and assessment of energy performance of buildings adressing indoor air quality, thermal environment, lighting and acoustics*, 44(0). 2007.

[56] CEN, *EN 16798-1:2019 Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acous*. 2019.

[57] L. Yang, H. Yan and J. C. Lam, "Thermal comfort and building energy consumption implications - A review," *Appl. Energy*, 115, pp. 164–173, 2014.

[58] M. A. Humphreys, "Outdoor temperatures and comfort indoors," *Batim. Int. Build. Res. Pract.*, 2(2), 1978.

[59] J. F. Nicol and M. A. Humphreys, "New standards for comfort and energy use in buildings," *Build. Res. Inf.*, 37(1), pp. 68–73, 2009.

[60] S. Barlow and D. Fiala, "Occupant comfort in UK offices-How adaptive comfort theories might influence future low energy office refurbishment strategies," *Energy Build.*, 39(7), pp. 837–846, 2007.

[61] A. Wagner, E. Gossauer, C. Moosmann, T. Gropp and R. Leonhart, "Thermal comfort and workplace occupant satisfaction: Results of field studies in German low energy office buildings," *Energy Build.*, 39(7), pp. 758–769, 2007.

[62] CIBSE, "TM46: energy benchmarks." CIBSE London, 2008.

[63] CEN, *EN 16798-2:2019 Energy performance of buildings - Ventilation for buildings - Part 2: Interpretation of the requirements in EN 16798-1 - Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air*. 2019.

[64] S. Kunkel, E. Kontonasiou, A. Arcipowska, F. Mariottini and B. Atanasiu, *Indoor Air Quality, Thermal Comfort and Daylight - Analysis of Residential Building Regulations*. Brussels, 2015.

[65] J. M. Daisey, W. J. Angell and M. G. Apte, "Indoor air quality, ventilation and health

symptoms in schools: an analysis of existing information.," *Indoor Air*, 13(1), pp. 53–64, 2003.

[66] A. P. Jones, "Indoor air quality and health," *Atmos. Environ.*, 33(28), pp. 4535–4564, 1999.

[67] D. J. Clements-Croome, "Work performance, productivity and indoor air," *Scand. J. Work. Environ. Heal. Suppl.*, 4, pp. 69–78, 2008.

[68] N. Michelot and M. Carrega, "Monitoring indoor air quality in French schools and day-care centres. Results from the first phase of a pilot survey." In: *Healthy Buildings 2012, 10th International Conference*, 2014, pp. 1–6.

[69] O. a Seppänen, W. J. Fisk and M. J. Mendell, "Association of ventilation rates and CO2 concentrations with health and other responses in commercial and institutional buildings.," *Indoor Air*, 9, pp. 226–252, 1999.

[70] JRC, "Methods for monitoring indoor air quality in schools," World Health Organization, Bonn, 2011.

[71] J. Atkinson, Y. Chartier, C. L. Pessoa-Silva, P. Jensen, Y. Li and W.-H. Seto, *Natural Ventilation for Infection Control in Health-Care Settings*. Canberra, 2009.

[72] A. K. Persily, "Evaluating building IAQ and ventilation with indoor carbon dioxide," *ASHRAE Transactions*, 103 (2), pp. 193–204, 1997.

[73] ASTM D6245-12, "Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation," West Conshohocken, PA, 2012.

[74] CEN, "EN 12464-1: 2011- Light and lighting- Lighting of work places- Part 1: Indoor work places," European Commitee for Standardization, Brussels, 2011.

[75] V. Fabi, R. Andersen and S. Corgnati, "Accounting for the Uncertainty Related to Building Occupants with Regards to Visual Comfort: A Literature Survey on Drivers and Models," *Buildings*, 6(1), p. 5, 2016.

[76] A. D. Galasiu and J. A. Veitch, "Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review," *Energy Build.*, 38(7), pp. 728–742, 2006.

[77] CEN, *EN 17037:2018 Daylight in buildings*. 2018.

[78] C. Reinhart, J. Mardaljevic, Z. Rogers and Leukos, *Dynamic Daylight Performance Metrics for Sustainable Building Design*. 2006.

[79] R. G. Hopkinson, "Glare from daylighting in buildings," *Appl. Ergon.*, 3(4), pp. 206–215, Dec. 1972.

[80] Berkowitz, "Improving the Energy Efficiency of Aging Commercial Buildings through Window Retrofits," BERKOWITZ, Pedricktown, New Jersey, 2014.

[81] N. G. Vardaxis, D. Bard and K. Persson Waye, "Review of acoustic comfort evaluation in dwellings—part I: Associations of acoustic field data to subjective responses from building surveys," *Build. Acoust.* 25(2), pp. 151–170, 2018.

[82] A. Laouadi and A. Parekh, "Lighting characteristics of complex fenestration systems." In *IBPSA-Canada Esim Conference*, 2006, pp. 1–7.

[83] EU, "Special Eurobarometer 468: Attitudes of European citizens towards the environment," 2017. [Online]. Available: https://data.europa.eu/euodp/en/data/dataset/S2156_88_1_468_ENG.

[84] EUROSAI, "Joint report on air quality," 2019.

[85] L. Myllyvirta and E. Howard, "Five things we learned from the world's biggest air pollution database," 2018. [Online]. Available: https://unearthed.greenpeace.org/2018/05/02/air-pollution-cities-worst-global-data-world-health-organisation.

[86] EEA, "Air quality in Europe — 2019 report — EEA Report No 10/2019," Luxembourg, 2019.

[87] BRITANNICA, "Smog- Atmosphere," 2020. [Online]. Available: www.britannica.com/science/smog.

[88] EMEP/EEA, "EMEP/EEA air pollutant emission inventory guidebook 2019," Denmark, 2019.

[89] EC, *DIRECTIVE 2009/125/EC of the European Parliament and of the Council – establishing a framework for the setting of ecodesign requirements for energy-related products (recast)*. 2009.

[90] ASHRAE, "ASHRAE 62.1-2010: Ventilation for acceptable indoor air quality," Atlanta, 2010.

[91] CEN, "EN 13779-2007: Ventilation for non-residential buildings – Performance requirements for ventilation and room conditioning systems," 2007.

[92] BREEAM, "BREEAM International New Construction 2016- Technical Manual," 2016.

[93] KOBiZE, "Wskaźniki emisji zanieczyszczeń ze spalania paliw – kotły o nominalnej mocy cieplnej do 5 MW," Warsaw, 2015.

[94] EEA, "European Air Quality Index- GIS Map application," *2017*. [Online]. Available: www.eea.europa.eu/themes/air/air-quality-index#tab-based-on-data.

[95] CEN, "EN 779-2002: Particulate air filters for general ventilation – Determination of the filtration performance," 2002.

[96] WHO, "The World Health Report 1999," 1999.

[97] DEA, "Implementing the Energy Performance of Buildings Directive – Country Reports 2018," 2019.

[98] Wikipedia, "Air Quality Index," 2020. [Online]. Available: https://en.wikipedia.org/wiki/Air_quality_index.

[99] IEP, "Air Quality Scale in Poland," *The World Air Quality Project*, 2015. [Online]. Available: https://aqicn.org/faq/2015-09-03/air-quality-scale-in-poland.

[100] E. H. Borgstein, R. Lamberts and J. L. M. Hensen, "Evaluating energy performance in non-domestic buildings: A review," *Energy Build.* 128, pp. 734–755, 2016.

[101] CEN, "EN ISO 52000-1:2017: Energy performance of buildings - Overarching EPB assessment - Part 1: General framework and procedures," Brussels, 2017.

[102] M.-H. Laurent, B. Allibe, T. Oreszczyn, I. Hamilton, C. Tigchelaar and R. Galving, "Back to reality: How domestic efficiency policies in four European countries can be improved by using empirical data instead of normative calculation." In: *ECEEE Summer study*, 2013.

[103] D. Majcen, "Predicting energy consumption and savings in the housing stock – A performance gap analysis in the Netherlands ." TU Delft, 2016.

[104] X. Shi *et al.*, "Magnitude, Causes, and Solutions of the Performance Gap of Buildings: A Review," *Sustainability*, 11(3), 2019.

[105] M. Rietkerk, J. Mastop and C. Tigchelaar, "Differences in real and theoretical gas consumption in households." In: *ECN*, 2015.

[106] P. X. W. Zou, X. X. Xu, J. Sanjayan and J. Y. Wang, "Review of 10 years research on building energy performance gap: Life-cycle and stakeholder perspectives," *Energy Build.* 178, pp. 165–181, 2018.

[107] M. Herrando, D. Cambra, M. Navarro, L. de la Cruz, G. Millán and I. Zabalza, "Energy Performance Certification of Faculty Buildings in Spain: The gap between estimated and real energy consumption," *Energy Convers. Manag.*, 125 (January 2014), pp. 141–153, 2016.

[108] E. Himpe, "Characterisation of residential energy use for heating using smart meter data." Ghent University, 2017.

[109] S. Seyedzadeh, F. P. Rahimian, I. Glesk and M. Roper, "Machine learning for estimation of building energy consumption and performance: a review," *Vis. Eng.* 6(1), 2018.

[110] H. Krstic and M. Teni, "Review of Methods for Buildings Energy Performance Modelling," *World Multidiscip. Civ. Eng. Plan. Symp. - Wmcaus*, 245, 2017.

[111] H. Bloem and L. Vandaele, "The building as the cornerstone of our future energy infrastructure - Outcome of the Dynastee Symposium." 2019.

[112] A. Janssens, "Reliable building energy performance characterization based on full scale dynamic measurements – Report of Subtask 1b: Overview of methods to analyze dynamic data." KU Leuven, 2016.

[113] B. Karlin, J. F. Zinger and R. Ford, "The Effects of Feedback on Energy Conservation: A Meta-Analysis," *Psychol. Bull.*, 141(6), pp. 1205–1227, 2015.

[114] S. Darby, "Making it obvious: Designing feedback into energy consumption," *Energy Effic. Househ. Appliances Light.*, pp. 685–696, 2001.

[115] R. Cohen and B. Bordass, "Mandating transparency about building energy performance in use," *Build. Res. Inf.*, 43(4), pp. 534–552, 2015.

[116] CIBSE, *TM47: Operational Ratings and Display Energy Certificates*. 2009.

[117] Boverket, "Boverkets byggregler (2011:6) – föreskrifter och allmännaråd, BBR." Boverket, 2019.

[118] VEA, "Toelichting voor de (kandidaat)-energiedeskundige type C voor de opmaak van het EPC voor publieke gebouwen." VEA, 2013.

[119] B. Staatsblad, "Belgisch Staatsblad 08.11.2007." Belgisch Staatsblad, 2007.

[120] DCLG, "Improving the energy efficiency of our buildings – A guide to display energy certificates and advisory reports for public buildings." DCLG, 2015.

[121] DCLG, "The Government's methodology for the production of Operational Ratings, Display Energy Certificates and Advisory Reports." DCLG, 2008.

[122] H. J. J. Valk and A. F. Kruithof, "Beleidskader Energieprestatie - Voorstel voor een beleidskader voor de energieprestatie van gebouwen." Ministerie van BZK, 2016.

[123] S. Roels, "Building energy performance assessment based on in-situ measurements." KU Leuven, 2019.

[124] D. Saelens and G. Reynders, "IEA-EBC Annex 58: Reliable building energy performance characterization based on full scale dynamic measurements; Report of subtask 4b: Towards characterization of buildings based on in situ testing and smart meter readings and potential for applications." KU Leuven, 2016.

[125] D. Kolokotsa *et al.*, "The role of smart grids in the building sector," *Build. Environ.*, 116, pp. 703–708, 2016.

[126] T. M. Lawrence *et al.*, "Ten questions concerning integrating smart buildings into the smart grid," *Build. Environ.*, 108, pp. 273–283, 2016.

[127] EC, "Clean energy for all Europeans package," 2017. [Online]. Available: https://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans_en.

[128] DEA, "Regulation and planning of district heating in Denmark," Copenhagen, 2016.

[129] A. Müller, M. Hummel, L. Kranzl, M. Fallahnejad and R. Büchele, "Open source data for gross floor area and heat demand density on the hectare level for EU 28," *Energies*,12(24), 2019.

[130] M. Fallahnejad, M. Hartner, L. Kranzl, and S. Fritz, "Impact of distribution and transmission investment costs of district heating systems on district heating potential," *Energy Procedia*, 149, pp. 141–150, 2018.

[131] E. Latõšov, A. Volkova, A. Siirde, J. Kurnitski, M. Thalfeldt, "Primary energy factor for district heating networks in European Union member states," *Energy Procedia*, 116, pp. 69–77, 2017.

[132] CEN, "EN 15316-4-5: Heating systems in buildings - Method for calculation of systems energy requirements and system efficiencies - Part 4-5: Space heating generation systems, the performance and quality of district heating and large volume systems," 2017.

[133] M. ENERGII, "DZIENNIK USTAW RZECZYPOSPOLITEJ POLSKIEJ 2017 poz. 1912 -

ROZPORZĄDZENIE MINISTRA ENERGII w sprawie szczegółowego zakresu i sposobu sporządzania audytu efektywności energetycznej oraz metod obliczania oszczędności energii," 2017.

[134] UNI, "UNI/TS 11300-1:2014 - Prestazioni energetiche degli edifici - Parte 1: Determinazione del fabbisogno di energia termica dell'edificio per la climatizzazione estiva ed invernale," 2014.

[135] UNI, "UNI/TS 11300-4:2016 - Prestazioni energetiche degli edifici - Parte 4: Utilizzo di energie rinnovabili e di altri metodi di generazione per la climatizzazione invernale e per la produzione di acqua calda sanitaria," 2016.

[136] MED, *Ministry of Economic Development. Applying the methods of calculating energy performance and definition of requirements and minimum standards of buildings. Decree 26.06.2015*. Italy, 2015.

[137] AGFW, "Arbeitsblatt AGFW FW 309 Teil 1 - Energetische Bewertung von Fernwärme - Bestimmung der spezifischen Primärenergiefaktoren für Fernwärmeversorgungssysteme," 2014.

[138] AGFW, "AGFW district energy systems," 2020.

[139] NEN, "NEN 7125:2017 - Energieprestatienorm voor maatregelen op gebiedsnuveau (EMG) - Bepalingsmethode," 2017.

[140] OIB, "OIB-Richtlinie 6 - Energieeinsparung und Wärmeschutz," 2019.

[141] I. Uriarte, A. Erkoreka, C. Giraldo-Soto, K. Martin, A. Uriarte and P. Eguia, "Mathematical development of an average method for estimating the reduction of the Heat Loss Coefficient of an energetically retrofitted occupied office building," *Energy Build.*, 192, pp. 101–122, 2019.

[142] H. Madsen *et al.*, "IEA-EBC Annex 58: Report of subtask 3, part 2: Thermal performance characterization using time series data – Reliable building energy performance characterization based on full scale dynamic measurements statistical guidelines." KU Leuven, 2016.

[143] C. Ghiaus, "Experimental estimation of building energy performance by robust regression," *Energy Build.*, 38(6), pp. 582–587, 2006.

[144] T. Bohlin and S. F. Graebe, "Issues in Nonlinear Stochastic Grey Box Identification," *Int. J. Adapt. Control Signal Process.*, 9(6), pp. 465–490, 1995.

[145] S. Marieline, "Characterisation of the Heat Loss Coefficient of Residential Buildings Based on In-use Monitoring Data," KU Leuven, 2019.

[146] B. Stein, T. Loga and N. Diefenbach, "Tracking of Energy Performance Indicators in Residential Building Stocks – Different Approaches and Common Results. EPISCOPE Synthesis Report No. 4." IWU, 2016.

[147] B. Stein, T. Loga and N. Diefenbach, "Monitor Progress Towards Climate Targets in European Housing Stocks - Main Results of the EPISCOPE Project - Final Project Report - (Deliverable D1.2)." IWU, 2016.

[148] N. Altmann-Mavaddat, O. Mair am Tinkhof, G. Simader, A. Arcipowska and D. Weatherall, "Report on existing monitoring initiatives and database systems; From databases to retrofit action: How European countries are using energy performance certificate (EPC) database systems - Request2Action Deliverable D2.1." Austrian Energy Agency, 2015.

[149] J. Rattenbury, V. G. Oñate, R. Fragoso, E. Costanzo, A. Androutsopoulos and D. Weatherall, "Recommendations on building Hubs support – Request2Action Deliverable D4.1." Energy Saving Trust, 2017.

[150] W. Rivers, M. Mclean, F. Downy and D. Weatherall, "Best Practices and practical advice on home energy efficiency advice tools – Request2Action Deliverable D3.1." Energy Saving Trust, 2015.

[151] P. Johansson, P. Wahlgren and J.-O. Dalenbäck, "Sweden – Differences between measured and calculated energy use in EPCs versus building permits – New field study 2016 – QUALICHeCK, Status on the ground." Chalmers University of Technology, 2017.

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