EXPLORING INNOVATIVE INDICATORS FOR THE NEXT-GENERATION ENERGY PERFORMANCE CERTIFICATE FEATURES

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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.

Across all features, the following conclusions are made:

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

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.

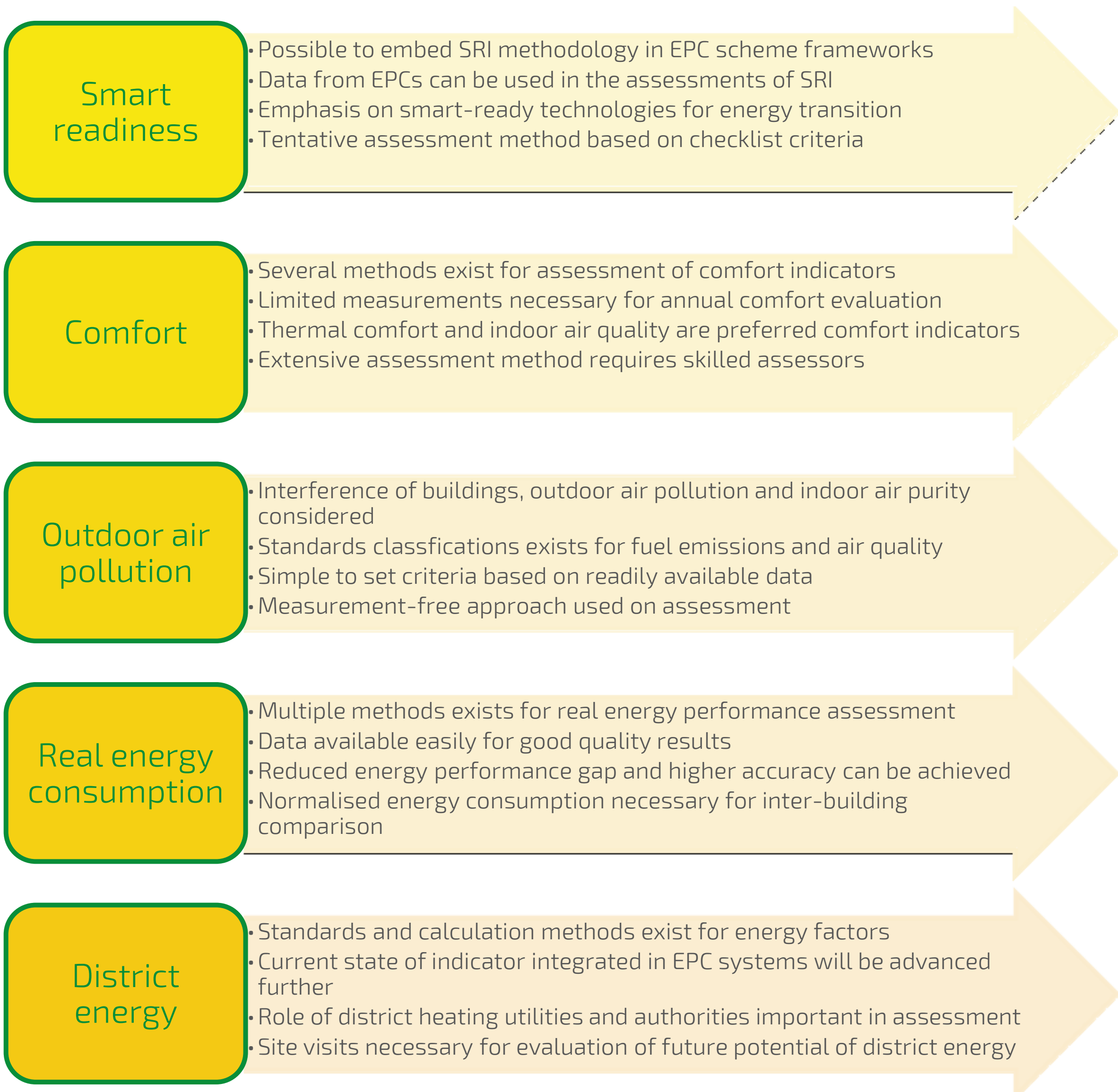


Figure 1: Overview of the five features

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 1: SMART READINESS

2.1 Overview of methods to assess the smartness of a building

Besides an important impact on the energy performance, smart buildings improve the quality of life for building users and owners through better comfort, increased safety and improved interaction. Far from the classical definition of a building as a shelter, modern buildings are complex concatenations of structures, systems and technology. Today, it is not enough **for a building to simply contain the systems that provide comfort, light and safety:** it is important to consider the building's impact on the grid and the global environment while continuing to adapt its services to the future needs of the occupants. To do this, a smart building relies on recent technology based on two pillars: connectivity and data. The Internet of Things (IoT) is seen as a way to bridge the gap between the two [3]. On the one hand, the goal of the smart building is to provide the user with the best possible facilities while optimising its resource consumption: obtaining accurate data about the needs of the occupants must be perfectly coupled with secure applications that allow the user to communicate their desires to the building. On the other, a smart building should also be able to play a role in wider energy systems and smart grids (see Figure 4).

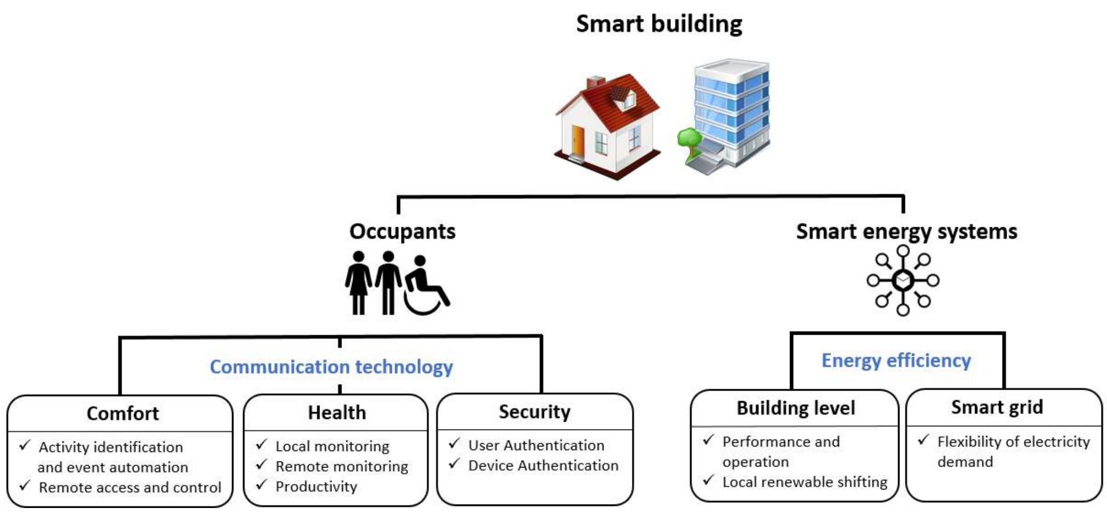


Figure 4: Smart building composition (adapted) [4]

Recent years have seen a large variety of smart building applications being launched on the market to improve building performance but also to satisfy human needs. While the concept and goals of a smart building are well defined [5], there is a growing need for a methodology to assess the degree of the smartness of a building.

As pointed out by Arditi et al. [4], measures regarding the building *modus operandi* are key elements to improve and assess the level of smartness of a building [6]. While some authors argue that the most important aspect to determine the smartness of a building is the ability to measure and monitor its services [7], others propose tangible indicators encompassing measures such as technological adaptability, individual comfort, environmental performance and organisation flexibility [8] or a more simple ratio between performance (in energy used or CO_2 emitted) and a reference building [9].

The Building Intelligence Quotient (BIQ) was proposed by the Continental Automated Building Association (CABA) [10] to rate automation systems in existing large office buildings and to support the implementation of new technologies. This includes measures such as the building automation environment, power distribution, voice and data systems, intelligent building systems features, facility management applications and subsystem operation in degraded mode. Although mainly conceived to evaluate sustainability issues, there are other well-known tools to assess building performance, such as the British Building Research Establishment Environmental Assessment Method (BREEAM), the American Leadership in Energy and Environmental Design (LEED, 2008) and the Hong Kong Building Environmental Assessment Method (HK-BEAM) [11]. Despite the strong similarity and comparable outputs amongst these three indicators [11], there exist some methodology differences between them. For instance, LEED bases its measurements on a direct points system whereas BREEAM weight factors between the distinct categories to calculate a relative target point. Yet performance levels of the baseline buildings are comparable, and less than 5% of buildings on the market receive an excellent score for energy performance for the three indicators.

None of these schemes directly consider the assessment of the capability of the building to communicate or adapt actively to changing situations. However, BREEAM considers new equipment and systems to optimise dynamically the use of energy within the building and a management plan to facilitate the operation of the building systems. Likewise, LEED promotes operational efficiency by including in its evaluation the presence of intelligent/automated technologies that contribute to reduce energy or water consumption.

Following the methodology of these schemes, other new systems have been developed to assess energy efficiency for specific building cases. The Labs21 Environmental Performance Criteria is a rating system to assess the environmental performance of laboratory facilities. Laboratories present a unique challenge for energy efficient and sustainable design, with their inherent complexity of systems and health and safety requirements. The typical laboratory is about five times as energy intensive as a typical office building and costs about three times as much per unit area [12].

More difficult still is the evaluation of the smartness of a building from an occupant point of view. A recent study used factor analyses to identify the features that makes a building smart from a user's perspective [13]. Results showed the existence of two diverse groups based on their reported perception of smart building functionalities. Group 1 was composed of professionals within "trading, banking and finance, engineering and construction" and Group 2 included professionals within the "information and communication" industry. While both groups chose technologies within the "smart building indoor environment" and "eco and social spaces" domains as essential parts of a smart building, Group 1 selected the "smart building skin" whereas Group 2 selected "intelligent information systems". This result is interesting because it shows that the smartness of a building as perceived by its users relies strongly on their background and experience. Furthermore, the results also show the privacy paradox of smart and sustainable buildings, with users rating "security systems" as the most important feature but indicating "an intelligent system which monitors people" as the least important [13].

Other wide-ranging building performance indicators are the European Level(s) [14], the Smartness Index (SI) [6], and the recent R2G scheme and DGNB system of awards [15]. The Level(s) scheme was developed as a common EU framework to evaluate the sustainability of office and residential buildings. It provides a set of indicators and common metrics for measuring the performance of buildings across their life cycle. It includes environmental performance, health and comfort, life-cycle cost and potential future risks to performance. The Smartness Index includes an experimental study in the construction industry in the US to identify several performance components across the economic, energy and occupant-related domains. The results of this work also suggested that designers and owners are more focused on energy issues than constructors and that professionals with fewer years of experience pay more attention to energy-related issues [6]. This is important because it illustrates the importance that the energy efficiency of a building is gaining over time.

The Ready2Grids (R2G) scheme was developed by the French Smart Building Alliance and the certifying body Certivéa to assess the level of services that a building can provide. This scheme stresses the need not only to cover the facilities inside a building but also its capacity to connect to other buildings in the grid. The R2G will include three complementary levels of performance, namely the capacity of the building (i) to communicate its consumption to the grid, (ii) to predict and communicate its energy needs and (iii) to adapt its services to the availability of energy in the grid. Finally, the DGNB 'Climate Positive' award is a recent initiative from the German Sustainable Building Council to reward buildings that make a positive contribution to achieving climate protection goals. To evaluate net values, the DGNB examines the absolute greenhouse gas emissions of a building in use, looking specifically at values for a period of one year [15].

Table 2 presents a benchmarking of the different schemes reviewed, highlighting the development of the concept of 'smartness' in buildings over the years.

Table 2: Benchmarking of different rating systems and schemes

	LEED	BREEAM	HKBEAM	BIQ	EPC-Labs21	SI	Level(s)	R2G	DGNB	SRI
Year	1998	1990	1996	2009	2002	2015	2017	*2018*	2019	*In progress*
Country	United States	United Kingdom	Hong Kong	Canada	United States	United States	EU	France	Germany	EU
Status of the scheme	In use	In use	In use	In use	In use	Study proposition	Testing phase	Testing phase	In use	Testing phase
Assessment method	Feature-specific criteria and energy cost budget method	Mixture of performance-based and feature-specific criteria	Performance-based and feature-specific criteria	Score system	Extension of LEED – Increased nbr of points (from 69 to 85)	Score system including economic, energy and occupant performance	System of scores by levels		System of points based on 3 energy efficiency indicators	Mixture of performance-based and feature-specific criteria
Type of assessment	On-site: US-GBC	On-site: Trained assessors	Online & On-site	Online	Online & On-site	Online & On-site			On-site	Online & On-site
Targeted building typology	Residential and non-residential	Residential and non-residential	Residential and non-residential	Office buildings	Laboratory buildings	Construction industry in the US	Residential and non-residential	Residential and non-residential	Residential and non-residential	Residential and non-residential
Age of building	New	New and existing	New and existing	New	New and existing	New	New and existing	New and existing	New and existing	New and existing
Strengths	No need for an assessor or training	Most largely implemented scheme (>250 000 buildings)	Different versions for new and old buildings	Easy implementation	Includes life-cycle costing processes	Includes economic performance	Considers value creation and risk factors	Grid flexibility	Award including occupant behaviour	Large scope (UE) and uniqueness of the solution
Weaknesses	US adapted	Cost	Lower inclusion criteria	Only targets existing office buildings	Only for laboratory facilities	US adapted	Not direct measure of “smartness” components	Specificity on the connectivity attribute	Reduced scope of application	Not launched yet

The development of a smart readiness indicator (SRI) in Europe

The revised EPBD (2018/844/EU) formalised the need for a common EU scheme for rating the smart readiness of buildings: the so called "smart readiness indicator" (SRI). The goal of the SRI is to provide a common methodology to assess the capacity of a building to use information and communication technologies and electronic systems to adapt its operation to the needs of the occupants and the grid and to improve the energy efficiency and overall performance of buildings. The SRI methodology is still under development and its approval agenda extends over the next two years [16]. Other European Commission funded projects relevant to the development of the SRI and future EPC schemes are: the U-Cert, a Dutch coordinated project started in 2019 intending to make the new certification schemes more practical and reliable via an holistic and user-centred approach; HOLISDER, a project coordinated in Spain and started at the end of 2017, focusing on the development of smart technologies at the building level to reduce energy consumption; and HOPE-ON, a small initiative developed by a local Swedish company in 2017 to create an holistic open platform to manage building appliances. Other EU projects indirectly affect the future of the SRI and EPC: BUILD UPON2, coordinated in Spain and started in 2019, intends to develop national strategies to improve the renovation rate across EU countries; IDEAS, started in Ireland in 2019, seeks to develop an innovative cost-effective building relying on renewable energy systems and adapted to the different European climate zones; and the NEWCOM and Fit-to-nZEB projects, coordinated in Austria and Bulgaria respectively, which aim at improving the qualification and certification of the blue-collar workers who inspect and control the buildings.

Most of these programmes are quite recent and are still ongoing. However, some of the first theoretical conceptualisation papers are promising and are already raising important questions for future building energy management systems. For instance, in an article written within the project HOLISDER, the authors described the need to involve final users to achieve good energy systems optimisation. They argue that smart home systems are insufficient to achieve desirable performances without a well-defined human-centric demand response programme supported by information [17].

2.2 Detailed SRI approach and calculation method

As discussed in the previous section most of the methods used in assessment and rating schemes fall far behind in 'smartness' aspects compared to the SRI method already being developed. Therefore, the focus of this and upcoming sections will be only on the SRI method and how it can be used for the development of the indicator for EPCs.

The SRI covers impacts related to the three pillars defined in the amended EPBD, namely (i) energy performance of the building, (ii) building users, and (iii) energy grid. During the revised version (2nd technical study) of the of the SRI methodology [16], nine relevant domains and seven impact criteria were identified:

Domains (see Figure 5)

1. Heating: thermal storage, emission control systems, generators and energy consumption for space heating
2. Cooling: thermal storage, emission control systems, generators and energy consumption for space cooling.
3. Domestic hot water: services dealing with the smarter control of generating, storing, and distributing potable hot water in a building.
4. Controlled ventilation: services for air flow control and indoor temperature control.
5. Lighting: electric lighting managed/controlled by a lighting system based on, for instance, time, daylight and occupancy.
6. Dynamic building envelope: control of openings and sun shading systems and/or windows.
7. Electricity: both on-site renewables and storage (and in the future, potentially plug loads).
8. Electric vehicle charging: technical services provided by buildings to electric vehicles (EV) through recharging points, e.g. for electric consumption management and storage capabilities.
9. Monitoring and control: sensor data which can be provided by technical building systems (TBS) and used by other services, and/or be combined into one overarching system such as a home energy management system (HEMS).

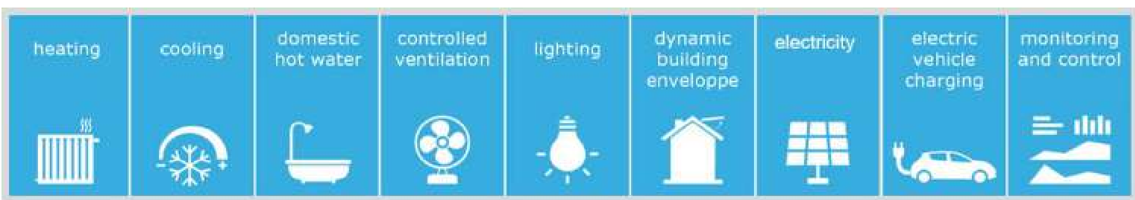


Figure 5: Visualisation of the nine domains covering the pillars defined in the amended EPBD

Impact criteria (see Figure 6)

1. Energy efficiency refers to the impacts of smart-ready services on energy saving capabilities. It is not the whole energy performance of buildings that is considered, but only the contribution made to this by smart technologies, e.g. energy savings resulting from better control of room temperature settings.
2. Maintenance and fault prediction: automated fault detection and diagnosis has the potential to significantly improve maintenance and operation of the TBS, eventually leading to better energy performance.
3. Comfort refers to the impacts of *services* on occupants' comfort, being the conscious and unconscious perception of the physical environment, including thermal comfort, acoustic comfort, and visual performance. This criterion differs from the 'comfort feature' in X-tendo as it focuses only on the systems/services of the building whereas the feature covers a broad range of assessments.
4. Convenience refers to the impacts of services on convenience for occupants, i.e. the extent to which services "make life easier" for the occupant, such as by requiring fewer manual interactions to control the TBS.

5. **Health and well-being** refer to the impacts of services on the well-being and health of occupants. Not being harmful in this respect is a strict boundary condition required of all services included in the SRI assessment. This category valourises the additional positive impact that some services could also provide, e.g. smarter controls could deliver an improved indoor air quality compared to traditional controls, thus raising occupants' well-being.
6. **Information to occupants** refers to the impacts of services on the provision of information on a building's operation to occupants.
7. **Energy flexibility and storage** refers to the impacts of services on the energy flexibility potential of a building.

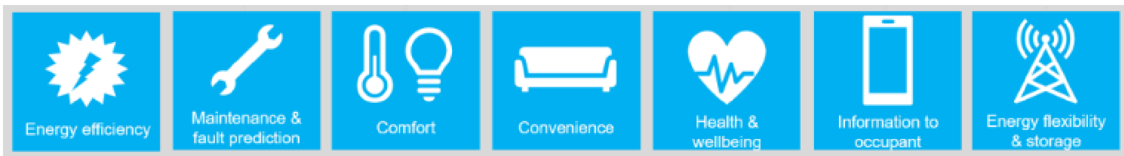


Figure 6: Visualisation of the seven impact criteria covering the pillars defined in the amended EPBD

NOTE: the development of certain smart readiness technologies within the building might be conditioned/strongly affected by the presence of smart metering technology. Smart meters will allow building users to engage with an in-home display which will provide real-time feedback on the effect of their behaviour on energy consumption and will support other forms of feedback and advice. Their presence has a direct impact on the availability of certain functionality levels for various domains. For instance, real consumption inputs are essential to provide users with daily information about their energy consumption.

2.2.1 How is the SRI calculated?

The smart readiness score of a building is a percentage that expresses how close (or far) the building is from maximal smart readiness. The higher the percentage is, the smarter the building. The total SRI score is based on the average of total scores on seven impact criteria and is measured as follows:

1. **Theoretical maximum calculation**: In a first step, an individual assessment calculates the theoretical maximum score that is achievable for each of the seven impact criteria in the building. The characteristics of each building mean that not every domain will be relevant in the score calculation of each impact criterion.
2. **Aggregated impact score per domain:** An aggregated impact score is then calculated for each of the nine domains as the ratio between individual scores and the theoretical maximum for that domain.
3. **Total impact score by impact criterion:** For each impact criterion, a total impact score is then calculated as a weighted sum of the domain impact scores. In this calculation, the weight of a given domain will depend on its relative importance for the impact being considered.
4. **Final SRI score:** The SRI score is then derived as a weighted sum of the seven total impact scores.

The SRI score is then calculated as:

$$N = A \times a + B \times b + C \times c + D \times d + E \times e + F \times f + G \times g$$

where:

- N is the total SRI score, weighted by domain
- A = the impact score (0–100) for energy savings on-site
- B = the impact score (0–100) for flexibility of the grid and storage
- C = the impact score (0–100) for comfort
- D = the impact score (0–100) for convenience
- E = the impact score (0–100) for health and well-being
- F = the impact score (0–100) for maintenance and fault prediction
- G = the impact score (0–100) for information to occupants
- a = the impact weighting (0–100%) for energy savings
- b = the impact weighting (0–100%) for flexibility of the grid and storage
- c = the impact weighting (0–100%) for comfort
- d = the impact weighting (0–100%) for convenience
- e = the impact weighting (0–100%) for health and well-being
- f = the impact weighting (0–100%) for maintenance and fault prediction
- g = the impact weighting (0–100%) for information to occupants.

The final aggregate score thus represents an overall percentage of the maximum score which the building could achieve (refer to Figure 7 to see how some of the non-eligible scores are marked as "-").

Given their nature, it is logical to deem that the different impact criteria have a specific weight. For example, the services in the heating domain might jointly account for 60% of the obtainable score for the "energy savings" impact category, whereas for other impacts such as "convenience" or "comfort", the relative weight of the heating domain is lower, e.g. 25%.

2.2.2 How are the weighting factors defined?

Following this idea, factors are weighted following a hybrid approach in which some have a fixed score and some a variable one:

For the impact criteria:

- Impact criteria "energy savings on-site", "maintenance and fault prediction", and "energy flexibility and storage" will be balanced based on their direct impact on the energy savings of the building.
- Since no objective sources are available yet, the impact criteria corresponding to the needs of occupants ("comfort", "convenience", "information to occupants", and "health and well-being") will follow an equal weighting.

For the domains:

- Since the contribution of the domain “monitoring and control” can be derived from the energy balance in all the domains, a fixed weighted value of 20% will be assigned to this domain over the seven impact criteria.
- Comparably, “dynamic envelope” will receive a fixed weighted value of 5% for all the impact criteria not related to the user's needs.

Figure 7 below shows a visual representation of the weighted approach. For example, for 'energy savings and operation' the weighting sums to 100% for two impact criteria (energy savings and maintenance & prediction) with energy balance method (75%), fixed weight (5%) and fixed weight (20%) in the respective domains in the left. By their nature, some domains have no effect on certain impact criteria. For example, “health and well-being” is only affected by the domains of ventilation, lighting, heating, cooling, and dynamic envelope, whereas the EV domain will not be assessed in the impact criteria of comfort or health and well-being.

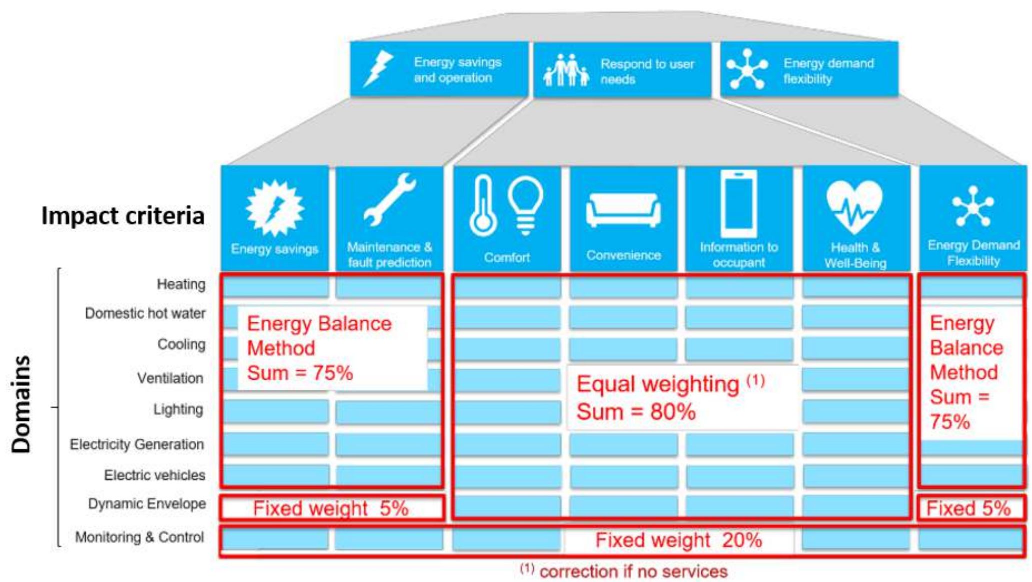


Figure 7: Visual representation of the weighted approach by impact criteria and domain

2.2.3 Which is the specific value of each impact criteria in the final SRI score?

When assigning the specific weight of the different impact criteria, we need to consider (i) the quantified degree of smartness related to the EPBD targets in terms of energy efficiency, and (ii) the ability to communicate these impact criteria to the public.

Taking these into account, equal weight was assigned for the three EPBD targets (33.3%) (see Figure 8):

- 33% for “energy savings and operation”, divided into 16.7% each for “energy savings” and “maintenance & fault prediction”.
- 33% for “user needs”, divided into 8.3% each for “comfort”, “convenience”, “health and well-being” and “information to occupants”
- 33% for “energy flexibility and storage”

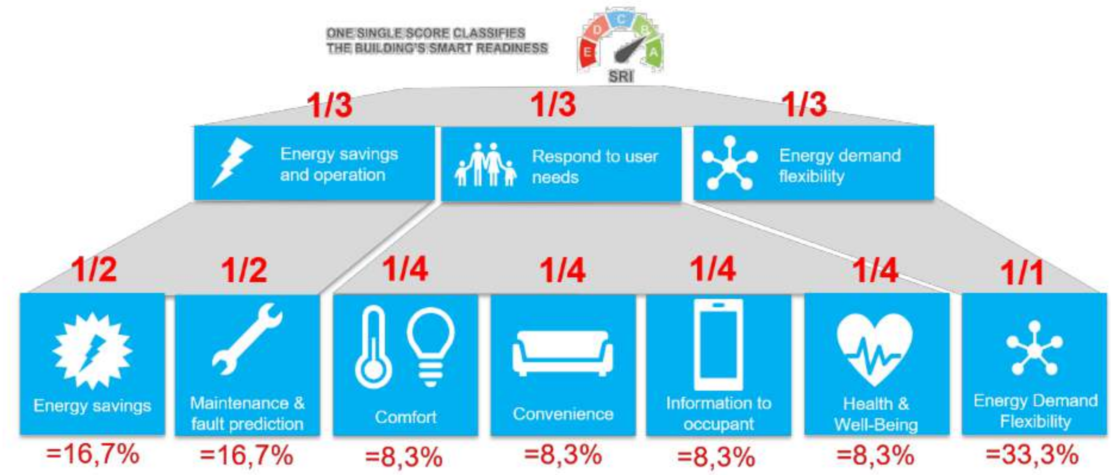


Figure 8: Aggregation of impact scores to a single score

- Climate adjustment

Although still under discussion, the development of the SRI methodology includes tentative schemas to adjust the impact of the different domains to the diverse European climates: North, West, South, North-East and South-East. Based on systematic evidence, a weighted score is calculated for each of the domains separately for residential and non-residential buildings. Some domains, such as the dynamic envelope of the building or monitoring and control, have fixed values.

- Selection of building-relevant domains: Triage

It is highly likely that due to local and site-specific contexts, some domains and services are not relevant, not applicable, or not desirable. For instance, the climate conditions can mean a building does not have a need for cooling, or the structural shape that it cannot support EV charging. The SRI methodology accommodates this by performing a triage process to identify the relevant services for a specific building, considering:

- The distinction between smart-ready (smart ready technologies (SRT) are already installed) and smart-possible (SRT can be installed) concepts
- The fact that the SRI should incentivise the uptake of SRTs
- The potential mutual exclusivity between some services
- The fact that some services might not be desirable from a policy perspective[2]
- Transparency of the assessed domains rather than comparability is preferred

[2] As a guiding principle, it could be considered that all services that are mandatory in a Member State's building code are mandatory in the SRI.

To this end, the solution communicates all the relevant scores (including the building score, the building maximum score and the theoretical maximum score; see Figure 9) and shows the domains not eligible for the building greyed out.

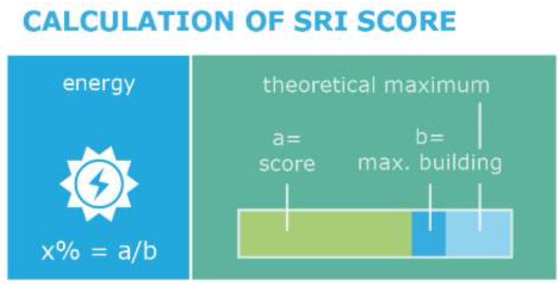


Figure 9: SRI score based on the maximum obtainable score per building

2.2.4 Proposed SRI assessment methods

Three methods are foreseen to assess SRI score (see Table 3). The scope of the methods is currently tentative. Additional guidelines may be developed by the EC and/or Member States to further specify the applicability and scope of the methods. Importantly, method C is not being developed currently, but is envisioned as a potential future evolution of the SRI methodology.

In the context of SRI feature in X-tendo the focus will be only on developing method A considering its suitability to the EPC schemes, as explained further in Section 2.8.

Table 3: Comparison of SRI assessment methods

	A – Simplified online quick-scan*	B – Expert SRI assessment	C – In-use smart building performance
Method	Checklist approach	Checklist approach	Measured / metered data
Means	Online	On-site inspection	In-use buildings
By whom	Self-assessment	Third-party qualified expert	TBS self-reporting their actual performance
Duration	15 minutes	Few hours	Data gathered over a long period (e.g. 1 year)
(tentative) scope	Residential buildings + non-residential	Non-residential + residential	Non-residential + residential (restricted occupied buildings)

NOTE: *With the aim to simplify method A and promote its use by the general public, the number of services to be assessed might be reduced from 54 to 27 (including items in the topics of "controllability and performance", "storage & connectivity" and "reporting of functionalities").*

2.3 Application of SRI assessment methods for the indicator

2.3.1 Use of methods for EPCs

The application of all the above-mentioned methods is independent of the EPC system, even when some of them share similar methodological calculations and could benefit from a parallel application (see Section 2.4 for more information). The experience of EPCs is not only relevant to the SRI with regard to the implementation but also to its methodology [16]. Indeed, both EPC and SRI stem from the EPBD so streamlining could work both ways. SRI could aim to leverage efforts made with existing schemes such as EPCs, HVAC inspectors, building inspectors, sustainability assessors etc. to make use of the existing training/accreditation and certification infrastructure to speed up the throughput and reduce the costs associated with establishing a pool of qualified assessors.

2.3.2 Applicability of methods to different building typologies

Most of the schemes in Table 2 consider the assessment of both new and existing buildings. The SRI is designed to be applicable to all building types (residential and non-residential), and to both new and existing buildings. At EU level, the indicator is not mandatory so far and its future applicability is expected to depend on each Member State [16]. Since the SRI relies on the use of new ICT and IoT, new buildings are likely to score better on this indicator. Nevertheless, new buildings represent only a small part of the EU building stock, so applying the SRI only to them would significantly limit its use; the SRI is designed to evaluate existing buildings as well. From a broad perspective, SRI could be used as an incentive to keep buildings up-to-date and motivate high quality and high energy efficiency renovation. The SRI might be key to helping existing buildings to achieve the goal of becoming nearly zero-energy buildings (nZEBs) without adding excessive materials and equipment, as it relies on relevant information (sometimes cheap to install) to optimise the overall building energy consumption. Importantly, the ongoing second technical study of the SRI includes the definition of the SRI features and calculation methodology, as well as an analysis of the value proposition and potential implementation pathways [16]. However, final decisions regarding the scope of its application (new vs. existing buildings) and the updating procedure of the SRI are part of the implementation process, starting in 2020.

Although most of the schemes consider the assessment of both residential and non-residential buildings, there are some indicators which have been developed to apply to one specific type of building. This is the case of the BIQ for laboratory facilities or the BIQ for office buildings.

Table 2 shows a schematic view of the different targeted buildings assessed in each of the schemes. Regarding the SRI, its inherent automation makes it ideal to contribute to the efficient management of common use buildings such as offices, department stores, hospitals, schools or museums. Yet the dependency on personal information on which this technology relies makes it especially interesting in the context of private buildings, such as residential homes or retail premises. This is especially relevant when the collected data is properly processed and transmitted to the final user, which enables personalisation of services.

2.3.3 Presentation of the indicator

The images used and the structure of the SRI aim to provide direct and clear information about the building's smart-ready technology (SRT) while facilitating its understanding by the public (not only experts). The buildings EPC and the energy label for household appliances are positive examples of members of the public, not only experts, using information like this when it comes to purchasing decisions. This suggests that the visual organisation of the information will determine its success and impact. Mnemonics can be used to simplify the processing and retention of information as well as to enable a comparison, while colour ranking, number of stars or series of numbers are commonly employed. Given the wide scope of user needs and potential implementation pathways, it is likely that offering a spectrum of media to communicate the SRI assessment and hierarchical layers of informational depth will offer the most value to the target audiences. An SRI score of 100%, meaning ideal inclusion of SRT within the building, could be indicated by a dark green colour. Furthermore, the assessment of the SRI will present (1) a total score for each building, complemented by three sub-scores ("energy savings and operation", "respond to user needs" and "energy demand flexibility") including seven impact criteria (see Figure 10).

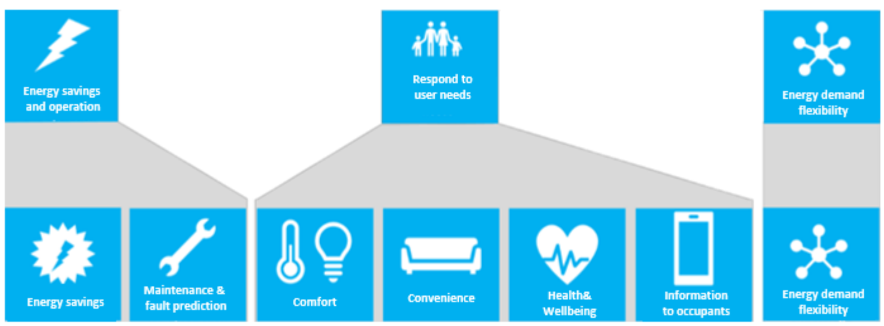


Figure 10: SRI sublabel and impact criteria

Each of the impact criteria is then assessed based on nine different domains gathering the diverse aspects a smart building needs to perform against. A 9x7 matrix containing the different scores per impact criteria/domain can be thus created (see Figure 11; "*note that SRI methodology is still under investigation and that the final format might be different*"). This is important because SRI contains information that can be presented at multiple levels. Therefore, at the sub-aggregate level it contains information on intrinsically more tangible aspects such as the energy efficiency performance of a control solution for a specific technical building system, or the delivery of indoor air quality.

IMPACTS

DOMAINS	Energy efficiency	Maintenance and fault protection	Comfort	Convenience	Health and well-being	Information to occupants	Energy flexibility & storage	SRI
Total	39%	18%	60%	71%	48%	59%	51%	46%
Heating	32%	18%	62%	55%	24%	74%	100%	
Sanitary hot water	17%	0%	45%	70%	67%	83%	0%	
Cooling	65%	51%	78%	72%	61%	55%	0%	
Controlled ventilation	41%	0%	55%	60%	34%	44%	-	
Lighting	85%	14%	90%	100%	83%	15%	-	
Dynamic building envelope	10%	0%	31%	56%	22%	46%	-	
Electricity	10%	0%	-	-	-	68%	0%	
Electric vehicle charging	-	38%	-	82%	-	84%	25%	
Monitoring and control	52%	43%	62%	72%	45%	64%	14%	

Figure 11: SRI assessment matrix – impact criteria/domain

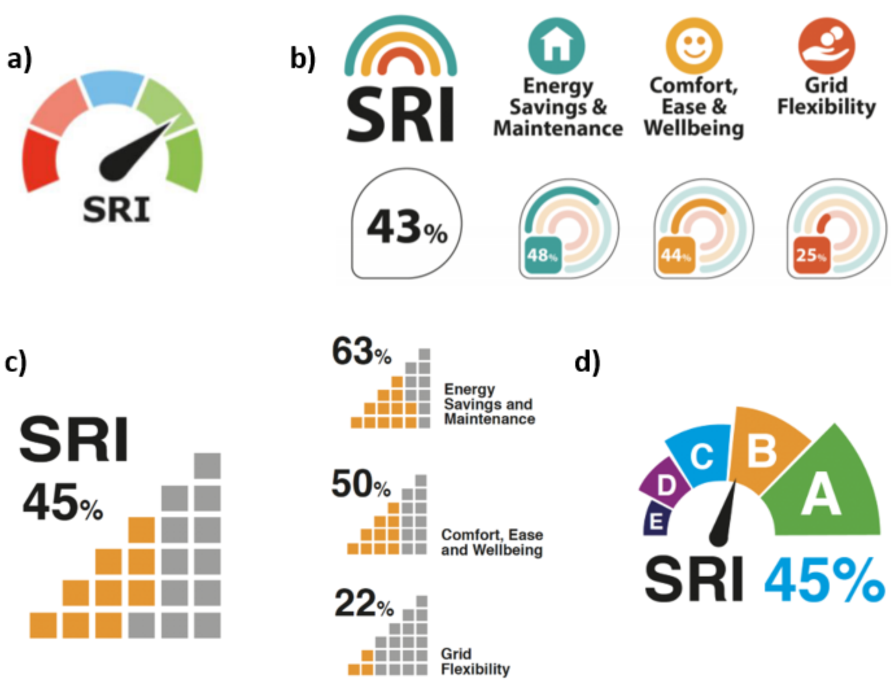


Figure 12: Sample SRI visualisation schemes being currently investigated

Multiple SRI visualisations are currently being tested with real users and its final form is still to be defined (see Figure 12). While some options include only the general SRI score

(Figure 12a and c), others are presented together with the three sub-scores on each of the sub-categories (Figure 12b and c). Although the implementation pathways may depend on national conditions (e.g. the regulatory framework for energy supply varies across different EU members) and building typology, the aim of the SRI is to provide a common framework for all countries and building types. Notwithstanding this, the fact that some Member States already require independent commissioning of large non-residential buildings lets perfect room for tying SRI into that process.

Data including both EPC and SRI assessment in real cases is not yet available since SRI is still in a testing phase. Within the X-tendo frame, a parallel assessment of SRI is accounted for in EPCs.

2.4 Linking SRI assessment methods to energy performance and EPCs

In the context of the EPBD, the impact of smart-ready services and technologies on the energy consumption of buildings is evaluated as a first key performance indicator. Smart services and technologies may unlock energy savings both by improving the energy efficiency at building level and by allowing the optimisation of energy flows on an aggregated energy grid level. Both impacts on energy performance are thus separately accounted below.

Building level: The calculation method used in the interim report to assess the energy performance improvement of a building is computed by taking into account the overall energy savings related to the upgrade of SRI systems [16], such as improving the smartness of the heating system by one or more levels of smartness (calculation method in EN 15232: Energy Performance of Buildings — Impact of Building Automation, Controls and Building Management, see Figure 13 for an example).

Residential

Climate region:	Western Europe
Building type:	Single family house
Construction period:	1960-1990
Retrofit level:	Renovated

SRT level	D	C (Reference)	B	A
Heating system				
BAC efficiency	1.09	1.00	0.88	0.81
Qheating	16433	15076	13267	12212
Cooling system				
BAC efficiency	1.09	1.00	0.88	0.81
Qcooling	214	197	173	159
Ventilation system				
BAC efficiency	1.08	1.00	0.93	0.92
Qventilation	902	835	777	768
Lighting system				
BAC efficiency	1.08	1.00	0.93	0.92
Qlighting	635	588	546	541
DHW system				
BAC efficiency	1.11	1.00	0.90	0.80
Qdhw	4460	4018	3616	3214

Saving	D->C	D->B	D->A	C->B	C->A	B->A
Heating	1357	3166	4221	1809	2865	1055
Cooling	18	41	55	24	37	14
Ventilation	67	125	134	58	67	8
Lighting	47	88	94	41	47	6
DHW	442	844	1246	402	804	402

Saving [%]	D->C	D->B	D->A	C->B	C->A	B->A
Heating	8%	19%	26%	12%	19%	8%
Cooling	8%	19%	26%	12%	19%	8%
Ventilation	7%	14%	15%	7%	8%	1%
Lighting	7%	14%	15%	7%	8%	1%
DHW	10%	14%	28%	10%	20%	11%
Total	**9%**	**19%**	**25%**	**11%**	**18%**	**8%**

Figure 13: Example of estimated energy performance improvement following the improvement of SRI for residential buildings in Western Europe

As can be expected, estimations presented in the interim SRI report showed that the largest savings are obtained when increasing the system smartness from level D to A, with a resulting 25% total energy saving estimated [16]. The results show a clear dependence on the original energy demand of the building prior to installing the SRTs.

Grid level: The goal of the SRI is also to assess the impact of smart buildings in relation to the energy grids. The capacity of the building to offer demand-response services such as self-consumption, self-production or storage services is expected to increase the renewable capacity of the energy grid as well as the energy efficiency of the system. Based on a literature review conducted within the interim report, it is estimated that the first category of flexibility (i.e. SRI scores of D and C) result in an estimated 5% increase of self-consumption [16]. In contrast, buildings with smartness levels B and A are expected to reach self-consumption levels close to 25% increase.

Smart-ready services contribute also to increasing energy security and the optimisation of flows in energy grids. Since the energy flexibility that can be offered by a building cannot be captured by a single-value indicator as it covers multiple dimensions (time, power, energy, rebound, etc.), the best way to assess the impact of this factor is to consider the reduction in GHG emissions and energy savings.

Detailed comparison between EPC and SRI schemes is required for the future development of a common assessment approach. Points of convergence and potential overlapping between the two assessment schemes can be summarised by theme:

Scope of application: There is a clear distinction between the implementation of EPC and SRI within Member States:

- For EPC, there is an outline of the methodology in the EPBD, but Member States can develop their own calculation methodology, software etc., so there is little comparability across Europe.
- For SRI, the calculation methodology is designed to be common to all countries. Member States can choose whether they implement the SRI or not, and whether they make it mandatory to all buildings, some buildings, or not mandatory at all. There may be some national deviations (e.g. weighting factors) but in general the methodology will be identical across Europe.

Maturity: While EPCs are quite mature and their characteristics are well established (at least for some Member States), SRI is a new indicator

Scale: EPCs and SRI both cover the majority of the EU's building stock. With this high degree of coverage, a large target convergence between EPC and SRI can be expected.

Building assessments and site visits/inspections: Building assessments are included in both schemes and site visits and inspections could be correlated. Importantly, shared assessment costs might reduce overall assessment costs.

Target audience: Both SRI and EPC should address the same public audience including property owners, facility managers, investors and tenants. Establishing links between the indicators could increase the target audience interested.

Actors directly involved in delivery: Building assessors, building service engineers, HVAC engineers and qualified building professionals are likely to be involved at some level in the delivery of services within EPC and SRI schemes. For other more product-focused initiatives, such as cybersecurity certification or smart meter technology (necessary for the implementation of some SRI features), specific professionals such as electrical engineers working for distribution system operators or manufacturers operating at the single market level will be necessary.

Certification: The issuance of a certificate to denote that a building or service within it has had a qualified assessment will be common ground for both schemes. The use of both indicators could end up reinforcing the value proposition. Potential SRI implementation pathways will be sensitive to trigger points generated by EPC assessment (e.g. inspections, renovations, etc.).

Quality assurance: This is related to certification and likely regulated in different ways within the Member States. These indicators could be inserted in the future within a much larger building renovation passport.[3]

Mandate: The mandates applicable to the schemes encompass (1) governmental, legally binding initiatives (such as those related to the EPBD), (2) governmental voluntary initiatives, (3) private sector mandates operated through an association and (4) private sector project-specific.

Organisation: Again, highly dependent on the specific Member State, various schemes are possible within one of the following organizational frameworks:

- Government managed with private sector delivery at Member State level
- Voluntary framework open for use by building profession
- Voluntary framework open for use by product manufacturers
- Government regulated with private sector delivery
- Private sector managed

Governance: Both indicators are likely to fall under the same governmental objective, facilitating its implementation and providing a robust strategy to reach it. However, conflicts of interest exist within member states. Local governments are responsible for managing issues regarding the (potentially) combined implementation of EPC and SRI such as assessors' certification, private sector action outlines or the potential economic interests prompted by the common implementation of both indicators.

Methodology: Finally, EPC status might be used to calculate the weighted factors within the SRI impact criteria. For buildings that have (or are in the process of obtaining) an EPC, the SRI weighting factors for energy savings could be derived from the EPC calculation directly.

2.5 Legal boundaries or requirements of assessment methods

Regarding data privacy

During the assessment process, the assessor (or an automated system) collects data on the various smart services present in a building (e.g. temperature regulation, EV charging capabilities and provisions on automated solar shading control). This provides personal information about the smart services that are present or missing in the building, the functionality level of these services and the building usage. On top of this, additional information is also recorded, including technical information on specific technical building systems or pictures and notes taken by the assessors during on-site inspections. This data, potentially interesting for commercial purposes, must in all cases follow a security process

[3] EU initiatives such as the digital logbook recently funded are expected to work on this during the upcoming years

to ensure compliance with the European General Data Protection Regulation (GDPR). The procedure is comparable to the one currently followed for EPC assessment. A smooth and secure process for retrieving previously entered SRI data will greatly support the efficiency of the SRI assessment and reduce its cost. This could be integrated within the regular update by the owner, facility manager or contractor every time the building receives an upgrade.

- Cybersecurity risks

More potentially dangerous are the risks associated with the constant connectivity and data sharing which characterises several SRT. IoT deployments can lead to hackers entering into the building system to get personal data or to demand ransoms from residents.

2.6 Ranking of existing methods to evaluate the smartness levels

The different schemes reviewed in Section 2.1 and summarised in Table 2 are now evaluated based on the capacity to assess the smartness[4] of a building. Table 4 gives a ranking based on expert judgement and a brief explanation is provided. Although the other methods do not significantly include smartness aspects in their assessments, they are presented as a comparison to the SRI method. The SRI method is so far the only method that has been designed to consider all the smartness aspects of a building.

Table 4: Comparison of the reviewed assessment schemes based on their capacity to evaluate the smartness level of a building

Method	Ranking[5]	Comment on feasibility/ explanation
Building level of smartness		
LEED	**	Does not evaluate smart technology within the building and connection to the grid
BREEAM	**	Does not assess smart technology or connection to the grid
HKBEAM	**	Does not assess smart technology or connection to the grid
BIQ	****	Only for office buildings
EPC-Labs21	*	Specific to laboratory facilities, shares LEED's methodology
SI	***	Just a value proposition; not yet a standardised scheme

[4] Smartness as defined in the EPBD EU directive

[5] Ranking scores are assigned based on the review in Section 3.1, but risk being subjective, based on the author's opinion

Level(s)	***	Includes new concepts such as resilience to climate change or risk factors, but lacks the evaluation of automation components
R2G	***	Promising indicator including connection to the grid but requires further development and case studies
DGNB	***	Powerful but with a reduced scope of application so far (award)
SRI	*****	Complete indicator designed to account for the diverse components making a building smart
Likert scale used for suitability: not at all (*), slightly (**), moderately (***), very (****), extremely (*****)		

2.7 SWOT analysis of the SRI assessment method

The implementation frame of the SRI together with its methodology makes it possible to embed within the existing EPC assessment. For instance, the target audience (e.g. property owners, tenants, facility managers, investors) of both and the actors (e.g. EPC assessors) involved in their assessment are the same. EPC data could be valuable to help assess the SRI of the building, thus reducing the total assessment time of the indicator. Similarly, SRI information could be used to support the assessment process of the EPC for new and existing buildings. Despite the potential benefits of combining assessment of both indicators, it is important to be aware of possible drawbacks, including increased assessment time and the need to train certified assessors.

Table 5 summarises the strengths and weaknesses of including SRI assessment in the current EPC scheme with regard to the opportunities and threats in the construction market (SWOT analysis).

Table 5: SWOT analysis of the SRI assessment method

Strengths	Weakness
Rapid coverage of SRI assessments if made mandatory within the EPC	Increased EPC time and cost
Third-party assessment should maximise assessment quality and market value	Do not include in their methodology the potential to be assessed through portable devices
Third-party assessment allows issuance of a trustworthy certificate	It will lower EPC credibility; not always high with all market actors
Assessment can directly inform owner/occupier via targeted advice	Requires extra training of EPC assessors
Increases energy efficiency renovation potential as both provide complementary information	Does not influence the design phases of a building (yet)

Opportunities	Threats
Complements existing EPC assessment	EPC assessors may not be trained/accredited for SRI assessment -> risks reputational damage
Can emphasise the use of SRT as an opportunity for the energy transition	If enough qualified assessors are not available there may be a risk of slowing down EPC deployment due to added SRI burden
Could make use of EPC energy balance data	Greater time and cost of EPC/SRI assessment could create resentment against EPCs and reduce conformity with EPC requirements
Assessment could be linked to online tools which personalise the information of interest for the users regarding both EPC and SRI	Risk to data security such as data thefts or misuse for commercial purposes
Positive impact on real estate value	

2.8 Proposed approach to develop the feature

Although the scope of the methods is still tentative, three methods have been described so far to assess the SRI score [18]. Additional guidelines may be developed by the EC and/or Member States to further specify the applicability and scope of the methods. Importantly, method C is not being developed currently, but is envisioned as a potential future evolution of the SRI methodology. The most recent analysis (published in February 2020) showed that, despite the differences in assessing time, methods A and B present comparable assessment outputs.

For this reason, X-tendo partners agreed to use method A (abbreviated) in the testing to assess in parallel both SRI and EPC. Method A has an estimated assessment time of 15 minutes and covers both non-residential and residential buildings. It is based on a checklist and the assessment process does not require external experts (self-assessment). More details of the variables covered in method A can be seen in the 3rd interim report (Annex C; Table 69, pages 356-361) [18].

As explained within Section 2.2, different building parameters such as type, characteristics or geographical location will determine the specific theoretical maximums and weighted values of the "domain x impact criteria" matrices. As discussed, the weighting for different domains and impact criteria will vary between buildings: for example, for most buildings aspects such as the general heating domain might account for 60% of the possible score for the "energy savings" impact category, whereas EV charging will only be significant in buildings that have the capacity to include charging points. The final SRI score will be represented as a percentage, where 100% will represent the maximum score. This main score could be also split into three sub-scores: "energy savings & maintenance", "comfort, ease & well-being" and "grid flexibility". Figure 14 shows as schematic view of the scoring process.

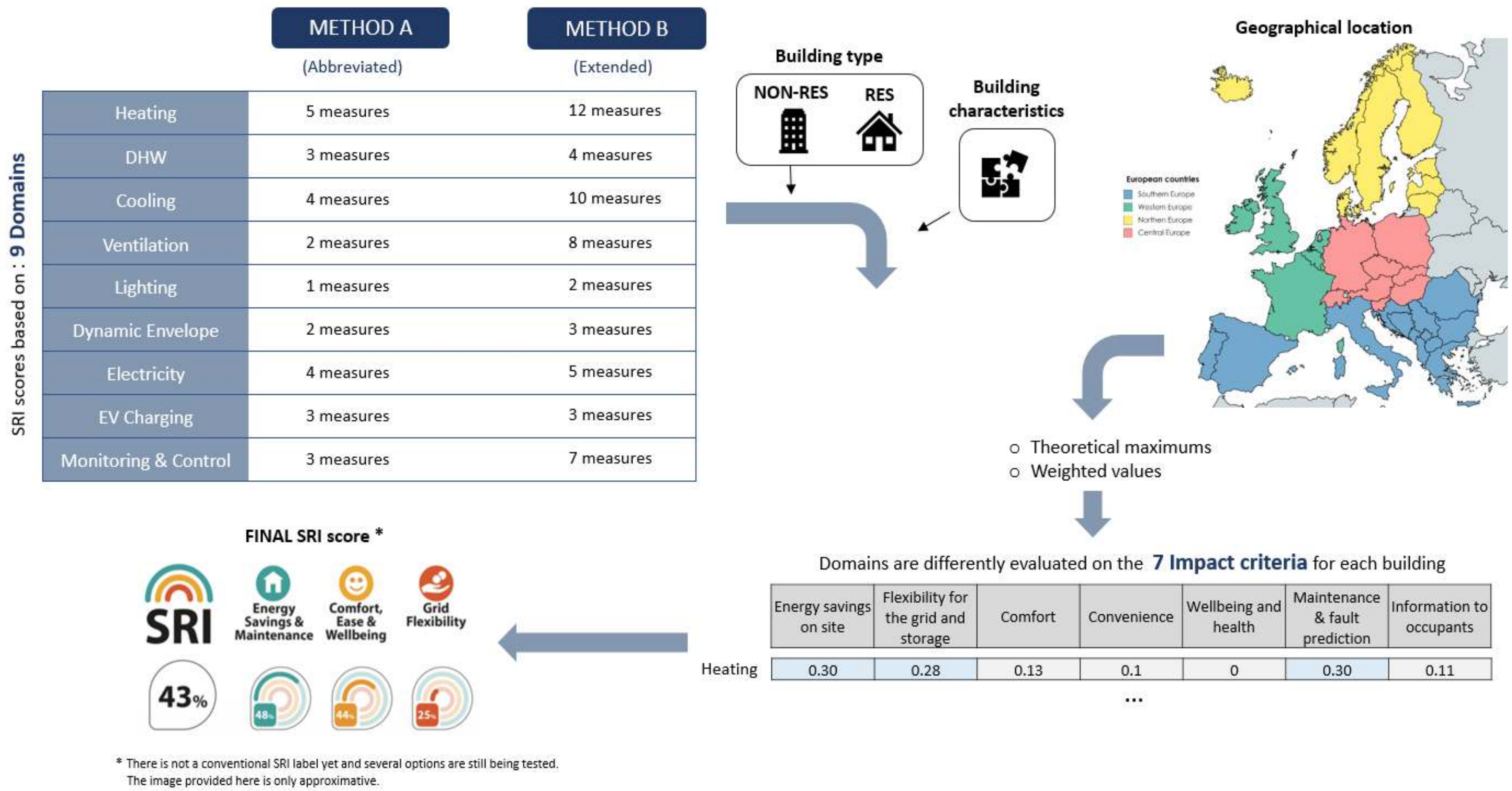


Figure 14: Indicative flow of SRI assessment approach

Key messages:

- Method A will be considered as the reference SRI assessment method within the X-tendo project. This is because it has equivalent outputs when compared to the more detailed method B together with a reduced assessment time.
- Not all buildings are evaluated equally. Different building parameters (type, characteristics, geographical location) will determine the eligible assessment facets (theoretical maximum) as well as the weighted values of each.
- The final SRI score is provided in the form of a percentage and subdivided in three subcategories matching EPBD objectives: "energy savings & maintenance", "comfort, ease & well-being" and "grid flexibility".

3 FEATURE 2: COMFORT

3.1 Overview of the methods to assess indoor environmental quality (IEQ)

In today's society people spend approximately 90% of their time in buildings, so IEQ has become an issue of increasing concern [19]. This has become more relevant in the current pandemic where people are staying indoors even more [18]. Occupant behaviour, awareness and level of acceptance of the indoor environmental conditions is essential for maintaining satisfactory IEQ. A large body of social science and environment-behaviour research demonstrates that improving IEQ has health benefits for occupants [20]–[22]. The International Performance Measurement and Verification Protocol (IMPVP) outlines concepts and practices for improved IEQ, that can be associated with energy conservation measures [23]. There are many energy efficiency related improvements (e.g. replacing windows, adding insulation etc.) in buildings that improve IEQ, especially with respect to thermal comfort, ventilation, lighting and acoustics. Current legislation under the EPBD [24] and EED [25] has pushed Member States in Europe to address the existing building stock through energy-efficient retrofits and achieve nZEB performance. EPCs present an opportunity to investigate the feasibility of improving both IEQ and energy efficiency in the existing building stock with well-designed retrofit measures.

Different retrofit measures under shallow, medium or deep retrofits hold great promise for improving IEQ as well as the energy efficiency of buildings. IEQ is mentioned in the multi-annual roadmap of 2020 [26] and recently amended EPBD (2018/844). However, the impacts of retrofits on IEQ are not always addressed in a cost-effective manner [27]. Deep energy retrofits (saving over 60% energy) can bring tangible and intangible benefits of enhanced performance and improved productivity in indoor environments such as residential buildings, offices, schools, colleges and commercial establishments. Only a few projects like ALDREN and RE-BUS have attempted to outline new methods for the evaluation of comfort in the light of harmonised EPC processes for the EU.

In this section, a comprehensive literature review from the existing research is presented and analysed. We assess how different methods for evaluating IEQ can be integrated in EPCs and applied to measure the "comfort" feature. The environmental factors of thermal comfort, visual comfort, acoustics and indoor air quality define IEQ [28]. Each of these is discussed in the following subsections with respect to the latest standards and research.

- Thermal comfort

According to ASHRAE 55 [29] and ISO 7730 [30] '*thermal comfort is that condition of mind which expresses satisfaction with the thermal environment*'. ASHRAE 55 and ISO 7730 specify the combination of indoor thermal environmental parameters (temperature, radiant temperature, humidity and air velocity) and personal parameters (metabolic rate and clothing insulation) for acceptable comfort conditions to occupants. There are two models to identify the thermal sensation in a space: the rational model (heat balance) based on predicted mean vote (PMV)/ predicted percentage of dissatisfied (PPD), applicable in conditioned environments (e.g. during winters when the heating is operational); and the adaptive comfort model, applicable in unconditioned environments (e.g. during summers when the building is naturally ventilated) [29], [30].

- Indoor air quality

Indoor air quality refers to the air quality within buildings. Acceptable indoor air quality refers to air without harmful concentrations of known contaminants, with which the vast majority of exposed people are satisfied. Poor indoor air quality is known to have acute and chronic effects on the health of the occupants [31]. It is directly related to the ventilation rates and concentration of indoor pollutants, which in turn are related to sick building syndrome (SBS), used to describe situations where occupants have acute health and comfort effects [32]. In closed environments, indoor air quality is related to both chemical and physical causes, such as carbon monoxide (CO) and dioxide (CO_2), radon concentration, environmental tobacco smoke, formaldehyde, volatile organic compounds (VOCs), ventilation rate, temperature, dampness, humidity, ionising and non-ionising radiation [33]. Provision of good outdoor air supply is known to provide acceptable perceived indoor air quality [34]. The World Health Organization (WHO) has published indoor air quality guidelines for selected pollutants and their health effects with the target of ensuring the provision of safer indoor environments [35].

- Visual comfort

Visual comfort is defined in the European Standard EN12665 as "a subjective condition of visual well-being induced by the visual environment" [36]. Visual discomfort can occur because of either too low or too high a level of light. Visual comfort is a subjective measure dependent on certain factors such as illumination, luminance and brightness, luminous spectrum and risk of glare [36]. The presence of a good visual environment (e.g. adequate natural and artificial lighting, reduced glare discomfort etc.) may add to the well-being and productivity of the occupants of a building [37].

- Acoustic comfort

Acoustic comfort is the presence of a comfortable acoustic environment without any uncomfortable noise [38]. Acoustic comfort is considered crucial for non-domestic buildings' IEQ and is generally given high preference among other IEQ indicators in offices and classrooms by occupants [39]–[41]. Occupants' satisfaction in workplaces can be improved by speech privacy and comfortable sound levels, which are identified as the main problems regarding acoustic quality in office workstations [42]. Building elements play a significant role in offering external and internal sound insulation by acting as a barrier, absorbing or reflecting the sound waves [43].

3.1.1 Analysis of existing building assessment, rating and certification systems for IEQ

There are several voluntary building rating and assessment systems around the world that integrate IEQ with health and well-being of occupants. These rating systems have established extensive, and very costly, criteria for evaluating both new constructions and existing buildings. Most of the indicators are based on best practices, national regulations or national/international standards. However, these rating systems are not mandatory at national level.

To understand comfort indicators and how they can be applied to EPCs, a few well-known systems were reviewed, including:

- BREEAM: Building Research Establishment Environmental Assessment Method (BREEAM) was launched in 1990 by Building Research Establishment UK, a world-leading, multidisciplinary building science organisation. BREEAM was the world's first environmental assessment method for buildings and is defined by building science and research. Performance is measured in nine categories: management, health and well-being, energy, transport, water, materials, waste, land use and ecology, and pollution

- DGNB: The basic system for assessing the sustainability of buildings was jointly developed by the German Sustainable Building Council (DGNB) and the Federal Ministry of Transport, Building and Urban Development (BMVBS), Germany in 2009. DGNB has developed a complete certification system for a wide range of building uses and quarters. The sustainability concept of the DGNB system is broad and extends beyond the well-known three-pillar model (social, economic, and environmental). It consistently considers all essential aspects of sustainable construction. These include the six subject areas ecology, economy, socio-cultural and functional aspects, technology, processes, and location.

- LEED: Leadership in Energy and Environmental Design (LEED) was created in 2000 by the US Green Building Council (USGBC), for rating design and construction practices that would define a green building in the United States. LEED consists of credits which earn points in seven categories: site selection, water efficiency, energy and atmosphere, materials and resources, IEQ, regional priority, and innovation in design.

- HPI: The Irish Home Performance Index (HPI) considers the quality of residential development under three categories: (i) costs, including energy, water and transport, (ii) wellbeing, such as comfort, indoor air quality, the levels of daylight, and other issues, (iii) planet, by considering how homes may help in reducing the ecological footprint.

- WELL: WELL is a performance-based system for measuring, certifying, and monitoring features of the built environment that impact human health and well-being. It was launched in 2014 by the International WELL Building Institute (IWBI). It assesses the impact on health and well-being by looking at seven concepts: air, water, nourishment, light, fitness, comfort, and mind.

In Table 6, a summary is given of the criteria related to comfort/health and well-being, with details of the indicators taken into account and the standards applied.

Table 6: Summary of criteria related to assessment of comfort in building certification systems

Assessment/ rating system	Criteria	Indicators	Standards applied	Ref
BREEAM	Visual comfort	1. Glare control (suggested design measures) 2. Daylighting (average daylight factor, average daylight illuminance) 3. View out (opening size, distance of occupant) 4. Internal and external lighting (EN13201 and EN 12464-2)	• CIBSE Lighting Guide 10 Daylighting and window design • BS 8206 Part 2. Code of practice for daylighting	[44] [45]
	Indoor air quality	1. Ventilation (national/industry standards) 2. VOC emission levels (ISO standards) 3. Natural ventilation potential (opening area)	• EN ISO 11890-2:2013 – Paints and varnishes • Determination of VOC content, Part 2 – Gas • Chromatographic method • ISO 16000-4: 2011 Diffusive sampling of formaldehyde in air • ISO 16000-6: 2011 VOCs in air by active sampling • EN ISO 16017-2: 2003 VOCs - indoor, ambient and workplace air by diffusive sampling • ISO 16000-3: 201123 Formaldehyde and other carbonyls in air by active sampling	
	Thermal comfort (for conditioned buildings)	1. Thermal modelling (PMV/PPD) (standard based) 2. Thermal zoning and controls (heating and cooling strategy) (standard practice)	• ISO 7730:2005	
	Acoustic comfort	1. Indoor ambient noise (equivalent sound pressure level – national regulations or good practice) 2. Sound insulation (national regulations or good practice values) 3. Reverberation time (national regulations or good practice	• Measurement of sound insulation: ISO 16283 series • Reverberation time: ISO 16283-1:2014	

		values)		
DGNB	Thermal comfort	1. Operative temperature (heating/cooling period) 2. Drafts (heating/cooling period) 3. Radiant temperature asymmetry (heating/cooling period) 4. Relative humidity (heating/cooling period)	• Measurement and simulation • DIN EN15251:2007 • EN ISO 7730 • DIN 4108-2	[46]
	Indoor air quality	1. VOCs measurement (specified values) 2. Ventilation rate (standard based)	• DIN ISO 16000:1/3/5/6 • EN15251: 2007	[47]
	Acoustic comfort	1. Room acoustics class (standard based) 2. Reverberation time (standard based) 3. Average equivalent sound absorption area (standard based)	• VDI 2569: 2016-02 • DIN 18041:2016-03 • DIN EN ISO 3382-2	[48]
	Visual comfort	1. Daylight factor (standard based) 2. Annual relative motive exposure (standard based) 3. Visual link with outside (specified values) 4. Absence of glare in daylight (standard based) 5. Artificial light (standard based) 6. Daylight colour rendering (specified values) 7. Exposure to daylight (specified values)	• DIN V 18599 • DIN 14057 • EN 12464-1	[49]
LEED	Minimum indoor air quality	Outdoor air rate (standard based) Natural ventilation:	• ASHRAE 62.1: 2016	[50]

		opening location and size (standard based)		
	IEQ performance	Measurements of CO_2 and TVOC (standard based)	• ISO 16000-6	
	Thermal comfort	Thermal comfort analysis conditioned and unconditioned spaces (standard based)	• ASHRAE Standard 55-2017 • ISO 7730-2005 • ISO 17772-2017	
	Interior lighting	1. Lighting quality (luminance – specified values)	• Specified values	
	Daylight and quality views	1. Spatial daylight exposure 2. Annual sunlight exposure 3. Illuminance 4. Direct line of sight to outdoors	• Specified values	
	Acoustic performance	1. HVAC noise 2. Sound transmission 3. Reverberation time (specified values)	• ASHRAE Handbook 2015 • ASTM E336-17a	
HPI	Indoor air quality	1. Ventilation (national regulations) 2. VOCs level (standard based)	• Building Regulations Part F TGD Ventilation 2009 • ISO 16000-4:2011	[51]
	Daylighting	1. Daylight factor	• Code for Sustainable Homes, HQE, Miljöbyggnad • BS 8206-2:2008 – Lighting for buildings	
	Acoustic comfort	1. Sound insulation 2. Indoor ambient noise level	• Adapted from DGNB/BNB and BREEAM • Building Regulations 2014 TGD Part E Sound	
	Summer and winter comfort	1. Summer comfort (risk of overheating) 2. Winter comfort (radiant asymmetry)	• Appendix P in the DEAP methodology, PHPP (Passive House Planning Package) • TGD Part L 2011	
WELL	Comfort	1. Accessible design (accessibility) 2. Exterior noise intrusion (sound pressure level) 3. Internally generated noise (equipment sound level) 4. Thermal comfort (conditioned and unconditioned zones) 5. Radiant thermal	• ISO 21542:2011 - Building Construction • ASHRAE Standard 55-2013 Section 5.3, Standard Comfort Zone Compliance • ASHRAE Standard 55-2013 Section 5.4, Adaptive Comfort Model	[52]

		comfort (conditioned spaces) 6. Olfactory comfort (source separation) 7. Reverberation time (standard based)		
	Air	1. Ventilation effectiveness & increased ventilation 2. VOC reduction 3. Internal moisture management 4. Operable windows 5. Displacement ventilation	• ASHRAE 62.1-2013 (Ventilation Rate Procedure or IAQ Procedure) • CIBSE AM10, Section 4, Design Calculations • ASHRAE Guidelines RP-949	
	Light	1. Visual lighting design (illuminance level) 2. Electric and solar glare control (shading) 3. Colour quality (colour rendering index) 4. Daylight modelling (spatial daylight autonomy) 5. Daylighting fenestration (size and design)	• Specified values based on ISO 8995-1:2002, EN15251:2007	

3.2 Description of assessment and calculation methods

The analysis of existing rating and certification schemes in Section 3.1 provided a glimpse of well-known methods that are used in the assessment of buildings from an IEQ perspective. This section elaborates on the selected methods and calculation approaches behind them that are relevant to EPCs. Additional details on each method are provided to understand their application in Section 3.3.

3.2.1 Thermal comfort

- Heat balance model

The heat balance model works in steady state conditions and assumes that the human body's thermoregulatory system maintains constant internal body temperature. It assumes that the thermal balance of the body is influenced by human physical activity (metabolic rate) and clothing preferences (clothing insulation). It also considers environmental parameters: air temperature, mean radiant temperature, air velocity and humidity. These factors form the basis of evaluation of thermal sensation for the whole body using the PMV/PPD indexes.

- PMV/PPD

Occupant satisfaction has been investigated through surveys of subjects in laboratory settings and actual buildings. In order to determine the physical and contextual conditions in which acceptable thermal comfort can be evaluated, Fanger [53] performed an experiment on 1,296 Danish students using a steady state heat transfer model. Fanger's model is a combination of theories of heat balance and physiology of thermoregulation to determine the ranges of comfortable temperatures for the occupants of the building. The comfort equation was derived and expanded into the ASHRAE seven-point thermal sensation scale known as the 'predicted mean vote' (PMV) index. It has the following range: +3 (hot), +2 (warm), +1 (slightly warm), 0 (neutral), -1 (slightly cool), -2 (cool) and -3 (cold).

The PMV equation is a function of environmental variables as:

$$PMV = f\,(t_a, t_{mrt}, v, p_a, M, I_{cl})$$

where

- t_a air temperature (°C)
- t_{mrt} mean radiant temperature (°C)
- v relative air velocity (m/s)
- p_a humidity (vapour pressure) (kPa)
- M activity level (w/m^2)
- I_{cl} clothing insulation (clo)

Further, based on the experimental studies by Fanger on PMV, an empirical relationship was established with 'predicted percentage dissatisfied' (PPD) as:

$$PPD = 100 - 95 \times \exp(-0.03353 \times PMV^4 - 0.219 \times PMV^2)$$

This relationship indicates exact symmetry with respect to thermal neutrality i.e. (PMV=0). This means that if PMV=0, a minimum of 5% dissatisfied people exists due to the difference in thermal comfort from person to person [54]. Figure 15 shows the relationship between PMV and PPD. The PMV/PPD model has been adopted by various standards e.g. ASHRAE Standard 55 and ISO 7730.

Depending on the values of PMV and PPD four types of comfort ranges are defined in the standard EN15251: 2007 [55] (superseded by EN16798-1 in 2019 [56]) based on previous ASHRAE 55 and ISO 7730 standards. The comfort ranges form the basis of the design and assessment of thermal comfort and energy performance of buildings as shown in Table 7.

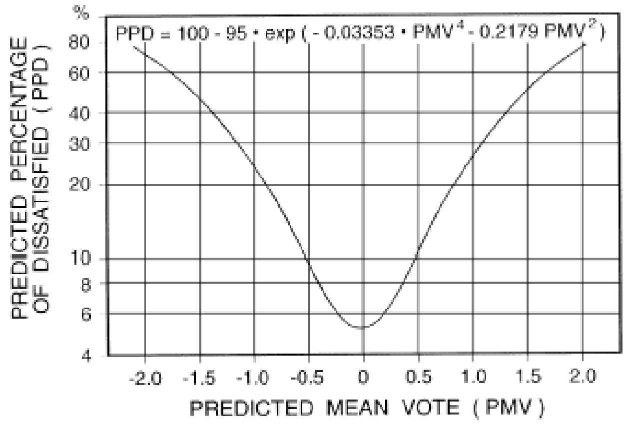


Figure 15: PPD as a function of PMV [29]

The PMV and PPD generally express thermal sensation as warm or cold for the whole body but a different criterion of local thermal discomfort can also be applied for design and dimensioning which includes draft, vertical air temperature differences, floor temperature and radiant temperature asymmetry, as described in ISO 7730. This model applies to people with light sedentary activity sensitive to local discomfort.

Table 7: Recommended categories for design of mechanically heated and cooled buildings [56]

Category	Explanation	PPD (%)	PMV
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like disabled, sick, very young children and elderly people	<6	-0.2 < PMV < +0.2
II	Normal level of expectation and should be used for new buildings and renovations	<10	-0.5 < PMV < +0.5
III	An acceptable, moderate level of expectation and may be used for existing buildings	<15	-0.7 < PMV < +0.7
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year	<25	-1.0 < PMV < +1.0

- Adaptive model

While the heat balance model is applicable to air-conditioned spaces, the adaptive model is applicable to naturally conditioned spaces. This allows for the occupants to adapt to the surrounding environment by three means: physiological (acclimatisation), behavioural (changing activity, clothing level, opening/closing windows) and psychological (cognitive, social and cultural variables) [57].

The experiments to establish the relationship between PMV and PPD were conducted in climatic chambers, so did not reflect the thermal perception of occupants in environments that allow adaptation [54]. The adaptive approach was derived from field studies that determined the real conditions of the thermal environment. In real situations, people constantly interact with the immediate environment and adapt to it, making it comfortable for themselves. To apply this method in the field, the space must have operable windows with no mechanical cooling. There can be mechanical ventilation with unconditioned air, and the heating system must not be in operation. Among the key findings from the field studies on adaptive thermal comfort, a correlation was established between the mean outdoor temperature (T_o) and indoor neutral temperature (T_n) by Humphreys [58] for 'free running buildings' (without mechanical cooling):

T_n= 11.9 + 0.534 T_o (coefficient of determination R^2= 0.94)

Figure 16 shows the acceptable operative temperature ranges for naturally conditioned spaces as per ISO 7730. This model accounts for local thermal discomfort effects for typical buildings. It also accounts for people adapting their clothing by relating indoor operative temperature to the outdoor running mean temperatures and excludes the humidity and air velocity from its calculations.

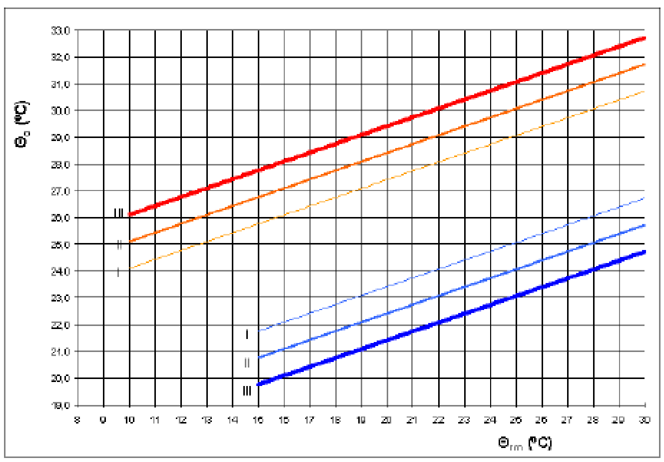


Figure 16: Acceptable operative temperature ranges for naturally conditioned spaces, $\boldsymbol{\theta rm} = \boldsymbol{outdoor\ running\ mean\ temperature\ and\ \theta o} = \boldsymbol{operative\ temperature\ (indoor)}$ [30]

Table 8: Adaptive comfort temperature limits [30]

Category	$\boldsymbol{\theta o}$ (°$\boldsymbol{C}$)
I	$\theta o - 2 \leq \theta i \leq \theta o + 2$
II	$\theta o - 3 \leq \theta i \leq \theta o + 3$
III	$\theta o - 4 \leq \theta i \leq \theta o + 4$
IV	$\theta i < \theta o - 4\ and\ \theta i > \theta o + 4$

The adaptive approach to comfort includes conditions compatible with low-carbon buildings [59]. Studies have shown that adaptive opportunities should be made an important part of future refurbishment strategies for existing office buildings, and that adaptive comfort models predict thermal sensation and thermal comfort better [60][61]. Adaptive comfort limits are given in Table 8.

- Running mean outdoor air temperatures

To calculate the adaptive comfort ranges during summer, the indoor air operative temperatures are predicted based on a function of the exponentially weighted running mean of the outdoor temperature [55]. The exponentially weighted outside running mean temperature accounts for time-dependency over which the occupants adapt to their environment and is calculated based on equations (1) and (2) below:

$$t_{rm} = (1 - \alpha)t_{ed-1} + \alpha t_{rm-1} \quad (1)$$

$$t_{rm} = \frac{t_{ed-1}+0.8t_{ed-2}+0.6t_{ed-3}+0.5t_{ed-4}+0.4t_{ed-5}+0.3t_{ed-6}+0.2t_{ed-7}}{3.8} \quad (2)$$

where

- t_{rm} the running mean indoor air operative temperature for today
- t_{rm-1} the running mean indoor air operative temperature for the previous day
- t_{ed-1} the daily mean external temperature for the previous day
- t_{ed-2} the daily mean external temperature for the day before (and so on)
- α a constant between 0 and 1 (recommended as 0.8 for use if the running means are calculated weekly)

The indoor air operative temperature (t_{rm}) obtained for the rooms using the outdoor air temperature (t_{ed}) was used to determine the comfort ranges and cross-evaluate them based on categories defined in EN 16798-1 [56]. These are shown in Table 9.

Table 9: Indoor operative temperature limits – EN16798-1[56]

Category	Lower limits	Upper limits
I	$t_{i\ min} = 0.33t_{rm} + 18.8 - 2$	$t_{i\ max} = 0.33t_{rm} + 18.8 + 2$
II	$t_{i\ min} = 0.33t_{rm} + 18.8 - 3$	$t_{i\ max} = 0.33t_{rm} + 18.8 + 3$
III	$t_{i\ min} = 0.33t_{rm} + 18.8 - 4$	$t_{i\ max} = 0.33t_{rm} + 18.8 + 4$

Note: These limits apply when $10 < t_{rm} < 30°C$ for the upper limit and $15 < t_{rm} < 30°C$ for the lower limit.

- Overheating risk

Overheating is a growing risk in Europe's residential building stock. Overheating is described as situations where the indoor temperature of a home becomes uncomfortably or excessively warm. This happens most often during warm weather in the summer season, but it can also happen in winter months due to airtightness and internal gains. Both sudden spikes in temperature and prolonged periods of excess heat can be difficult for people to cope with, especially if they have an underlying health condition. Only a few Member States have requirements regarding the overheating risk in existing buildings and new buildings. The UK standard assessment procedure, for example, includes an additional appendix for its calculation. This evaluates the risk of overheating for the months of June, July and August. Average mean temperature above 23.5°C is predicted to bring a high risk of overheating. Several factors are considered in the calculation such as solar gains, natural ventilation, air change rate, thermal mass, weather data and internal gains. Chartered Institution of Building Services Engineers (CIBSE) standards specify the criteria for overheating [62]. The EN 16798-2:2019 (Annex-E) [63] also specifies a method for evaluation of annual temperatures in terms of percentage outside the comfort ranges. These criteria can be used for assessment of overheating in summer and winter; however, this requires measurements.

3.2.2 Indoor air quality

A common standard index for indoor air quality does not exist. Indoor air quality is therefore expressed as the required level of ventilation or CO_2 concentrations. It is accepted that the indoor air quality is influenced by emissions from people and their activities (bio-effluents, cooking), from the building and furnishings and from the HVAC system [63]. A recent study among European countries showed that regulations for indoor air quality in domestic buildings were not comprehensive and need additional attention as they were recognised to be the most crucial aspect in building codes by the focus countries: Belgium (Brussels Region), Denmark, France, Germany, Italy, Poland, Sweden and the UK (England and Wales) [64]. A review of studies on indoor air quality highlighted [65] inadequate ventilation causes health-related symptoms due to high concentrations of CO_2, exposure to VOCs, moulds and microbial VOCs and allergens. Many studies have investigated the influence of indoor CO_2 on occupants' health and perceived air quality [66]–[68]. A study on the association of CO_2 with occupants' health in commercial and institutional buildings, covering 30,000 occupants in about 400 buildings, indicated the prevalence of SBS symptoms [69].

- CO_2 concentration

The CO_2 concentration is considered an effective indicator of the rate of ventilation per occupant [69]. Since there are no other low-cost methods available for measuring the concentration of indoor pollutants, it is used as a reliable proxy for measuring indoor air quality [70][55]. European standard EN 6798-2:2019 [63] defines the limits of concentration expected in different IEQ categories based on non-adapted occupancy requirements above outdoor concentration (default: 400ppm) assuming a standard CO_2 emission of 20 L/h/person.

- Ventilation rate or air change rate

The outdoor ventilation rates vary in different zones of buildings and depend on the fresh air requirements for that zone and requirements of different health criteria. Ventilation rate impacts the indoor air quality in terms of concentration of indoor airborne pollutants and CO_2 [71]. It also affects the thermal comfort and indoor humidity levels. The steady state decay method using the concentration of CO_2 can be used to determine the air change rate in a zone.

The air change rate (A_S) can be calculated based on the average CO_2 generation rates [72][73] as:

$$A_S = \frac{6\ X10^4 n\ C_p}{\{V(C_S - C_R)\}}$$

where A_S is the air change rate [h^{-1}], n is the number of people in the space, C_p is the average CO_2 generation rate per person (generally 0.46 [$l.min^{-1}.person^{-1}$]); V is the volume of the room [m^3]; C_s is the steady state indoor CO_2 concentration [ppm]; C_R is the CO_2 concentration in supply air (outdoor air) [ppm].

Ventilation rate requirements are defined for residential and non-residential buildings in EN 6798-2:2019 [63] for different categories under three different methods: (i) perceived air quality, (ii) using limit values of gas concentration (CO_2), and (iii) based on pre-defined ventilation flow rates. Ventilation rates can be achieved by different ventilation systems: mechanical, natural or hybrid (which combine mechanical and natural principles)

- Mechanical ventilation

Mechanical residential ventilation systems mostly consist of self-contained equipment with elementary air ducts if needed. Mechanical ventilation ensures the provision of regulated ventilation control for different zones of the building. These are identified in four categories: (i) exhaust ventilation systems, (ii) supply ventilation systems, (iii) balanced ventilation systems, and (iv) un-ducted units for single rooms.

- Natural ventilation

Residential natural ventilation systems use stack effect and wind pressure to drive the ventilation airflow through the building. Typical inlet components are facade grilles, window grilles, roof window ventilation flaps and air inlets. Typical extract components include extract stack ducts. The system is typically designed to allow air entry in living rooms and bedrooms, and to extract air from kitchens, toilets and bathrooms. The operation of the ventilation system can be based on always-open ventilation openings, which provide acceptable indoor air quality on weekly, monthly and annual levels. The operation can also be automated, based on sensors of e.g. humidity or CO_2. Manual control of ventilation is not considered a natural ventilation system as it must be observed and regulated manually. EN 6798-2:2019 [63] lists the natural ventilation requirements based on (i) air changes per hour (ACH), (ii) supply air flow per person, and (iii) perceived indoor air quality for adapted persons.

3.2.3 Visual comfort

Standard EN 12464-1 [74] describes minimum standards of illuminance for workplaces that are required to be maintained to fulfil visual comfort and performance needs [74]. EN 6798-2:2019 [63] also lists the criteria for lighting required in different buildings and spaces. A literature survey by Fabi et al. [75] covered several psychological (attitudes), social (occupancy), physical (direct sunlight) and contextual (orientation) driving forces responsible for visual comfort in buildings. Occupants find it challenging to maintain good visual comfort as individuals have varied perception of glare and lighting levels in workplaces [76]. Loss of privacy is also a factor that could be considered for visual comfort.

There are three aspects that are generally studied to evaluate visual comfort, and these include the lighting levels, presence of glare and quality of outdoor view. Some of the commonly used metrics to assess visual comfort are described below.

- Assessing lighting levels
  - Illuminance

Illuminance at a surface I_D is defined as a physical quantity measured in lux that is calculated as a ratio between the luminous flux falling on the surface with an area (A_{ill}).

$$I_D = \frac{d\varphi}{dA_{ill}} [lux]$$

where I_D is illuminance [lux]; φ is luminous flux.

Therefore, illuminance is used as a single criterion to assess the availability of the amount of light falling at a single plane that is easy to measure using a lux meter. As per the standard EN-12464-1 [74], the minimum amount of illuminance required in a standard office work plane is 500 lux. This metric has certain limitations as (i) it does not indicate any information about the quality of light, (ii) it does not refer to the type of light such as artificial or daylight, and (iii) it does not account for glare as it does not measure the observer's perspectives.

- Daylight factor

The daylight factor (DF) for daylight access is applicable under the International Commission on Illumination (CIE) overcast sky. It is useful for early design decisions and is a useful technique for assessing daylight potential of interior spaces. Daylight factor does not consider direct sunlight and its effects.

$$DF = \frac{E_I}{E_O} \times 100\%$$

where:

- DF the daylight factor measured at a specific point (%)
- E_i available lux indoors at a specific point on a working plane (lux)
- E_o simultaneous available lux outdoors under a CIE overcast sky (lux)

The daylight reaching any point inside a room is usually made up of three components: (i) sky component, (ii) externally reflected component, and (iii) internally reflected component.

If there is no external obstruction like trees, buildings etc. the externally reflected component is omitted. Several techniques, manual as well as computerised, may be used to calculate these components for a building. In side-lit rooms, the maximum DF is near the windows, and is due to the sky component. In the initial stages of building design, the average DF may be used to assess the adequacy of daylight:

$$\text{Average DF} = \frac{W}{A}\frac{T\theta}{(1-R^2)}$$

where:

- W area of the windows (m^2)
- A total area of the internal surfaces (m^2)
- T glass transmittance corrected for dirt
- Θ visible sky angle in degrees from the centre of the window (deg)
- R average reflectance of area A

The values of these quantities are determined from the given data and W, T and R are corrected by using factors given in the EN 17037 Daylight Code [77][78].

- Spatial daylight autonomy

Spatial daylight autonomy (sDA) is defined by the amount of daylight that a particular space receives during the standard operational hours (8:00 to 18:00) on an annual basis [79]. The hourly illuminance grids are used on the horizontal work plane to map the daylight received. sDA is calculated through computational simulation with parameters such as location and weather conditions throughout the year. The percentage of light that a specific point receives above a required threshold illumination within the annual daytime hours is termed as sDA [79].

$$sDA = \frac{\sum_i (w_f . t_i)}{\sum_i t_i} \in [0, 1] \text{ with } wf_i \begin{cases} 1 \text{ } if \text{ } E_{daylight} \geq E_{limit} \\ 0 \text{ } if \text{ } E_{daylight} < E_{limit} \end{cases}$$

where t_i is each occupied hour in a year; w_{fi} is a weighting factor depending on values of $E_{Daylight}$ and E_{limit} that are the horizontal illuminance at a given point due to the sole daylight and the illuminance limit value, respectively.

sDA uses the geographic location and annual weather data containing the global, diffuse and direct irradiance measurements. Therefore, it is advantageous over the daylight factor, D_F. Another benefit of this metric is the ability to calculate artificial light savings, which is possible by measuring the daylight received during each hour and providing sufficient artificial light if the total is below a minimum threshold.

- Measuring the impact of glare
  - Daylight Glare Index

To measure the impact of glare on visual comfort, metrics like the Daylight Glare Index (DGI) are used. This considers large glare sources such as windows and specifically diffuse sky visibility through the window. The DGI metric was studied using human subjects in day-lit interiors, where the sky brightness was measured and given a position index and size [79]. This is not considered to be accurate when there is direct light or reflections present in the field of view. DGI is a correlation between the source of luminance, size and its position in the field of view against a background of sky luminance, with a small percentage of the source luminance compensating for additional eye adjustment to the visible luminance. The DGI value generally varies from 18 to 31, where 18 corresponds to barely perceptible glare and 31 or greater corresponds to intolerable glare.

- Annual sunlight exposure

The annual sunlight exposure (ASE) metric is intended to help designers limit excessive sunlight in a space. While ASE is a crude proxy for glare phenomena, it measures the presence of sunlight using annual hourly horizontal illuminance grids rather than luminance measures, so it is technically not a glare metric. It evaluates the potential source of visual discomfort from direct sunlight. LM-83 [77] provides preliminary guidance for recommended ASE limits, cautioning that spaces with ASE values exceeding 10% will likely result in visual discomfort. ASE is defined as the percentage of an analysis area that exceeds a specified direct sunlight illuminance level, e.g. 1000 lux, for more than a specified number of hours, e.g. 250 hours per year. ASE values range from zero to 100%, with the latter suggesting that the entire floor area of the space in question exceeds the simulated value of 1000 lux for at least 250 hours per year. To reduce the potential for glare and thermal stress, designers should aim for low ASE values (preferred threshold: $ASE_{1000,250h} < 3\%$ of analysis area, and nominally acceptable threshold: $ASE_{1000,250h} < 7\%$ of analysis area).

- Outdoor views

It is desirable to provide comfortable outdoor views for building occupants to connect them to the natural environment. Views connect the indoors with outdoors and are highly desirable for residential, office, healthcare and commercial buildings. The factors on which outdoor views depend are the optical characteristics, colour of glazing, size and shape of openings, surrounding lighting levels and composition of the outdoor scene. For this purpose, the method defined in LEED manual BD+C [50] can be used to determine the quality of views:

A direct line of sight to the outdoors via vision glazing for 75% of all regularly occupied floor area must be achieved. View glazing in the contributing area must provide a clear image of the exterior, not obstructed by frits, fibres, patterned glazing, or added tints that distort colour balance.

Additionally, 75% of all regularly occupied floor area must have at least two of the following four kinds of views:

- multiple lines of sight to vision glazing in different directions at least 90 degrees apart
- views that include at least two of the following: (1) flora, fauna, or sky; (2) movement; and (3) objects at least 25 feet (7.5 metres) from the exterior of the glazing
- unobstructed views located within the distance of three times the head height of the vision glazing; and
- views with a view factor of 3 or greater, as defined in "Windows and Offices; A Study of Office Worker Performance and the Indoor Environment"

Calculation should include any permanent interior obstructions. Movable furniture and partitions may be excluded. Views into an interior atrium may be used to meet up to 30% of the required area.

3.2.4 Acoustic comfort

The indoor system noise criteria (sources such as ventilation system, dishwasher etc.) of some spaces and buildings are given in terms of A-weighted sound pressure levels (dB(A)) normalised with reverberation time in EN16798-1 [56]. These criteria are used to assess the relative loudness as perceived by the human ear using a measuring instrument. These criteria apply to sources from both outside and inside the building so that relative loudness is measured and used to limit the sound pressure levels inside the space. This method is very much suitable for assessment in EPCs.

Noise levels can exceed these levels in case of occupants opening windows or the operation of HVAC units. Retrofits can enable the reduction of indoor noise, while addressing solutions for thermal comfort and energy efficiency [80]. Noise criteria do not causally relate to energy performance, but the relationship depends on the opening of fenestrations. For example, to minimise outdoor noise occupants may close windows in summer; this would limit natural ventilation and cooling energy may be required to maintain indoor thermal comfort. The WELL standard comprehensively lists several criteria such as sound barriers, masking, absorption and mapping to assess the acoustics of a space in dwellings, offices and commercial buildings utilising on-site assessments and document verification processes [52]. Similarly, LEED also outlines a comprehensive set of criteria that may be applicable to assessment for EPCs [50].

Table 10 shows a list of indicators that could potentially be explored and used for assessment of acoustic comfort. All the associated standards are also listed in the table.

Table 10: Description of some acoustic indicators used [81]

Indicator	Description	Standards
STC	Airborne sound transmission class, calculated as R_w	ASTM E413
$L_{Aeq,nT}$	Equivalent continuous sound pressure level (background noise levels)	EN 16798-1:2019
$L_{n,w}$	Weighted standardised impact sound pressure level	ISO EN 12354-2
R_w	Apparent airborne sound reduction index	ISO EN 12354-1
R_t	Reverberation time	ISO 3382-2:2008

3.3 Application of assessment methods for the indicator

3.3.1 Voluntary or mandatory methods for EPCs

Table 11 gives an indicative list of indicators under each category. To assess each category minimum and alternative/additional indicators have been identified and listed. However, no assessment has yet been made on which category is voluntary or mandatory for EPCs. This will be further studied in X-tendo based on individual country and building stock requirements.

Table 11: List of required indicators

Category	Minimum required indicators	Alternative/additional indicators
Thermal comfort	PMV/PPD (conditioned spaces), overheating risk (summer, winter)	Adaptive comfort (unconditioned spaces), radiant thermal comfort, drafts
Visual comfort	Illuminance level, size of fenestrations	Spatial daylight autonomy, daylight factor, glare control, luminance quality, annual sunlight exposure,
Acoustic comfort	Indoor ambient noise level	Sound insulation, reverberation time, exterior noise intrusion, average equivalent sound absorption area
Indoor air quality	Ventilation rate, CO_2 concentration, operable windows	VOC level, internal moisture level, olfactory comfort

3.3.2 Applicability of methods to different building typologies

Table 12 lists several indicators (methods) showing their applicability to different building typologies along with existing and new buildings. Out of all the indicators only radiant asymmetry and drafts are generally not applicable to new buildings, though may apply if they are poorly designed. They are often a problem in old buildings with cold surfaces due to insufficient insulation causing uneven heating of air in the room. The building envelope is generally leaky and may have developed gaps or cracks causing drafts.

Table 12: Overview of applicability of each indicator to different buildings

Category	Indicators (methods)	Existing buildings	New buildings	Residential buildings	Non-residential buildings (office, hospitals, hotels, schools etc.)
Thermal comfort	PMV/PPD (conditioned spaces)	✔	✔		✔

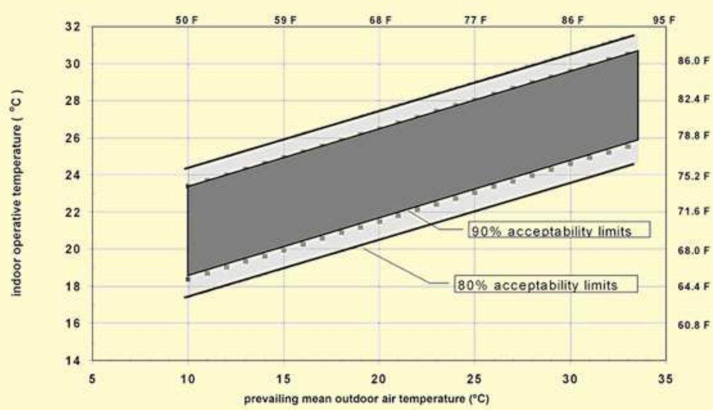
	Overheating risk	✓	✓	✓	✓
	Adaptive comfort (unconditioned spaces)	✓	✓	✓	✓
	Radiant asymmetry	✓		✓	✓
	Drafts	✓		✓	✓
Visual comfort	Illuminance level	✓	✓	✓	✓
	Daylight factor	✓	✓	✓	✓
	Size of fenestrations	✓	✓	✓	✓
	Spatial daylight autonomy	✓	✓	✓	✓
	Annual sunlight exposure	✓	✓	✓	✓
	Outdoor view	✓	✓	✓	✓
Acoustic comfort	Indoor ambient noise level	✓		✓	✓
	Reverberation time	✓	✓		✓
	Exterior noise intrusion	✓		✓	✓
	Average equivalent sound absorption area	✓	✓	✓	✓
Indoor air quality	Ventilation rate	✓	✓	✓	✓
	CO_2 concentration	✓	✓	✓	✓
	Operable windows	✓	✓	✓	✓
	Olfactory comfort	✓	✓	✓	✓

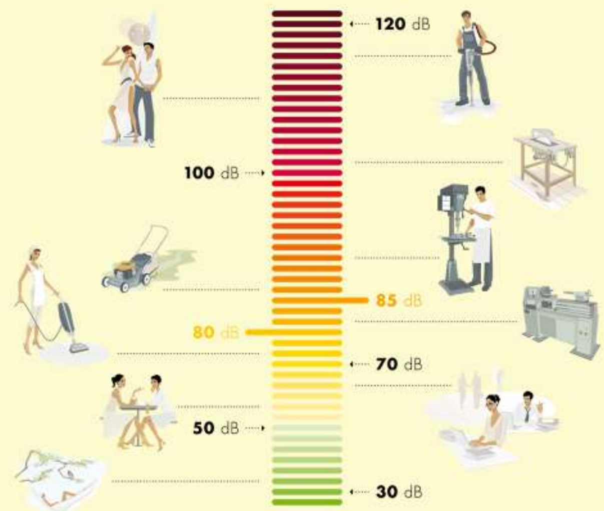
The application of several indicators to different building typologies does not vary much for residential and non-residential buildings. In the case of thermal comfort, PMV/PPD have not been tested or robustly developed for residential buildings and are more suitable for non-residential buildings with varying activities. Methods such as equivalent sound absorption area might not be suitable for residential buildings as the volume of spaces is generally not large. Indicators such as radon concentration are more relevant for residential buildings as radon tends to accumulate in high concentration areas such the lower ground floor, basement and ground floor that are not well ventilated and often occupied in residential buildings.

3.3.3 Presentation of the indicator

Table 13**Error! Not a valid bookmark self-reference.** illustrates a few examples used for presentation of ranking or score. Many methods have no scale but are represented only by their threshold criteria as defined in standards. It is possible to define innovative scales for the purpose of EPCs depending on the method to be used in the assessment of comfort.

Table 13: Examples of ranking/scale/score/threshold used for indicators

Category	Indicators	Ranking/Scale/Score
Thermal comfort	PMV/PPD (conditioned spaces)	 ASHRAE scale (-3[cold], -2[cool], -1[slightly cool], 0 [neutral], +1[slightly warm], +2[warm], +3[hot])
	Adaptive comfort (unconditioned spaces)	Acceptability limits used (70-90%) based on number of occupants. Light grey area represents 70% acceptability and dark grey represents 80-90% acceptability 
Visual comfort	Illuminance level	Minimum requirements according to occupancy (e.g. office=500 lux, corridor 100 lux etc.)
	Daylight factor	50% of usable area throughout the building should have DF (> 3% very good, > 2% medium, > 1% slight, < 1% none)
	Size of fenestrations	Values for WWR (window-wall ratio) should be between 20-60%.
	Spatial daylight autonomy	Refers to the % of floor area that receives 300 lux of daylight for min. 50% of annual occupied hours (LEED requirement 55-75%)
	Annual sunlight exposure	Refers to the % of floor area that receives 1000 lux of direct sunlight for min. 250 occupied hours per year (LEED requirement max. 10%)

<table>
<tr>
<td>Acoustic comfort</td>
<td>Indoor ambient noise level</td>
<td>Should not exceed 40 dB indoors


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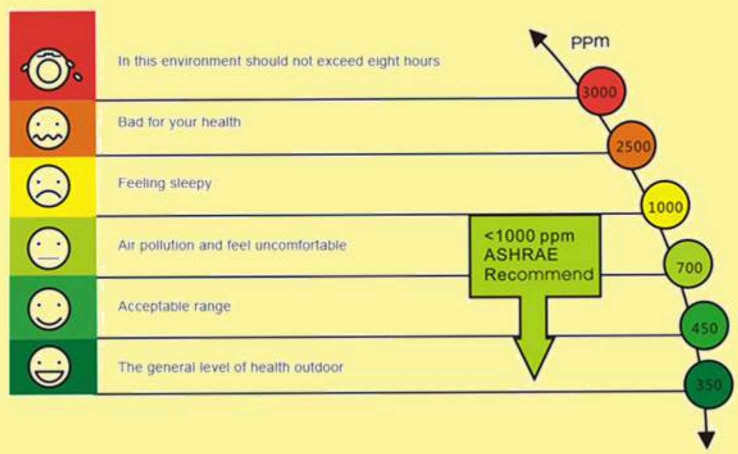
<tr>
<td>Indoor air quality</td>
<td>CO_2 concentration</td>
<td>Specified values based on occupancy in standards


Source: https://iotfactory.eu/
</td>
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3.4 Linking indicators to energy performance and EPCs

- Thermal comfort

Thermal comfort has a direct correlation with indoor air temperature. To maintain indoor air temperature heating/cooling is required, which consumes energy. The changes in the energy performance of buildings can be observed during different seasons across different climate zones where the requirements for heating or cooling vary. In Northern Europe, the indoors requires heating in winter months and energy consumption is highest in these months to ensure thermal comfort. Provision of energy efficient strategies can also maintain thermal comfort effectively, such as natural ventilation, solar-shading and passive solar gain. Approximately 64% of the energy used in households is used in meeting the required heating demand [82].

- Visual comfort/daylight

Adequate lighting is necessary for comfortable viewing and strongly depends on the activity and areas where lighting is required. To maintain a required level of illuminance throughout the day, artificial lighting is used, which consumes energy on a daily basis. Achieving visual comfort by means of artificial lighting affects the energy requirement of a building and thus impacts its energy performance strongly. Approximately 14% of energy used in households is used in lighting [82].

- Acoustic comfort

Acoustic comfort has an indirect relation with energy performance. The acoustic performance of a space is influenced by the level of insulation. Often thermal insulation improves the acoustic performance of a space as well as the energy performance. Similarly, windows affect thermal as well as acoustic insulation. Often, houses with poorly insulated or leaky windows provide low acoustic comfort from outdoor noise. The presence of ventilation openings also negatively affects acoustic comfort.

- Indoor air quality

A supply of fresh outdoor air improves indoor air quality. The outdoor air can be provided either by natural ventilation or mechanical ventilation. Mechanical ventilation maintains a required level of indoor air quality and, therefore, impacts the energy performance of a building. Next to the auxiliary energy needs, ventilation also requires conditioning of supplied air, for which energy is used.

IEQ indicators are strongly linked with building energy consumption. There are aspects of IEQ in several EPC schemes, e.g. overheating, ventilation, lighting, heat comfort, etc. However, only a few countries have specific indicators for this, or one aggregated indicator. Countries such as Greece, Ireland and Italy collect very rudimentary information on comfort aspects, such as good air quality, thermal comfort satisfaction or overheating risk, based on observation or off-site calculations made by the auditor. Although the extension of EPC aspects such as comfort has been highlighted by many Member States, there has been no progress in the EPC schemes in this regard.

3.5 Legal boundaries or requirements of assessment methods

During the assessment of comfort indicators, the auditor or assessor would collect data on aspects such as temperature, humidity, CO_2 levels, usage of spaces, temperature regulation etc. Additionally, specific photographs or notes would be taken during the assessment. Collection of data on several indicators would require consent from the owners as the analysis of data would reveal occupant behaviour, making it vulnerable to misuse. Data could be exploited commercially if not regulated. Therefore, for data privacy and security purposes compliance with GDPR must be followed along with regulations under current EPC systems. There are no legal boundaries already defined for any of the listed methods, so each method would be checked for its legal boundaries separately in terms of data being collected.

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

Table 14 evaluates the assessment methods for the four indicators discussed earlier for their application to EPCs based on their feasibility of use. Although there are no prior references to identify the suitability of methods for EPCs, their feasibility is assessed through expert judgement considering the complexity of their use in terms of evaluation procedure (e.g. measurements, on-site/off-site assessment), time, cost and overall effort.

Table 14: Feasibility of assessment methods for EPCs

Method	Ranking	Comment on feasibility/ explanation
Thermal comfort		
PMV/PPD	***	Requires extensive monitoring and occupant data collection (clothing, metabolic activity etc.)
Adaptive comfort	***	Only indoor temperature monitoring required (applicable only in non-conditioned period e.g. summer)
Thermal satisfaction survey	****	Can be conducted easily on-site with the occupants in high-occupancy buildings
Overheating risk	****	Requires annual evaluation of indoor temperature levels
Radiant asymmetry	**	Suitable for existing buildings and can be determined with on the spot measurement
Drafts	**	Suitable for existing buildings but requires expensive instruments for measurement
Visual comfort		
Illuminance	*****	On the spot measurement and easy to determine but does not differentiate between artificial and daylight
Daylight factor	****	Only applicable for assessing daylight levels indoors but ignores effect of direct sunlight
sDA (spatial daylight autonomy)	*	Requires annual simulations for calculation but calculates

		only daylight during operational hours
Annual sunlight exposure	*	Used to measure direct sunlight and as a proxy for glare. Determines visual discomfort due to glare
Outside views	*****	Easy to determine and calculate
Size of windows	*****	Relatively easy for on-site assessment and usually available as an input for EPC assessment
Acoustic comfort		
Indoor ambient noise level	****	Easy to measure and determine
Reverberation time	**	Suitable and relevant for larger spaces only
Exterior noise intrusion	****	Easy to measure and determine
Average equivalent sound absorption area	****	Can be calculated using information about the building
Indoor air quality		
Ventilation rate	****	Requires expensive instruments for measurement but can be calculated using CO2 in non-conditioned zones. Easily determined where mechanical systems are present
CO_2 concentration	****	Easy to measure on-site and small-time interval for reading
Operable windows	*****	Easy to note and use the information
VOC concentration	*	Expensive measurement device
Olfactory comfort	*****	Suitable for commercial/ office buildings and easy to determine based on subjective outputs
Likert scale used for suitability: not at all (*), slightly (**), moderately (***), very (****), extremely (*****)		

3.7 SWOT analysis of the comfort assessment methods

Overall, there are many assessment methods available to assess the IEQ indicators. Each method has its pros and cons but a general evaluation of the methods in the context of EPCs is given in Table 15 for each indicator.

Table 15: SWOT analysis of the IEQ assessment methods for EPCs

Strengths	Weaknesses
Thermal comfort	
EN/ISO standard methods available for assessment of summer/winter comfort	Long-term and short-term monitoring necessary for assessment (seasonal/annual)
Variety of measuring instruments are available	Few experts with knowledge of all the indicators
Online training material and tutorials available	No established rating or scale to be used directly in EPCs
Indoor air quality	
EN/ISO standard methods available for assessment	Measurements necessary for evaluation
Proxy measurement possible through CO_2	Variation in assessment for different buildings
Visual scale available to use	Expensive instruments to measure air quality
Visual comfort	
EN/ISO standard methods available to assess lighting levels and glare	Simulations necessary for most methods for evaluation
Guidelines available for different building typologies	Difficult to assess during overcast conditions on-site
Acoustic comfort	
EN/ISO standard methods available to assess acoustic performance	Measurements necessary for evaluation
Guidelines available for different building typologies	Mostly suitable for office and commercial buildings
Opportunities	**Threats**
Thermal comfort	
Most important driver for renovation for residential and tertiary sector	Potential on negative impact on energy performance score
High awareness of thermal comfort among end-users	Variable benchmarks for thermal comfort in different climates of Europe
Very relevant for productivity gains	Objections against using too expensive measurement methods
Indoor air quality	

Ventilation guidelines already included in building regulations of many Member States	Health impacts are not well understood by end-users
Very relevant for productivity gains	Too many metrics to select for assessing indoor air quality
Visual comfort	
Relatively low investments needed to meet the standard guidelines	Confusion in selection of best method for measurement
Well-established guidelines that can be adopted in EPCs	Low priority given compared to thermal comfort and indoor air quality
Acoustic comfort	
Well-established guidelines that can be adopted in EPCs	Expensive instruments for measurements
Can be combined with thermal comfort measures	Not considered as an important driver in renovation

3.8 Proposed approach to develop the feature

The literature review of the existing rating and certification systems and IEQ indicators provided details regarding the relevant indicators, criteria and parameters used to assess comfort in buildings. Most of the existing systems focus on granting rankings based on extensive criteria (e.g. technical, verification, measurements and assessments), generally with longer monitoring time requirements for evaluation (e.g. monthly/annual). The assessment of comfort for EPCs should be done in a relatively shorter time and with less effort to reduce the cost of assessment and increase the affordability for the end-user (cost is a big barrier for many households).

For the further development of the comfort indicator in the X-tendo project these constraints will be addressed and considered in the approach that will be tested in buildings. The assessment methods would consist of checklists (observations/measurements), surveys and on-site monitoring depending on the requirements of the individual parameter (see Figure 17). The approach will be developed to keep the assessments adaptable, affordable and time effective.

Four main indicators will be assessed within the comfort feature: (i) thermal comfort, (ii) indoor air quality, (iii) visual comfort, and (iv) acoustic comfort. To identify the overall IEQ level, all four indicators will be assessed independently based on multiple criteria. Under each criterion, certain parameters must be met to achieve a required score. The score will be awarded using the relevant assessment method (e.g. checklist, survey, monitoring etc.). A description of indicators, criteria and parameters is given below with an indication of the weightages assigned to them. An individual rating/scoring process is proposed for the comfort feature as shown in Figure 17. A combined rating with a single value will give an overall idea of the indoor environment but will not specify the problem areas and there is a greater chance of making errors in applying corrective measures. Therefore, an individual rating for all four indicators is proposed to provide more details for interventions.

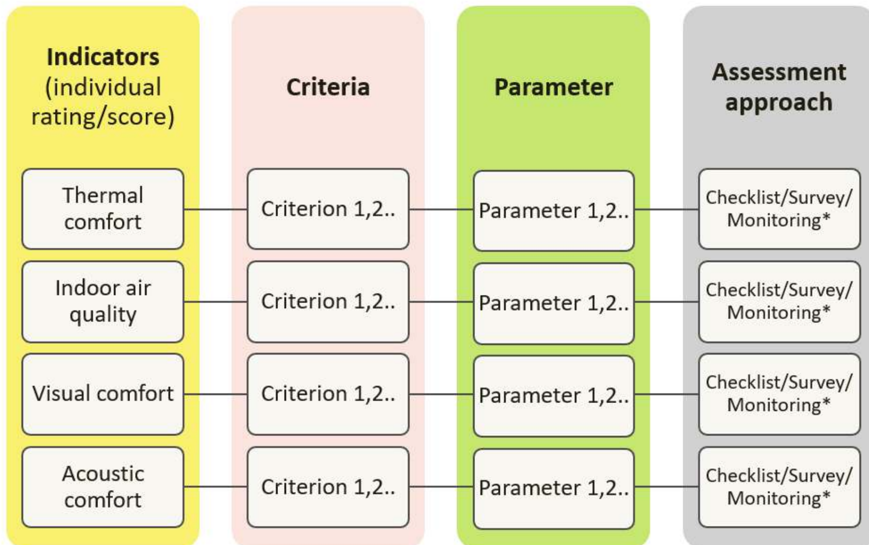

Figure 17: Individual rating process

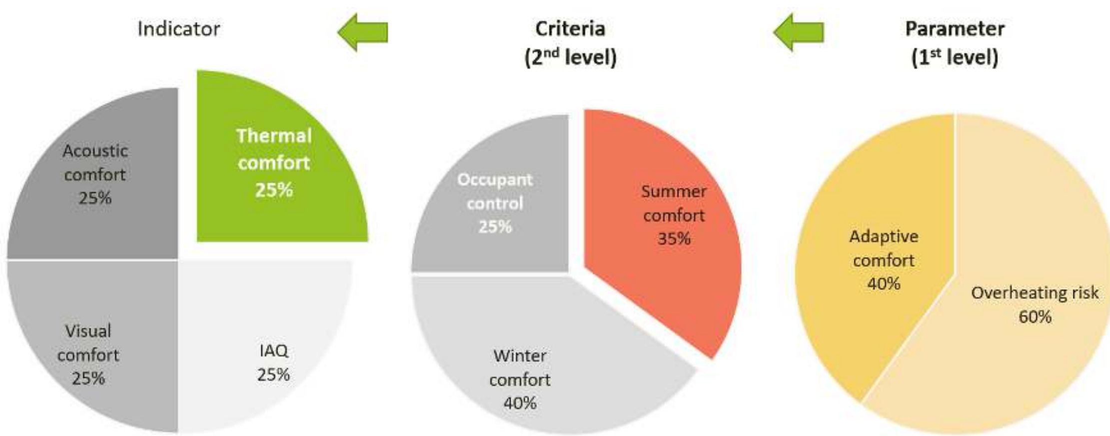

Figure 18: An example of two levels of weightage for the thermal comfort indicator

A description of the terms used in the comfort feature assessment is given below (refer to Figure 17 and Figure 18):

1. Indicators: This refers to the four main components of the comfort feature. These components will be assigned equal or different relative weightage (e.g. in Figure 18, thermal comfort = 25%, visual comfort = 25%, indoor air quality = 25%, acoustic comfort = 25%) depending on the different aspects, e.g. region, type of buildings etc. Each indicator will be assessed based on several criteria.
2. Criteria: The criteria are the aspects that are required to be assessed under each indicator. The list of criteria is prepared based on existing literature. Criteria will be assigned different or similar relative weightage (e.g. in Figure 18, for indicator

thermal comfort: summer comfort = 35%, winter comfort = 40%, occupant control = 25%) based on expert inputs. A criterion of occupant control is also included for all indicators, as this has been found to be an essential aspect in maintaining a satisfactory level of indoor comfort. Since each indicator interacts in certain ways with the other, which are often complicated to determine in the assessment. However, the occupant control criterion does consider how occupants may react to the combined effect of two or more main indicators (e.g. closing the window partially to block noise but continue to ventilate for fresh air). Occupant behaviour is generally challenging to measure and predict. Each criterion will be evaluated based on certain parameters via different assessment methods (checklist/survey/on-site monitoring).

3. **Parameters:** A list of parameters will be prepared to assess each criterion based on the impact on comfort and health and well-being of the occupants. A relative weightage will be assigned to each parameter based on expert inputs (e.g. in Figure 18, for the criterion *summer comfort*: overheating risk = 60%, adaptive comfort = 40%). Each parameter can obtain a score of 0 (worst) to 10 (best) which is assessed using a checklist, survey, on-site monitoring etc. Individual scales for each parameter will be developed in further work.

An example of an exhaustive list of criteria and parameters (description tree) is given in Figure 19.

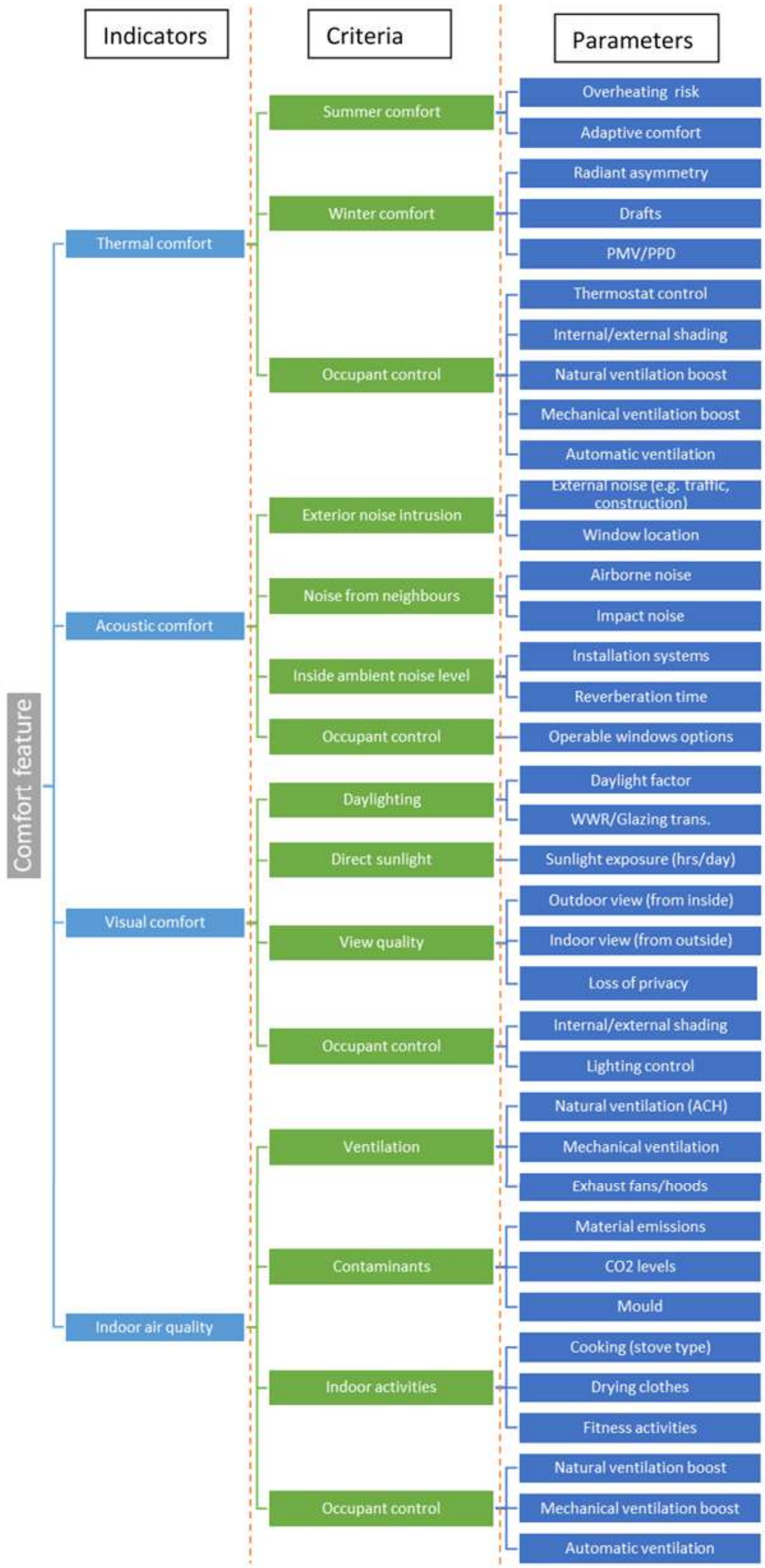

Figure 19: A description tree of indicators, criteria and parameters

The proposed scale to be used for the comfort feature in EPCs is given in Table 16.

Table 16: Scoring to the corresponding labels

Label for comfort feature	Score (maximum achievable fraction)
Very bad	0% < score ≤ 30%
Bad	30% < score ≤ 40%
Acceptable	40% < score ≤ 60%
Good	60% < score ≤ 80%
Excellent	80% < score ≤ 100%

The scores will be calculated individually for the four indicators (see Table 17) based on Table 16.

Table 17: Individual ratings for indicators

Indicator	0%----------------------100%	Label
Thermal comfort	90%	Excellent
Indoor air quality	80%	Good
Acoustic comfort	65%	Good
Visual comfort	50%	Acceptable

4 FEATURE 3: OUTDOOR AIR POLLUTION

4.1 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.

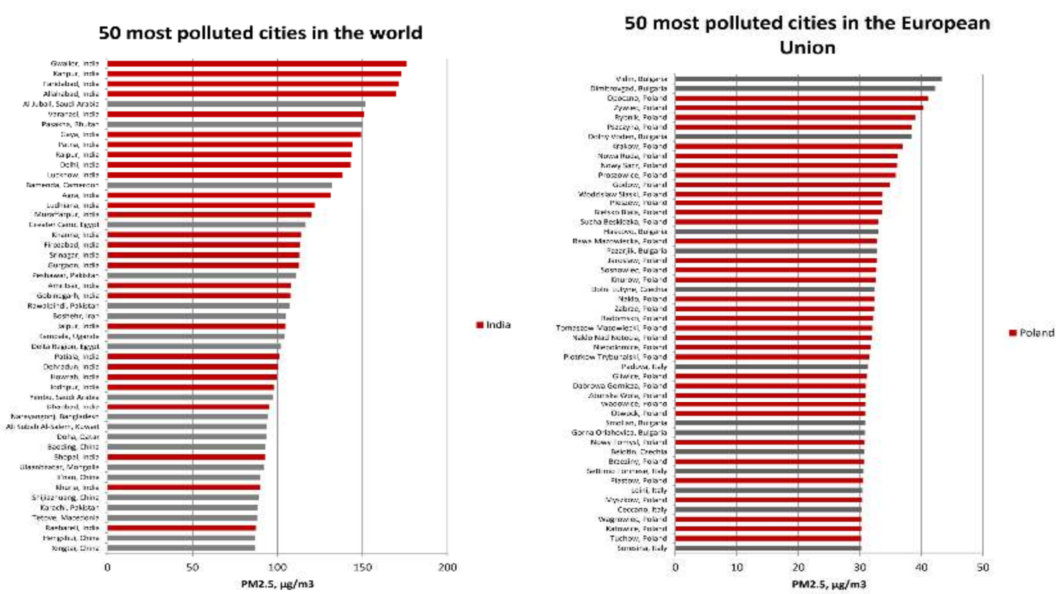

Figure 20: The 50 most polluted cities in the world and in the European Union [85]

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.

4.2 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.

4.2.1 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)[6].

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.

4.2.2 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

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

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).

4.3 Description of assessment methods

4.3.1 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 18 .

Table 18: Emission rates of coal [93]

Pollutant	Unit	Fixed grade				Mechanical grade
		Nominal heat output of the boiler [MW]				
		≤ 0.5	> 0.5 - 5 ≤	≤ 0.5	> 0.5 - 5 ≤	> 0.5 - 5 ≤
		Natural draught burner		Forced draught burner		
Sulphur oxides	g/Mg	16,000 x s				
Nitrogen oxides		2,200	1,000	2,000	3,000	3,200
Carbon monoxide		45,000		70,000	20,000	10,000
Carbon dioxide		1,850,000	2,000,000	1,850,000	2,000,000	2,130,000
Total suspended particulates		1 000 x A^r	1 500 x A^r			2 000 x A^r
Benzo(a)pyrene		14				3.2

s - total sulphur content expressed as a percentage [%]

A^r - ash content expressed as a percentage [%]

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 21 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.

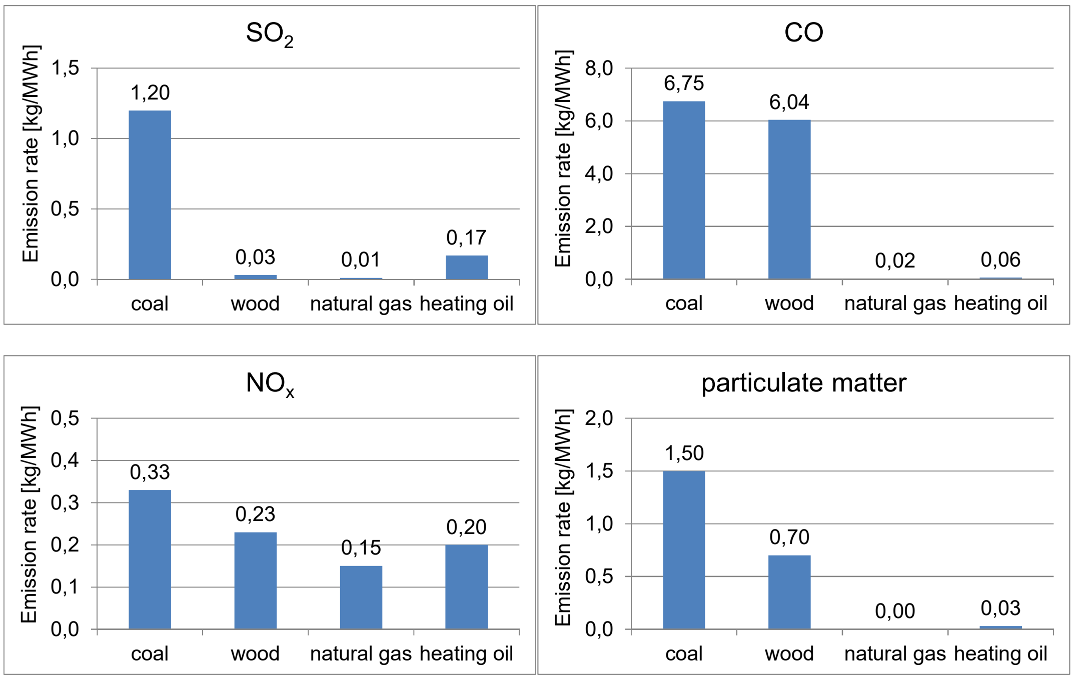

Figure 21: Emissions of pollutants generated during combustion of different types of fuel in boiler with heat output ≤ 0.5 MW. Source: Own calculations based on [93]

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 19, the index bands are complemented by health-related recommendations for both the general population and sensitive populations.

Table 19: 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	Consider reducing physical activities, particularly outdoors, especially if you

	such as sore eyes, a cough or sore throat	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 20, the example ranges of pollutant concentration limits for the EU CAQI (Common Air Quality Index) are presented.

Table 20: Index levels of the EU CAQI [94]

Pollutant	Index level (based on pollutant concentrations in µg/m³)					
	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.

4.3.2 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[7] (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).

4.4 Application of assessment methods for the indicator

4.4.1 Voluntary or mandatory methods for EPCs

Methods listed in Section 4.2 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, 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.

[7] 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

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.

4.4.2 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).

4.4.3 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 22 gives a comparison of scales for EU CAIQ, US AQI and PL IJP for PM2.5.

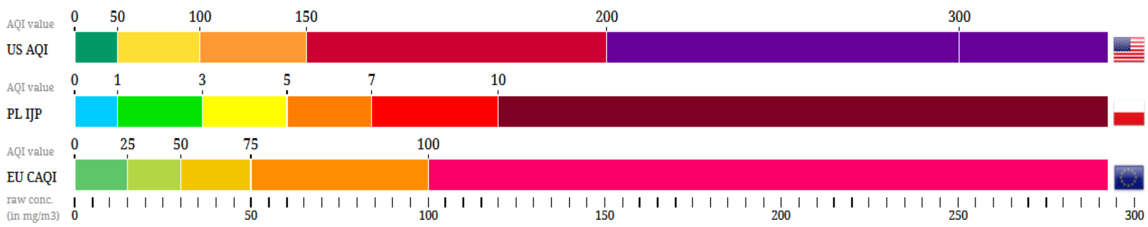

Figure 22: Comparison of scales for EU CAIQ, US AQI and PL IJP for PM2.5 [99]

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.

4.5 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 4.2 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.

4.6 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.

4.7 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 21 and Table 22. The ranking of the methods is presented based on expert judgements.

Table 21: 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 22: 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 (*****)		

4.8 SWOT analysis of the assessment methods

To assess the usefulness of the described methods, a SWOT analysis is given in Table 23 and Table 24. 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 23: 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 24: 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

4.9 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 23 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.

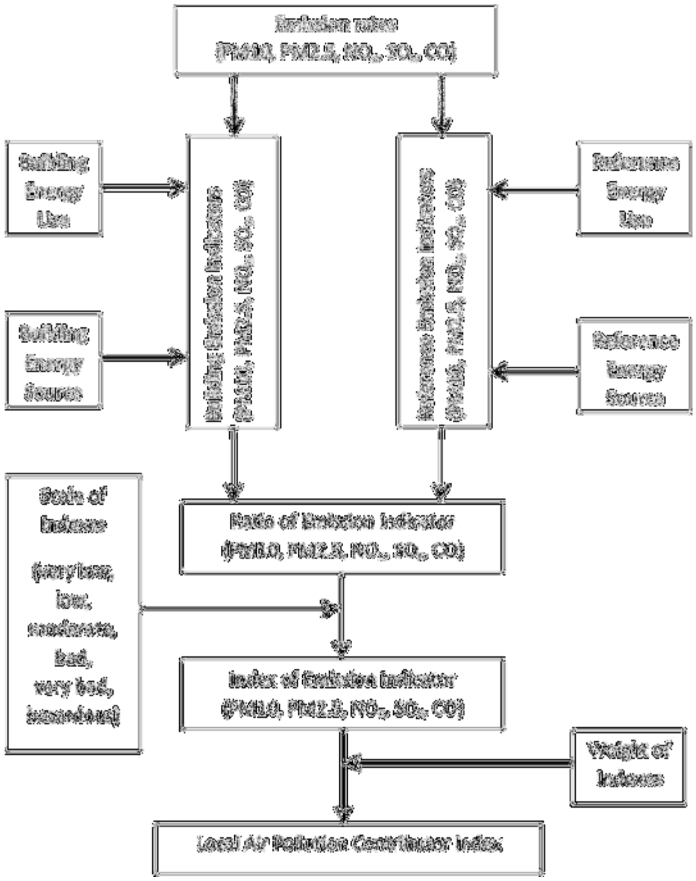

Figure 23: Scheme of local air pollution contributor index estimation procedure

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 24 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.

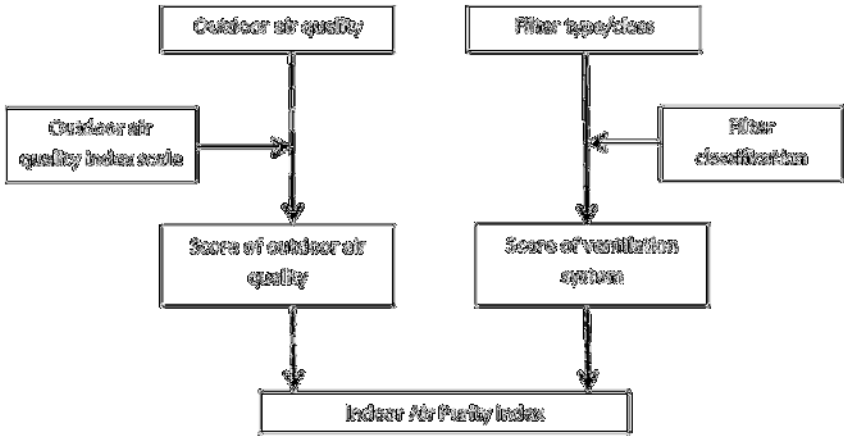

Figure 24: Scheme for indoor air purity index estimation procedure

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.

5 FEATURE 4: REAL ENERGY CONSUMPTION

5.1 Overview of the assessment methods for real energy consumption

This overview describes state of the art approaches for energy performance evaluation based on measured energy consumption. The scope of the study comprises methods for energy performance evaluation that may use all energy consumed or produced at the location of the building as an input. This includes energy consumption of building-related utilities (such as heating, ventilation, etc.), but also plug loads or electric vehicle charging. The final energy can be delivered by any energy carrier, such as fossil fuels, electricity, thermal energy, or biomass. Submetering may be applied to distinguish between different applications or energy origin (renewable versus non-renewable sources). It may also serve to exclude specific energy consumption or production from the analysis.

The methods described in this overview may include all or only part of the building energy consumption. They can comprise the final energy delivered to the building by all energy carriers or, for instance, be limited to the gross energy for space heating. They will not capture full details of energy usage for different applications, the energy user profile over time or in relation to bidirectional aspects (produced versus consumed energy).

Different methodologies exist to evaluate the energy performance of buildings. Table 25, mainly based on a review paper [100], compares the principles of building energy performance evaluation methodologies. In addition to the methods included in the review paper, measured energy consumption can also directly be used as an energy performance indicator after limited post-processing of the data.

Table 25: Comparison of principles for building energy performance evaluation methodologies [100]

Method	Inputs needed	Accuracy	Applications	Restrictions
Engineering calculations	Simplified building information	Variable	(i) Design, end-use evaluations (ii) Highly flexible	Limited accuracy
Simulation	Detailed building information	High	(i) Design (ii) Compliance (iii) Complex buildings (iv) Cases where high accuracy is necessary	Dependent on user skill and significant data collection
Statistical	Dataset of existing buildings	Average	(i) Benchmarking systems (ii) Simple evaluations	(i) Dependent on statistical data (ii) Limited accuracy
Machine learning	Large dataset	Average to high	(i) Buildings with highly detailed data collection	(i) Model construction is complicated

			(ii) Complex problems with many parameters	(ii) Does not consider direct physical characteristics
Limited post-processing	Data of measured energy consumption	Variable (depending on building-only energy performance)	(i) Simple evaluation (ii) Historical benchmark	Includes non-standard influences

These methodologies can be divided in two groups:

- Methodologies based on calculated energy consumption
- Methodologies based on measured energy consumption

These groups can be further divided into subtypes according to EN ISO 52000-1 [101]. These types are adopted in Table 26.

Table 26: EPB assessment types according to EN ISO 52000-1 [101]

Type	Subtype	Input data			Type of application
		Use	Climate	Building	
Calculated (asset)	Design	Standard	Standard	Design	Building permit, certificate under conditions
	As built	Standard	Standard	Actual	EPC, regulation
	Actual	Actual	Actual	Actual	Validation
	Tailored	Depending on purpose			Optimisation, validation, retrofit, planning, energy audit
Measured (operational)	Actual[a]	Actual	Actual	Actual	Monitoring
	Climate corrected	Actual	Corrected to standard	Actual	Monitoring or energy audit
	Use corrected	Corrected to standard	Actual	Actual	Monitoring
	Standard	Corrected to standard	Corrected to standard	Actual	EPC, regulation

[a] *This is not energy performance, because essential corrections are missing.*

Various studies and publications [100], [102], [103] have demonstrated a gap between real (measured) energy performance and theoretical (calculated) performance of a building, referred to as the energy performance gap. The energy performance gap of buildings can be significant [104] and often is [105]. Previous research has identified that the actual energy consumption in buildings could be as much as 2.5 times the predicted or simulated consumption [106], but no clear or definitive quantification is available [104] . Figure 25 depicts quantified examples of the relative energy performance gap as observed for faculty buildings in Spain [107].

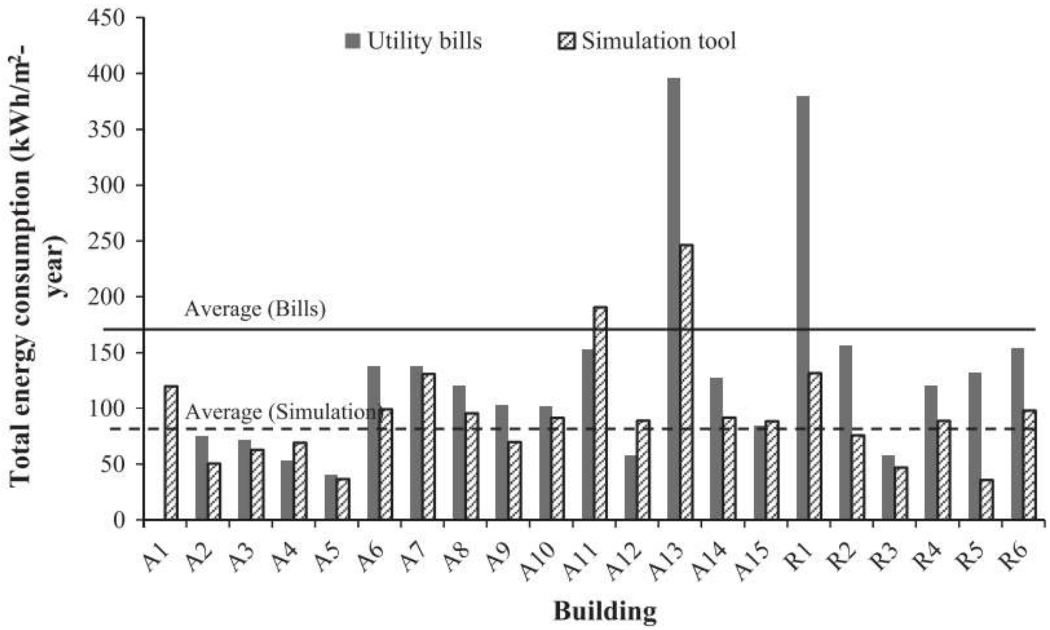

Figure 25: Total energy consumption, both theoretical (estimated by simulation tool) and real (measured values from utility bills) of faculty buildings in Spain [107]

This gap is misleading and is a source of confusion for non-building performance experts. Most end-users of EPCs – homeowners, potential tenants or buyers – are non-building performance experts.

Most energy performance assessment methods for EPC schemes make use of calculations, either simplified or detailed according to standardised methods. Energy performance calculations can also be executed using simulation models. These simulation models typically represent building and system components with more detail and use higher frequencies for the calculation time step executed using a computer program. All of these calculation methods are based on physical laws describing the energy balance of the building, unit or subsystem. They are also referred to as descriptive or white-box models [108].

The input often consists of an extensive dataset that is usually available in the design of a new or retrofitted building. Otherwise, it needs to be collected on-site by an energy expert, which is time-consuming. These models do not calculate energy performance accurately or estimate actual (or expected) real energy consumption [104]–[106]. The most significant causes leading to the performance gap of buildings can be attributed to the following aspects [104]:

- Occupant behaviour
- Micro-environment

- ‘Design versus as-built’ issues

In the context of energy consumption in buildings, occupant behaviour includes occupants’ interactions with and operation of windows, thermostats, lights and blinds, and their movement between spaces [104]. The microenvironment refers to the outdoor climatic conditions of the location of the building for the time period in which the measurements of the actual energy consumption took place, such as air temperature and humidity, solar irradiation and wind speed and direction. Design versus as-built issues concern the difference in technical characteristics used in the calculation versus those observed in the as-built phase. Examples of such influencing parameters for the energy performance gap include the thermal transmittance of the building envelope or the energy efficiency of the heating system. Also, excessive simplification such as the use of default values in energy performance calculation models contributes to the design versus as-built performance difference. These default values are retained in case the required information is not available and cannot be obtained from inspection. The default values are usually defined in a conservative way, resulting in underestimated energy performance of the building. For example, in the Flemish EPC calculation method, if no airtightness measurement test result is available, a default value for v_{50} – the air leakage at 50 Pa per unit envelope area – of 12 $m^3/(h.m^2)$ is used.

Additionally, the translation of final energy consumption to primary energy consumption by application of the primary energy conversion factor alters the difference between actual and calculated energy consumption. Consequently, the relative difference of the electrical energy part in the total energy consumption enlarges when expressed in terms of primary energy due to a much larger primary energy conversion factor for electricity compared to other energy vectors. Also, the EPC methodology may use default values set on a European level, while more detailed information on a national level is used for the calculation of the actual primary energy consumption. Most of all, expressing energy performance in terms of primary energy consumption is confusing to end-users as it is unclear how it relates to final energy consumption known from metering and energy bills.

Instead of calculated energy performance, energy performance can be based on measured energy consumption. The most straightforward approach is simply to include the measured energy consumption in the EPC in relation to a reference, usually in this case the historical energy consumption data. Statistical modelling and machine learning techniques could be used, based on data of energy consumption complemented by other data such as outdoor climatic conditions. These methods based on measured data are also referred to as data-driven models. In fact, machine learning can be categorised as a subset of statistical modelling [109]. These data-driven models have the advantage that on-site visits are no longer required for energy performance assessment of the building, reducing the complexity of the simplified calculation methods currently in use or even replacing them. Measured energy consumption, however, incorporates the influence of user behaviour, micro-environmental conditions and energy consumption not included in the EPC. This necessitates post-processing of the data. The non-EPC energy consumption needs to be identified and separated from the energy consumption that is to be included according to the EPC assessment method. For some building services it is less common that these are considered, e.g. energy consumption of appliances (plug loads), cooking, mechanical escalators and elevators. This may also depend on the building or space categories. It is also possible that this energy is only accounted for as a contribution to the internal heat gains and not necessarily in the final energy consumption. In this case, the internal heat gains originating from appliances are considered in a non-standard way. Furthermore, the influence of user-related aspects and climatic conditions (outdoor, but also indoor environmental conditions deviating from comfortable conditions) on the energy consumption needs to be excluded by some form of normalisation to allow for comparison over time and between different buildings. It is also more complicated to disaggregate the energy consumption available for the different energy vectors into their constituents to facilitate tailored renovation advice.

Data-driven models can be further subdivided in two categories:

- Black-box models, in which the model structure and the model parameters are identified from the data only
- Grey-box models or hybrid models that combine a mathematical description of the building's physical model, for which model parameters are identified by fitting it to the measurements.

Furthermore, the energy performance of a building can be predicted using detailed model calibration [110], in which a detailed building model is combined with measurement data to calibrate the model. Detailed model calibration is time consuming and requires high-quality input data and high-level expertise to develop.

The integration of real (i.e. actual measured) energy consumption data in EPCs could provide added value to the existing energy performance evaluation methods or even serve as the basis for alternative evaluation methods, replacing the existing energy performance evaluation method. Where an energy performance rating method – an evaluation method in which an energy performance indicator is compared to one or more references – is based on measured energy consumption, this is also referred to as *operational rating*. In theory, a performance-based rating approach should be based (and is in almost all other industries) on "requirement setting" and "compliance" checking by measurements [100]. The actual measured energy consumption can be obtained from energy bills, energy meter readings or building energy monitoring systems in various levels of detail concerning time resolution of the measurement data, subsystem measurement locations and variety of monitoring parameters. Data from smart meters can be complemented by data on other parameters such as geometrical building characteristics and weather data obtained from various sources e.g. online databases or IoT devices. Due to an increasing availability of data from smart meters and on-site measurement devices, improved accuracy is feasible [111] and thus the relevance (and accuracy) of this method will increase.

5.1.1 Approaches used to assess real energy consumption

Different approaches for the inclusion of real energy consumption in EPCs can be distinguished and, for this overview, categorised in the following three main groups.

Building-level simple approach

The simple approach consists of simply adopting the total measured energy consumption of the building in the frame of the EPC assessment method. The values of the actual measured energy consumption per energy carrier can be obtained directly from energy meters or derived indirectly from energy bills. This data acquisition and processing should preferably be organised in an automated manner but can also be done manually. The measured energy consumption is aggregated and included as such or normalised to compensate for the influence of external factors such as climatic conditions, size or occupancy, in order to exclusively represent the energy performance related to the building or a part of it. The measured energy consumption can either be displayed:

- In addition to the existing energy performance indicator; or
- As a replacement for the existing energy performance indicator.

Examples of Member States that have implemented this approach in EPC assessment schemes for part of the building stock can be found in Sweden, the UK and Flanders (Belgium) (see Section 5.2.1.2).

Building-level detailed approach

In the detailed approach, a part or multiple part of the energy balance of the building is determined, such as the energy consumption for domestic hot water or the heat transfer through the building envelope. This can comprise the direct characterisation of parameters related to the energy performance of the building or components of it that can serve as

- An accurate value of input parameters of (simplified) energy performance calculation methods; or
- An energy performance indicator to complement existing indicators.

The parameters that can be derived include the heat loss coefficient, the global solar aperture coefficient, efficiency of the heating system, airtightness, and the dynamic behaviour of the building. The building-level detailed approach also includes the disaggregation of energy consumption across its constituent parts. Separation between gas use for domestic hot water and for space heating, or quantification of electricity use for appliances, are not typically considered in EPCs but can be done. These parameters can be translated into models as currently in use for energy performance certification. Some of these parameters can also be implemented directly as an energy performance indicator, complementing or substituting existing indicators. An example of this is the heat transfer coefficient of the building envelope – a parameter that represents the amount of heat transferred between indoor and outdoor environment per unit of envelope area and per unit of temperature difference [W/m^2K]. This could replace or complement the U-value of the various building envelope components or the overall U-value of the building envelope.

Also included in this category of approach is a detailed model calibration in which the various inputs of a fully descriptive law-driven model of a building system are tuned to match the measured data [110]. Such a detailed model calibration approach requires considerable time, effort and expertise for development together with detailed input data regarding building characteristics and usage profiles.

More information on building-level detailed approach is given in Section 5.2.2.

- Stock-level model development

Datasets on building stock level allow us to improve and validate existing methods, develop alternative models and set benchmarking levels for evaluation. These concern the overall building energy consumption or performance, but also physical performance characteristics of part of the building or systems enable the development of improved models and benchmarking performance levels. This approach differs from the previous approaches in the level of application. Rather than a single building, large sample datasets of the complete building stock or subsets of it are used to develop methods for use in parallel with existing EPC calculation methods or derive new models to improve parts of existing EPC calculation methods. In relation to individual buildings, the models can be used to determine typical performance of similar buildings that can serve as a baseline for comparison. Alternatively, the models can be used as energy performance determination methods in themselves, applied for certification or complementing existing assessment methods.

Some of these approaches may also use data obtained from on-site experiments, such as co-heating experiments [112]. Although on-site experiments on unoccupied buildings are useful for quality assurance and characterisation of new or renovated buildings, this report focusses on the use of methodologies to characterise and assess the actual energy performance of buildings starting from on-site monitored data of in-use buildings. This may also comprise compliance checking as a means for quality assurance for new or renovated buildings (see for instance the QUALICHeCK project), or energy awareness services providing direct feedback to building users [113][114]. More information on stock-level model development approaches with some examples is included in Section 5.2.3.

5.2 Description of approaches used for the assessment of real energy consumption

5.2.1 Building-level simple approach

The first approach is the most straightforward. It consists of the inclusion of the yearly final measured energy consumption as an indicator in the EPC scheme. The value can be translated to primary energy level or normalised to the size of the building, the number of occupants, the weather or to exclude other influences to allow for correct comparison amongst buildings. A simple inclusion of the yearly total energy consumption as an energy performance indicator can have a purely informative purpose, or it can be coupled to requirements for evaluation of the energy performance. The latter consequently requires a benchmark reference and influences that are not directly building-related (such as user behaviour) need to be excluded from the energy performance indicator. The energy consumption of previous years, from similar buildings or modelled energy consumption can be used as a reference. The EPC assessment methods in Sweden, Flanders (for public buildings only) and the UK (for public buildings only) are examples of the building-level simple approach. More information on these methods is given below with examples.

5.2.1.1 Normalisation

Different options exist for adapting the total actual energy consumption to minimise the influence of various parameters for improved comparison between buildings. These include considering the following aspects:

- Weather
- Building size
- Building use
  - Building function
  - User-related aspects (occupancy, behaviour, etc.)
- Indoor environmental conditions and quality of service provision
- Energy consumption not covered in EPC calculations or atypical energy consumption
- Basis for comparison (final energy, primary energy, CO_2 emissions, exergy, share of energy from renewable sources etc.)

Normalisation to standard weather conditions is usually done by the heating degree days method. This only takes outdoor temperatures into account, generally available from a national weather station. Solar radiation is only indirectly reflected (via its influence on outdoor temperature and by assumptions; the baseline temperature reflects internal and solar heat gains). Methods incorporating solar radiation along with outdoor temperature are also available. In principle, the normalisation should only be executed on the part of the energy consumption that is influenced by weather conditions and the space heating energy consumption. Domestic hot water and other uses are much less influenced by outdoor climatic conditions. The same holds true for space cooling. If this is disregarded, the relative error increases for low energy buildings, because space heating makes up a lower share of total energy consumption compared to less efficient buildings.

Normalisation to size can be based on floor area, volume, building envelope area or another characteristic (e.g. equivalent surface area of a sphere with the same volume as the building unit). Normalisation to occupancy can be based on the number of building users. Additionally, occupancy profiles could be included in the normalisation factor. This is easy if the data source is available. Discounting the effect of user behaviour is much more complicated and not applied in the building-level simple approach. This is the most important downside of this method: the influence of user behaviour makes the building-level simple approach less suitable for comparison between buildings. However, this can also be an advantage, especially when combined with a good benchmark, triggering both building energy performance and user behaviour change.

The translation to primary energy consumption can be done if the total energy consumption per energy carrier is available. This is done using the primary energy conversion factors as set on a national level (possibly adopting the values from EU directives). The translation to CO_2 emissions can be done in a similar way.

In addition to the aspects briefly described above, the indoor environmental conditions and service provision requiring energy should also be considered when comparing buildings. The energy performance of buildings with different levels of indoor environmental quality (e.g. indoor temperatures, ventilation levels) or with different levels of quality of provision of services should not be compared without some form of compensation (e.g. by use of a weighting factor).

Note that the normalisation can be applied to the total final actual energy consumption for the evaluated building, or to the benchmark value of energy consumption. The first method is the most applied and results in fixed benchmarking levels for various buildings of the same type, allowing comparison between buildings. The second method establishes the best link with the actual energy consumption as can be found on the energy bills, ideally to be renewed annually. An example of the deployment of tailored benchmarks can be found in the UK, developed by CIBSE [115] (TM46/47 [62][116]).

5.2.1.2 Examples

- Sweden

In Sweden energy performance certification based on real energy consumption is implemented for both newly constructed and existing buildings that undergo thorough renovation.

The set of evaluation criteria consists of:

- maximum measured energy consumption (specific yearly primary energy consumption [$kWh_{prim}/(m^2.year)$])
- maximum average heat transfer coefficient (U_{max} [$W/(m^2.K)$])
- maximum capacity of installed electrical heating [W/m^2]

The measurement procedure can be chosen by the building owner but is usually executed according to the EPC procedure in which energy bills are collected by an independent energy expert who reports the measured energy consumption. The procedure requires a measurement period of 12 months within two years after completion of the building. The measured energy consumption is the sum of the yearly energy consumption delivered for heating, comfort cooling, domestic hot water and electricity use for purposes other than heating. The yearly energy consumption for heating is corrected for regional climatic conditions. The total amount is recalculated to primary energy and divided by the heated floor area. The calculation is done using following relation [117]:

$$PE_{pet} = \frac{\sum_{i=1}^{6}\left(\frac{E_{uppv,i}}{F_{geo}} + E_{kyl,i} + E_{tvv,i} + E_{f,i}\right).PE_i}{A_{temp}}$$

where

- PE_{pet} primary energy indicator [$kWh/m^2.year$]
- E_{uppv} delivered energy for heating [kWh]
- F_{geo} geographical factor to account for climatic variation [-]

- E_{kyl} delivered energy for cooling [kWh]
- E_{tvv} energy delivered for domestic hot water [kWh]
- E_f electricity delivered for other than heating [kWh]
- A_{temp} heated floor area [m²]
- PE_i primary energy factor per energy carrier i (electricity, district heating, district cooling, biofuel, oil and gas) [-]

Measurement of the domestic hot water use is legally required but considered economically not feasible. In practice, a standardised domestic hot water use is considered together with the attribution of solar thermal panels or recovery of waste heat, if any. The electricity consumption for applications other than heating is monitored using smart meters which allow for a segregated measurement of heating and applications other than heating. For the building permit application, the building owner can opt for verification by theoretical calculation or based on measured energy consumption. It is strongly encouraged to already include a calculation of the predicted energy consumption in the construction permission request. The input for this calculation is completed by standardised input for climatic conditions (depending on the geographical location), building use and user behaviour according to the Swedish programme for standardisation and verification of energy performance of buildings (SVEBY).

If the measured use does not comply to the requirements, an external energy expert can be appointed. Only 6% of local governments apply sanctions if energy requirements are not fulfilled.

Some specific aspects in the Swedish approach:

- It is not required that the calculated energy consumption (building permit application) and the measured energy consumption are similar. Both need to comply separately to the threshold of the requirements.
- Smart meters have been deployed on a large scale since 2009, facilitating the monitoring.
- Energy performance calculation uses a commercially developed software tool. For the design of residential buildings, a simple calculation program is allowed. For non-residential buildings dynamic calculation software (according to EU standards) is advised.
- BIM (building information modelling) is applied but currently only for pilot cases.

Flanders (Belgium)

In Flanders (Belgium), existing public buildings need to display the EPC (see Figure 26) on a publicly accessible and visible location in the building. The energy performance indicator is the sum of the measured yearly energy consumption per energy carrier recalculated to primary energy and normalised to the useful floor area and standard climatic conditions [118]. A benchmark is added by means of a coloured bar scale with the indicator value for the maximum of the scale and for an average building of the same type (e.g. post office, library).

Figure 26: Example of an EPC for public buildings used in Flanders [119]

In addition to the indicator, advice is included tailored to the specific building. The advice is based on an on-site building audit (following a questionnaire) to be completed by the energy expert. A database with information gathered in the frame of this mandatory EPC assessment is publicly available.

- United Kingdom

In the UK (England and Wales), EPCs (see Figure 27) of public buildings are based on operational rating and referred to as display energy certificates (DECs) [120].

Currently DECs are mandatory for public buildings over 250m², only valid for 10 years and must always be displayed prominently at a location clearly visible to the public. They must be accompanied by an advisory report that contains recommendations for improvement of the energy performance of the building. For buildings with a floor area of 1000m² or more, a DEC is valid for 12 months and the advisory report for seven years. For these buildings, DECs must include operational ratings for the previous two years. For private buildings, a DEC can be commissioned on a voluntary basis.

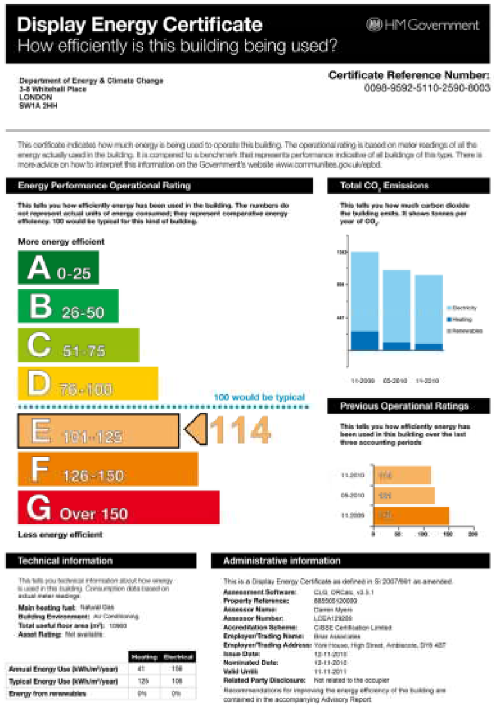

Figure 27: Example of a display energy certificate (DEC)

The operational rating is based on meter readings of the energy consumption during the last 12 months and is compared to a hypothetical building with a typical performance for its type (the benchmark). The operational rating is a numerical indicator shown on a scale from A to G, determined by the government-approved operational rating methodology [121] using approved software and executed by an accredited energy assessor. The various types of energy consumption are brought together on a common basis (actual annual CO_2 emissions of the building) so that the performance can be compared between buildings. Typical performance for that type of building would have an operational rating of 100.

Aspects of the UK EPC assessment based on operational ratings include:

- Normalisation for weather is done by heating degree days method using regional values
- Normalisation for occupancy is done in the case of significantly larger periods of occupancy compared to the predefined (category-specific) occupancy period
- (Avoided) CO_2 emissions due to the contribution of renewables are included below the zero line of CO_2 emissions
- Application of composite benchmarks for mixed-use assessment
- Exclusion of separable energy uses (not typical of that building type) facilitated by separate metering.

- Netherlands

In the Netherlands, the EPC calculation method is explicitly not intended to estimate the real energy consumption of an individual building. It is, however, intended to closely match the average energy consumption for the whole of the Netherlands, by including an average, representative building use (e.g. internal heat gains, indoor temperature) in the method. In 2016, a study was done to analyse the option of two parallel methods, one based on calculations next to another based on measurements. It was chosen not to introduce this direct coupling for the following reasons [122]:

- The large influence of user behaviour on real energy performance
- Policy preference to have uniform requirements (e.g. maximum values) for the entire country
- The anticipated high complexity of such a method.

5.2.2 Building-level detailed approach

Replicable methodologies to characterise and assess the actual energy performance of buildings are being developed embedded in a statistical and building physical framework starting from on-board monitored data of in-use buildings in the frame of IEA EBC annex 71 “Building energy performance assessment based on in-situ measurements”. The work within annex 71 further builds on the work done in the frame of IEA EBC annex 58 “Reliable building energy performance characterization based on full scale dynamic measurements”.

Identification of building behaviour as well as the identification of physical parameters for quality assurance methods are explored within annex 71. The global as-built heat loss coefficient (HLC), based on measured data during normal operating conditions, can be determined using different methods. The most important options are the following methods [123]:

- Average method
- Linear regression models
- Energy signature model
- AR(MA)X models
- Grey box models.

This actual heat loss coefficient accounts for the transmission heat (gains and) losses through the building fabric and optionally the infiltration losses. Efforts have been made to further detail the output of data-driven modelling that distinguishes the heat flow paths for different boundary conditions (e.g. outdoor air, ground, non-heated adjacent spaces). These require advanced measurement data as an input. When this data is not available, as is usually and in the case of adoption in EPC schemes most likely the case, it is suggested to limit the complexity of the model and only deduce the overall building thermal properties [124].

More information on the determination methods is given in Annex 1.

The aspects concerning normalisation (see Section 5.2.1.1) are also relevant for a building-level detailed approach.

5.2.3 Stock-level model development

The third approach consists of top-down methodologies for the analysis of energy performance of buildings or groups of buildings. These methodologies use statistical techniques to predict or evaluate energy performance based on sufficiently large datasets of multiple buildings. This approach allows us to improve and validate existing methods, develop alternative models, and set benchmarking levels for evaluation. These concern the overall building energy consumption or performance, but also the physical performance characteristics of part of the building or its systems enable the development of improved models and benchmarking performance levels.

More information on the methods used in this approach is included in Annex 1.

The aspects concerning normalisation as described for the building-level simple approach (see Section 5.2.1.1) may also be relevant for this approach.

5.3 Application of assessment methods for the indicator

5.3.1 Use of methods for EPCs in different countries

The following findings are mainly adopted from a BPIE study published in 2014 [2]; in 14 of 28 EU countries, both the actual and calculated energy consumptions are foreseen for EPC assessment schemes, depending mainly on building type or building age:

- For some countries, the actual energy performance methodology applies only for non-residential (e.g. Slovenia) or other specific type of buildings (e.g. Flanders and UK (England and Wales); public buildings with minimum floor area)
- In others (e.g. Estonia, Latvia[8]) the evaluation of the actual energy consumption is extended to all the existing buildings while, for new buildings, the energy consumption is calculated.

For three Member States, the following additional information was found on the applied methods using measured energy consumption:

- In Sweden, the approach is part of a mandatory EPC assessment scheme, but an alternative to the verification based on measurements of energy consumption is foreseen in the option for verification by theoretical calculation.
- In the UK, energy performance rating of public buildings based on measured energy consumption is mandatory for public buildings and can be commissioned for non-public buildings on a voluntary basis.
- In Flanders, the procedure based on measured energy consumption is mandatory for existing public buildings. The EPC based on measured energy consumption needs to be displayed on a publicly accessible and visible location in the building since January 2009 for buildings with useful floor area ≥ 1000m²; since January 2013

[8] In Latvia for new buildings a method based on calculation is implemented if measured data is not available.

for buildings with useful floor area ≥ 500m²; since January 2015 for buildings with useful floor area ≥ 250m².

The methods applied in Sweden, the UK and Flanders can be categorised as approach 1: building-level simple approach. Further information is included in Section 5.2.

5.3.2 Applicability of methods to different building typologies

All methods described in Section 5.2 are applicable to both new and existing buildings. In the case of new or renovated buildings, a period after commissioning is required to obtain the necessary measurement data as an input to these methods. Additionally, co-heating or other on-site experiments that need to be performed on unoccupied buildings can be more easily executed for new or renovated buildings prior to occupancy or operation. This allows for more detailed building characteristic determination that can improve the model detail and accuracy. Furthermore, for new and renovated buildings, energy performance indicators based on measurements can serve as a compliance check for quality assurance purposes, also including quality of workmanship. For existing buildings, an additional important value is the incorporation of operational performance. It is also possible to evaluate user behaviour and energy consumption of applications outside the scope of current EPC evaluation methods to trigger improvement. All methods require measurement infrastructure to be installed.

There are no limitations regarding the building typology: the presented approaches can be implemented for all typologies. Some aspects may, however, possibly require additional attention when considering the use of measured energy consumption in EPC methods:

- Privacy legislation needs to be respected by compliance to the GDPR. This may require special considerations, especially measures for buildings with a limited number of occupants, such as individual dwellings. (Measured data can be part of a secure logbook where the building user decides who gets access.)
- In some buildings, energy cost allocation is based on parameters other than energy consumption at sub-metering level. For these buildings, such as older multifamily houses, the disaggregation of total measured energy consumption over common areas and private areas and the allocation of the energy consumption of the common areas to the individual end-users may pose additional difficulties.
- For some large and complex buildings with atypical use (tertiary buildings), a method based on measured energy consumption may be favourable, since the assumptions are less straightforward to make, and it is more difficult to include atypical uses in a general calculation method. On the other hand, for the purpose of comparison, atypical use needs to be excluded or considered separately.
- A method based on measured energy consumption is also more effective for buildings with less frequent user turnover, as the user behaviour is reflected in the measurement results. This is also relevant in the case of buildings being sold or let, as afterwards building characteristics or use (e.g. occupancy profile) may be different, rendering historical energy consumption data less useful as a reference for the specific building.
- For buildings that make use of certain energy sources, such as wood/pellets or heating oil, the use over time is difficult to track. It may even render methods

implementing analysis over periods with a smaller time-step using high time resolution impossible.

On the other hand, methods based on measured energy consumption can take the effects of more innovative technologies into account. This is favourable for existing buildings that make use of such innovative technologies, but it will also stimulate innovation in technologies for the improvement of energy performance of buildings.

5.3.3 Presentation of the indicator

The assessment methods for real energy consumption can deliver one or more of the following energy performance (and related) indicators as output:

- Yearly or monthly (primary) (specific) energy consumption [kWh/month] [$kWh_{prim}/(m^2.year)$]
- Yearly or monthly (primary) (specific) energy consumption per application [kWh/month] [$kWh_{prim}/(m^2.year)$] (e.g. space heating and domestic hot water)
- Share of energy from renewable sources [%] [-]
- Yearly or monthly CO_2 emission [kg/month] [$kg/(m^2.year)$]
- Yearly or monthly CO_2 emission per application [kg/month] [$kg/(m^2.year)$] (e.g. space heating and domestic hot water)
- Avoided CO_2 emission by use of energy from renewable sources [kg/month] [$kg/(m^2.year)$]
- Heat loss coefficient [W/K] [$W/(m^2.K)$]
- Global solar aperture coefficient [m^2]
- Thermal capacity [J/K] [$J/K.m^3$]
- Wind induced infiltration [m^3/h] [$m^3/(h.m^2)$]

These can directly serve as an energy performance indicator for inclusion in EPC assessment or indirectly provide a more accurate input for simplified energy performance calculation methods. Also, disaggregation of energy consumption over its constituents, the quantification of user behaviour effect (splitting building-related energy consumption from occupant's energy consumption), and the identification of energy from renewable sources can be useful outputs for direct or indirect purposes in EPC assessment methods.

The performance indicator value can be compared to a reference value or reference scale or ranked in categories. The reference quantification (baseline) can be based on historical energy performance, typical performance of similar buildings, simulated (expected) energy performance, potential energy performance (from building-specific audits or reviews) or a performance level determined by regulatory methodology [100]. A noteworthy special case is the notional building approach in which the baseline for energy performance is determined for a building with partly the same and partly reference characteristics by calculation or simulation, which means that it is less relevant for EPC methods based on measured energy consumption (apart from e.g. calibrated simulation).

5.4 Linking the assessment methods to energy performance and EPCs

Currently user acceptance of EPCs is hampered by the interpretation of the energy performance indicator. This indicator is expressed as the annual characteristic specific primary energy consumption. The adjective 'characteristic' means it is determined at standardised conditions concerning outdoor and indoor environmental conditions and building use. This inherent nature of the indicator and especially the fact that it is expressed in primary energy makes it difficult to comprehend or to link it to energy bill or metering information. Furthermore, the discrepancy between calculated and measured energy performance, the energy performance gap, is detrimental for trust in EPC relevance. Including an indicator expressing energy performance in terms of yearly or monthly actual energy consumption would mitigate both aspects that are currently disadvantageous to successful achievement of energy efficiency and decarbonisation goals in the building sector.

This feature directly reflects the real energy performance of the building. It may enable direct user feedback and would additionally allow for quality assurance in the case of building commissioning (new or renovated buildings) and evaluation of operational energy performance. Furthermore the real energy consumption feature (and the integration of smart metering) interlinks with the development of smart grids and the growing importance of smart buildings in the broader energy system in terms of integrating energy from local renewable sources and better demand-side management and energy storage opportunities [125][126].

These methodologies can provide a valuable feature for EPCs, either in addition to existing energy performance indicators and benchmarks or as standalone replacements. The resulting indicators can be included as information or accompanied by minimum energy performance requirements or benchmarks for evaluating the energy performance of the building or its components. Some of the presented methods also enable determination of input parameters for simplified energy performance calculation methods currently in use in EPC methodologies. This input can automatically be inserted in software tools, reducing costs and risk of errors by on-site inspection and manual data processing. The methods can also increase the accuracy of current EPC models. This in turn will improve monitoring of Member States' progress toward long-term objectives regarding energy efficiency, the share of renewables and the reduction of greenhouse gas emissions.

5.5 Legal boundaries or requirements of assessment methods

Legislation on privacy needs to be respected. This is part of the EU Clean Energy for All Europeans package [127], which includes compliance with relevant EU data protection and privacy legislation. Adequate measures need to be taken to comply with the GDPR.

Where this feature is used for evaluation purposes, influencing aspects other than those strictly related to the building energy performance need to be excluded to allow objective comparison amongst buildings or in relation to the reference (minimum) performance.

Measurement procedures need to be controllable. For manual meter readings in existing buildings not yet equipped with smart meters or on-site monitoring provided by a building energy monitoring system, adequate control measures need to be foreseen in the procedures to minimise fraud. Special considerations need to be made for measurement of energy delivered by bulked properties such as wood.

5.6 Ranking of methods for assessing their feasibility for the feature

The different approaches described in Section 5.2 are evaluated based on their suitability to assess the energy performance of a building or part of it based on actual measured energy consumption in Table 27. The ranking is done through expert judgements on the suitability of the methods for EPCs.

Table 27: Ranking of methods for real energy consumption

Method	Ranking	Comment on feasibility/ Explanation
Real energy consumption		
Approach 1: building-level simple approach	****	Data usually is available. User behaviour influence is included. Normalisation is required. Very low cost. GDPR requires measures for buildings with few inhabitants, e.g. individual dwellings
Approach 2: building-level detailed approach for use • as an additional energy performance indicator • as input for simplified calculation methods	****	Can be easy to overly complex. Very low to very high cost, depending on requested level of detail of output and available input. HLC is a suitable candidate GDPR compliant
Approach 3: stock-level model development.	*****	Requires availability of datasets. Limited cost per building (unit). GDPR compliant
Likert scale used for suitability: not at all (*), slightly (**), moderately (***), very (****), extremely (*****)		

5.7 SWOT analysis of the assessment methods

Table 28 summarises the advantages and disadvantages of including energy performance assessment based on real energy consumption in EPC assessment frameworks and in relation to the broader context (SWOT analysis).

Table 28: SWOT analysis of methods for real energy consumption

Strengths	Weaknesses
Data is available and will increase in quantity and quality	Duration of measurement period for the design calculation is still required
Clear and simple for building owner	Needs to account for user behaviour, weather

	and/or indoor environmental quality or at least requires information for correct interpretation in relation to these aspects
Can be linked with cost-benefit analysis for renovation measures	Need for differentiation for functions (also within functions) in non-residential buildings complicates method development (e.g. atypical uses or uses not covered in EPC) and development of requirements, benchmarks
Improved accuracy	Smart aspects not necessarily covered (use of on-site produced renewable energy, electrical vehicle charging etc.)
Includes quality of workmanship and operational performance	Attention needed for landlord/tenant split
Opportunities	**Threats**
Extensive automation possible, reducing cost	Must be GDPR compliant
Parallel implementation can simplify calculation methods	Strict enforcement is difficult
Increase of user acceptance especially compared to EPC schemes currently widely in use	Proprietary and diverse communication protocols (lack of open communication standards)
Triggers innovative energy performance improvement measures and user behaviour change	Fraud (e.g. manual meter readings, bulked energy carrier quantification)
Decentralized energy systems and energy from renewable sources	Citizen security (e.g. data privacy, cybersecurity risks)
Improved tailored renovation advice	
Increased trust in the market to better trigger investments	
Calculation methods can be improved based on large-scale monitoring results	
Links with energy performance contracting	
Improvement of policy instruments (monitoring of effects and prioritisation of measures)	
Closing of energy performance gap	

5.8 Proposed preliminary approach to develop the feature

Real energy consumption feature methods for further analysis within the scope of X-tendo were selected based on a scoping analysis from literature review, contact with experts and representatives of EPBD implementing bodies and international collaboration on the topic. Based on this preliminary scoping analysis, two approaches were identified as candidates most suitable for inclusion in EPC schemes. Within each approach category, one best option method was suggested for further elaboration:

- Building-level simple approach
- Building-level detailed approach: whole building heat loss coefficient (HLC)

The third approach, namely stock-level model development, was not retained for further analysis.

More enhanced detailed building- and district-level approaches will become available in the future, but more research is necessary to fine-tune the combinations of measurement set-up and analysis methods in relation to the accuracy requirements and cost and time constraints. The second method (HLC) was also evaluated to be currently not feasible for inclusion in EPC schemes for similar reasons. It is the most promising method of building-level detailed approaches, and with some limited further research (for e.g. automation of procedure) will be ready for cost-effective implementation in EPC schemes in a future context of broad-scale sensor deployment and increasing availability of data. A brief description of the concept of the HLC method is therefore included in Annex 1.

The building-level simple approach method combines features that are included in the initial selection of options for methods and indicators identified as suitable for including real energy consumption in EPCs. A brief description of the method is given below.

- Building-level simple approach method for the determination of energy performance based on real energy consumption

    - Description

This method is based on the EPC method (operational rating) as implemented in Sweden and extended with optional modules for normalisation or correction to allow for inter-building comparison. These optional modules are based on other methods such as the EPC method (operational rating) implemented in England and Wales. The method requires measurement infrastructure for monitoring of all energy constituents and per energy carrier. Only the domestic hot water use monitoring can be replaced by using a calculation model. In essence, the method can also be applied based on billing information. If only billing energy consumption information is available, normalisation options are limited and in most cases modules for calculated energy consumption are used to complete the missing data, such as for the implementation of the heating degree day method. The output is an energy performance indicator, the "**energy use indicator**", representing the yearly specific primary energy consumption of the building.

Normalisation or correction of the indicator to standard consumption or external conditions is included for:

- Size of the building unit (floor area)
- External weather conditions (heating and cooling degree days method)
- Energy carrier (primary energy factors)

It is optional for:

- Indoor thermal comfort level (inclusion in HDD/CDD)
- Indoor air quality level
- Service provision

The inclusion of an additional optional indicator of share of renewable energy and of additional optional user behaviour benchmarking can be considered. These are not included in the visualisation (see Figure 28).

- Visualisation of the determination method

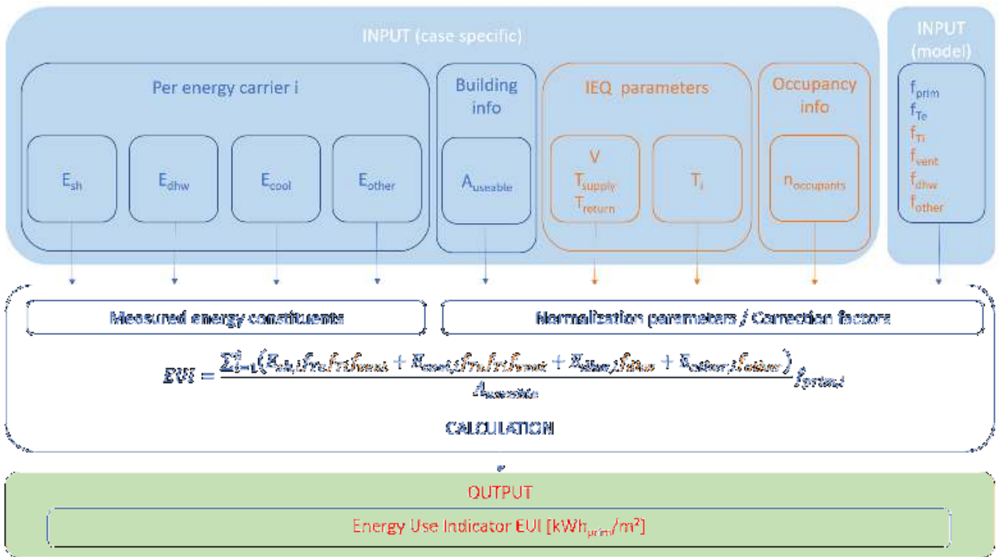

Figure 28: Energy use indicator calculation process

- Input parameters

The input parameters per energy carrier and the optional indoor environmental quality parameters (indoor temperature, ventilation air flow rate, supply and return air temperatures) are obtained from monitoring infrastructure. Only the domestic hot water use monitoring can be replaced by using a calculation model.

Per energy carrier I (i: 1…6; electricity, district heating, district cooling, biofuel, oil and gas)*:

- $E_{sh,i}$ Energy delivered for space heating by energy carrier I [kWh]
- $E_{dhw,i}$ Energy delivered for domestic hot water by energy carrier I [kWh]**
- $E_{cool,i}$ Energy delivered for space cooling by energy carrier I [kWh]
- $E_{other,i}$ Energy delivered for other purposes (excl. non-EPC) by energy carrier I [kWh]

All parameters: Net energy inputs for the time period considered (1 year)***

- f_{prim} Primary energy conversion factor for energy carrier I [kWh_{prim}/kWh]

Building info:

- $A_{useable}$ useable floor area of the building (unit) [m^2]

Indoor environmental quality (IEQ) parameters (optional):

- T_i Indoor air temperature [°C]
- V Ventilation air flow rate [m^3/h]
- T_{supply} Temperature of supply air [°C]**** (May be substituted by T_e)
- T_{return} Temperature of return air [°C]**** (May be substituted by T_i)

- $\eta_{th,HRU}$ Thermal efficiency of heat recovery unit [-] (1 representative value for operational efficiency; only in case of heat recovery system)
- $\eta_{th,sh}$ Thermal efficiency of space heating system [-] (1 representative value for operational efficiency, to translate ventilation net energy losses to final energy consumption)

Occupancy info (optional)

- $n_{occupants}$ Number of occupants [-]

* Non-EPC related energy consumption needs to be disentangled and excluded from the analysis, e.g. social housing common washing room energy consumption

** E_{dhw} measurement is economically not feasible in EPC framework (Swedish method); alternatively a modelled value is allowed; $E_{dhw}=f(n_{occupants}$ or $V_{building})$.

*** 1) Net: referring here to the exclusion of the use of on-site produced and on-site used (or stored within considered period of time) or exported renewable energy. 2) If indicator share of renewable or total on-site renewable energy production is wanted, additional submetering is required.

**** Calculation of ventilation heat loss for implementation of f_{vent} (only to this part of heat losses).

6 FEATURE 5: DISTRICT ENERGY

6.1 Strategic value of the neighbourhood for district energy

To achieve a decarbonised built environment, district heating (and cooling) has a key role. Numerous studies have shown that especially in densely populated areas district heating and cooling using renewable and excess heat from various sources are cheaper than renovating the buildings to a very low level of heat demand (e.g. Heat Roadmap Europe, progRESsHEAT, Hotmaps). In order to reach a 100% renewable energy system by mid-century numerous existing buildings have to be connected to an existing or a newly built district heating and cooling system.

In order to estimate the suitability of a neighbourhood for district energy various approaches exist. In Denmark, since the 1970s the entire country has been classified into three types of regions regarding the feasibility of different heat supply types: district heating areas, gas network areas and individual areas. These have been calculated according to national standards [128]. In district heating areas all buildings must be connected to district heating, and in gas network areas all buildings must be connected to the gas network. Thus, in Denmark this is used as a regulatory instrument.

Since the adoption of the EU Energy Efficiency Directive in 2012, all Member States must perform a comprehensive assessment of efficient heating and cooling in their countries. This includes a mapping of current demand for heating and cooling, potential future development of this demand, mapping of resource potentials, and an assessment of the technical and economic feasibility of different saving and supply options, both via district heating and via individual heating. These analyses could serve as a basis for the identification of district heating priority areas. If a building is located in a district energy priority area, this information could potentially be integrated into its EPC in order to increase the awareness of the building owners, renters, tenants, facility managers etc. on potential connections to district heating/cooling in the future. They would then be informed that potentially in the near to mid-term the public authority might implement an obligation for connecting the building to district energy.

Within the Horizon 2020 project Hotmaps a heat demand density map for the whole of Europe at a 100 x 100 m resolution has been developed [129]. This data is freely available and usable. Furthermore, a simple calculation module for identifying potential district heating areas based on thresholds for heat demand density and overall heat demand in connected areas has been derived [130]. The map together with the calculation module could be used to identify suitable regions for district heating. This information could then be made accessible for integration into EPCs around Europe. However, a number of open questions have to be clarified before the integration of such information into EPCs would be possible: e.g. Which threshold values for the identification of areas suitable for district heating should be used in the developed module? What data should be used for this estimation: EU wide estimations, as described before, if no local data is available? How valuable is this information in an EPC, if it is not based on local data? How should such information then be presented in EPCs in order to be clear that this might be a rough estimation?

Such strategic information related to the importance of a neighbourhood for district heating in a future energy system could become relevant for EPCs in the coming years. Currently, no database on buildings and buildings' energy demand for heating and cooling is available for all locations in Europe that could be used for deriving reliable estimations of the importance of single buildings for district heating systems in order to be integrated into EPC schemes. However, several regions across Europe are working to set up reliable databases to identify district heating priority areas. Such information could also be presented in EPCs. In X-tendo, an indicator will not be derived estimating the importance of a neighbourhood for district heating in a future low-carbon energy system, as such indicators depend largely on regional initiatives and their use for building owners, tenants or planners will be limited. Instead, two other indicators will be developed related to district energy: an indicator reflecting the future development of district heating systems and an indicator on the suitability of the building for low temperature district heating and thus to allow for the development of more efficient and less carbon-intensive district heating systems. These will be explained in detail in the following chapters.

6.2 Overview of the assessment methods for district energy indicator

The aim of the district energy indicator is to develop the capacity of EPCs to assess and report on the potential for the building to benefit from or contribute to future development of district heating (and if relevant also district cooling) networks. This concern:

- The future decarbonisation of heat generation in district heating systems
- The required transformation of district heating towards fourth generation (smart, lower temperature) systems.

In this context two different indicators/methods will be developed:

- Indicators to consider present and medium-term planned development of local district heating in the primary energy factors (PEFs) and carbon emission factors (CEFs) used in EPCs
- Indicators for the expectable supply line and return temperatures in the building's heat distribution and transfer system.

This feature is, therefore, directed towards two different target groups:

- Building owners/builders/designers should be provided with indicators to assist in making the building fit for fourth generation district heating.
- Public authorities should be provided with indicators on the future development plans of district heating utilities.

Medium-term development of primary energy, renewable energy and carbon emission factors of district heating systems

The EPBD recast 2010/31/EU states that Member States shall increase the number of NZEBs in their countries. In this context, a numerical indicator of primary energy consumption should be included for characterising the buildings' energy efficiency (Article 9). Furthermore, the EPC should provide information about the actual impact of heating and cooling on the energy needs of the building, on its primary energy consumption and on its carbon emissions [24].

In order to calculate the primary energy consumption of a building a relation between the energy need of the building and the primary energy consumption is needed. This ratio is called the primary energy factor (PEF). To comply with the EPBD recast many Member States have implemented methods for calculating PEFs for different heating and cooling supply systems. This is also the case for PEFs from heat supply via district heating.

Latõšov et al. [131] have analysed the applied national standards and regulations for setting or calculating the PEFs for district heating in different Member States. They found that many of the methods applied can be classified into the following three categories:

- Use of single fixed values:
  - A national authority sets one single value for district heating PEF to be used for all district heating systems in the country
  - This is applied in the following countries: Bulgaria, Denmark, Estonia, Finland and France
  - Denmark is a special case: three different values of PEF are applied depending whether the building complies with different renovation standards.
- Use of differentiated fixed values:
  - For different types of supply in district heating different PEFs are defined by a national authority
  - Differences between countries regarding supply technologies for which PEFs are defined and how they are applied to the different district heating systems
  - This is applied in Austria, Czechia, Hungary, Slovakia, Slovenia, Latvia, Lithuania and the UK.
  - In Austria a detailed calculation according to EN 15316-4-5 is also allowed [132]

- Use of values calculated for each district heating network:
  - For each district heating network in the country a PEF is calculated
  - This is applied in Poland, Italy and Germany.

Thus, methods for deriving the PEF for the use of calculating primary energy demand in buildings vary remarkably between different countries in the EU.

- Supply line and expectable return temperatures in the heat distribution system of the building

The temperature level (supply/return line temperature) of the heat distribution system within buildings influences the efficiency of heat supply systems. This becomes especially important when low-exergy heat supply systems are used. This means that heat supply technologies such as solar thermal, heat pumps or fourth generation district heating networks (low temperature district heating) can only be efficiently implemented where the heat distribution system inside buildings is designed to work at low temperature levels. In order to evaluate the potential for changing a building's energy supply system towards more efficient systems, it would be beneficial to include the temperatures in the heat distribution system in the EPC of a building. Further details are discussed in Section 6.3.

6.3 Description of approaches used for the assessment of district energy

6.3.1 Integrating primary energy, renewable energy, and carbon emission factors in EPCs

In the following section, we describe the standard calculation in EN 15316-4-5:2017 [132], which is applied or can be used alternatively in several Member States. Also, we describe the methods used in Poland, Italy and Germany. We also focus on aspects of the implementation of the legal procedure to set the ground for suggesting a new indicator for expectable future development of the PEF for a selected district heating network.

- EN 15316-4-5:2017 [132]

This standard provides a general framework for factors, which weights various parts of the district heating network (in principle also for district cooling networks) corresponding to their part of energy in the system. This formula for example can be used to calculate the PEF (and the corresponding carbon emission factor and renewable energy factor) for a district heating network that has several different heat supply units and exports energy. The exported energy could be in the form of electricity from a combined heat and power (CHP) unit.

$$f_{we;des} = \frac{\sum_{cr} E_{in;cr} * f_{we;cr} - E_{exp} * f_{we;exp}}{\sum E_{del}}$$

where

- $f_{we;des}$ weighting factor of the energy system
- $E_{in;cr}$ energy content of the energy carrier supplied to the system (cr)
- $f_{we;cr}$ weighting factor of the energy carrier (cr)
- E_{exp} energy emitted to an external system or external network
- $f_{we;exp}$ weighting factor of external energy
- E_{del} total delivered energy

In addition to this weighting formula, the standard provides formulas for evaluating a renewable energy factor, an excess heat factor and a CHP portion. On the supply side most of the data in the standard is dedicated to diverse types of CHP technologies. In addition, there is a small portion of handling excess heat and waste incineration plants. Appendix B in EN 15316-4-5:2017 offers key data for the calculation such as emission factors, renewable energy factors and some values for identifying the network losses, such as a heat loss value for new and old networks and electrical energy used by the pumps.

- Calculation and reporting of PEFs in Poland

In Poland, where district heating is used to supply the heat in a building, the primary energy resource factor (PRF) of the district heating system must be integrated in the EPC. The PRF is equivalent to the PEF as used in this document. The value of the PRF should be provided by the district heating company to calculate primary energy consumption of a building connected to the network. In theory, district heating companies are obliged to publish a PRF value each year on the basis of the previous year's consumption of fuels and sales of heat. However, not all district heating companies fulfil this requirement. A methodology for calculation of the PRF from district heating is given in the Regulation of the Minister of Energy of October 5, 2017 [133] regarding the detailed scope and method of preparing an energy efficiency audit and methods of calculating energy savings.

The PRF, marked with the symbol "$W_{P,c}$", for the heating network, regardless of the amount and type of heat sources and technologies used to generate and supply heat to the final customer, is calculated according to the following formula:

$$W_{P,i} = \frac{\sum_i (w_{P,i} * H_{ch,i}) - \sum_l (w_{el} * E_l)}{\sum Q_{K,i}}$$

where

$w_{P,I}$ coefficient of non-renewable primary energy input, appropriate for the final energy carrier concerned, as appropriate fuel or energy source used

$H_{ch,I}$ amount of energy introduced in the fuel, including biomass or biogas, up to heat sources supplying heat to a given heating network, both for boilers of the heating part and cogeneration units, calculated as the product of the amount of this fuel and its calorific value, as well as the amount of heat waste from industrial installations or the amount of heat generated in renewable energy installations (excluding biomass or biogas sources already used to supply heat to the network) per calendar year preceding the year in which the assessment is made, expressed in *MWh / year*

w_{el} coefficient of non-renewable primary energy input for electricity from mixed production, as specified in the table in the Regulation of the Minister of Energy

E_l the sum of the gross amount of electricity measured at the generators, generated annually from a cogeneration system, per calendar year p preceding the year in which the assessment is made, expressed in *MWh / year*

$Q_{K,l}$ amount of heat delivered from the heating network to consumers in the calendar year preceding the year in which the assessment is made, expressed in *MWh / year*

Calculation and reporting of PEFs in Italy

If the building (or the building unit) is connected to a district heating network, the annual amount of energy deriving from district heating calculated in standard use conditions is indicated on the EPC. The primary energy performance index, based on which the building energy class is determined, depends on this energy calculation. The building's thermal energy needs are calculated according to the Italian National Technical Standard UNI/TS 11300-1/2014 [134], independently of the heat generation system. With a connection to a district heating system, energy loss factors related to the customer substation are calculated according to the Italian National Technical Standard UNI/TS 11300-4/2016 [135] and applied. In this way, the thermal energy supplied, in standard use conditions, by the district heating system to the customer substation is calculated. Consequently, with the application of the PEF of the thermal energy distributed by the district heating network, the annual primary energy is calculated. The PEF must be provided by the district heating utility.

According to the Decree of the Minister of Economic Development "DM 26/06/2015", concerning the application of the methodologies for calculating the energy performance of buildings [136], district heating and district cooling utilities need a certification for the PEF of the thermal energy supplied to buildings. The certification must be issued by an accredited certification body.

The certification procedure is not yet available and, as regards the national legislation, it is possible for district heating and district cooling utilities to use the current technical standards for the calculation of the primary energy conversion factor: UNI EN 15316-4-5/2008, which is the transposition for Italy of EN 15316-4-5/2007. The more recent Standard UNI EN 15316/2018 (transposition for Italy of EN 15316/2017) is not yet applicable in Italy, as the national annexes and modules are under development. If the utility is not providing the PEF for the thermal energy delivered at the building substation, a "reference" value (fixed at 1.5 by DM 26/06/2015 [136]) has to be considered.

Calculation and reporting of PEFs in Germany

In Germany, the calculation of the PEF is performed according to regulation FW 309 published by the German District Heating Association AGFW [137]. The calculation follows the power bonus approach principle. The calculation of the PEFs of the different supply plants can be modelled in a process chain using life-cycle data from various sources. Alternatively, such factors are given in the regulation. However, for each district heating network a primary energy factor must be calculated based on the supply technologies used in the network and the split of energy supplied by these technologies.

The calculation of the PEF for each network must be performed by a certified expert. Experts are certified by the AGFW according to regulation FW 609 [136]. They must have a finished engineering degree or technical career and several years of working expertise in the field of (district) heating and cooling and must pass an exam to become certified. The certification for each expert must be renewed regularly. In order to do so, different options are stated in regulation FW 609, e.g. repeating the exam or taking part in regular experience exchange. Also, the expert calculating the PEF for a specific network must prove their independence from the network utility.

For calculating the PEF the district heating utility sends data on the heat, fuel and electricity balance of the network to the certified expert. The expert then calculates the PEF according to regulation FW 309. All data as well as the calculation is then sent to AGFW, which proofs the data and the calculation. If the calculation is approved the certificate is issued and sent to the utility as well as published on the DESI website [138].

Certificates have a validity of three years in general. If the calculation is based on balancing data of a period of at least three years, the validity of the certificate can be prolonged to 10 years. While the PEF is calculated within the FW 309 framework, no renewable or carbon emission factors are included. Also, potential future development of the PEF for the district heating network under consideration is not included in the procedure.

- Calculation and reporting of PEFs in the Netherlands

In the Netherlands, district heating and cooling companies have to calculate their primary energy and carbon emission factors according to the method stated in the standard NEN 7125:2017 [139]. All the following calculations are done periodically and normally once a year.

The PEF of the distribution grid is determined with the following formula, if all of the incoming and outgoing energy flows are measured values.

$$f_{P;XD;tot} = \frac{\sum_{ci}\left(E_{XD;in1;ci} * f_{P;del;ci}\right) - E_{XD;exp1;el} * f_{P;exp;el} + \sum_{ci}\left(E_{XD;in2;ci} * f_{P;del;ci} * \Delta\varepsilon_{chp;el} * f_{P;exp;el}\right)}{Q_{XD;out;tot}}$$

If the values for the incoming and outgoing energy flows are calculated and possibly measured the following formula is applied:

$$f_{P;XD;tot} = \frac{f_{XD;gen;tot}}{\eta_{XD;dis}} + \frac{W_{XD;aux;tot}}{Q_{XD;out;tot}} * f_{P;del;el}$$

where

- $f_{P;XD;tot}$ primary energy factor of the district heating or cooling grid.
- $E_{XD;in1;ci}$ energy consumption by the energy system per energy carrier c_i on an annual basis, for all generators with the exception of CHP, *in MJ*
- $f_{P;del;ci}$ primary energy factor for the relevant energy carrier

- $E_{XD;exp1;ci}$ supply of electricity by the energy system for all generators with the exception of CHP, *in MJ*
- $f_{P;exp;el}$ primary energy factor for exported electricity
- $E_{XD;in2;ci}$ energy consumption by the energy system per energy carrier c_i on an annual basis, exclusively for CHP, *in MJ*
- $\Delta\varepsilon_{chp;el}$ annual average loss of the electrical conversion number of the CHP installation
- $Q_{XD;out;tot}$ total annual customer demand for heat or cold in the network, *in MJ*
- $f_{XD;gen;tot}$ primary energy factor of the heat or cold supply by the joint heat or cold generators through the network
- $\eta_{XD;dis}$ distribution efficiency of the distribution network per year
- $W_{XD;aux;tot}$ annual amount of purchased electrical auxiliary energy for the collective energy system, *in MJ*
- $Q_{XD;out;tot}$ heat or cold supply from the energy system to the customer I on an annual basis, *in MJ*
- $f_{P;del;el}$ primary energy factor for energy purchased on one's own plot for electricity

The calculation of the CO_2 emission coefficients also differs depending on whether all energy flows are measured, or are available as a mix of measured and calculated values.

If all of the energy flows are measured the CO_2 emission coefficients can be determined by two methods. In method A, the reference plant supplies the fossil share of the lost electricity. This means that the required fuel and emissions are allocated to the heat supplied by CHP.

$$K_{CO2;XD;until} = \frac{\sum_{ci}\left(E_{XD;in1;ci} * K_{CO2;del;ci}\right) - E_{XD;exp1;el} * K_{CO2;exp;el} + \sum_{ci}\left(E_{XD;in2;ci} * f_{p;del;ci} * \Delta\varepsilon_{chp;el} * K_{CO2;exp;el}\right)}{Q_{XD;out:until}}$$

In method B, the efficiency of the reference plant is only used to determine which part of the fossil fuel and emissions from the CHP is attributed to the heat supply.

$$K_{CO2;XD;tot} = \frac{\sum_{ci}\left(E_{XD;in1;ci} * K_{CO2;del;ci}\right) - E_{XD;exp1;el} * K_{CO2;exp;el} + \sum_{ci}\left(E_{XD;in2;ci} * K_{CO2;del;ci} * \Delta\varepsilon_{chp;el} * f_{P;exp;el}\right)}{Q_{XD;out:until}}$$

If the values of the incoming and outgoing energy flows are calculated and possibly measured the following formula is used.

$$K_{CO2;XD;until} = \frac{K_{CO2;XD;gen;tot}}{\eta_{XD;dis}} + \frac{W_{XD;aux;tot}}{Q_{XD;out;tot}} * K_{CO2;del;el}$$

where the new symbols mean:

$K_{CO2;del;ci}$ CO_2 emission coefficient for purchased energy for the relevant energy carrier c_i

$K_{CO2;exp;el}$ CO_2 emission coefficient for exported electricity

$K_{CO2;XD;gen;tot}$ CO_2 emission coefficient of the heat or cold supply by the joint heat or cold generators through the network. Where XD stands for HD, WD, CD (heat distribution network, hot tap water distribution network, and cold distribution network)

The standard provides different calculations of the energy factor and carbon emission factor for the three types of distribution networks (heat, hot tap water, cold). Each of these calculations is separated into three main parts: the calculation of distribution losses of the network, the calculation of the energy factor for the supply and the calculation of the auxiliary energy. The calculation of the renewable energy, primary energy and carbon emission factors for a network can be determined when knowing the supply of heat/cold to the network via different technologies together with the auxiliary energy and the heat/cold supplied to the customers. Where the heat supplied to the customers is not known or measured, e.g. if the district heating system is under construction, the heat/cold supplied to the customer is calculated via estimating the distribution losses in the network.

- Distribution losses in the network

If measured data on the total amount of heat delivered to the customers and the total amount of heat fed into the network is available, this can be used. Otherwise, a standard calculation is provided. This calculation is based on the monthly average temperature of the water in the distribution network and the monthly average ambient temperature. With these values and several other parameters regarding the pipes, such as heat resistance, the monthly heat losses are calculated and summed for the yearly total heat loss according to the following formula:

$$Q_{net;total} = \sum_{mo} t_{mo} * \sum_{j} \left(\frac{L_j * (T_{net;mo} - T_{amb;mo})}{R_{net}} \right)$$

where

- $Q_{net;total}$ total distribution losses in the network over one year, *in MJ*
- t_{mo} number of days in the respective month *mo*
- L_j length of the pipes in network part *j*, *in m*
- $T_{net;mo}$ average temperature of the water in the distribution network in month *mo*, *in °C*
- $T_{amb;mo}$ average ambient temperature around the distribution pipes in month *mo*, *in °C*
- R_{net} specific thermal resistance of the pipes in the network part *j*, *in Km/W*

⦿ Energy factor heat generation for collective heat supply

The calculation of the PEF and CO_2 emission coefficient is divided into two temperature levels (low and high temperature). The standard [139] also provides different calculations for different heat supply technologies such as gas or oil-fired boilers, heat pumps, cogeneration installations, residual heat, geothermal energy, intermediate collective heat supply and collective solar collectors.

⦿ Auxiliary energy

The auxiliary energy is modelled in three parts: the annual amount of purchased electrical auxiliary energy for the distribution network (for pumps), the annual amount of used auxiliary electrical energy from solar energy systems for space heating and hot water (which can also be calculated with formulas given in the standard) and the annual amount of purchased auxiliary electrical energy for the generators. These three sources are summed to give the overall auxiliary energy demand.

6.3.2 Indicators related to supply line and expectable return temperatures in the heat distribution system of the building

In the following we discuss different indicators related to the temperatures in the building's heat distribution systems that could be integrated into EPCs.

⦿ Flow and return temperature of the heat distribution system in the building

The required heat load of a given building with its technical properties (e.g. average thermal resistance of envelope, airtightness, compactness, etc.) and site-specific properties (orientation, solar gains, etc.) varies over time depending on different factors, most importantly the outdoor/ambient temperature and the share of the floor area that needs to be heated at a certain moment. This implies that the temperature levels (supply and/or return line temperature) of the heat distribution systems typically vary over time. While the supply line temperature level might be controlled by more recent boiler technologies, heat pumps or district heating networks, it remains constant or needs to be set manually for older boiler technologies. The return line temperature, on the other hand, is defined by supply line temperature, the thermal energy that is transferred by radiators and pipes to the indoor environment and the flow rate through the piping system. In contrast to the supply line temperature, the return line temperature is more difficult to control. Additional sensors and processing units are needed, which are available from a technical point of view, but not yet implemented in most buildings. In theory, the resulting return line temperature could also be calculated, e.g. by considering the logarithmic mean temperature difference. However, suboptimal configuration and control strategies and missing hydraulic balance of the heat distribution system in apartments, in combination with individual temperature levels in different rooms and different apartments, dominate the actual return line temperatures, making theoretical calculations almost complete defective. Thus, in order to analyse the temperature level (average, maximum, minimum) of a heat distribution system in a building, measurement over a longer time period (days or a few weeks) during the heating season is necessary.

Usually, information on the actual temperature level or the temperature difference between the return and supply line of the heat distribution system is gathered when a building is connected to a district heating system. In such case, the energy transferred from the district heating to the building in the heat transfer station is measured. This is usually done by measuring the volume flow together with the temperature difference[9] between supply and return side. These measurements are done continuously but cannot be accessed directly. In order to get any information on the return line temperature, either direct information on the temperature level or the volume flow and the transferred energy needs to be stored. Since heat transfer stations usually accumulate the measured data, the volume flow, next to transferred energy, is the most available information on the return line temperature. Because the data is accumulated in these stations, it can be accessed only as the sum over a certain period. A typical resolution for buildings with old heat transfer stations (10-30 years, depending on country) is annual data. More recent technologies store monthly data on the energy demand and the associated volume flow. The most recent technologies allow for storing daily data up to real-time data that is automatically transferred to grid operators.

Although the temperature levels of the heat distribution system could be measured even if the building is not connected to district heating, such a measurement is usually not undertaken. This is also because such a measurement is expensive, and a technician must visit the building at least two times for installing and removing the measurement instruments. The gathered data must then be analysed, and the results reported.

- Type of heat distribution system in the building

Besides measuring the temperatures of the heat distribution system in the building, a look at the installed technologies themselves can give an indication about the temperature level of the system. Relevant indications in this respect can be given by both the type of heat transfer system (e.g. radiators) as well as the type of regulation (e.g. control of valves and control of circulation pumps). Regarding the heat transfer system, different types can be distinguished with respect to their effective heat transmission area (types, age and size of radiators, floor heating). Since the different technologies are associated with distinctive temperature levels, they allow a quick and easy estimation of the temperature levels.[10]

Besides the control technology (e.g. thermostat valves) of the individual heat transmission systems (radiators), the following systems are commonly used to control the circulation

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[9] Actually, the absolute temperatures of supply and return line are measured. However, as this data is used to charge the customers for the transferred heat, it needs to be calibrated. In order to reduce the error margins, the calibration of typical heat transfer stations is done for the temperature difference and not for the absolute temperature levels, and the temperature differences are stored instead of temperature levels. The transferred heat is then calculated by multiplying volume flow and temperature difference.

[10] The actual indicator derives from a non-linear relation between the temperature differences against the indoor temperature on the one hand and the effective heat transmission surface area and the heat load of the room/building on the other.

pump and thus the volume flow through the heat distribution pipes: not regulated and/or manually controlled (on/off, manually switched between different rotation speeds), pressure regulated and temperature regulated. The latter is sometimes combined with a signal processing unit that considers the outdoor air temperature and calculates the return line temperature that is needed to ensure that the required heat can be transferred to the rooms. With such temperature-regulated heat distribution systems, low return line temperature levels (compared to what is possible with the existing heat radiation system and the heat demand of the building) can be achieved throughout the year. This is not easy to ensure with other control systems such as pressure-regulated systems, let alone unregulated or manually regulated systems.

- Existing standards

In the Netherlands, the energy performance standard for provisions at district level [139] provides a method for classifying distribution networks in the buildings. The networks for the distribution of heat, cold and hot tap water are distinguished. Also, two different temperature levels for the heat distribution systems are distinguished. However, it is not clearly stated how these temperature levels are to be obtained.

In Austria, the type of heat distribution system has to be defined in the EPC; the heat transfer area (small/large) as well as the system temperature (min/max) is stated. The regulation for the calculation of energy savings in buildings provides reference systems to be used in the EPC if no information is obtained on site. Reference values are given for different types of heat supply systems as well as types of buildings [140].

6.4 Application of assessment methods for the indicator

6.4.1 Voluntary or mandatory methods for EPCs

- Primary energy, renewable energy and carbon emission factors

In all countries, it is mandatory to state the primary energy demand and the CO_2 emissions of the building in its EPC. Thus, where a building is connected to district heating, a PEF and a CO_2 factor must be used in order to calculate the related primary energy demand and CO_2 emissions. For different countries, different methods for deriving these factors are used and implemented in national legislation (see Section 6.3 for further details). These methods are mandatory to be used in EPCs. In none of the countries has an approach been found that needs to state the future expectable development of the primary energy or carbon emission factors of district heating.

- Necessary supply line and expectable return flow temperatures in the distribution system

No country's EPC integrates indicators that show the necessary supply line temperature or the expectable return flow temperature.

6.4.2 Applicability of methods to different building typologies

- Primary energy, renewable energy and carbon emission factors

There is no difference in the calculation between new or existing buildings because the calculation is related to the network and not to the building. For new buildings, if the network is nearby and the values are calculated, these can be used in the EPC. If the district heating/ cooling system is yet to be built, a different approach must be taken; the calculation of the factors cannot then be based on a relation between the energy supply to the network from the different technologies and the supply from the network to the customers. In this case the calculation must be done via estimating the supply from the network to potential customers via calculating the losses in distribution. An approach for how this can be done is given e.g. in the calculation standard for the Netherlands [139].

The main aim of integrating indicators on the future development of PEF, REF and carbon emission factors is to drive the development of the district heating supply towards low-carbon and efficient supply technologies. This is not dependent on the type of building

- Necessary supply line and expectable return flow temperatures in the distribution system

The necessary supply line temperature and the expectable return flow temperature can be developed for both existing and new buildings. For existing buildings, it is necessary to visit the building and measure the heat transfer area and check the type of regulation of the distribution system. For a new building, this information is usually determined in the planning phase. Thus, it should be easily possible to calculate these indicators for both existing and new buildings.

The main aim of these indicators is to detect the building's suitability to be supplied by district heating systems working at lower distribution temperatures. This also is not related to the type of building supplied by a (potential) district heating system.

6.4.3 Presentation of the indicator

- Primary energy, renewable energy and carbon emission factors

PEF and REF are unit-less; the carbon emission factor is usually in $kgCO_2/MWh$. This would also apply for the proposed indicators on potential future factors. It is possible then to also calculate the ratio between the current values and the expected future values to visualise the level of ambition of the district heating system to increase energy efficiency and decrease CO_2 emissions. This could be ranked in the EPC. Both the absolute values and the ratios could be shown in the EPC against the average values of all district heating systems in the country. With this a type of benchmarking figure could be included, making it easy for EPC user to see and understand the current state as well as the level of ambition to change.

- Necessary supply line and expectable return flow temperatures in the distribution system

These proposed indicators are both temperatures. Thus, the unit would be °C or K. A categorisation into different temperature classes would be possible for these indicators.

6.5 Linking the assessment methods to energy performance and EPCs

- Primary energy, renewable energy and carbon emission factors

In general, the indicators in this field are related to the district heating system. Thus, they only indirectly reflect the energy performance of the building. The higher the useful energy demand of the building, the higher the absolute values of primary energy consumption, renewable energy consumption and CO_2 emissions. At the same time the primary energy consumption and the CO_2 emissions of the building are indicators directly related to the rating of the building and expressed very prominently in the EPCs of many countries. Also, the primary energy consumption of a building is considered in several national regulations. Thus, the lower the value the easier it is to fulfil building law requirements. This is e.g. the case for Poland where primary energy consumption is explicitly stated in building laws.

These indicators are not linked to other features within X-tendo. However, they have a strong link to existing EPC schemes in different countries and how the primary energy consumption, the use of renewable energy and the CO_2 emissions are currently derived. The approach to be developed in the course of X-tendo must therefore consider the differences in calculations in the different Member States.

- Necessary supply line and expectable return flow temperatures in the distribution system

The necessary supply line temperature is related to the potential efficiency of heat supply systems. This is especially relevant for renewable energy supply on the one hand and for efficient heat distribution in district heating systems. For several renewable energy supply technologies, efficiency decreases significantly with higher supply line temperatures. This is especially relevant for the supply from solar thermal systems as well as from heat pumps. Both technologies can be used in district heating systems as well as inside buildings. The distribution losses in district heating systems also depend on the temperatures in the heat distribution pipelines. The higher the supply line and the return flow temperatures in the district heating pipelines, the higher the losses in the system. Thus, lower necessary supply line temperatures and expectable return flow temperatures decrease potential losses in the district heating system. This again reduces the primary energy consumption as well as the CO_2 emissions in the district heating system and the building.

6.6 Legal boundaries or requirements of assessment methods

- Primary energy, renewable energy and carbon emission factors

The balance data for calculating the PEF, REF and CEF must be provided by the network utilities. The same applies to the estimated balancing values for future points in time as needed for the calculation of the proposed indicator.

- Necessary supply line and expectable return flow temperatures in the distribution system

The necessary input information and data must be determined by entering the building and apartment. Thus, the same legal issues apply as for the overall EPC development.

6.7 Ranking of methods for assessing the feasibility for the feature

Table 29 presents a qualitative assessment of the feasibility of integrating the described methods for calculating PEF, REF and CEF as well as the necessary supply line and expectable return temperatures in the EPC calculation process.

Table 29: Ranking of methods for district energy feature

Method	Ranking	Comment on feasibility/ Explanation
Indicators related to the district heating/cooling system		
PEF, REF, CEF (integration of potential future development)	***	Indicator for the current PEF is already integrated in the EPC schemes of nearly all EU countries Method would rely on a certification scheme of measures and the calculation of related indicators; this might be a challenge in countries where no certification schemes for calculating the PEF of individual district heating systems currently exist
Necessary supply line and expectable return temperature of the heat distribution system in the building	****	Indicators can be easily calculated after on-site visits. Calibration might be a challenge and depends on discussions with building experts in countries
Likert scale used for suitability: not at all (*), slightly (**), moderately (***), very (****), extremely (*****)		

6.8 SWOT analysis of the assessment methods

The following two tables present a qualitative estimation of the strengths, weaknesses, opportunities and threats related to a potential adoption of the methods to calculate and include future PEF, REF and CEF (Table 30) and to estimate necessary supply line and expectable return flow temperatures in the distribution system (Table 31) in EPCs.

Table 30: SWOT analysis of primary energy, renewable energy and carbon emission factors

Strengths	Weaknesses
For PEF, REF and CEF, standards and calculation methods exist in nearly all countries in the EU. The calculation for the current state indicators is already included in existing EPC schemes. Regular updates of the standards may allow for the integration of further adaptations.	The proposed indicator would incur further work for the district heating utility as well as for the certification expert.
Some countries already have certification schemes for calculating values of each district heating system in place. These could be forerunner countries.	
Opportunities	**Threats**
District heating utilities could show their ambition with an indicator in the EPC. The feature would build up the need for district heating utilities to develop and publish a strategy on how to improve these indicators in the mid-term future. Public authorities would have information about the future development plans of the district heating utilities in their region.	The proposed indicator could be relevant for district heating utilities when it comes to national regulation, so their interest might be low and even negative.

Table 31: SWOT analysis of necessary supply line and expectable return flow temperatures in the distribution system

Strengths	Weaknesses
The proposed indicators could be easily calculated from on-site visits, which usually have to be performed anyway.	Calibration of correction factors is not straightforward and needs an intensive stakeholder discussion process with building experts.
The theoretical concept of calculating these values is well defined.	
Opportunities	**Threats**
The potential of having this information for the planning of district heating supply systems is very relevant.	It might be difficult to find an agreement on the correction factors in the stakeholder discussion process.

6.9 Proposed approach to develop the feature

- Expected future performance of district heating
  - Calculation in a nutshell

The estimated future performance of each district heating system should be expressed via the PEF, REF and CEF for a future point in time. Based on estimated future balancing data (plant capacities, full load hours, CO_2 factors of electricity) and a roadmap for implementation, these values should be calculated by certified experts according to national or EU standards (e.g. EN 15316-4-5:2017). The calculation should then be approved by a recognised association or authority. In the EPC, these values can be used to express future primary energy, renewable energy and CO_2 emissions of the building or for calculating tailored recommendations.

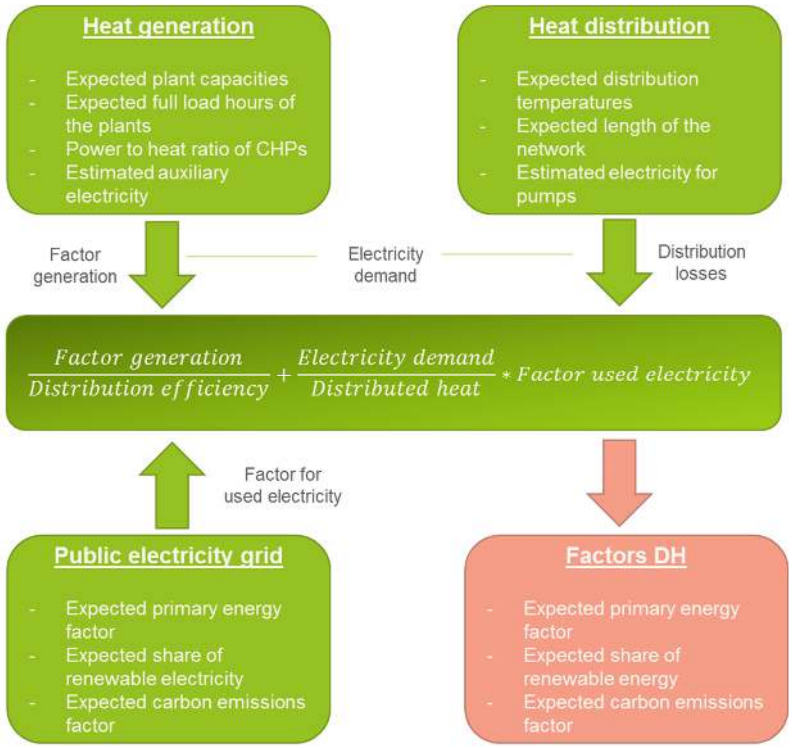

Figure 29: Calculation flow for first method

Figure 29 shows the input data and information needed for the calculation distinguishing between heat generation, heat distribution and the public electricity grid. Assumptions have to be made for all of these values reflecting a predefined future year.

- Difficulties / Questions to be answered
  - Estimation of data for future years for a district heating system (mainly plant capacities and full load hours)
  - Estimation of data for future years for the public electricity grid so that it is accepted by the district heating utilities and authorities
  - Method for verification between roadmap of district heating utility and estimated data

- Heat distribution and transfer system

  - Calculation in a nutshell

The heat distribution and transfer system of a building should be characterised by the necessary supply line temperature and the expectable return temperature. Both values should represent temperatures at the supply side for a central heat supply system, even if such a system is not currently in place. The basis for the calculation is the necessary heat load of the building. Via the available heat transfer area in the building, the maximum temperature at the end of the supply line is calculated. The temperature losses in the heat distribution system are then estimated via the isolation, length and location of the supply lines. The temperature reduction in the return line, on the other hand, is estimated based on the existing control system of the heat distribution system.

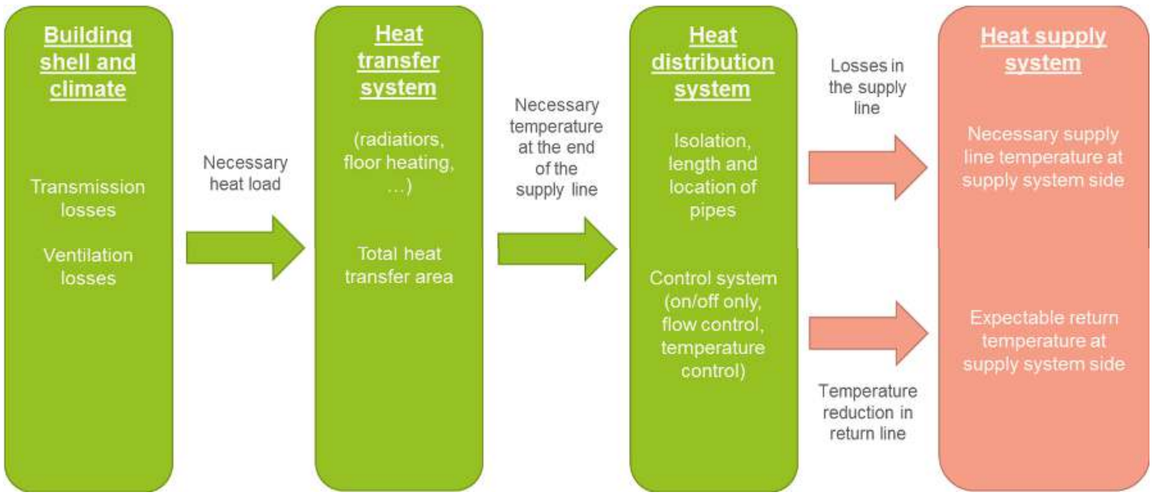

Figure 30: Calculation flow for second method

Figure 30 shows the input data and information needed for the calculation distinguishing between the building shell and climate, the transfer system and the heat distribution system. While some of the needed input data is already used in current EPC calculations, other parts are new, like heat transfer area or control systems for temperature reduction in the return line.

- Difficulties / Questions to be answered
  - Estimation of the correlation between the control system type and the temperature reduction in the return line
  - Estimation of suitable correction factors between theoretical and practical values in general

7 FINDINGS

This section presents a summary of key findings (Table 32) 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 32: 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	Implement ation of a certificatio n 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 measurement s	Estimation of filter classification 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	Monitoring and operation	Thermal comfort and	Pollutant emission and	Real energy consumption	All indicators

performance	at the building level and improved interoperability with the grid	indoor air quality have a strong link with energy performance	indoor air purity have a strong link with building thermal and installation characteristics	directly links with energy performance and additional operational (energy) performance Potentially contributes to mitigation of energy performance gap	have a strong link to the energy performance of the building

8 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.

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ANNEX 1

Feature 4: Real energy consumption

Building-level detailed approach methods

Method overview

Different detailed methods for determining building energy performance or related parameters for use in evaluation methods based on measured data during normal operating conditions are described in this annex. An example is the determination of the global as-built heat loss coefficient (HLC) [123].

Determination of the in-use HLC by average method does not require a detailed physical model of the building. Only the total area of the windows and scheduled occupancy data are required [141] in addition to the already widespread monitoring data (e.g. indoor temperature, weather conditions, heating system energy inputs and electricity use). The HLC is defined based on the energy balance equations using this input data. However, the accumulation term and the solar gains are hard to estimate accurately. Careful setup of the boundary conditions of the experiment (e.g. the weather conditions of the testing period and the indoor temperature conditions) can remedy this. In simple steady-state models, the parameters are found using classical methods for linear regression [142]. Such steady-state techniques provide sub-optimal use of the information embedded in the data and provide information only about the heat transfer coefficient and gA-values.

Energy signature models are a data-driven models that express heating energy consumption in function of weather variables [112], e.g. heating degree days (HDD).

$$Q = c_1 + c_2.HDD + \varepsilon_t$$

where

- Q heating energy consumption
- C_1 coefficient representing the baseline energy consumption [kWh]
- C_2 coefficient representing the heating energy consumption per degree temperature decrease below the base temperature [kWh]
- HDD heating degree days [-]
- ε_t error term [kWh]

Coefficients c_1 and c_2 define the energy signature. Coefficient c_2 defines the relation between the energy consumption and the heating degree days and is an indicator for the whole building heat loss. Coefficient c_1 is an indication of the weather-independent energy consumption (if the base temperature is estimated correctly) [108]. The energy signature can be used to evaluate the overall heat transfer coefficient of the building which is equal to the regression coefficient of the energy consumption – exterior temperature relation, divided by the heat loss area of the building and the base temperature [112]. The base temperature is the temperature above which no heating is needed considering the heat gains. It is mostly used to correct for outdoor climatic conditions to compare energy consumption for different years or to a reference. Classical energy signature models fall short in identifying other constituents than energy consumption for heating (those that are not related to weather conditions)

Energy signatures are the most well-known data-driven energy consumption models and are typically applied when occasional meter readings of the gas or heat use are available (yearly or monthly values). They are only useful if measurements include space heating energy consumption. Energy signature models are static models that do not account for time-dependency of the data. Data should be aggregated to at least one day (although some experts recommend longer time periods). For time intervals shorter than one day, dynamic models are recommended. The assumptions made for application of linear regression are not always satisfied: Annex 58 subtask 1b report [112] describes two approaches to mitigate these issues; namely robust regression of heating load curve based on Q-Q plot as proposed by Ghiaus [143] and linear regression considering dynamic and solar gain effects [143]. Such methods also are referred to as pseudo-dynamic linear regression models in which a dynamic correction is added to the regression (see Figure 31).

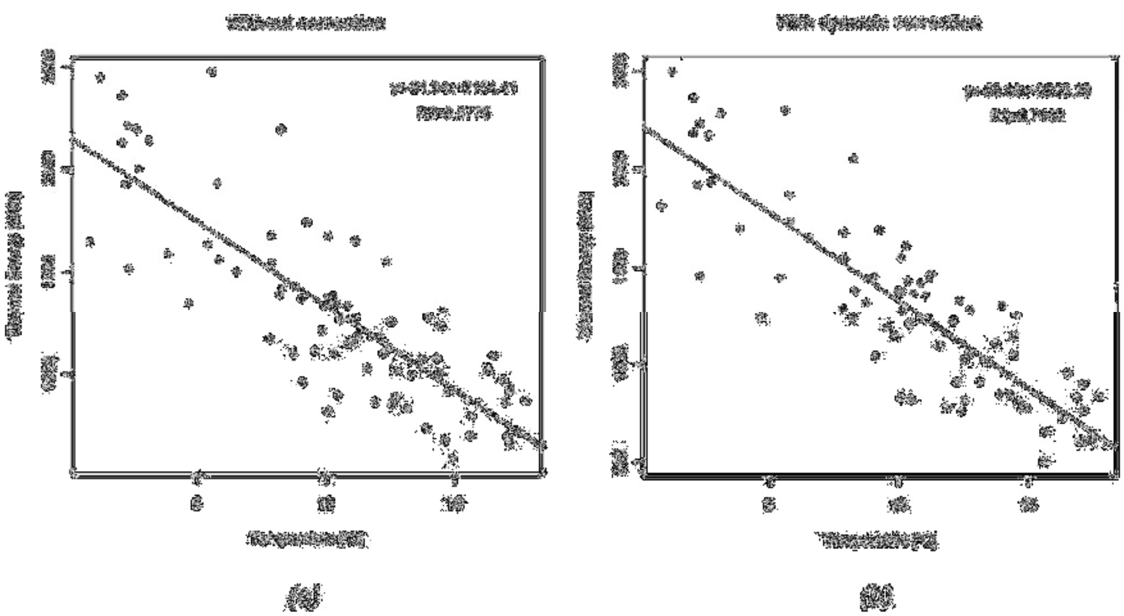

Figure 31: Total heat transfer coefficient determined from energy signature (daily data), (a) with and (b) without correction for the dynamic effect [143]

Auto-regressive models with exogenous inputs (ARX-models) provide information about the HTC and gA-values as well as some limited information about the dynamics, usually expressed as time-constants [142]. ARX can be classified as black-box models; they describe the external relations between the inputs and the outputs of the system, although the structure is often also based on the heat-balance equation of a building. Similar methods as used in classical linear regression such as ordinary least squares method is used. In addition to the (weather) input variables ('exogenous inputs'), time lags of the output variables are added as input variables in the model, so called auto-regressive inputs

[108]. These serve to deal with the dynamical properties of the system. ARX is more accurate for estimating energy consumption of a full heating season compared to classical linear regression models. ARX is also applied for real-time forecasting purposes. Dynamics can be captured in ARX models with data at hourly or daily time steps. Also, interior temperature is usually an input in most examples in the literature.

Grey-box modelling is a modelling approach where prior physical knowledge is combined with data-driven statistical modelling techniques [144]. Data with high time-resolution is used representing the dynamics of the building and both linear and non-linear effects can be modelled. In a grey-box model a set of continuous stochastic differential equations (SDEs) describing the thermal dynamics of the building are combined with a set of discrete measurement equations to form a continuous-discrete time state-space model (CTSM). The stochastic differential equations describe the physical model, usually linear R-C networks for building or building components (see Figure 32Error! Reference source not found.).

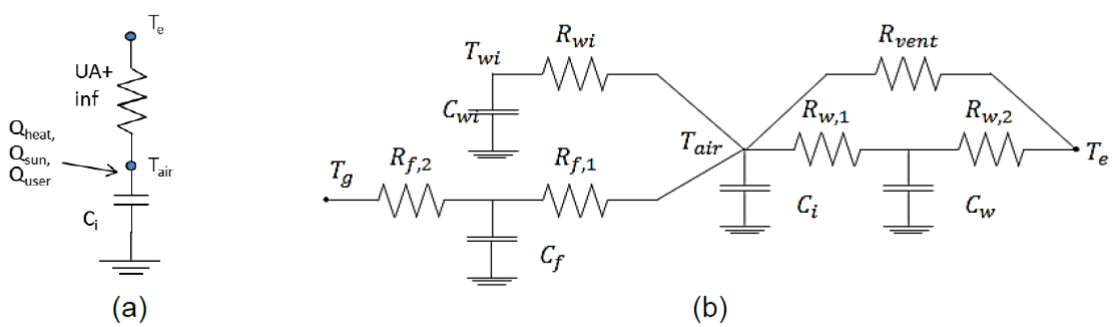

Figure 32: Examples of electric analogy of R-c network of (a) first order model and (b) fourth order model

The model parameters are directly interpretable as building physical properties (heat transfer coefficients, thermal capacities, solar aperture, wind-induced infiltration). A parameter estimation scheme for CTSM is freely available in the open source R-package CTSM-R[11]. For a basic setup, measurements are needed for indoor air temperature, heat input, outdoor air temperature, global radiation and wind speed and direction. Indoor air temperature monitoring is usually part of the building energy monitoring system but can alternatively easily be installed as one or more separate sensors. Heat input data is generated by heat sensors, ideally for each application separately (domestic hot water and space heating, etc.), but can also be derived from gas or electricity use monitoring. The other parameters can be obtained from an on-site weather station with air temperature, wind speed and direction sensors and pyranometer. Furthermore, the dynamic response of the building needs to be captured by the measurements, which can ideally be obtained from dedicated heating experiments on the unoccupied building.

[11] http://ctsm.info

Grey-box methods in general deliver more reliable and accurate results at the cost of more detailed input compared to ARX. However, if the purpose of an experiment and the subsequent modelling is to provide only the stationary parameters, for instance the HTC, then it might be overkill to consider the grey-box models over the input-output models [142]. As in many fields, in recent years artificial intelligence (AI) in general and more specifically machine learning techniques have been proposed to forecast building energy consumption and performance. Machine learning can be categorised as black-box models and consists of computer algorithms that learn from existing data. The learning process can be supervised or unsupervised. A review [109] is available that describes the four main machine learning approaches: artificial neural network (ANN), support vector machine (SVM), Gaussian distribution regression models, and clustering. It also describes feed forward networks (FFN), radial basis function networks (RBFN) and recurrent networks (RNN). Time series decomposition approaches can be used for diurnal profile recognition. This can be done based on hourly data. Event detection, appliance signature generation and (constant cyclic or peaking) pattern recognition techniques can be used to identify different constituents of energy consumption e.g. separating domestic hot water from space heating energy consumption by applying smoothing techniques after assumption that domestic hot water demand causes large spikes in the time series. This requires high frequency data with time steps of 1–10 minutes. Additional measurements are needed compared to ARX (e.g. interior temperature).

Calibrated simulation methods use dynamic energy balance computation together with measured data to determine the energy performance. Figure 33Error! Reference source not found. depicts the principle of calibrated simulation using measured data for outdoor climatic conditions and use and operation of the building [100].

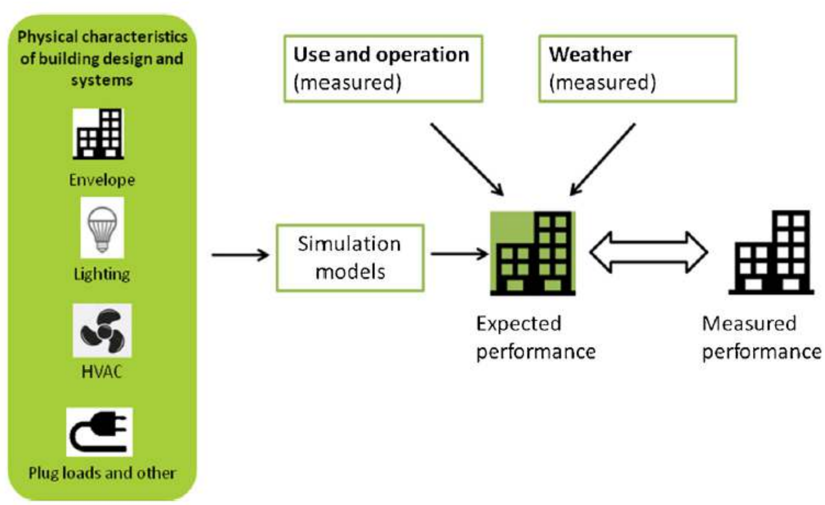

Figure 33: Evaluation of energy performance in existing buildings by calibrated simulation [100]

Simulation often requires iteration to reach desired levels of accuracy and the results are highly dependent on the level of expertise of the practitioner. The use of calibrated simulation methods has been shown to be effective, but requires significant effort and a range of problems have been detected concerning standardisation, complexity, accuracy of inputs, uncertainty evaluation and automation [100]. At the current stage, therefore, calibrated simulation is less suitable for integration in EPC frameworks and is to be reserved for complex evaluations involving several interlinking efficiency measures.

- Selection of methods suitable for EPC: determination of the heat loss coefficient

This chapter contains a brief description of the concept of the determination method of the whole building heat loss coefficient (HLC). It is considered the most promising building-level detailed approach method for implementation in EPC schemes in a near-future context.

This method is based on the method to determine the whole building HLC as analysed in the frame of IEA EBC Annex 71. The HLC describes the thermal insulation quality (including thermal bridges) and airtightness of a building envelope in a single factor [145]. It also captures the dynamic behaviour of the building to some extent (depending on the analysis method). It can be used as an input in calculation methods to determine the energy performance of the building (unit). The main advantages of inclusion of the HLC based on on-board monitoring are simplification of inspection procedures and increased accuracy. Quantification of user influence on heating demand is also possible. If the accuracy of the HLC can be improved (<10%) implementation of HLC for quality control purposes or direct certification of the energy performance of the building envelope can be considered. The method is described for residential buildings, but can also be applied to non-residential (with optional ventilation measurements).

- Visualisation of the characterisation method

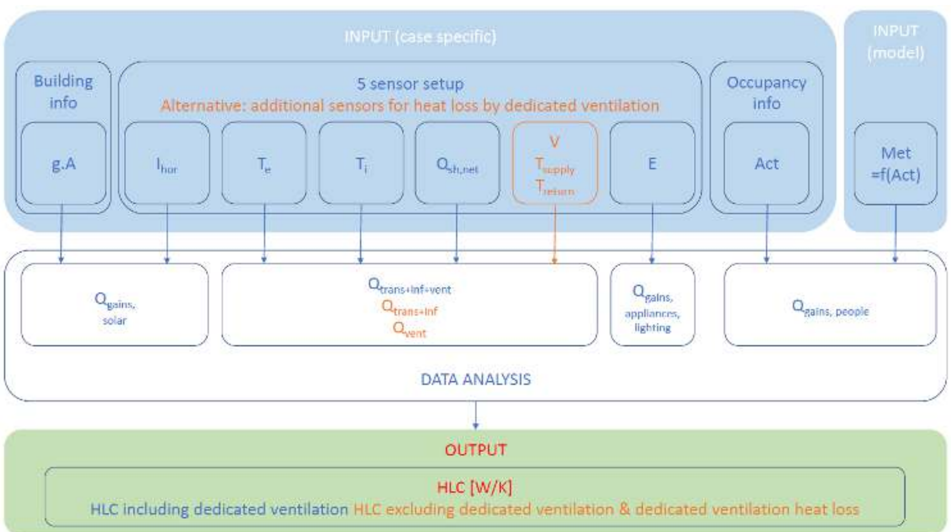

Figure 34: HLC calculation process

- Input parameters

Six main variables are shown to have a large impact on the HLC estimate: the net heat input for space heating, the solar gains, the internal heat gains, the heat losses by intended ventilation, the interior temperature, the exterior temperature. For an accurate estimation of the HLC, each of these variables must be adequately represented by data collected by the sensor setup. With a reduced monitoring setup – the five sensor setup [145] – an accuracy <35% can be reached. This does not require prior knowledge of the envelope performance, geometry or occupants, although limited input of building and occupancy information can contribute to augmented accuracy.

The five-sensor setup is used for monitoring following parameters:

- T_i Indoor air temperature [°C]: Living room air temperature sensor
- T_e Outdoor air temperature [°C]: Local air temperature sensor
- I_{hor} Global horizontal radiation [W/m²]: Local pyranometer
- E Electricity use [W]: Electricity smart meter
- $Q_{sh,net}$ Net energy for space heating [Wh/h]: Heat meter

Additional sensors for monitoring of ventilation heat losses (optional):

- $Q_{ventilation}$ Ventilation heat loss [Wh/h]: $\dot{V}_{vent}$, T_{supply} and T_{return} (and $\eta_{th,HRU}$ if any)

Building info:

- *g.A* Solar absorption [m²] (1 value to be fitted by analysis model)

Occupancy info:

- *Act* Activity level profile per occupant

Data analysis is done using an ARX model preferably. Grey-box modelling (building physical model (RC) with statistical analysis) can also be considered.

Stock-level model development methods

The stock-level model development approach consists of top-down methodologies that use statistical techniques on datasets of multiple buildings. The purpose of these models can be to improve or validate existing methods, develop alternative models or set benchmarking levels for evaluation. These concern the energy consumption or performance of a building, a part of a building, its systems or building components. This annex contains a description of the most important purposes of stock-level models and the methods to develop such models.

Figure 35Error! Reference source not found. depicts the principle of evaluation of building performance by comparison with statistical benchmarks [100].

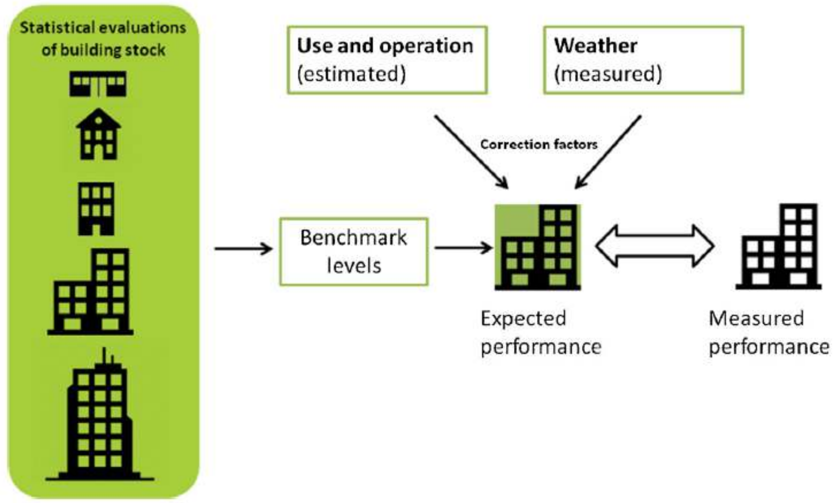

Figure 35: Evaluation of building performance by comparison with statistical benchmarks [100]

The datasets can also be used for the monitoring of policy measures in view of achieving the long-term objectives related to energy performance of buildings or to quantify and explain the energy performance gap. A review [100] of a variety of statistical techniques that have been used for these purposes contains a brief description of the principal statistical methods for benchmark development and evaluation of building energy performance. A summary of the applications is included in the following Table 33 adopted from this review study.

Table 33: Summary of principal statistical methods for benchmark development and evaluation of building energy performance [100].

Algorithm	Applications
Simple and multivariate linear regression	Simple models for building performance based on a few characteristics
Change-point regression	Model the non-linear effects of external conditions, e.g. below a certain external temperature, heating systems are switched on
Gaussian process and Gaussian mixture regression	Prediction of dynamic performance, with an understanding of uncertainty. Flexible models, but more complex
Stochastic frontier analysis	Effective when there are large numbers of efficient buildings and a few that inefficient. Outliers may make the method ineffectual, as residuals will be large
TOPSIS	Can be used to develop effective benchmarks, based on regressions
Data envelopment analysis	Evaluates the technical efficiency and improvement potential of buildings. Can only be applied to buildings within the original dataset
Correction factors	Relate building performance to physical

	parameters, useful for benchmarking

Machine learning techniques that have been applied to predict and evaluate energy performance in different situations, such as for the development of energy performance benchmarks, are also described, including artificial neural networks and clustering analysis. These techniques are listed in the review paper specifically for application for non-domestic buildings, but the methods can be used for domestic buildings as well. Examples of studies applying these techniques are included and referred to in the review study [100] .

Illustrative examples of benchmark development using linear regression can be found in the US and Canada (Energy Star Rating and portfolio manager building energy performance benchmarking system for commercial buildings, also applied by LEED certification for operation and maintenance of existing buildings), Australia (National Australian Built Environment Rating System (NABERS)) and the UK (TM46 [62]) [115]. In the TABULA and EPISCOPE projects [146], stock models are developed for residential buildings based on synthetical average buildings (theoretically developed archetypical buildings) for building stock relevant subgroups. These can be used for benchmarking to compare distinct, real buildings or be used for basic scenario analysis. To account for the energy performance gap, the calculated energy consumption of the average buildings is calibrated by adaptation factors derived from measured values for energy consumption per energy carrier. In the final EPISCOPE report different sources to obtain this data are mentioned: national/regional energy balances, national registries, data from energy suppliers, EPC data or own field surveys. However, wide information gaps concerning the actual state as well as the trends concerning building thermal insulation and energy supply systems were identified. Recommendations to improve the data situation by applying regular monitoring concepts were compiled [147]. The importance of inclusion and verification of energy consumption data for the calibration of building stock models is emphasised, adding proof to the relevance of monitoring infrastructure and data acquisition in the built environment. The resulting tools can be used for policy guidance and continuous monitoring of energy performance in the building stock in relation to the targets. Furthermore, in the frame of the EPISCOPE project, a pilot study of the municipality of Sønderborg in Denmark examined how the energy savings mentioned in EPCs issued before and after refurbishment activities can be validated against energy consumption measurements [148] .

The concept of hubs specifically on building energy renovation is explored in the frame of the Request2Action project. Real energy consumption can be part of the information gathered by national hubs on building energy renovation or related tools such as home energy check tools linked to databases. This data can be used to formulate refurbishment advice or for the calibration of calculation models to mitigate the energy performance gap. Examples of energy renovation hubs or home energy check tools that include the gathering of real energy consumption of households can be found in Belgium (ZetJeWoningOpDeKaart tool), Italy (Portale4e), the Netherlands (VerbeterUwHuis tool), Portugal (Portal CasA+) [149] and the UK (SMAP tool) [150]. Furthermore, the Zeus database system by the federal states of Salzburg, Styria and Carinthia in Austria, records actual energy consumption for comparison with calculated energy demand [148].

In the pilot projects of Request2Action [148], the Netherlands Enterprise Agency has carried out a study [105] comparing the calculated energy demand of the EPC and the real energy consumption (as a base for financing the retrofits), describing deviations and underlying causes. In the EU project EPATEE tools and knowledge are disseminated to EU Member States for a better evaluation of their energy efficiency policies. One of the main topics subject to study in this frame is the difference between the actual and calculated energy consumption and the consequences for the energy savings achieved on the level of the building stock. Examples of these studies include the Netherlands and the UK. In the QUALICHeCK project, EPCs and quality of works compliance frameworks were analysed. In a pilot study in Sweden [151], the difference between measured and calculated energy consumption in EPCs versus building permits was studied.

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