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1 Executive Summary

The **Energy flexible DYnamic building Certification** (E-DYCE) project aims at pursuing the following main objectives:

S01. To deliver a methodology for dynamic certification of buildings based on openly available resources and tools for technology and service providers, effectively creating an evolving, technology neutral ecosystem.

SO2. To generate substantial saving (about +1 energy class) in buildings certified through a dynamic scheme, benefiting owner, tenant/user and the service provider and thus incentivizing all three.

SO3. To leverage the savings generated and reinvest in energy efficient refurbishment and optimisation, scaling up the number of buildings certified to the level that can provide policy makers with meaningful data.

During the project, a methodology for an hourly certification of buildings will be defined. Additionally, E-D-DYCE specifications will support operational optimisations considering energy consumptions, comfort conditions and renovation roadmaps. The approach faced in this project aims at combining different levels of smartness (from low-tech to high-tech) including the valorisation of the Free-Running potential of buildings. This specific issue will allow for a full inclusion of traditional and historical buildings in energy certification.

Deliverable 1.2 – "Definition of dynamic and operational EPC specifications" introduces main E-DYCE challenges connecting the issues treated during the project with the EPBD 2018 Directive.

In particular, the following main open issues will be detailed in **Section 2** of this report:
1. Free-running and passive technologies;
2. The smart readiness vision;
3. Energy metering and district network communication;
4. Dynamic hourly models and performance gap; and
5. Renovation and operation roadmap.

These issues are localized in the EPBD background and analysed for the current state of the art. Furthermore, for each issue are underlined the main E-DYCE specifications, including relevant indicators or methodologies.

- Concerning Free-running (FR), two FR modes are identified: mode A – when the building does not have heating/cooling systems, and mode B – when systems are turned off. Furthermore, comfort evaluation models are detailed in line with current Standards and different methodologies to calculate fictitious energy uses of FR buildings are reported.

- Focussing on the smart readiness vision, a general introduction to the smart building vision is reported, while the Smart Readiness Indicator is described in line with the EU Delegate Act. E-DYCE potential correlation with SRI is also discussed.

- Considering energy metering and district network a calculation methodology is detailed together with a background on progressive diffusion of smart energy metering.

- Furthermore, different energy performance gap indices are reported and methodologies to adopt calibrated dynamic models to check operational rating shortly introduced.

- Finally, a reminder of the approach that E-DYCE will follow to define renovation and operational roadmap is reported considering hybridisation from a past EU project. In this approach, different renovation scenarios will be compared, by using the E-DYCE hourly simulation module, to define optimized solutions.

Additionally, **Section 3** introduces main E-DYCE specifications, the logical followed approach and correlated E-DYCE modules and services. In this section the open, scalable and technology-neutral E-DYCE vision is presented and potential end-users are shortly identified. Furthermore, E-DYCE verification approaches based on KPIs are shortly introduced. KPIs are grouped into the following main families:

1. Energy and energy efficiency (including reduction in energy needs);
2. Free running operation and potential exploitation (including temperature performances);
3. Comfort/quality (including thermal comfort improvement, indoor air quality and visual comfort);
4. Smartness readiness; and
5. Correlated indicators (including Energy demand forecast; Economic indices; and Climate change impact indices).

Section 4 is devoted to collect a large list of key performance indicators (KPIs) and to identify the most important ones to be eventually implemented in E-DYCE prototyping approaches (1^{st} order of importance). A general overview of mentioned KPIs is given together with tables of comparison. For each mentioned KPI is given a short explanation and calculation methodology/expression. Secondly, the required inputs to calculate/monitor KPIs are given.

Main E-DYCE issues will focus on hourly energy certification and on comfort analysis (including an IEQ approach) to valorise the FR usage of buildings. KPIs will be further investigated in the next deliverables, and most important ones will be included in the E-DYCE platform considering given calculation/monitoring inputs.

2 General localisation of main E-DYCE innovations in the EPC background

2.1 *E-DYCE DEPC introduction*

2.1.1 E-DYCE main objectives (remind) and objectives of the report D1.2.

E-DYCE, Energy flexible Dynamic building Certification, focusses on the development of a dynamic certification of buildings, supporting real time optimisation of energy consumption and comfort and addressing also renovation roadmaps. Additionally, the E-DYCE logical approach combines smart technologies with low-tech solutions including the valorisation of the free-running potential of buildings in EPC labelling. This specific point is essential, not only to reduce energy needs and valorise climatic-conscious passive techniques, but also to take into account and valorise historical buildings and traditional buildings especially in Mediterranean areas, which rely, among other solutions, on natural ventilation. E-DYCE will also present a strong focus on end-user changes in behaviour and on the personalization of E-DYCE outcomes for different end-users, i.e., tenants and users, building operators, owners, etc., to collect feedbacks on building performances and recommend adaptation and retrofitting actions toward a reduction in energy uses and an increase in energy performance of end-users' living spaces.

Several aspects will be faced during the project and this deliverable (D1.2) aims to define dynamic and operational EPC specifications, focussing mainly on the introduction of E-DYCE-covered open issues and on their connection with the EPBD-2018 Directive – see Section 2. Additionally, this deliverable introduces a definition of verification KPIs for the mentioned domains – see Section 3 and 4 –, which include free-running and passive technologies for building comfort and lower energy usage, the smart readiness visions, the usage of energy metering and district communication supporting information and optimisation actions, and the adoption of hourly dynamic models increasing feasibility and reducing performance gaps by combining monitored and calculated indicators. The E-DYCE vision – see Section 3 – is conceived to be open, scalable, and technology neutral, and includes different potential configurations being able to be adapted to different user profiles and smartness levels, from low-tech (traditional buildings with minimal probes) to high-tech (advance services including previsions). E-DYCE allows for an operational and dynamic approach supporting user satisfaction, working on user information and expectations, and defining different KPI levels and aggregations according to service configurations and specific end-user requests.

2.1.2 EPBD-2018 considered issues

Section 2.1.2 underlines major points of EPBD 2018 that will be faced during the project, and main issues in which EDYCE will contribute/support additional compatible approaches. Additionally, E-DYCE will test and consider several indicators, in line with point (41) of the Directive EPBD-2018 (The European Parliament and the European Council, 2018), to analyse potential solutions to support the following list of main issues.

> "(41) … Member States are able to choose to further supplement this by providing additional numerical indicators, for example for the entire building's overall energy use or greenhouse gas emissions."

Main open issues that are planned to be faced in E-DYCE will concern:
- Free-running and passive technologies;
- The smart readiness vision;
- Energy metering and district network communication;
- Dynamic hourly models and performance gap; and
- Renovation and operation roadmap.

Each of these issues is detailed in the following points of this Section.

Further issues, concerning a customized approach for different end-user profiles, are introduced in Section 3 demonstrating the versatile vision proposed by E-DYCE.

2.2 *Free-running and passive technologies*

Directive 2018/844 of the European Parliament and of the Council states that:

(15)

> "*It is important to ensure that measures to improve the energy performance of buildings do not focus only on the building envelope, but include all relevant elements and technical systems in a building, such as **passive elements** that participate in **passive techniques** aiming to **reduce the energy needs for heating** or **cooling**, the energy use for **lighting** and for **ventilation** and hence **improve thermal and visual comfort**.*"
>
> DIRECTIVE (EU) 2018/844 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency.

Point (15) underlines the importance of supporting and improving the adoption and the valorisation of passive techniques and connected elements able to reduce the energy needs of buildings for heating, cooling, lighting and ventilation. Furthermore, it underlines the need to support passive techniques to increase thermal and visual comfort in building spaces.

Considering current energy consumption trends, a clear rise in energy needs for space cooling was underlined. In 2010, global consumption for cooling reached 1.25 PWh and, in the same year, the cooling consumption of the residential sector was 4.4% of total cooling and heating needs in the building sector (Harvey et al., 2014; Santamouris, 2016). This ratio is estimated to reach, at European level, 35% in 2050 and 61% in 2100, a growth that is principally due to the rise in cooling loads (Chiesa, 2017a; Isaac and van Vuuren, 2009; Santamouris, 2016). For example, in the USA, air-conditioning systems consume about 400 TWhel each year, an amount that corresponds to 40billion dollars (Akbari, 2007), while in the EU energy consumption for cooling is expected to surpass 44,430 GWh by 2020 corresponding to 18.1 millions of CO_2-eq tonnes (Adnot, 1999). Roughly speaking, in parallel to a constant growth in cooling energy needs, it is also underlined that the possibility to exploit potential free-running cooling in buildings, but also free-running heating and ventilation, is strongly untapped and the valorisation of local FR potentials it not sufficiently supported by regulations or certifications.

For this reason, E-DYCE considers all passive techniques mentioned in EPBD 2018, i.e., for heating, cooling, lighting and ventilation, but will include a specific focus on low-energy and passive approaches for space cooling and ventilation based on the maximisation of passive heat gain prevention, modulation and especially dissipation techniques. In any case, it is essential to remember that the E-DYCE followed approach is conceived to be technology neutral, focussing on a performance and methodological vision rather than to the application of a list of predefined specific technologies.

2.2.1 What is a free-running building

As mentioned before, the proposed DEPC approach will be able to consider the calculation of the free-running potential of buildings in their energy performance. At present, in fact, the free-running building mode is not sufficiently considered in the EPC, e.g., it is not possible to label a building without a heating system, although the certification may be released in some national/regional applications by considering a standard fictitious heating system with low efficiency. Furthermore, current steady-state approaches adopted in several national technical standards for EPC do not allow to correctly define the cooling potential of several low-energy technologies, such as ventilative cooling strategies, while the benefit of free-running ventilation (and of ventilative cooling in general) is rarely included in standard rating conditions – see for example (Plesner, 2018). This is evident by current ongoing discussions and efforts in updating current national regulations adopting new EU standards, CEN M/480, e.g., EN ISO 520016-1:2017, focussing in particular on the possibility to increase the performance of the estimation of cooling needs in buildings. Nevertheless, the social and economic impacts of the passage from steady-simple approaches to dynamic energy performance certification (DEPC) need to be considered – e.g. (Murano, 2020) –. Furthermore, the need to speed up dynamic calculations (with hourly or sub-hourly temporal granularity) to correctly define overheating phenomena in buildings was underlined by several researches on passive and low-energy cooling strategies, including the works of IEA EBC Annex 62 on Ventilative cooling (Heiselberg, 2018; Holzer and Psomas, 2018; Kolokotroni and Heiselberg, 2015).

Hence, it is essential to valorise the possibility to largely include natural and low-energy technologies in building energy performance analyses, especially concerning cooling needs, thanks to a dynamic approach. This vision aims at considering and valorising the potential of these solutions. Furthermore, the same approach may allow to i. consider traditional house management for reaching comfort – e.g., the ability to manage houses in southern countries to reach summer comfort conditions without air conditioners, ii. increase social inclusion, and iii. positively impact the real estate market. The ability of people to react toward restoring comfort conditions under discomfort (Nicol et al., 2012) includes the possibility to take advantage from the different thermal behaviours of each building space – potentially including semi-outdoor and outdoor spaces, e.g. (Du et al., 2014) – under free-running conditions, which is characterising traditional usages of houses, for example in Mediterranean climates, e.g. (Chiesa, 2019a). According to space orientations and seasonal variations, tenants of traditional houses adapt to climatic conditions including changes in space scheduling and usage (e.g., winter gardens, summer pergolas, ...) following a bioclimatic building operation. This vision differs considerably from the one of mechanically controlled spaces, being a mechanically controlled residential unit working on fixed temperature set points.

The inclusion of free-running issues in building modelling and monitoring requires large efforts to overcome several challenges. These challenges include, among others, the definition of specific key performance indicators (KPIs), the definition of methodologies for their verifications in both simulation and monitoring phases and the assessment of standardized methods to include FR issues in reference buildings, considering design, asset and operational ratings, thus opening the path toward their translation in potential standards. This project mainly refers to KPIs and basic definitions of specifications for free-running valorisation in energy performance analyses. E-DYCE will adopt a dynamic simulation approach following current standards and will utilize, during simulation phases, existing hourly energy simulation tools, such as EnergyPlus and Dial+. Where dynamic is here considered as hourly-simulation approach.

In order to introduce E-DYCE free-running specifications, a basic definition of what is a free-running building is needed. It is hence possible to state that a building is working in free-running (heating and/or cooling seasons) when one of these two following modes is set:

A. Mechanical systems are not installed; or
B. Mechanical systems are turned off.

Mode A includes not only vernacular buildings, but also traditional and heritage buildings. For example, typical residential units in southern European Mediterranean areas, such as in hottest areas of Apulia and Sicily (Italy), they do not have a heating system, being local-climatic heating needs very limited and eventually covered by small movable equipment (e.g., electric personal stoves). In Italy alone, 8.6% of buildings do not have heating installed (ImpresEdilNews, 2015; ISTAT, 2013; TECNOBORSA, 2015). Additionally, the certification process of traditional heritage buildings without a heating system, e.g., with only a fireplace installed, is still an open issue. For example, in Italy the D.Lgs. 192/2005 (and further modifications) supports the adoption of a virtual heating system characterized by a mean statistical COP in order to define a virtual energy need (Certificazione-Energetica.it, 2017). The EPC will report the usage of an equivalent heat generator system, although Regional legislation may suggest different approaches, like avoiding the EPC-definition for these buildings. Similarly, focussing on the cooling season, the penetration of the air conditioning market in Europe is low, i.e., in the residential sector this index arrives to about 8% (Santamouris, 2019, 2016), suggesting that these spaces are working in free-running, with the exclusion of small movable equipment (e.g., personal fans, movable small coolers, etc.). The majority of residential and small office spaces in the European building stock do not have a mechanical cooling system, adopting other cooling strategies such as ventilative cooling solutions. This suggest that a methodology to include a performance definition of their behaviour will support not only the valorisation of untapped cooling potential of free-running technologies, but also a positive evaluation and certification of traditional and historical buildings in line with their FR potential exploitation.

Similarly, Mode B mainly refers to neutral thermal periods in which nor heating neither cooling systems are operated, being the ambient conditions favourable to maintain internal comfort. Nevertheless, Mode B also includes hybrid and intelligent management of mechanical systems, considering the possibility to use them only when natural and low-energy strategies are not sufficient to reach the desired comfort thresholds, e.g., during the hottest hours of a summer day. The possibility to valorise, in the E-DYCE DEPC approach, indicators supporting the free-running mode of a building, is expected to also support the adoption of smart hybrid solutions and reduce the number of operation hours of equipment (and consequent energy needs and $CO_{2\text{-eq}}$ emissions) without losing comfort conditions. Furthermore, a dynamic management of free-running mode, may also support a smart control of overheating phenomena, taking into account the free running potential, i.e., ventilative cooling, also in new nZEB buildings. Several recent studies, have in fact underlined that overheating phenomena were now underlined in the winter season and in neutral thermal periods, especially in totally insulated buildings with a perfect airtightness, not only in southern countries, but even in northern and colder European territories (Flourentzou and Bonvin, 2017; Kolokotroni and Heiselberg, 2015; Larsen et al., 2012).

Mode A and Mode B are characterised by a different vision, and for this reason these two modes will firstly subdivide E-DYCE labelling approaches and the related list of KPIs. Mode A, will mainly refer to comfort evaluations, with potential inclusion of the risk for mechanical system installations, while Mode B, will mainly refer to energy needs and reduction of energy uses due to the inclusion of passive technologies, being their usage potentially activated in alternative to mechanical systems or in mixed intermittent heating or cooling mode (see the definition in EN ISO 52016-1:2017 (EN ISO, 2017a)).

For Mode B, discomfort conditions that may occur under continuous free-running operation (during occupied hours) will be transferred into fictitious energy needs in order to compare scenarios and buildings especially in design and asset rating. Furthermore, the positive effect on the heating/cooling needs due to controlled free-running activations will be considered and valorised (e.g., night ventilative cooling during hours in which the mechanical system is not operating).

In Mode A, a similar approach may be followed by defining a free-running DEPC that may be potentially comparable with mechanical buildings, e.g., by adapting the methodology suggested in ISO-TR 52018-2 Annex D (CEN ISO/TR, 2017) to integrate fictitious cooling usages into the overall indicators of the building's energy performance. It is important to state that in E-DYCE, in line with suggestions for naturally ventilated spaces, a parallel approach evaluating the comfort performance of buildings will be adopted in respect to the mechanical comfort theory, considering adaptive comfort models (see §2.2.2). This approach will be used in Mode A, but also in Mode B when free-running mode is working in a continuous cycle during occupational hours (considering a continuous activation of the FR mode for a sufficient time to not be characterized like simple intermittent mode). Roughly speaking, Mode B will represent the majority of buildings if the subdivision is made at a yearly base. Nevertheless, by downscaling this subdivision at a seasonal base, we can expect to have, especially for residential and small office buildings, free-running Mode B in the heating season (e.g., for building with a heating system and the usage of FR in a limited number of hours or days in which mechanically heating is not needed to maintain the required set-point(s)), but free-running Mode A in neutral and cooling seasons (e.g., in buildings with a heating system, but without cooling systems). Furthermore, considering this seasonal subdivision, and focussing especially on the cooling season, it can be possible on the one hand to define the seasonal (or different time-step) fictitious energy usage, but also, on the other hand, to adopt an alternative performance analysis and comparison methodology among buildings, by following an opposite approach: transferring building energy needs into virtual discomfort values.

Table 1 – Considered FR Modes

Mode	Heating system	Cooling system	Rating mode*	Design/Asset	Operational
A	No	No	Rating will be based on Comfort indicators. Fictitious energy usages will be defined for comparison with buildings not using FR mode.	Comfort Fictitious energy	Comfort
B.1	Yes	Yes	Rating will be based on energy usages. Fictitious discomfort may be defined for comparison with FR buildings. The free-running	Energy (fictitious comfort)	Energy FR activations

			behaviour will be divided into short operational periods (intermittent mode) and long periods of operation.		
B.2	Yes	No	Winter performance evaluations will be based on energy rating, while summer evaluations on comfort rating. Fictitious summer energy needs are calculated using the approach followed in FR Mode A. In winter, the methodology used for FR Mode B.1 is adopted.	Energy (winter+ fict. summer) Comfort (summer)	Energy Comfort FR activation
B.3	No	Yes	In Summer building evaluations will adopt the energy rating, while in winter comfort rating will be assumed. Fictitious winter energy needs are calculated adopting the approach of FR Mode A. In summer, the methodology used in FR Mode B.1 is adopted.	Energy (summer+ fict. winter) Comfort (winter)	Energy Comfort FR activation

*During the project different methodologies to evaluate the fictitious cooling/heating needs (see below) will be tested for each Mode following a SWOT approach and elaborating data from Demos and large set of simulations using the E-DYCE parametric dynamic simulation module.

2.2.2 Thermal comfort models for free-running buildings

Thermal comfort is one of the most important attributes of a building, probably the second one after stability, being the "primary function of a building to provide shelter" (Nicol et al., 2012). This consideration is in line with philosophical and theoretical architectural visions – e.g., the reflection on primitive huts by the abbé Marc-Antoine Laugier in the XVIII century – and confirmed by studies on vernacular architectures and bioclimatic archetypes – see for example (Ferrari, 1925; Rudofsky, 1977; Sayigh, 2019). Furthermore, one of the most relevant issues for building occupants is to get the right temperature in their living spaces. Nevertheless, thermal comfort is directly related to different domains: thermal physiology (heat production and usage in humans), physics (heat transfer from body skin to the environment), sociology (reactions to the environment), and building fields (space design to better guarantee thermal user requirements). Similarly, it is possible to identify different thermal comfort definitions based on different visions. For example, thermal comfort can be defined following a physiological approach as the "absence of driving impulse from cutaneous and hypothalamic receptors causing the body to counteract with physiological adaptation" (Benzinger 1979 in (van Treeck and Wolki, 2019)). Similarly, it is also referred as the "condition of mind, which expresses satisfaction with the thermal environment" (ASHRAE, 2010). Comfort sensation is hence connected to the energy balance between heat production and heat losses in the interactions between our body and the environment, considering that our body reacts to the environment to maintain the inner part of the body in an almost constant temperature of about 37°C [36-38°C] (Nicol et al., 2012). When a modification occurs (e.g., in human activities or in environmental conditions) the human body generally activates a reaction based on: i. physical adaptations, inducting a physical change (active/reactive behaviour such as putting up a jacket if feeling cold); ii. physiological adaptations, activating changes to reply to stimuli for acclimatization; or by iii. psychological adaptations, considering natural expectations connected to a specific climate and the reason to be in a place. For example, referring to the latter adaptation, it is possible to mention the fact that in summer on a beach we accept temperatures considerably higher than the ones accepted in a living space, being the fact to be exposed to the sun a voluntary act connected with specific thermal expectations. Clearly, the neutral temperature sensation, which is a condition in which thermal comfort is reached not requiring adjustments, is also function of the naturalness of climate, being people living in hotter regions able in adapting to hotter conditions in respect to inhabitants of a cooling-dominated climate (Santamouris, 2019).

Thermal comfort conditions may be expressed in terms of evaluation scales considering levels of comfort and discomfort. Clearly thermal perception is a subjective issue, nevertheless general indices may be derived according to statistical considerations. One of the scales commonly used is the one adopted by ASHRAE Standard 55 (ASHRAE, 2017a) that bases on a 7-step domain from -3 (cold) to +3 (hot) passing through neutral conditions (0) – the scale may be potentially extended to a larger domain [-5, +5] (van Treeck and Wolki, 2019). Similarly, it is also possible to mention the Belford scale, divided also into 7 steps, from 1 (much too cool) to 7 (much too warm), in which comfortable (neither warm nor cool) is rated 4.

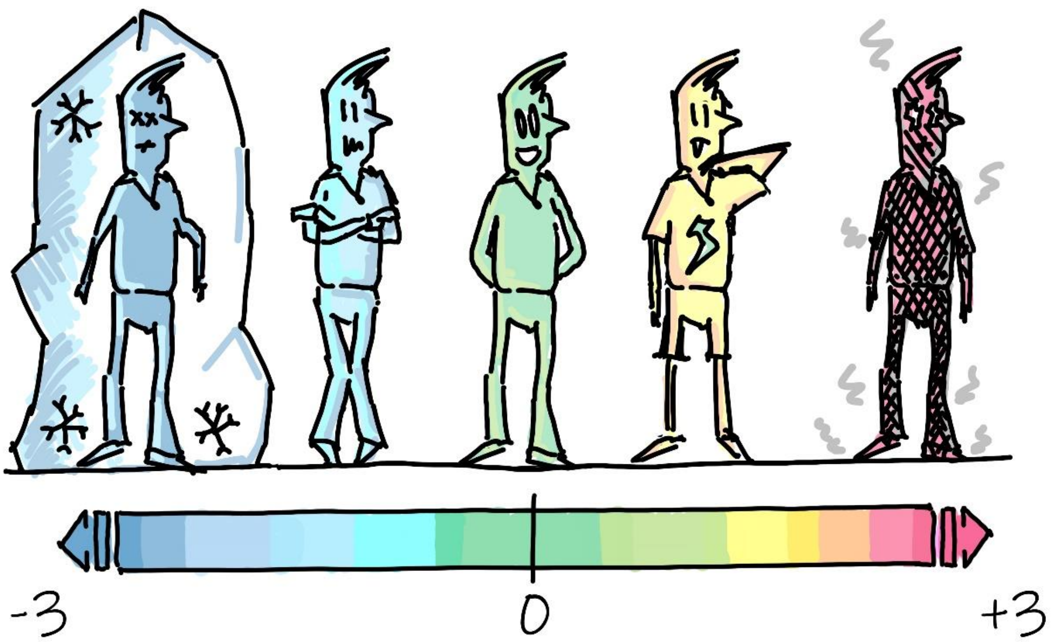

Figure 1 – Iconic representation of the ASHRAE 7-point thermal comfort scale.

Different thermal comfort indices are available and may be distinguished according to different criteria, for example assuming rational and empirical bases, e.g., ASHRAE Handbook Fundamentals (ASHRAE, 2017b) or EN ISO 11399. Some thermal comfort indices are adapted to specific climatic conditions, e.g., tropical climates – see for example the TSI (Tropical Summer Index) –, or adapted to specific countries or locations. For example, for India several thermal comfort models are available, e.g., for hot-humid and hot-dry climates it is possible to quote the mentioned TSI, the Sharma and Ali's TSV (thermal sensation vote) (Sharma and Ali, 1986a), the Indraganti and al. thermal sensation vote (Indraganti, 2010), focussed on the adaptive approach, or the seasonal corrected PMV for north India residential buildings (Singh et al., 2011) – see also (Pellegrino et al., 2016). Especially, for outdoor conditions (Coccolo et al., 2016), it is possible to refer to thermal indices (e.g., PMV or SET), empirical indices (e.g., ASV – actual sensation vote, or TSV), and linear equation indices. For example, between linear equation environmental indices it is possible to include the WBGT (Wet bulb globe temperature index) which is used for indoor comfort monitoring especially in hot industrial spaces – see EN ISO 7243:2017 (EN ISO, 2017b)–, or for cold climate the WCI (wind chill index). Similarly, among linear equations it is possible to mention indices of equivalent homogeneous temperatures and equal thermal environment. Among them, it is possible to mention the operative temperature (T_{op}) that is a synthetic index for comfort analysis, especially used in closed spaces – when air velocity is almost null and relative humidity values are in the comfort range (e.g., 30-70%). At these conditions (negligible air velocities and comfort humidity values), the T_{op} may be estimated as the mean between two other parameters influencing the heat balance: the dry-bulb air temperature and the mean radiant temperature.

$$T_{op} = \frac{\vartheta_{air}+MRT}{2}$$

While the same index may be estimated including air speed by adopting the following expression:

$$T_{op} = \frac{\vartheta_{air}\sqrt{10v}+MRT}{1+\sqrt{10v}}$$ (CISBE guide A, 2006) (Nicol et al., 2012)

Considering internal spaces, there are 6 main parameters correlated to comfort and thermal sensation: four environmental parameters (dry build temperature; humidity, i.e., water vapour, relative humidity, ...; air relative velocity; and mean radiant temperature) and two personal parameters (activity, i.e., metabolic rate; and clothing). The influence of environmental parameters is evident under local climatic effects (e.g., asymmetrical radiation) (van Treeck and Wolki, 2019), while tabular values of met are reported in standards (e.g. EN ISO 7730 and 8996) and in literature – see for example (EN ISO, 2005, 2004; Nicol et al., 2012). Clo values are also summarized in standards (e.g., ISO 9920) and in literature – see for example (ASHRAE, 2017a; EN ISO, 2009). Typical assumed clo values in internal conditioned spaces may be assumed, i.e., 0.5 clo for typical summer clothing and 1.0 clo for typical winter clothing. Similarly, it is also possible to define the clo value by summing the insulation values of each worn clothing element, i.e., by assuming tabular values (EN ISO, 2005; Nicol et al., 2012).

Nevertheless, for the purpose of E-DYCE, some of the most diffused ISO, ASHRAE and EN standards are mainly referenced.

Steady-state uniform conditions – Mechanically controlled buildings

For thermal moderate environments (internal conditioned spaces) it is possible to refer to the thermal comfort model defined in ISO 7730:2005 (EN ISO, 2005). This standard base on the well-known Fanger model (Fanger, 1970) to calculate expected thermal sensation in steady-state uniform conditions. This approach is based on a single equation defining the equilibrium/disequilibrium between body balance equation and the perceived comfort defined on the ASHRAE-mentioned 7-point scale (van Treeck and Wolki, 2019). The body thermal sensation, based on the 6-parameters mentioned above, may be estimated defining a body-global predicted mean vote (PMV). The loss of neutrality arrives when – given clo and met levels – the heat flow is not the same of the one defined for neutral optimum comfort level corresponding to PMV = 0. The PMV is a static score and may be correlated to thermal discomfort or thermal dissatisfaction, by considering a second index defining the predicted percentage of dissatisfied (PPD) – people that in a given environment are experiencing too hot or too cold sensations. Specific thermal discomfort may also be defined by local body effects, i.e., radian asymmetries, draughts, vertical temperature gradients, and warm/cold floors (ISO 7730). Considering the global sensation, the PPD may be derived by the PMV using specific correlations – see for example (van Hoof, 2008), figure 2, and the KPI description in further sections –, e.g., Fanger PMV = 0 → to a PPD of 5%. By fixing the range of PPD that may be accepted, the same may be defined in terms of PMV ranges. Assuming the latter, for the given metabolic rate and clothing, it is possible to extract the accepted ranges of operative temperatures for mechanically-controlled spaces. For example, a 6% of PPD will result in a PMV variation range of [-0.2, +0.2] that for typical office conditions, i.e., met = 1.2 and clo = 0.5 in summer and = 1.0 in winter, corresponds to an operative set point value of 21°C for heating and 25.5°C for cooling. Hence, the choice of the PPD range may be used to define thermal space categories – see for example Table 2. For example, in a single office, for a metabolic rate of 70 W/m^2 (1.2 met) the suggested operative temperature is defined to be for Category A, B and C in winter (1.0 clo) respectively equal to 22.0±1°C, ±2°C, and ±3°C, and in summer (0.5 clo) 24.5±1.0°C, ±1.5°C, ±2.5°C.

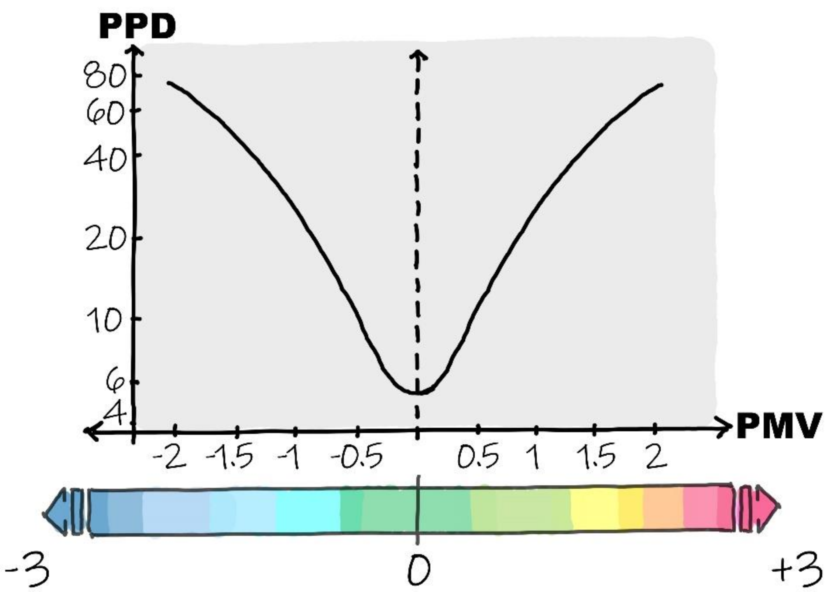

Figure 2 – PPD expressed as function of PMV – ISO 7730:2005.

Similarly, the EN 16798-1:2019, which substitutes previous EN 15251:2008, reports in Appendix B different default categories to design mechanically heated and cooled buildings referring to PMV and PPD indices – see Table 2. Referring to the CEN standard (see Table B.2 of EN 16798-1:2019), default operative temperature values for an office space (met = 1.2, RH%= 50%) are respectively for Categories I, II, III, and

IV in winter (clo = 1.0) 21.0°C, 20.0°C, 19.0°C, and 18.0°C, while in summer (clo = 0.5) are 25.5°C, 26.0°C, 27.0°C, and 28.0°C.

Table 2 – Categories of thermal environmental space units – ISO 7730:2005.

Space comfort category ISO 7730	Global body thermal state		Local body discomfort				Space comfort categories EN
			PD [%]				
	PPD	PMV	DR (draught risk)	T_{air} vertical differences	Cold/hot pavement	Radiant asymmetry	
A	< 6%	-0.2<PMV<+0.2	<10%	<3	<10	<5	I
B	< 10%	-0.5<PMV<+0.5	<20%	<5			II
C	< 15%	-0.7<PMV<+0.7	<30%	<10	<15	<10	III
nd	< 25%	-1.0<PMV<+1.0	-	-	-	-	IV

Also ASHRAE Standard 55 (ASHRAE, 2010) includes a methodology to define acceptable thermal conditions in occupied spaces considering conditioned environments – see below for unconditioned spaces. The following items are considered: the operative temperature, the humidity limits, the elevated air speed control, the local thermal discomfort conditions, and temperature variations. The first (operative temperature limits) is based on two potential methodologies:

- Using comfort zone definitions in the psychrometric chart – see Figure 3;
- Adopting computer calculations of PMV – this is in line with ISO 7730:2005.

Two classes are assumed, i.e., 90% of acceptability and 80% of acceptability, referring respectively to a PPD ≤10% (-0.5 ≤ PMV ≤ +0.5) and PPD ≤20% (-0.85 ≤ PMV ≤ +0.85). Similarly to the above-mentioned Operative Temperature approach, the humidity is also evaluated by using psychrometric charts, defining that the absolute humidity (humidity ratio) should not exceed 12 g/kg. The increase of air velocities allows to increase the acceptable maximum operative temperature under specific conditions. The use of the psychrometric chart is subject to some given limitations (e.g., it applies to Operative Temperature only) that are mentioned in the Standard.

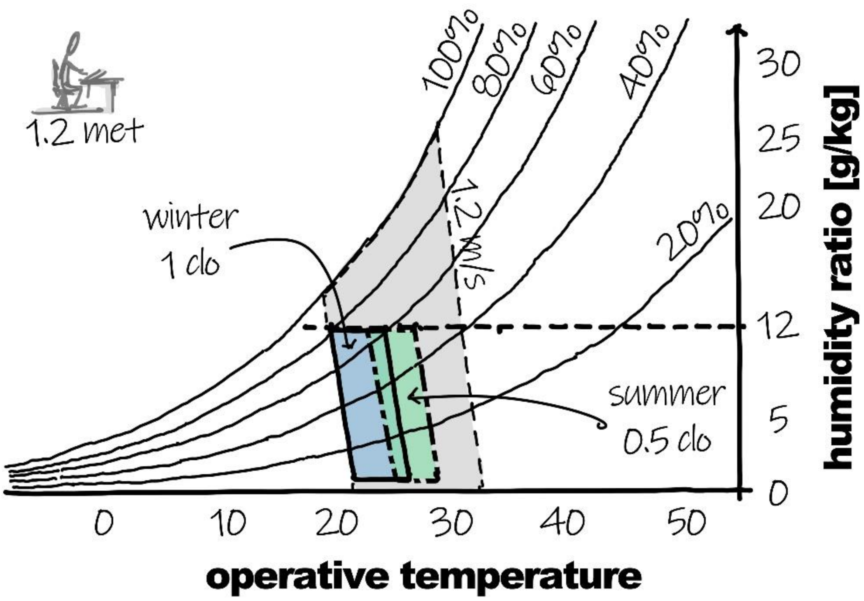

Figure 3 – Graphical comfort zone representation on psychrometric chart – ANSI/ASHRAE 55.

Acceptability and adaptation – Free-running buildings

People thermal sensation and comfort perception are affected by adaptations (behavioural and expectation-driven), and not only by the 6 variables mentioned before (de Dear and Brager, 2002). Humans, such as introduced before, are in fact able to adapt to discomfort conditions in order to restore their thermal comfort. Adaptive comfort standards include these aspects, which are connected to psychological issues, clothing preferences, and conscious actions and behaviour (van Treeck and Wolki, 2019). In the case of free-running buildings, e.g., naturally ventilated ones, the mechanical-mentioned approach is not able to correctly define the comfort expectation of people (Humphreys, 1976). Different studies, which analyse correlations between environment conditions and comfort sensations – e.g. the LBNB, UCB Berkeley studies (de Dear and Brager, 2001) plotting observed indoor operative temperatures as function of outdoor temperature index ET*, or (de Dear and Brager, 2002) plotting the observed indoor comfort temperature as function of the mean outdoor air temperature –, have demonstrated that the qualitative behaviour of people follows the PMV lab-predicted curve only in buildings that are mechanically controlled and that behave under almost uniform conditions. Differently, in naturally ventilated spaces the PMV-predicted curve is not able to represent the qualitative behaviour of people. Tenants of naturally ventilated buildings are in fact able to accept a larger range of operative temperatures in respect to the PMV/PPD model presented in EN ISO 7730.

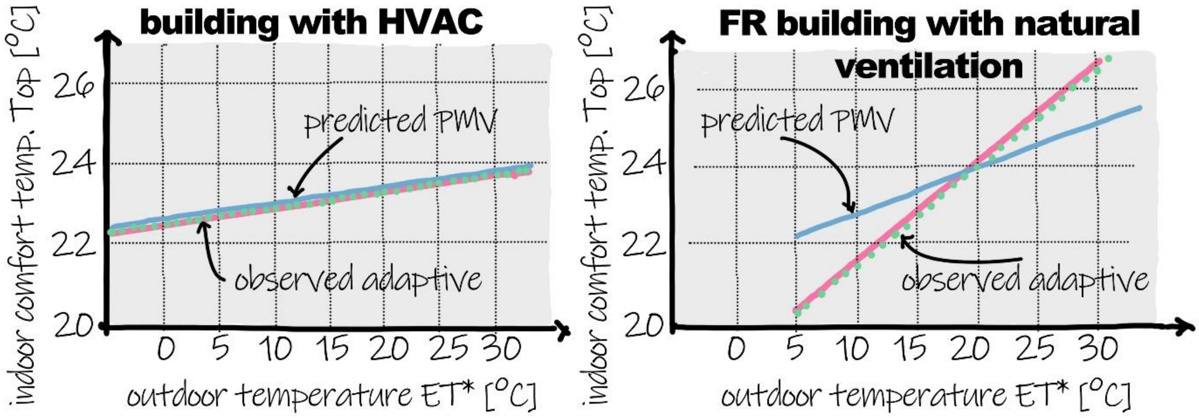

Figure 4 – Observed indoor comfort operative temperatures plotted as function of outdoor temperatures – elaboration from LBNB 2001 – see also (Grosso, 2017)

The last version of ISO 7730 (2005) has included several innovations in respect to previous 1994 edition, including the important recognition of the fact that people may be subject to adaptations according to different local climatic conditions (see item 10 of this standard). Furthermore, the same item 10 mentions that larger acceptability ranges may be considered in hot climates for naturally ventilated spaces overpassing the PMV given operative temperatures. Nevertheless, it also implicitly considers buildings with very small PMV variations as superiors and consider that higher satisfaction levels are reached in buildings with higher air-tight and mechanical controlled conditions (Lamberts et al., 2013). Furthermore, the same reference reminds that it is very complex to guarantee such a precise measurement of the environment even considering that sole the clothing preferences considerably impact PMV, supporting the idea that for FR buildings other approaches need to be adopted. Similarly, the work of Arens et al. (Arens et al., 2010) on the realism of “class A” found that the higher class (A and Cat I), in ISO, European standards, and ASHRAE standard, does not confer “relative satisfaction benefit to individuals or to realistic building occupancies” and that the further 2 classes (B and C, or categories II and III) show very limited differences in satisfaction. This suggests cautions in the application of this sole approach (Lamberts et al., 2013) especially for FR spaces, needing an adaptive comfort model. Occupants show different expectations in respect to the HVAC mode, e.g., mechanically heated/cooled/ventilated buildings, free-running buildings, or mixed-mode buildings (Hensen and Lamberts, 2019). The adaptive opportunities are connected to user expectations and behaviours under specific conditions – see for example Figure 5. The need to consider an adaptive comfort approach in free running operated spaces mainly refers, such as it was underlined in previous research projects on passive systems, like PASCOOL, to face criticalities in classic mechanical comfort models “when comfort criteria are applied to the predicted thermal conditions in proposed buildings” considering the importance “in supporting design choices and avoiding unnecessary ‘high’ energy air-conditioner path” (Baker and Standeven, 1996). This may refer to those labelling levels in which standard conditions are adopted, being real users able to directly give a final judgement.

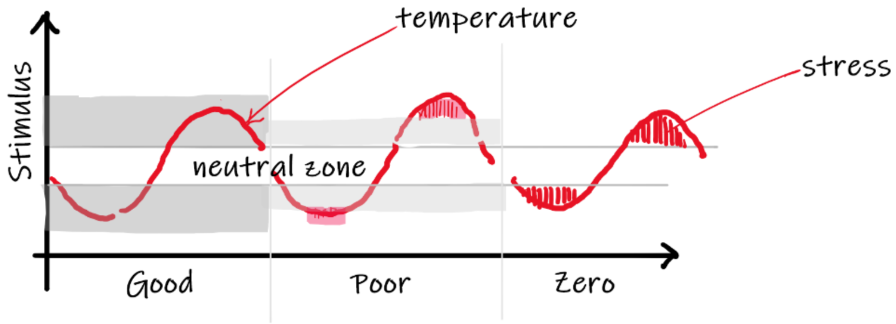

***Figure 5: different adaptive opportunities under changes in environmental stimuli (e.g. FR - good, mixed - poor, and mechanical-modes - zero). Elaborated from* (Baker and Standeven, 1996)**

Among large studies on adaptive models, ASHRAE Report 884 (de Dear et al., 1997) focusses on the development of a variable standard temperature using the adaptive thermal approach. Fixing the fact that thermal preferences are different from thermal neutrality (Lamberts et al., 2013), the mentioned ASHRAE Report includes 3-main adaptation processes: i. behavioural (e.g., opening windows, activating fans, ...); ii. physiological (acclimatization); and iii. psychological (e.g., adapting comfort expectations under different climate conditions). The vision works to combine adaptive and static approaches. From the ASHRAE standard point of view, Standard 55 includes some of the most recent findings on comfort issues (ASHRAE, 2017a). Considering the approaches to define acceptable thermal comfort conditions, this standard includes a part devoted to conditioned spaces – see above –, and a second part devoted to unconditioned spaces. The latter adopts the adaptive model of de Dear and Brager connecting mean outdoor temperatures (changed to weighted daily mean (Lamberts et al., 2013)) with acceptable indoor operative temperatures. Upper and lower limits are given for 90% and 80% of acceptability levels.

European standards also include adaptive comfort models for non-mechanically cooled buildings in the EN 15251:2007 (European Committee for Standardization, 2007), supporting EPBD 2003 version. Under the new CEN Mandate/480, this standard was replaced by the EN 16798-1:2019 (European Committee for Standardization, 2019), including thermal environment, indoor air quality, humidity, and lighting. Such as mentioned before for conditioned spaces, this standard defines four categories of the indoor environment quality (I, II, III, and IV) – see table 3, where the “Medium” level represents the normal level, while the “High” category is devoted for occupants with special needs.

Table 3 - EN 16798-1:2019 environmental quality categories.

Categories	Expectation
IEQ_{I}	High
IEQ_{II}	Medium
IEQ_{III}	Moderate
IEQ_{IV}	Low

This Standard reports that for building without a mechanical cooling system, adaptation effects will be considered adopting the adaptive comfort methodology – see also Annex B and section B2.2 of the standard. This methodology “only applies for occupants with sedentary activities without strict clothing policies” and in spaces in which “thermal conditions are regulated primarily by the occupants”. The adaptive approach is suggested for office buildings and other similar building typologies (including residential buildings) focussing on the usage that may be primarily interested by human occupancy, giving the above-mentioned limitations, including the possibility to not only adapting the environment (e.g., opening a window), but also adapting the clo level. Upper defined limits are used to design passive thermal control and buildings in order to avoid and prevent overheating phenomena. In case in which natural ventilation and building design choices (e.g., bioclimatic issues) are not able to guarantee the defined comfort category, this needs to be mentioned in building design documents, and for E-DYCE to be referred to the proposed dynamic label. The adaptive model is based on regressed operative temperature plotted as function of the external running mean temperature. This approach is considered to be applied to summer and shoulder seasons (neutral spring and autumn periods), while for winter, the same temperature control limits of mechanically cooled buildings are applied. Adaptive thermal model is hence conceived for FR cooling applicability defining adaptive criteria: upper and lower temperature limits according to categories I, II, and III. The running mean temperature is calculated in line with expressions defined in Annex B, item B2.2 (European Committee for Standardization, 2019), and is function of the daily running mean outdoor temperature. Table 4 reports the given upper and lower limits for indoor operative temperature (ϑ_o) for the three mentioned categories on the base of the optimal operative temperature (ϑ_c). The application of these limits is limited in the running mean temperature domain (+10°C, +30°C).

Table 4 - EN 16798-1:2019 Adaptive upper and lower limits for the internal operative temperature

Categories	Expectation	ϑ_c = Optimal ϑ_o	ϑ_o Upper limit	ϑ_o Lower limit
I	High	$\vartheta_c = 0.33\vartheta_{rm} + 18.8$	ϑ_c +2	ϑ_c -3
II	Medium		ϑ_c +3	ϑ_c -4
III	Moderate		ϑ_c +4	ϑ_c -5

Figure 6 compares adaptive thermal comfort limits for the indoor operative temperature considering ASHRAE 55:2013 and EN 16798-1:2019 standards, while a comparison between ASHRAE and EN 15251 was reported in (Nicol and Humphreys, 2010). Early discussion works in IEA EBC Annex 80 (Shady, 2020) support the applicability of adaptive thermal comfort models in the range 1-1.3 met and a mean running temperature in the range 10°C-33.5°C – see also (Boerstra et al., 2015).

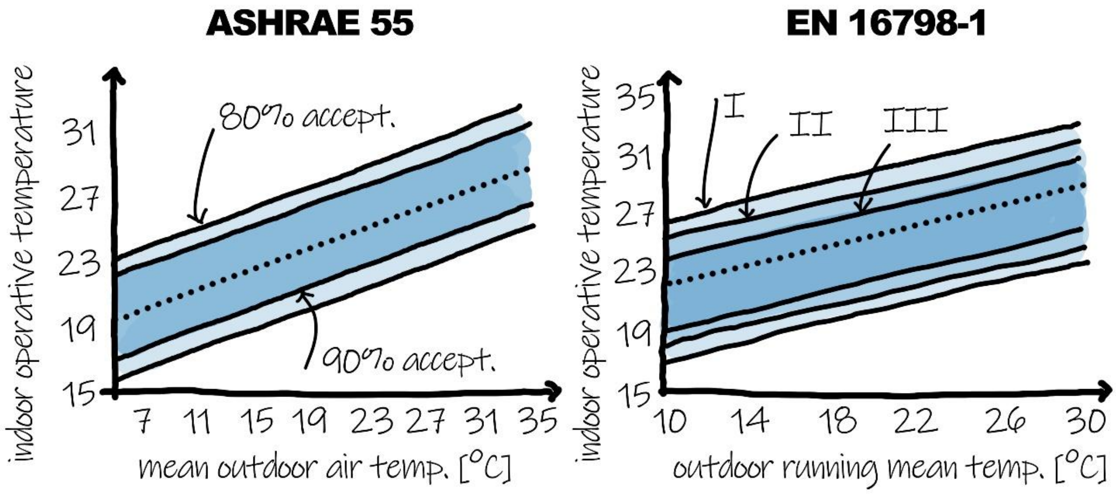

Figure 6 – Upper and lower limits for indoor operative temperature in adaptive thermal model for different thermal comfort categories.

Additionally, in low energy-cooling there are some specific solutions that, instead of reducing the space temperature, act on the thermal comfort perception, such as comfort/microclimatic ventilation (Grosso, 2017). Comfort/microclimatic ventilation is based on the principle that an increase in the air velocity will affect the body heat dissipation and consequently a rise in comfort temperature may be considered due to the reduction in the perceived temperature. This compensation of a higher room temperature by an increased air velocity rate is also underlined in EN ISO 7730 (EN ISO, 2005), in ASHRAE 55, and in EN 16798-1:2019. This additional compensation effect is shortly detailed in the following Section 2.2.2.1.

Additional information on adaptive thermal comfort models may be found in framework and review papers, such as (Carlucci et al., 2018a; de Dear et al., 2020; Hellwig et al., 2019) and in reference books, e.g. (Humphreys et al., 2020; Nicol et al., 2012; Roaf et al., 2023).

2.2.2.1 Additional compensation effects

Specific correlations and expressions were defined in literature describing the potential compensation effect of high velocities to counterbalance high operative temperatures. The virtual increase in comfort temperature may be correlated, in fact, with airflows. In line with EN 15251 and the outcomes reported by (Nicol, 2004), the following expression may be adopted – see also (Du et al., 2014):

$$\Delta T_{comf} = 7 - \frac{50}{4 + 10 \cdot v_{air}^{0.5}}$$

Other researchers supported different models, several of which are climate-correlated. For example, for humid climates, it is possible to mention the following equation, based on the integration of 11 different existing models (Szokolay, 2000):

$$\Delta\vartheta_{comf} = 6 \cdot \left(v_{air,skin} - 0.2\right) - 1.6 \cdot \left(v_{air,skin} - 0.2\right)^2$$

Where the temperature compensation effect of increased air velocities is function of the effective air velocity, based on the air velocity at skin level [m/s] – the expression is valid for air velocities lower than 2 m/s. Among the climate-correlated expression it is possible to mention the expressions of (Du et al., 2014; Su et al., 2009) elaborated for Chines climates.

Additionally, also in ASHRAE Handbook of Fundamentals (ASHRAE, 1989) a correlation between air velocities and perceived reduction in temperature is given following a tabular approach – see Table 5. The same values may be interpolated to define the following correlation (R^2=0.999) (Chiesa and Grosso, 2015a):

$$\Delta\vartheta_{v,air} = 2.319 \cdot v_{air} + 0.4816 \quad [°C]$$

The expression defines the mean perceived reduction in temperature due to airflow activation as function of the air velocity.

Table 5 – **Correlations between air-velocities and equivalent variations in comfort temperature thresholds – ASHRAE Fundamentals** – see also (Grosso, 2017).

Air velocity [m/s]	Equivalent Δϑ [°C]	Thermal sensation
≤ 0.25	≤ 1°C	nd
0.26 - 0.50	1.1 - 1.6	Pleasant
0.51 – 0.75	1.7 – 2.2	Pleasant (airflow perception)
0.76 – 1.00	2.3 – 2.8	Pleasant – slightly uncomfortable
1.01 – 1.50	2.9 – 3.9	Slightly uncomfortable – uncomfortable
> 1.5	> 3.9	Discomfort

Additionally, ISO 7730:2005 includes a potential variation in upper accepted temperatures due to increased air velocities. Correlations are based on Appendix G of the ISO standard that directly mentions the possibility to adopt increased air velocities to compensate heat sensations due to temperature increasing phenomena. Mentioned air flows may be generated by both opening windows or activating fans. Given correlation lines (equal total skin heat balance lines) are referred to a reference condition that is set at 26°C and 0.2 m/s of air velocity. Such as it may be expected, benefits are function of clo and met levels, and are expressed as function of the differences between the mean radiant temperature and the air temperature. For sedentary metabolic conditions, the supported effect is defined in the domain of temperature variations till 3°C and air velocities below 0.82 m/s.

Furthermore, EN 16798-1:2019 considers in Annex B, item B.2.3, the effect of increased air velocities under summer conditions to compensate for growth in operative air temperatures. According to this standard, the compensation may be applied (see Table B.4) for indoor operative temperatures higher than 25°C and only for artificially increase airflows driven by personal controlled means. The suggested differences in perceived internal operative temperature ($\Delta\vartheta_o$) are expressed for three air velocities, keeping in mind that an air velocity >0.8 m/s is able to move office papers from desks. The mentioned air velocities are 0.6 m/s, 0.9 m/s, and 1.2 m/s, while the corresponding differences in operative temperatures are respectively 1.2°C, 1.8°C, and 2.2°C, showing a lower potential in respect to the mentioned ASHRAE standard to expand the temperature upper limits.

2.2.3 Potential free-running building evaluation logics

In order to evaluate a building that works in free-running conditions and/or to evaluate the free-running potential in design rating, it was demonstrated that an additional issue needs to be considered: the comfort/discomfort levels. As it mentioned above, in free-running conditions mechanical equipment (e.g., heating/cooling) is absent or turned off. For this reason, it is not present a direct energy consumption/need for guaranteeing the set indoor comfort thresholds (e.g., heating set point temperature or cooling set point temperature). Hence, the main issue is the ability of the building and building components to reach and maintain space comfort conditions by interacting with the environment in free-running mode. In energy evaluations of building performances, the energy efficiency is reached by reducing the amount of energy needs in order to maintain the set acceptable comfort levels, while in free-running spaces the main topic becomes the deterioration of comfort thresholds. For this reason, additional key performance indicators (KPIs) and methodologies are needed in order to define and evaluate comfort levels. Furthermore, this issue introduces an additional challenge correlated to the adoption of proper comfort models, considering the differences in people perception and acceptability threshold in mechanically and naturally heated/cooled spaces – see the previous section.

For example, the adaptive comfort approach may work for free-running mode – see additional limitations mentioned in previous section and in quoted standards –, especially when passive/natural technologies are the sole used solutions (FR Mode A), while mixed intermittent mode is expected to work on fixed set point temperatures, adopting comfort models for mechanically treated space, and eventually defining adapting additional thresholds.

Current building simulation scheme adopted in EPBD technical standards of MS is based on Figure 7 and eventually supports passive and free-running potential in combination with HVAC systems, but does not consider these contributions as an independent voice, like it is for Renewable Energies.

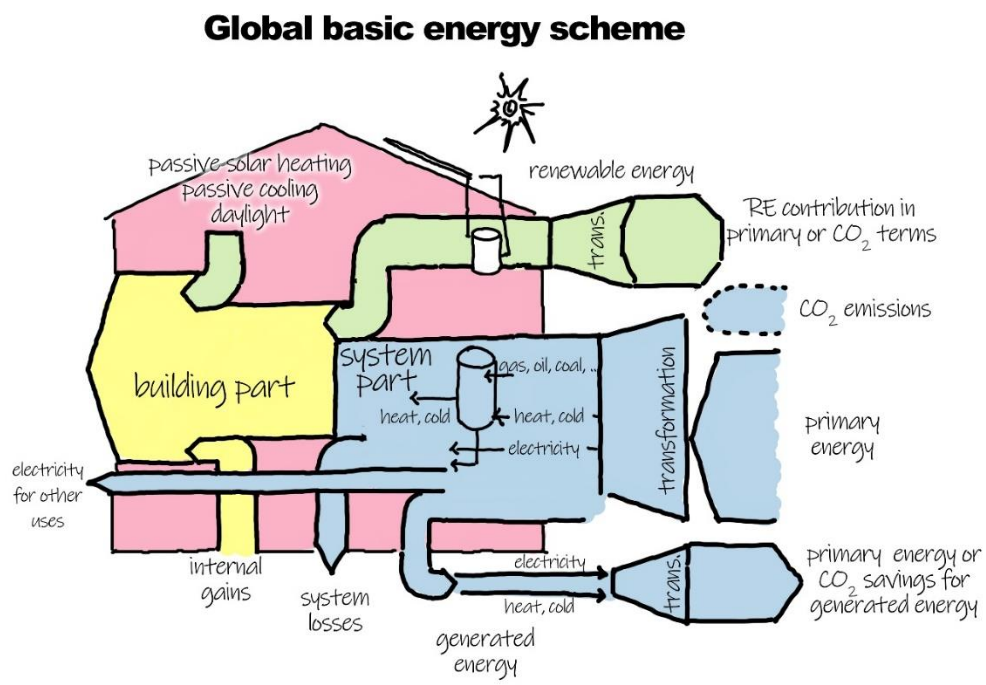

Figure 7: Current global basic energy scheme in Building simulation

Differently, in a FR building, in both Mode A and B, a larger contribution may arrive by activation of FR-strategies – that may be expanded during design building definition considering the lack or the reduced activation of systems, e.g. by maximising the bioclimatic building potential and by valorising typical actions of people living in traditional houses, such as moving inside internal spaces according to seasons or day-time –, while mechanical primary energy needs/consumptions are substituted by discomfort in both time-based and intensity-based dimensions – see Figure 8..

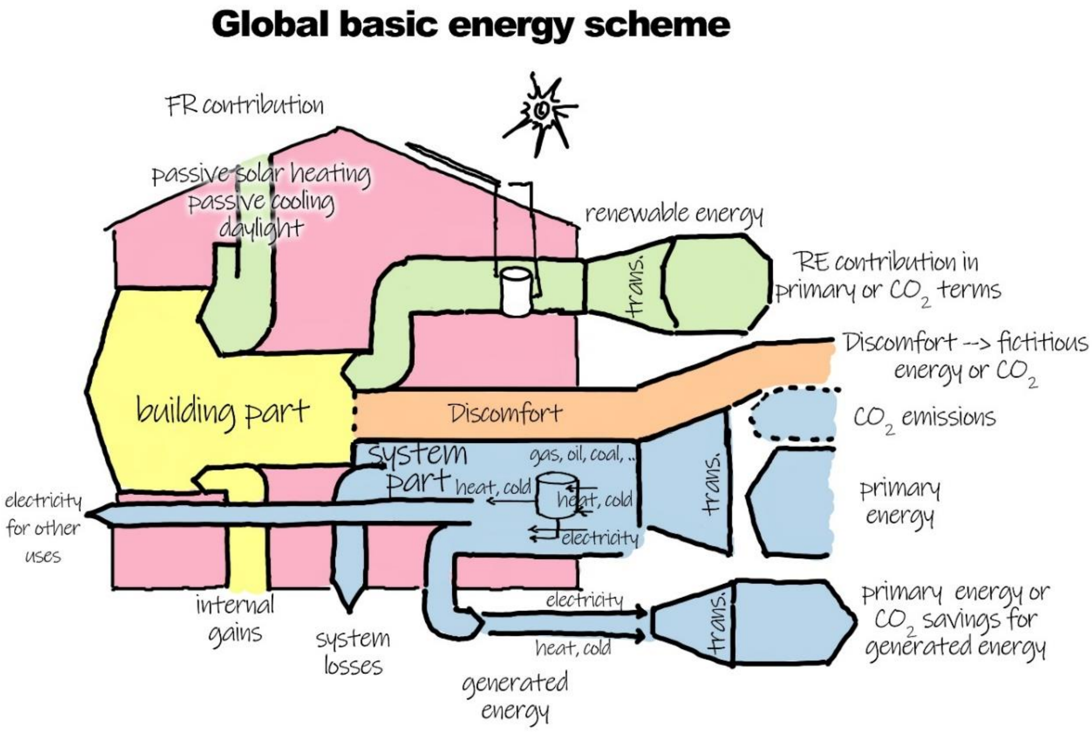

Figure 8: Potential E-DYCE Free-running integration scheme

In order to evaluate the FR-potential and potential exploitation, it is important to define proper methodologies to: i. focus on the comfort/discomfort domain and eventually include these aspects in EPC; ii. transpose discomfort condition into fictitious "virtual" energy needs to compare FR-behaviours with mechanically-driven buildings. Furthermore, FR will impact on different KPIs domains – e.g., from energy performances (fictitious), comfort/discomfort performances, FR potential exploitations – such as will be defined in the further section of the report devoted to KPIs.

Focussing on FR EPC, three methodologies are mentioned and will be tested during the project to compare results and suggest a consolidated E-DYCE approach for FR performance evaluation and certification. The mentioned approaches underline the need on the one side to translate discomfort conditions into fictitious energy needs to allow building comparison with fully-mechanically treated spaces (and potentially to define an opposite translation of energy needs into fictitious discomfort), and on the other side to define local FR potential to evaluate the exploitation performance of this potential.

Method 1: The first method to define the fictitious needs of a building without active systems is to simulate an equal building with a "virtual" system assuming an average statistical COP and system definition, including typical operational schedule. Roughly speaking, a traditional building without a heating system (e.g., South-Mediterranean houses or a mountain old lodge with only a fireplace) will be labelled (design and asset rating) such as in the case of active-heated buildings. This approach may result in **high underestimations of the FR potential** especially in summer, discouraging the usage of natural heat sinks and minimising the positive effect of local FR potential. This will be evident even if the statistical COP and fictitious active system data are assumed in line with higher efficiency solutions on the market, being losing the positive effect of FR potentially connected with bioclimatic building choices (e.g., the adaptive comfort evaluation of a naturally ventilated building with medium air infiltration rates). This vision eliminates FR behaviours by imposing the fictitious energy needs of a virtual building with the same configuration, but including a mechanical system. It can be easily adapted to steady-state monthly calculations, and eventually may include a reduction factor condensing standard potential benefit from passive systems. In hourly calculation approaches, this vision may be overpassed by method 2.

Method 2: the second method refers to building simulation approaches, considering fictitious energy needs of a typical active system, but coupled with the potential effect of FR and passive techniques (e.g., natural ventilation) in reducing cooling/heating loads. Especially for the summer season, the inclusion of the positive effect of solutions such as ventilative cooling in heat gain dissipation will support an evaluation of the FR potential and of the potential of passive technologies. It would be important to correctly define operational control points to avoid additional active-system energy needs due to negative activation of low-energy modes. For example, it is important to avoid ventilation-driven overheating under uncomfortable environmental conditions. This approach will not consider comfort/discomfort analyses, nor the benefit from the adoption of FR comfort models, being based on mechanical cooling/heating set points, but will limit the underestimation of the FR potential like the one of Method 1, even if the same may be eventually adopted. This method may be considered especially for FR mode B.1, when the FR mode is activated following discontinuous scheduling (short periods, or specific periods, like night ventilation) under hourly simulations, although it can be applied also to FR mode A, e.g., by comparing heat gains with heat potential dissipation by ventilative cooling (summer season) for the same time-period, or alternatively comparing heat losses with passive heat gains (winter season). The approach is in line with specific usage of hourly and dynamic simulation tools, e.g., EnergyPlus (DOE and NREL, 2020), Dial+ (ESTIA, 2017), WindChill and SperaVent (Grosso, 2011) and others – see the reviews on ventilative cooling tools in (Kolokotroni and Heiselberg, 2015) and in (Belleri, 2014). Assuming ventilative cooling as an example, a simplified hourly tool defining the potential in covering heat gains at hourly base trough ventilation was developed during the work of the IEA EBC Annex 62. This tool calculates the heating balance point temperature of a sample space unit (single-zone building) and, when overheating is underlined at hourly base, it verifies if the calculated overheating intensity may be dissipated by different ventilation airflow levels. The tools classify hours according to different conditions, including those in which overheating may be covered by different ventilation rates and those in which mechanical cooling is needed – see also (Belleri et al., 2018; Belleri and Chiesa, 2018). Similarly, advanced simulation tools, such as EnergyPlus and Dial+ allow for an advanced verification of the ventilative cooling potential supporting design choices and analysing the performance of passive/hybrid solutions in reducing cooling needs and in calculating residual cooling energy usages. Similarly, tools such as WindChill and SperaVent allow to calculate building cooling thermal needs in line with the hourly methodology described in EN ISO 13790:2008 and to compare them with the hourly dissipative potential of naturally controlled ventilation adopting stack and wind-driven bi-zonal flows (Grosso, 2017). Similarly, the same approach may be translated into steady-state simplified procedures, by calculating on the one side heat gains and net energy needs (e.g., cooling needs to dissipate internal and solar gains) and on the other side the potential dissipation from passive technologies adopted in FR (e.g., natural controlled ventilation) assuming the reference mean monthly environmental conditions. This comparison (between needs and cooling dissipative potential) may be defined at hourly base or in an aggregated timing approach – see for example the monthly-base early-design approach described in (Chiesa and Grosso, 2017; Grosso, 2017) that considers monthly mean conditions and a 24-h balance cycle for both cooling and IAQ requirements. On the methodological point of view, the environmental labelling scheme ITACA (ITACA, 2016) has included in the current version for the non-residential building scheme, see standard UNI PdR 13.2:2019 (UNI/PdR, 2019), a KPI supporting the estimation of natural ventilation potential in covering standard IAQ ventilation requirements. In particular, ITACA adopts a quantitative-analytical approach in evaluating the natural ventilation effectiveness in non-residential buildings with motorised apertures. This evaluation is done by defining a performance indicator and assigning points to the comparisons between the different categories of recommended volumetric airflow rate values for ensuring an acceptable indoor air quality (defined in line with current standards) and the estimated operative values. In this approach, the recommended airflow values are classified and proposed based on the estimated percentage of people dissatisfied with the level of air pollution in the room. This air pollution either originates from the occupants thus depending on the number of occupants regardless of the occupancy duration, or it comes from the building elements and thus it is relative to the surface area of the space to be ventilated, in line with different standardisation approaches. The operative airflow rate value through the automatic apertures, on the other hand, is determined on an average monthly basis, and is a combination of wind-driven and buoyancy-driven airflows adopting the monthly-based early-design approaches mentioned before. The wind-driven flow rate depends on the speed and direction of the wind, the terrain roughness characteristics, the dimensions of the building, and the position and size of the inlet and outlet apertures. While, the buoyancy-driven values are affected by the height difference between the outlet and inlet apertures, their sizes, and the difference between the average monthly outdoor temperatures and the indoor set point values in cooling and heating seasons (UNI/PdR, 2019).

This approach defines, in both the hourly/sub-hourly balance and in the simplified monthly-steady balance, the impact of free-running inputs by considering in the building energy balance only the residual cooling needs to be dissipated by mechanical systems after ventilative cooling treatments. The same methodology may be applied to the winter season or to other voices in building energy balances.

Method 3 (ISO-TR EN 52018-2 – Annex D suggestions).

The third methodology is based on the approach defined in **Annex D** of the **ISO-TR EN 52018-2:2017** (CEN ISO/TR, 2017). Unlike method 1 that under-evaluates free-running operation, this method positively considers the benefit of FR under specific environmental thresholds, and includes the following benefits:

- “slightly stimulate” the performance of building without active cooling;
- Positively support the adoption of good design strategies to increase summer comfort;
- “moderately discourages the installation” of active cooling systems in existing/new buildings.

From a methodological point of view, the proposed approach is based on the following steps.

Firstly, the building is simulated in free-running (for buildings with an active cooling system, the building is assumed to work in free-running only with active cooling mode set to off) to evaluate thermal comfort. Secondly, the method introduces a risk index defining the probability [0-1] for the installation of active cooling systems under overheating. In this step a value of 1 is directly set for building with an active cooling mechanism and a ranging value in the domain [0-1] or [0.25-1] according to the obtained overheating risk, supporting a statistical correlation between discomfort and probability to install a cooling system during the building operational usage – see Fig. 9. The threshold (lower limit of the domain) is defining the limit of a condition in which overheating is almost negligible. The approach allows to valorise well-designed buildings and to penalise others, but limiting this penalisation to 1 (like in active cooled spaces). Thirdly, EPB indicators are defined assuming active cooling or fictitious cooling needs by multiplying the needs by the set weighting indicator [0-1] – see sample equations. For fictitious active mechanism a fixed cooling efficiency and primary energy conversion factor is defined considering it favourable in respect to "best overall active system" available on the market. Final results are hence assumed to define the global EP building indicator.

$$EP_{cool} = EP^{*}_{cool} \cdot FC_{risk}$$

Where FC_{risk} is the fictitious cooling weight correlated to the overheating risk. The Primary Energy may be substituted with Net Energy according to specific requirements. This indicator may be defined as follows:

$$FC_{risk} = \begin{cases} 1 & \Leftarrow AC_{on} \vee FR_{mode} \geq max \\ y_m + \left(\left(\frac{B_v - th}{max - th} \right) (1 - y_m) \right) & \Leftarrow th < FR_{mode} < max \\ 0 & \Leftarrow FR_{mode} < th \end{cases}$$

Where *FR* = free-running, AC = Active Cooling, B_v = monitored/simulated building value to be evaluated, *max* = limit of the forbidden zone (unacceptable discomfort zone), *th* = is the threshold below which overheating risk is almost null, and y_m = weight set for $B_v = th$ (e.g., 0 or 0.25).

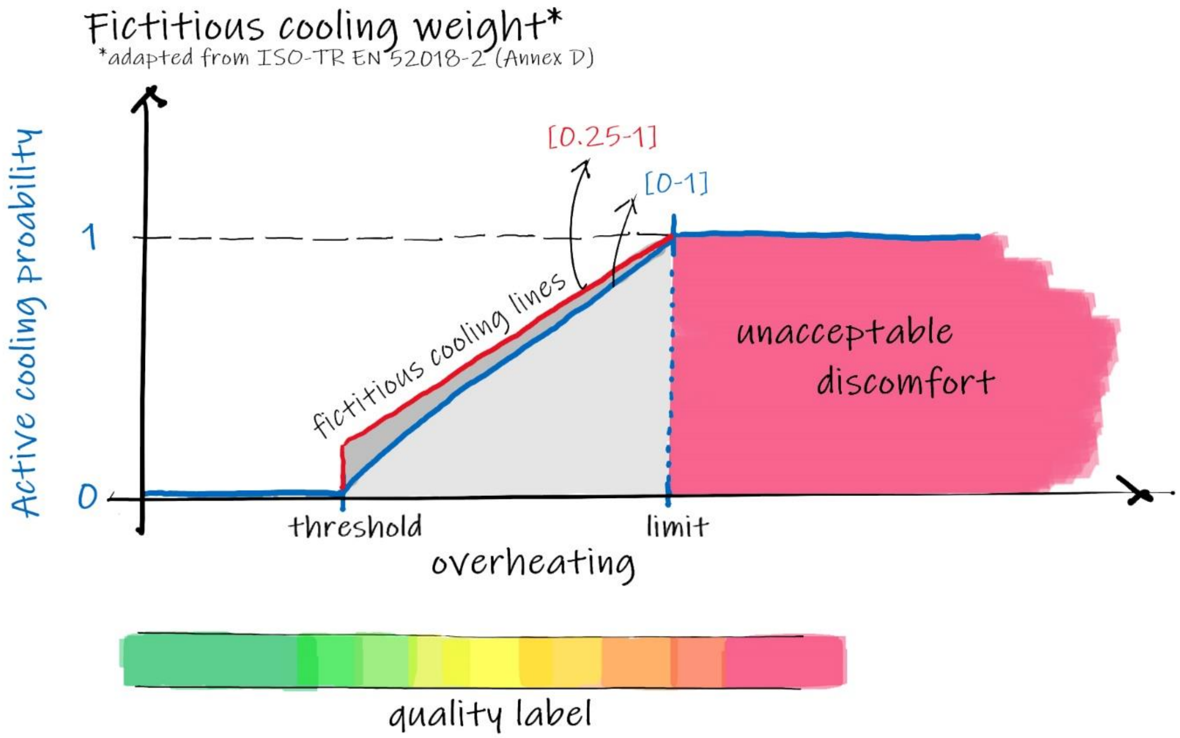

Figure 9: *Weighting criteria for fictitious cooling definition, elaborated from ISO-TR EN 52018-2:2017*

The standard suggests that this approach may be adapted to additional boundary conditions, e.g., window activations, acting on reducing cooling needs and on modifying overheating risks. Considering this latter possibility, it is clear that the approach may be easily adapted to evaluate the potential effect of ventilative cooling or other passive/low-energy cooling techniques in reducing EP_c. Furthermore, the method opens to several interpretations, including its translation to hourly evaluation of the fictitious needs, balancing the "virtual" cooling needs as a fraction of simulated active building ones in respect to discomfort intensities. A sensitivity analysis on this point will be conducted during the project considering simulated and monitored cases. It is clear, as it is also suggested in the above-mentioned Annex D, that the assumption of both the maximal limit value (e.g., overpassing of comfort upper limits, e.g., the ones of Class III in adaptive comfort model of EN 15251 and the new EN 16798-1:2019) and especially the threshold value (over which overheating is assumed) represents itself an indicator, potentially defining a comfort quality label. In all cases, when a FR building is not able in guaranteeing the required comfort temperature category, this inadequacy needs to be underlined not only in the design document (see EN 16798-1:2019, item 6.2.2), but also in the proposed FR Certification by adopting one or more of the FR KPIs adopted in E-DYCE.

Referring to E-DYCE FR modes, this approach may be adapted for Mode A (without active system) to define fictitious energy needs assuming a higher threshold based on adaptive comfort models. The fictitious cooling lines may, for example range from comfort class II to III or from class III to class III+*n* °C. Similarly, in Mode B (active system off) the approach may help in defining both, a fictitious activation line of the system – when deactivated for long periods (e.g., an occupied FR day) – following an approach similar to the Mode A one, but limiting in ranging from class II to III (or even I to II), and a fictitious intermittent activation line – when modulated or on/off activations arrives in short periods – basing the model on mechanical comfort approaches (e.g., Fanger) and more strict requirements. Clearly, the definition of standard profiles requires a high amount of statistical data, while we will perform a sensitivity analysis by massive simulations and demo-data production. Figure 10 shows a potential sample application in an hourly-defined vision.

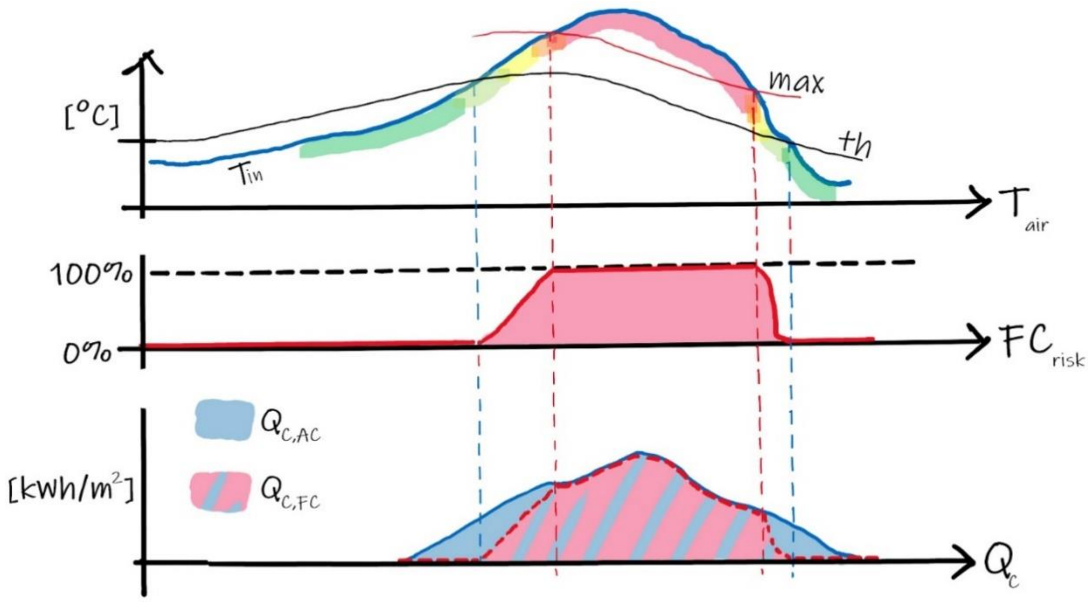

Figure 10: *Simplified schematic application of the proposed approach for hourly analyses*

Potential additional methodologies may be identified and tested during the project, including a clearer connection between the intensity of discomfort and the fictitious cooling need, adding a positive evaluation of the quality of the design/operational choices in exploiting the local FR potential. E-DYCE will also valorise passive elements, especially in their ability to reduce energy needs and increase comfort conditions by translating discomfort (or energy use) into comfort (no energy use).

In all cases, such as mentioned before, it will be possible to translate discomfort values into "virtual" fictitious energy needs. Nevertheless, it can be also possible to inverse this calculation to translate energy needs (e.g., cooling ones) into "virtual" discomfort values to perform comparisons. Fully FR building – without a mechanical system – will take advantages from the definition of a comfort label at design and asset rating. Furthermore, also the operational evaluation of comfort levels will support a direct correlation between expected-standardised and real behaviours supporting tenants' communication and self-optimisation. Similarly, for mixed-mode buildings, comfort evaluations may support the definition of mechanical system activation scheduling.

This will take advantages by seasonal analyses being mainly usable for the cooling season when in residential and small offices cooling systems are not installed or are mainly based on personal units or on domestic split units serving single room (or movable) that are used only in hottest conditions. Experiences on national tools to rate comfort conditions may be underlined, for example in Denmark. Potentially adaptation of similar approaches to E-DYCE will be expanded considering E-DYCE demo case outputs.

During the project, different time-step and spatial granularities will be checked to define how to simplify building simulation (thermal zoning, sensor positioning, ...) without losing the general building/unit performances. Furthermore, analyses on approaches to monitor free-running potential will be defined considering long and short-term monitoring and coupled simulations to identify potential performance gaps or discrepancies and refine efficiency. Finally, a series of actions in translating FR and comfort-correlated KPIs into information for different end-users will be developed and tested supporting user consciousness and behaviours.

2.3 *The smart readiness vision*

2.3.1 General introduction to intelligent building conceptions

ICT technologies are impacting more and more our society. The diffusion of new smart technologies, like Internet of Things (IoT) components, are changing our vision of technologies and computers arriving to define a world in which smart technologies (ST) are everywhere, giving to things additional functions, like sensing and actuating. Even in the building domain, that is a sector in which innovations are slowly introduced for cultural and methodological issues (Celanto, 2007), it is clear that we are facing a real revolution (Chiesa, 2017b; Kalay, 2006). This revolution is based on the data itself, changing and innovating the way in which we may use it (Mayer-Schönberger and Cukier, 2013; Nielsen and Bourlot, 2012). At sociological and philosophical level, it is possible to mention four main axes of influence that ICTs have on the human life – see the European research '*The Onlife Initiative*' (Floridi, 2015):

- the reduction of boundaries between real and virtual world;
- the hybridisation between the natural and the artificial worlds;
- the transition from scarcity to abundance of information; and
- the transition from the primacy of the entity to the primacy of the interaction.

Clearly, all of these aspects are impacting in different domains of our society, and are also impacting building and urban sectors, opening new visions and innovation paths, e.g., smart city, smart buildings, smart technologies – see (Chiesa, 2020, 2015). Similarly, ICT and data-correlated innovations are supporting new approaches toward optimisation and prevision, considering changes in the way in which we produce, elaborate, represent, analyse, and optimise data-production processes and actuation controls. Focussing on the building sector and on building intelligence, E-DYCE will consider the smart vision in energy building performances, including smartness and smart readiness potentials driven by intelligent building technologies.

Intelligent building (IB) is a multi-defined issue that refers mainly to IBs conceptions given by different visions. In line with previous researches, e.g. (Wang, 2010), it is possible to identify at least 3 main IB definition-classes in standards and guideline approaches:

1. Performance-based definitions;
2. Services-based definitions;
3. System-based definitions.

In the **performance-based** definition **approach**, IBs are defined by listing the performances that a building should reach in accordance to user profiles (tenants, owners, designers, managers, ...) rather than considering specific provided technological solutions and systems. This vision includes the IB adaptation capacities to optimise energy and environmental performance. An optimisation that is based on the ability to react to internal/external inputs and conditions including changes in requirements due to upgraded user needs. This approach is for example underlined by the EIBG (European Intelligent Building Group) and by the U.S IBI (Intelligent Building Institute). In the first case, an IB is a building conceived to give its users the most efficient environment. Furthermore, IB uses and manages resources in an efficient way in order to minimise life costs (hardware and facilities). In the second case, "an IB provides a highly efficient, comfortable and convenient environment by satisfying 4 fundamental demands: structure, system, service and management, and optimizing their interrelationship" (Wang, 2010). The IB performance approach is in line with several building design and technical management methodologies, such as the need-performance-driven design approach, that was for example defined in Italy since the 50's (Chiesa and Casetta, 2020; Ciribini, 1968), and parallel performance-approaches defined at international levels, e.g. (Carpo, 2013; Hensel, 2013). Detailing the Italian vision, attention is given to a specific behaviour (performance) that is required to a given object (building) without focussing on the technology that will be used to perform it. This method is directly opposed to the object-driven vision (traditional design/management approach) in which a given object (building) is described according to the specific technological characteristics that will be chosen for its construction/operation. The performance-driven approach starts by user profile definitions, identifying user activities and related classes of needs. For each class of needs a list of specific needs is defined, arriving to a requirement background definition. Requirements, which are the technical transposition of needs, are furthermore characterised by potential indicators to check the performances – technical answer to requirements – of the given object (spaces/technical elements/systems...). Among national standards defining this methodological approach, it is possible to mention the Italian architectural technology vision that considers the building quality by defining WHAT it is expected by the building rather than HOW the building is done – see UNI 9289:1981, UNI 8290-2:1981 (requirements), and UNI 11277:2008 (retired).

In the **service-based vision**, IBs are defined in respect to services and quality of services provided by the building. This approach is adopted by the JIBI (Japanese Intelligent Building Institute) which defines an IB as a "building with the service functions of communication, office automation and building automation, and is convenient for intelligent activities" (Wang, 2010). In particular, JIBI focuses on:

i) IB as a place to receive and transmit information and to allow efficient management;
ii) IB as a method to assure users' satisfaction;
iii) IB in order to provide a rational building management;
iv) IB supporting fast, flexible and economical response to sociological, environmental, working-demand, and business-strategy changes.

While, for the **system-based approach**, IBs can be described by listing technologies and technological systems that a smart building should include. An application of this definition may be envisaged in the Chines IB design standard GB/T50314-2000, in which "IBs provide building automation, office automation and communication network systems, and an optimal composition integrates the structure, system, service and management, providing the building with high efficiency, comfort, convenience and safety to users" (Wang, 2010).This concept includes 3 automation axes: building automation, communication automation, and office automation.

Other authors underlined five fundamentals features defining smart homes: i. automation; ii. multi-functionality; iii. adaptability; iv. interactivity; v. efficiency (Lê et al., 2012). While (Al Dakheel et al., 2020) defined, in a recent review on smart building features, four macro-categories of IB features: i. Climate response; ii. Grid response; iii. User response; iv. Monitoring and supervision. The same work underlined 9 representative KPIs assessment domains: overall building energy performance; DSM assessment; RES assessment; RES mismatch; grid interaction; storage performance; building operational evaluation; technical losses/failure; user involvements. Such as it will be defined below, some of these assessment KPIs are included in the SRI definition.

Nevertheless, whatever it is the chosen IB definition, an IB needs to not only include different IT and ICT technologies, but also to properly integrate and coordinate system functions, supporting and requiring for an interdisciplinary approach, and working toward a smart readiness vision.

2.3.2 The Smart-tech vision in EPBD 2018

The Directive 2018/844 of the European Parliament and of the Council amending EPBD introduces the provision to define a *Smart Readiness Indicator* (SRI) able to rate buildings in respect to their smart readiness (The European Parliament and the European Council, 2018). Starting from introductory statements, the Directive underlines the following aspects connected to ICT and smart devices in buildings:

(29)

"(…) Targeted incentives should be provided to **promote smart-ready systems and digital solutions** in the built environment. This offers **new opportunities for energy savings**, by **providing consumers with more accurate information** about their consumption patterns, and by **enabling the system operator to manage the grid** more effectively."

(30)

"The **smart readiness indicator** should be used to **measure** the capacity of buildings to **use information and communication technologies and electronic systems** to **adapt** the **operation** of buildings **to the needs of the occupants and the grid** and to **improve the energy efficiency** and **overall performance of buildings**. The smart readiness indicator should raise awareness amongst

> building owners and occupants of the value behind building automation and electronic monitoring of technical building systems and **should give confidence to occupants** about the actual savings of those new enhanced-functionalities. Use of the scheme for rating the smart readiness of buildings should be optional for Member States."
>
> (31)
>
> "In order to adapt Directive 2010/31/EU to technical progress, the power to adopt acts in accordance with Article 290 TFEU should be delegated to the Commission to supplement that directive by establishing the definition of the **smart readiness indicator** and a methodology by which it is to be calculated. (…)"

In particular, Annex IA ("COMMON GENERAL FRAMEWORK FOR RATING THE SMART READINESS OF BUILDINGS") of the Directive 2018/844 states that the Commission shall establish the definition of SRI and a calculation methodology to "*assess the capabilities of a building or building unit to adapt its operation to the needs of the occupant and of the grid and to improve its energy efficiency and overall performance.*" SRI needs to focus on aspects able to improve "energy savings, benchmarking and flexibility", supporting "*enhanced functionalities and capabilities*" from the adoption of devices more interconnected and intelligent. Among the potential features to be considered the Annex mentions "*smart meter, building automation and control system, self-regulating devices for the regulation of indoor air temperature, built-in home appliances, recharging points for electric vehicles, energy storage and detailed functionalities*". These features need to work following an interoperable approach considering "*benefits for the indoor climate condition, energy efficiency, performance levels and enabled flexibility*".

Three key functionalities are underlined in the suggested method:

> **Key functionality 1**: "*the ability to maintain energy performance and operation of the building through the adaptation of energy consumption for example through use of energy from renewable sources*";
>
> **Key functionality 2:** "*the ability to adapt its operation mode in response to the needs of the occupant while paying due attention to the availability of user-friendliness, maintaining healthy indoor climate conditions and the ability to report on energy use*";
>
> **Key functionality 3:** "*the flexibility of a building's overall electricity demand, including its ability to enable participation in active and passive as well as implicit and explicit demand response, in relation to the grid, for example through flexibility and load shifting capacities*".

Moreover, the methodology needs to consider the "***interoperability** between systems (smart meters, building automation and control systems, built-in home appliances, self-regulating devices for the regulation of indoor air temperature within the building and indoor air quality sensors and ventilations)*" and the positive influence of **existing communication networks.**

The same EPBD 2018 requires in Articles 8(10) and 8(11) that the Commission will adopt a delegated Act establishing an optional common Union scheme for rating the SRI (Smart Readiness Indicator), including a definition and a calculation methodology for SRI. Furthermore, the Commission is also in charge of adopting and implementing acts to detail the potential modalities to effectively implement the mentioned scheme. A first technical support study was accomplished under EU Commission DG Energy and released in August 2018 thanks to the work of an expert group (Verbeke et al., 2018) – see the https://smartreadinessindicator.eu/. Furthermore, a second technical support study on Smart Readiness Indicator for Buildings was launched in December 2018 and, in September 2020, the Final report was published by the Publication Office of the EC (European Commission. Directorate General for Energy and

Vito, 2020a, 2020b). This second report established the potential scheme for SRI definition and a calculation method that was beta-tested using a devoted spreadsheet and a triage to define the evaluation domains.

Recently, the 14th October 2020, the European Commission has adopted the **Delegate Regulation** (EU) C(2020) 6930 "supplementing Directive (EU) 2010/31/EU of the European Parliament and of the Council by establishing an optional common European Union scheme for rating the smart readiness of buildings" (European Commission, 2020a). Furthermore, the European Commission has also adopted the **implementing regulation** C(2020) 6929 final "detailing the technical modalities for the effective implementation of an optional common Union scheme for rating the smart readiness of buildings" (European Commission, 2020b). These documents formally adopted the approach proposed by the expert group, including the numerous received feedbacks. Member States (MS) are now able to receive (on a volunteer base) the SRI calculation scheme and in starting a checking phase for optional National implementations. Even if the SRI allows actions of self-checking about the smart readiness level of their proper (or managed) buildings or building units, the SRI certification should only be issued by a "qualified or accredited experts". A description of the SRI calculation method is summarized in Section 2.3.3.

In addition to the SRI development, the EPBD 2018 (The European Parliament and the European Council, 2018) supports additional smart technological issues. In particular, in the Amendments to Directive 2010/31/EU, the Article 2(3a) introduces a definition for "building automation and control systems". These are considered to support "energy efficiency, economical and safe operational of technical building systems through automatic controls and by facilitating the manual management of those technical building systems". Furthermore, Article 2a(f) references national initiative promoting smart technologies, while attention is given to setting system requirements and requirements connected with the installation of self-regulatory devices – Art. 8(1). Furthermore, Articles 14(4) and 15(4) for non-residential buildings, and Articles 14(5) and 15(5) for residential ones support the possibility of MS to lay down requirements to support the equipment of electronic monitoring systems and building owner/manager information (residential buildings), automation and control systems by 2025 (non-residential buildings).

All of these aspects clearly identify a high interest in the development of strategies, methodologies and solutions supporting and implementing the adoption and the diffusion of building automation and control systems including monitoring and end-user information. A topic that is implemented in the E-DYCE platform logical definition.

2.3.3 General introduction to Smartness Readiness Indicator (SRI)

The above-mentioned technical support study, funded by the EC and led by VITO, introduces the definition and the calculation methodology for a common European SRI. The adoption by the EC of the approach via the Delegate Act and the Implementing Regulation defines a roadmap to implement SRI. A potential connection between SRI and the energy labelling approach may be envisaged, even if not fixed at present. As it is underlined by critical comments on the draft of the mentioned documents before their adoption, the SRI has the benefit to be based on a checklist that defines the method, which may be easily adopted. In parallel, MS may define whether adopting the SRI and how to implement the definition and the method at national level.

2.3.3.1 SRI definition

In line with the art.2 of the Delegate Act of the European Commission (European Commission, 2020a), the SRI (smart readiness indicator) is "**an indicator that informs on the rating of smart readiness of a building or building unit in line with Article 8(10) of Directive**". Similarly, in art. 3, the functionalities of SRI are reported that are summarized here below:

- rate and communicate the smart readiness of a building or building units, informing in particular *economic operators and additional stakeholders* (e.g., *planners and building operators*);
- assess the building/building-unit capabilities *to adapt its operation to the needs of the occupant and of the grid and to improve its energy efficiency and overall in-use performance* (i.e., improving *energy savings, benchmarking and flexibility, and enhanced functionalities and capabilities provided by more interconnected and intelligent devices*);
- include the smart readiness rating and smart readiness scores for *pre-defined key functionalities, impact criteria, and technical domains* (see below);
- potentially include extra-information (i.e., inclusiveness, connectivity, interoperability, cybersecurity, and data protection).

The SRI is hence characterized to be an indicator defining and informing end-users about the smart readiness of a building/building unit including rating systems and sub-scorings related to predefined issues faced in the rating methodology.

Additionally, such as it was mentioned before, the SRI may be used at user level to perform a self-assessment of the SRI potentiality of their own buildings (art. 6 of the C(2020) 6929 final (European Commission, 2020b)), nevertheless, only qualified or accredited experts will be in charge of releasing a certification (art. 4). This certification will expire in maximum 10 years, even if significant changes will require a new certification, such as arrives for Energy Performance Certificates. In order to release and fill in a SRI certification, an assessment phase is defined to collect information. It is suggested by the EC Implementing Regulation C(2020) 6929 final, art. 5, that SRI may be coupled with EPC, including the connected inspections. That's clearly an opportunity for next generation of EPC.

2.3.3.2 SRI calculation method

The defined SRI calculation methodology defined by the EC Delegated regulations will follow the approach described in Annexes I to VI of the Act, while SR rating is defined in Annex VIII. The SRI Certificate information are specified in Annex IX, while SRI certifier experts are expected to include competences from the ICT field. Additionally, MS may decide if implementing SRI at National level, defining if the entire or only a part of their territories is considered and the categories of buildings to be involved. Furthermore, MS may decide whether to use the SRI certificate on a *voluntary or mandatory basis* or not. In all cases, MS that will implement SRI schemes "shall establish an independent control system" (art. 9 of the Delegate Act).

The methodology to calculate the SRI rate and score is here summarized adopting the mentioned Delegated Act (European Commission, 2020a) and the Annexes of the Commission Delegated Regulation (European Commission, 2020c). Furthermore, the Final Report of the Expert Group (European Commission. Directorate General for Energy and Vito, 2020a) is also considered.

The EC SRI calculation methodology is defined in line with SRI definitions and functionalities. It allows to adopt disaggregated SR scores (percentage) able to define SR for one or more of the following points (Annex I, art. 5):

- the three key functionalities of SRI defined in the EPBD 2018 (see above);
- the SR impact criteria defined below;
- the SR technical domains defined below.

SRI calculation focusses on the assessment (current or planned – design stage) of smart-ready services and on the level of functionality of these services. A list of smart-ready services is predefined and is organized in the given technical domain. According to Annex VIII, the SR rating will be subdivided into 7 classes reported in Table 6.

Table 6: Smart readiness rating – 7 classes (European Commission, 2020c)

higher	--					lower
90-100%	80-90%	65-80%	50-65%	35-50%	20-35%	<20%

The calculation of the total SR score (for SRI rating) is based on a pyramidal approach, by multiplying disaggregated impact scores by weighting factors. The SRI scoring pyramid is based on 5 levels, from top to bottom:

i. total SRI score;
ii. SR scores of the three key functionalities;
iii. SR scores of 7 defined impact criteria (Annex II);
iv. SR scores of 9 defined technical domains (Annex IV)
v. Scores for services in the specific technical domain.

The defined impact criteria are subdivided for the 3 key functionalities (each criterion is connected to only one functionality), while the 9 technical domains refer to all impact criteria – see the schematic restitution in Figure 11. Services will be defined by MS by elaborating a SR service catalogue including the list of services, the functionality levels, and correlated scores for impact criteria. Each MS may eventually define different service catalogues according to building typologies (Annex VI).

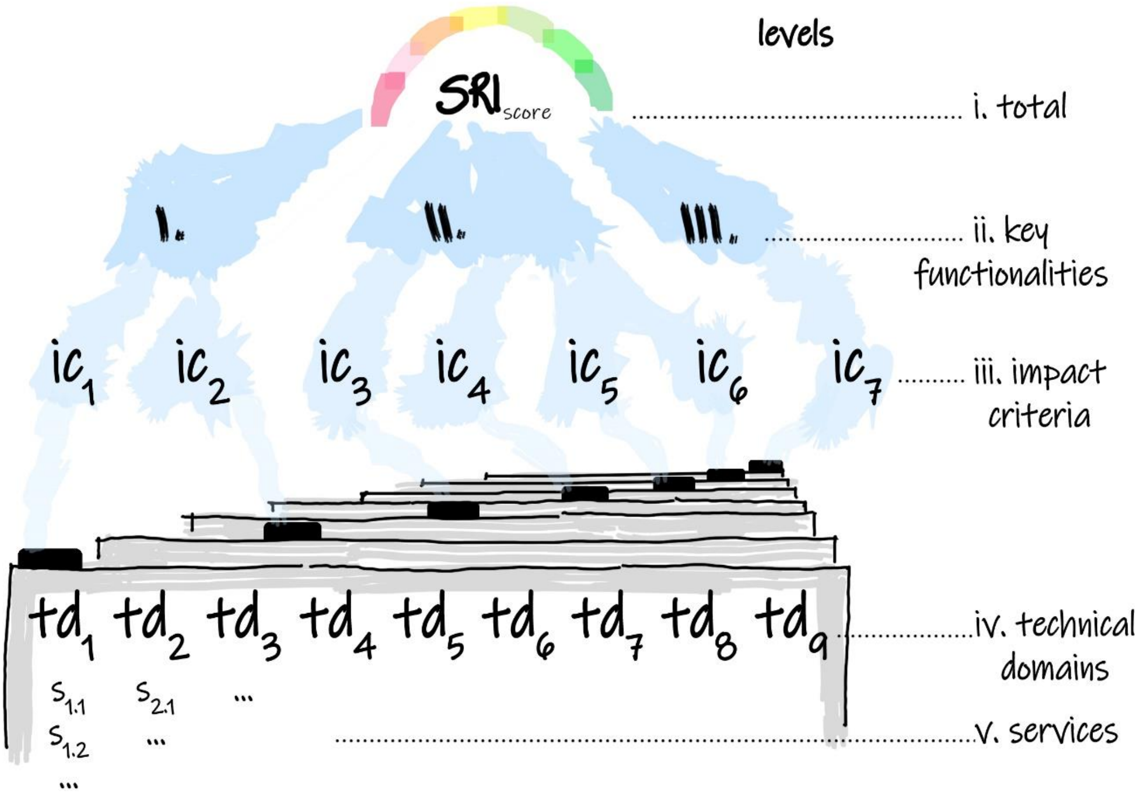

Figure 11: Basic approach for SRI scoring

Each sub-level score is weighted to be scaled in the upper-level score. For levels from i. to iv. this is based on weighting factor definitions, while for levels iv. (this level combines both) and v. the functionality SR scores are normalized by the maximal functionality score for the technical domain.

For example, the total SR score is given by the following expression (Annex I):

$$SR_{total} = \sum_{f=1}^{3} W_f \cdot SR_f$$

Where f is the specific key functionality (from 1 to 3 – according to EPBD 2018 definitions), W_f is the weighting factor criteria for the specific functionality, SR_f is the SR score for the specific functionality, which is derived by the weighted sum of sub-levels scoring (correlated impact criteria). The sum of all weighting factors in an upper level is assumed to reach 1, being each score level expressed in a percentage number. For example, $W_{f\text{-}1} + W_{f\text{-}2} + W_{f\text{-}3} = 1$.

The calculation of SR scores for impact criterion ($_{ic}$) is defined by (Annex I):

$$SR_{ic} = \frac{\sum_{d=1}^{N} W_{d,ic} \cdot I_{(d,ic)}}{\sum_{d=1}^{N} W_{d,ic} \cdot I_{\max(d,ic)}} \cdot 100$$

Where *d* is the specific technical domain and *N* (Annex IV) is the number of technical domains in the specific impact criterion, $W_{d,ic}$ is the weighting criteria for the specific technical domain in the given impact criterion, and $I_{(d,ic)}$ and $I_{max(d,ic)}$ are respectively the sum of services' scores in the given domain and the maximal functionality scores for the same sum of services.

Weighting criteria are defined by MS and may change according to climatic zoning, building types (e.g., residential or non-residential), and eventually expected impact of climate changes (Annex V). During the future process for SRI adoption in MS, specific connected open issues will be faced. For example, concerning the definition of a SRI scoring for complex buildings, where specific zones may be characterized by different service implementation levels (e.g., Hospitals, Schools, Universities, ...). For these building types, will be important to define zoning methodologies and/or to set minimal requirements to assume a service to be included in the building SR score – e.g., considering the percentage of occupied surfaces, i.e., 30%. See also other suggestions and comments delivered during the beta-testing phase during the second technical report definition.

The general MS interest in adopting SRI may benefit by the fact that this indicator is independent of user behaviours, being based on the presence of offered services. For this reason, SRI score may assume a high potential value as indicator in the rent and real estate market, supporting its adoption by large properties to promote renting choices. The SRI certificate may help interested tenants in identifying the smartness services offered at global and specific levels, e.g., by visualising the SR scores for technological domains and impact criteria (e.g., lighting).

2.3.3.3 SRI assessment procedures

In line with the Technical Expert Reports, it is possible to identify three potential assessment methods to define the SRI score:

- Method A – simplified;
- Method B – Expert SRI assessment;
- Method C – in-use smart building performance.

The definition of assessment methodologies is still under development and includes elements to be further detailed by MS during SRI implementation. Currently, they are Method A and B that are mainly under development. For example, the X-tendo EU co-funded project is developing Method A, supporting a reduction in the number of considered services (e.g., from 54 to 27) to spread SRI applications to generic users (Zuhaib, 2020a). Differently, Method C is currently mentioned as a potential future evolution, leaving its development open to explorations. Table 7 underlines current main differences between the three mentioned methodologies, in line with the second Technical study supporting EC to the development of a SRI for buildings. It is evident a difference in between the simplified Method A and Method B, considering changes in service lists and in involved users, supporting on the one side mainly self-assessment, and on the other side mainly certification development. Both methodologies work at design and asset rating level.

Table 7: SRI potential assessment methods (European Commission. Directorate General for Energy and Vito, 2020b)

	A – simplified method	B – expert SRI assessment	C – in-use smart building performance
Approach	Checklist – limited, simplified service lists	Checklist - full-service catalogue	Measured/Metered data (domains may be restricted)
Where	**On-line self-assessment** (On-site inspection)	**On-site inspection** (On-line self-assessment)	**actual performance**
Who	end-users (third-party qualified experts)	third-party **qualified experts** (end-users)	Tenants self-reporting -For E-DYCE open to technical qualified experts (e.g., energy manager, ESCOs)
Timing	1 hour or less	½ or 1 day (depends by the complexity)	Data elaboration from at least 1 year of measurements
Building type	Residential and small non-residential	Non-residential and residential	Non-residential and residential
Limitations			Only occupied spaces
Label	No (self-check); Yes (qualified experts)	Yes (qualified experts)	Potentially (qualified experts)
Design/operational	Design	Design	Operational

2.3.3.4 E-DYCE implications

SRI will be considering in E-DYCE KPIs definition. In particular, E-DYCE enables the 3 key functionalities in line with EPBD 2018 and the mentioned Commission Delegated Regulations (Annex I):

- energy performance and operation;
- response to the needs of the occupants; and
- energy flexibility, including the ability of the building or building unit to enable participation in demand response.

Furthermore, the seven impact criteria [energy efficiency, maintenance and fault prediction, comfort, convenience, health/well-being and accessibility, information to occupants, energy flexibility and storage] and their univocal correlation with a key functionality are assumed. Finally, the nine technological domains [heating, cooling, DHW, ventilation, lighting, dynamic building envelope, electricity, electric vehicle charging, and monitoring and control] listed in Annex IV are also assumed. To apply the SRI indicator in the project, a simplified service catalogue will be defined for pursuing E-DYCE Objectives and Innovations – including free-running functionalities, i.e., controlled natural ventilation for both cooling and IAQ, and dynamic building optimisation considering user information and suggestions – and considering Demo case boundary conditions (climate, building typology, ...). Furthermore, the Triage approach described in the Technical Report will be used to support the definition of the higher smart-possible levels of the buildings (technologies that may be installed, relevant for the building). This definition process will follow on the one side the suggested service catalogue proposed by the Expert Group in their Second Report (European Commission. Directorate General for Energy and Vito, 2020a) and connected spreadsheets, and on the other the information provided by Annex IX (European Commission, 2020c). The collection of needed information to define the SRI KPI will be included in the E-DYCE inspection and data collection process.

E-DYCE EPC approach will define a minimal SRI level to be reached by buildings focussing on specific services, e.g., the presence of a temperature sensor cloud connected with data storage to cover primary KPIs in operational and FR evaluations. Nevertheless, advanced integrated E-DYCE functionalities will require higher SRI levels, increasing the smart services that will be available in a building.

2.3.4 Potential smartness/behavioural building evaluation logics

In addition to the requirement to define the SRI and to assess a SRI calculation methodology, the EPBD Directive 2018/844 (EPBD III° version) underlines additional provisions connected to building smartness technologies. These include electronic monitoring, automation and control, and different user-profiles' information – see the previous Section 2.3.2. E-DYCE platform includes the SRI calculation, considering the design rating (simplified approach focussing on some E-DYCE connected services). Additionally, in E-DYCE specific steps toward a draft elaboration of post monitoring data to verify the usage of mentioned E-DYCE SR services will be defined in order to connect demo outputs with SRI in-use performances. Nevertheless, also additional aspects connected to building smartness will be treated. In particular, E-DYCE will include data collection from smart monitoring solutions following a technology neutral approach and data restitution to end-users filtered according to different user profiles (e.g., tenants, owners, energy managers, additional secondary users like public administration or energy providers, customized profiles). The E-DYCE logic is based on the possibility to include not only dynamic simulation engine supporting the translation form steady-state to dynamic standardized building simulation for design and asset rating, but also an operational analysis of building performances thanks to the integration of electronic monitoring solutions. Particular attention is given to existing simulation solutions, aiming at making the approach open and scalable and focusing on the methodological workflow based on KPIs' calculation, performance evaluations and user information. The process is conceived to be open to automation and control system integration, including different levels of smartness and of user activation – form self-activation on the base of KPIs customized restitution, to fully automated building behaviours without requiring direct user actions. This specific aspect of the E-DYCE approach will be mainly treated in further projects, while the approach developed in this project deals with the definition of primary E-DYCE functions – see Section 3.

2.4 *Energy metering and district network communication*

In the Directive 2002/91/EC of the European Parliament and the Council presents in the article 5 that the "*new buildings with a **total useful floor area over 1000 m²** shall ensure that technical, environmental and economic feasibility of alternative systems*". In the list presented by the Directive as an alternative system, the district or block heating or cooling is suggested. In the EPBD recast of 2010 (EPBD 2010/31/EU), the subject of district heating or cooling was broadened by attributing its definition as:

Article 2

Definitions

(…)

19.

"' district heating' or 'district cooling' means the distribution of thermal energy in the form of steam, hot water or chilled liquids, from a central source of production through a network to multiple buildings or sites, for the use of space or process heating or cooling."

Compared with the former EPBD (EPBD 2002/91/EC), the new requirement for a new building was recast in terms of **considering all the new buildings** must be taken into account high-efficiency alternative systems, if available. This requirement is new due to the absence of a minimum total useful floor area condition and the particularity that the district energy system must be *"based entirely or partially on energy from renewable sources"*. It also worth mentioning that for the existing buildings the *"Member States shall encourage, in relation to buildings undergoing a major renovation, the consideration and taking into account of high-efficiency alternative systems, (…), in so far as this is technically, functionally and economically feasible."*. In the same EPBD, it is introduced the concept of *"intelligent metering systems"*:

Article 8

Technical building systems

(…)

2.

"**Member States shall encourage the introduction of intelligent metering systems whenever a building is constructed or undergoes a major renovation**, whilst ensuring that this encouragement is in line with point 2 of Annex I to Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity. Member States may furthermore encourage, where appropriate, the installation of active control systems such as automation, control and monitoring systems that aim to save energy."

Following the 2010 EPBD, it was published in 2012 the European Directive 2012/27/EU on energy efficiency, also known as EED, where it was established the target of reducing by until 2020, 20% of the predicted 2020 EU primary energy consumption. In the EED, several mandatory measures were described, in which was presented various requirements relatively metering and billing of the building stock. It is also presented by the European Union, the potential energy savings that might be achieved if implemented district energy systems and high-efficient cogeneration systems. Due to this fact, the DEPC will also take into account the energy metering related to the district energy network.

2.4.1 General introduction to energy metering

In the Dynamic Energy Performance Certificate, the role of energy metering is highly important. With the installation of smart energy meters in a building, it is possible to measure and gather electricity, heating and cooling consumption data in a building, which will therefore provide the understanding of how the building systems dynamically interact with the measured indoor/outdoor conditions and user actions. In other words, the provided information from the energy meters will display the dynamic involvement of the energy supply in the building whenever the indoor/outdoor conditions change, e.g., increase/decrease of heating/cooling needs, occupation behaviour, weather daily and seasonal variation, etc.

Metering is typically made on different types of energy carriers: electricity, heat (in hydronic heating and cooling systems) and gas. The data provided by the meters varies depending on the carrier. 'Smart' meters typically provide frequent reading (i.e., hourly or faster) of these parameters which can be communicated automatically to data acquisition systems for logging purposes. On top of this, some meters also have possibilities to impact the energy flow directly (e.g., by providing a power limitation on their output, or circuit breaking).

Beyond energy demand, the data from these meters inform about the performance of building systems. An example of this is the measurement of return temperature in heat networks, which provides an insight into the effectiveness of the heat transfer in the end-devices (e.g., radiators) in the building.

In the market, several manufactures have a different range of smart energy meters with different functionalities. The manufacturer Kamstrup A/S is one of the main responsible for installing and replacing smart meters in the Danish district heating network as a reference is described the smart meter model from Kamstrup, the heat flow meter "MULTICAL® 603". This device is a hydronic smart energy meter that can be installed in several thermal installations of heating, cooling or heating and cooling for measurement of the energy consumption, flow rate and fluid temperature. Besides this, the equipment can also be used for leakage control, power and flow limiter and energy measurement in open and close systems (Kamstrup, 2020). It is a smart meter that has a long lifetime, up to 16 years, and its sensors can measure a wide temperature range. It also has the particular function of being easy to integrate with previous installed Kamstrup's static flow sensors. This device has the advantage of being possible to be used remotely and to configure its settings without having the need to access it on the site personally. With the functionality of being able to access the meter remotely, the information of heat/flow readings can be sent to the utility company or a consultant company allowing them to identify the heat load and water usage profiles and detect errors in the system. The data logger can be programmable to deliver the collected information by the sensors in yearly, monthly, daily, hourly and minutely resolution. Furthermore, the supported communication modules are Modbus, BACnet, M-bus, wireless M-bus and analogue outputs, which promotes higher flexibility to match the requirements of an installation.

2.4.1.1 Smart metering required parameters

In power systems, smart electricity meters typically deliver accumulated energy demand with hourly resolution or higher. Some also provide possibilities for faster readings, as well as extra parameters such as instant power, voltage, activate and reactive power.

In the smart energy meters that can be installed in buildings connected to heat networks, the parameters that are usually required are the following: i. Energy consumption (accumulated measured values) in kWh, MWh, GJ or Gcal; ii. Water consumption (accumulated measured values) in m^3; iii. Flowrate (instantaneous measured value) in m^3/h or litres/h; iv. Temperature (measured in the supply and return, where the values can be averaged throughout a period of time, e.g., hourly-averaged and instantaneous measurement) in ^oC; and v. Power (instantaneous measured value) in kW or MW. Some meters also provided volume integrations of supply and return temperatures. The smart meters can also be equipped with an error log which detects and stores in the device memory the anomalies occurred in the sensors to inform the end-user and the utility company about them. Regarding the data resolution, it must be at least hourly, depending on the system where the meter is installed. There are also third-party systems, used in some companies, that in connection with the smart meter's data or other data sources, may access possible errors in smart devices performance.

2.4.1.2 Communication challenges with district network

The real energy measurements collected by the smart meters will allow understanding the building physics and the existing interactions between the building, occupants, systems and outdoor conditions. In the section above, 2.4.1.1, it is listed the parameters that are determined by the devices. From these parameters, it is possible to develop several methodologies to assess the energy performance of the building regarding the outdoor/indoor conditions, building characteristics and the DH (District Heating) network.

From the smart energy meter measurements, two of the KPIs can be withdrawn to understand the energy consumption of the building. These are the cumulative energy usage (Q) and water consumption (V_{water}) for a year per square meter area, given by the following equations, respectively:

$$Q/_A \ [kWh/m^2 \cdot year]$$

$$V_{water}/_A \ [m^3/m^2 \cdot year]$$

By having the temperature values, it is calculated the temperature difference using the equation here below for each time span, which is an indicator used by the DH utility company to evaluate the heat transfer performance of a specific end-user. As a side note, some companies have a punishing extra fee that is charged to the end-users that have low-temperature drops between the supply and the return circuits.

$$\Delta T = T_{supply} - T_{return} \ [°C]$$

When complemented the data from the smart meter with the weather measurements collected by the closest meteorological station from the building's location, it is possible to understand the influence of the different outdoor conditions on the building's energy consumption. At Aalborg University, it was developed a straightforward methodology to withdraw some features of the building, when the household heating consumption is aggregated with the weather dataset. The outdoor variables necessary for the calculations are the external temperature, the wind speed and the solar radiation. The methodology is presented below.

To determine the heat consumption of the system, it needs to estimate the heat balance in the building (space), through the following equation:

$$E_{transmission} + E_{ventilation} = E_{heating} + E_{solar} + E_{internal} \ [W]$$

Where the heat losses through the envelope materials (transmission) and the ventilation (ventilation system and infiltrations) are equal to the heat gains from the heating system (heating), solar radiation (solar) and the internal loads from people and equipment (internal). The above-mentioned equation can be formulated as a linear function where the heating consumption is dependent on the outdoor temperature:

$$E_{heating}(T_{out}) = -(UA + n\rho c_p)T_{out} + \left[(UA + n\rho c_p)T_{int} - E_{solar} - E_{internal}\right]\ [W]$$

Where:

T_{out}	Outdoor temperature [^{o}C]
T_{int}	Indoor temperature [^{o}C]
U	Overall thermal transmittance coefficient of the building's envelope [W/m^{2o}C]
A	Overall area of the building's envelope [m^2]
n	Ventilation volume rate [m^3/s]
ρ	Air density (kg/m^3)
c_p	Specific heat constant for constant pressure [J/kg^{o}C]

From the values of the energy consumption and the outdoor temperature measured by the sensors, it is plotted the following graph (**Fejl! Henvisningskilde ikke fundet.**) for the heating and no-heating seasons for each building:

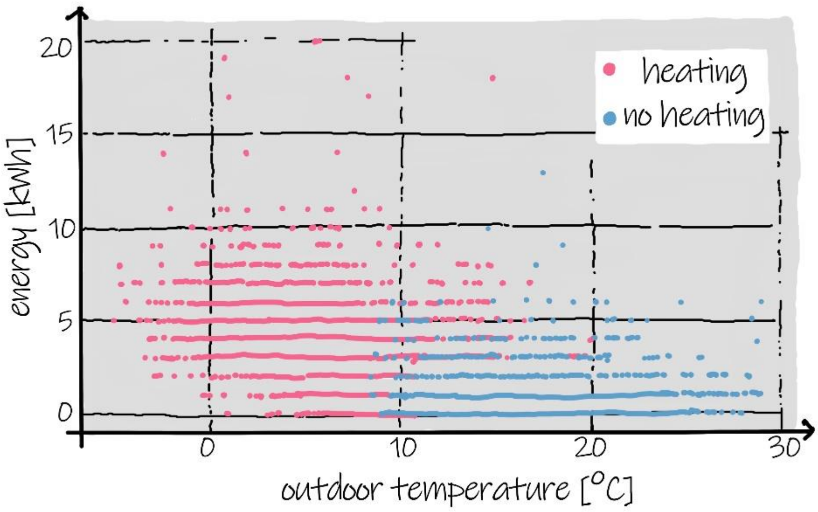

Figure 12: Daily energy usage and daily mean outdoor temperature

In **Fejl! Henvisningskilde ikke fundet.** is seen the dependency of heating energy and the outside temperature as predicted by the latter equation. To clarify the relationship between the values, it can be applied the methodology presented in (Gianniou et al., 2018b), where the energy variable is the daily consumption measured by the smart meter and the outdoor temperature is the daily average. This methodology was used to consider the influence of the latent thermal mass effects in the building. Figure 13 exemplifies the result of the dataset after summing the energy measurements throughout the day and plotting them by the daily mean outdoor temperature.

From the last plot, it is formulated two linear regressions, to express the relation between the heating usage and the external temperature mathematically, as seen by **Fejl! Henvisningskilde ikke fundet.**.

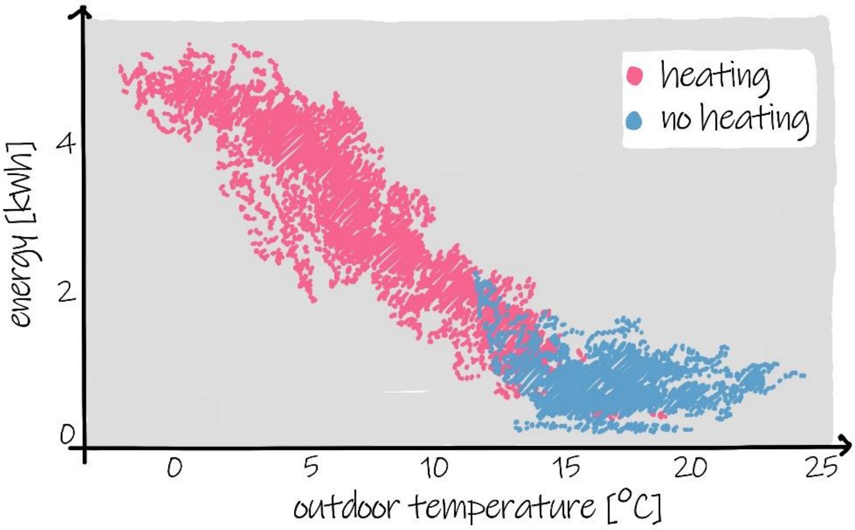

Figure 13: Daily energy usage and daily mean outdoor temperature

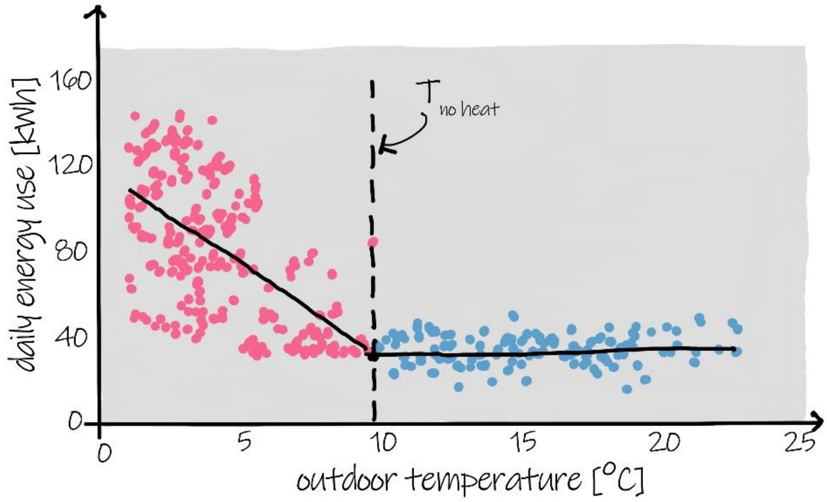

Figure 14: **Linear regressions for heating and no-heating seasons.**

The linear expressions are described by the following equations:

$$E_{heating}(T_{out}) = \begin{cases} m_H \cdot T_{out} + b, & Heating\ season \\ E(T_{No\ Heat}), & No\ heating\ season \end{cases}$$

The first equation here-above, from the linear regression, is the same as the previously defined equation, where the m_H-value is dependent on the building's envelope, ventilation systems and the airtightness. Furthermore, the b-value is dependent on the combination of the different factors present in the heat balance (envelope materials, solar radiation, ventilation and internal loads). The no-heating season equation represents the relation between the overall heating consumption and the outdoor temperature in the no-heating season. If this value is constant, then it represents that the system was shut-off, but if it is not constant, then it might mean the space heating system is still working even during warmer days, which may happen in buildings that have underfloor heating. The variable $T_{No\ Heat}$ is the temperature limit, when the external temperature is higher than the threshold, the space heating is turned off. A high value might represent a building where the people are only comfortable with high indoor temperatures, due to preferential choices (occupancy behaviour) or that the building itself has low indoor temperatures even with high outside temperatures (high-energy buildings). When the variable $E(T_{No\ Heat})$ is constant but higher than zero, it represents a smart energy meter that is measuring a building's heat consumption for both space heating and domestic hot water (DHW) production. Therefore, it is possible to estimate how much energy is required to warm the DHW in the building, which is highly dependent on user behaviour. In contrast, if the variable is almost zero, it means that the space heating is shut-off, and the smart energy meter is not measuring the DHW production.

By taking into account the m_H-value, it is possible to withdraw some conclusions regarding the building characteristics. The dataset from the energy meters collects the heating readings in different outside conditions. By filtering the data points for a specific outdoor condition, it is possible to isolate a particular building characteristic (energy component). The filtering conditions are seen in Table :

Table 8: Dataset filtering conditions

Energy component	Radiation (R_d)	Wind speed (v_{wind})
Temperature/Transmission	0	Low
Infiltration/Ventilation	0	High
Solar gain	High	Low

To isolate the period where the outdoor temperature only influences the energy demand, the new dataset will only be constituted by data points measured when the radiation is equal to zero (night period), and the wind speed is low. The ventilation component can be extracted when the radiation is also null, but the wind speed must be high. For the solar gains factor, it is estimated when the filtered dataset is during daytime (radiation is high), and the wind speed is low. By applying the same reasoning as above, the new filtered datasets are represented in scatterplots (energy consumption and outdoor temperature) and their linear regressions are developed for the heating season. Several m-values are obtained from the following:

Temperature/Transmission condition:

$$E(T_{out}) = m_1(T_{out}) \times T_{out} + b_1$$

Infiltration/Ventilation condition:

$$E(T_{out}) = m_2(v_{wind}) \times T_{out} + b_2$$

Solar gains condition:

$$E(T_{out}) = m_3 \times T_{out} + b_3(R_d)$$

Therefore, a new set of coefficients are estimated to evaluate the impact that the considered outdoor conditions have on the building's energy performance. These coefficients are calculated through the equations:

$$R_{temp} = m_1\ [kWh/°C]$$

$$R_{inf} = m_2\ [kWh/°C]$$

$$R_{solar} = b_3\ [kWh]$$

The value R_{temp} represents the influence of the outdoor temperature has on the overall building's energy demand. Therefore, the lower the value, the higher is the energy consumption for space heating due to transmission losses. The R_{inf} and R_{solar} follow the same reasoning as R_{temp}, the lower the values, the higher the ventilation losses, and the solar gains will be in a building. It is predicted that the same methodology should work for district cooling systems, where, the R_{solar} probably will have good accuracy.

By having the values R_{temp}, R_{inf} and R_{solar}, it is possible to assess the dependency that the building's heating consumption has regarding the external conditions, and consequently reveal the real building's characteristics, i.e., transmission losses through the envelope, gains through glazing areas and heating losses through air leakages and ventilation. However, as seen by the equations, all linear regressions are dependent on the outdoor conditions. This implies that each filtering condition must have a significant and wide distribution of data points for a good performance of the results. It is estimated that for countries that there are lower radiation or wind speed levels, this methodology performs poorly. Therefore, each filtering condition must be assessed, taking into account the local weather characteristics before making any conclusions.

The real influence of these factors with the measured energy consumption, when compared with the predicted energy consumption, from the EPC, will determine the energy performance gap that may exist and highlight which factor has the highest contribution for the difference. The different parameters concerning the building can be visualised in a parallel coordinates plot. In a parallel coordinates plot, it is represented the variables calculated above, such as temperature difference (ΔT), total water consumption (in m^3), linear regression slope for the heating season (m_H in kWh/°C), linear regression slope for the no-heating season (m_{NH} in kWh/°C), linear regression slope when only considering temperature ($m(T_{out})$ in kWh/°C), both R-coefficients and the threshold outdoor temperature where the heating season is shut-off ($T_{No\ Heat}$). By aggregating these values with some information regarding the building from the current EPC, it is possible to have a better assessment of how the different variables influence energy consumption. The variables used in the plot are the number of rooms, the number of bathrooms (showers), the energy consumption in the no-heating season, construction year of the building, year of the last major renovation in the building, the measured yearly energy consumption per square meter area and the estimated, by the EPC, yearly energy consumption per square meter area. The parallel coordinates plot can be used in the DEPC to express the results from the analysis of the district energy network by the smart meters, as seen in **Fejl! Henvisningskilde ikke fundet.**. In the figure, it is presented two different reference buildings which represent the possible best (green) and worst (red) case-scenarios of the building that is being assessed. Furthermore, the DEPC assessment results are shown in yellow, representing the values obtained by the DEPC of the building. The reference buildings allow to visualise and compare them with the DEPC results, to identify which variables are performing well (close to the green values) from the variables that are performing poorly (close to the red values).

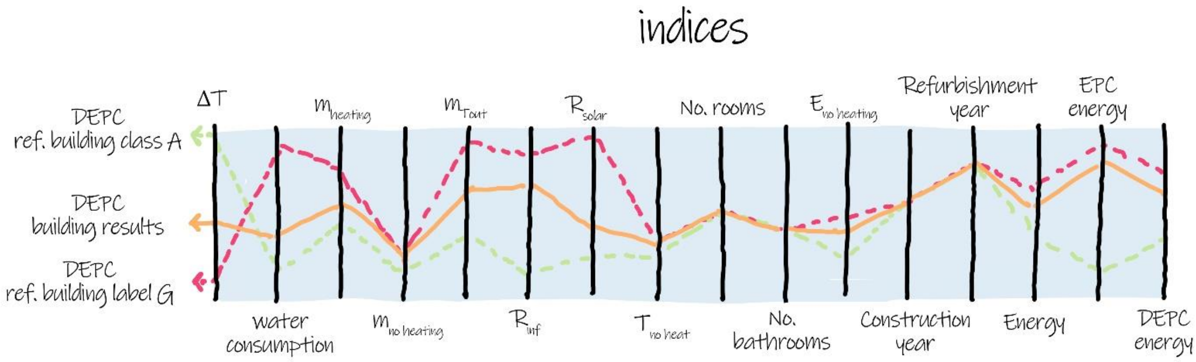

Figure 15: DEPC parallel coordinates plot – Results.

<u>Other methodologies</u>

For the analysis of large datasets of buildings, the calculation of several new variables might become computationally challenging. Therefore, new methodologies to apply for district heating smart data are being developed to extract more information of the end-users. One of the methods is data clustering, from the Machine Learning domain, which is based on several algorithms that evaluate the different building's parameters and groups the buildings with similar characteristics between each other. These methodologies have already been used in smart electricity data to cluster consumers with identical behaviour to tailor energy efficiency programs for target users, as seen in (Azaza and Wallin, 2017). For the case of district heating data analysis, several studies have been developed by applying different clustering algorithms to undertake the group categorisation and determine which algorithms are the most suitable for this specific dataset. As an example, in (Wang et al., 2019) it was applied the method "Gaussian mixture model" (GMM) in different featured variables of a DH dataset from Sweden. Also, in (Gianniou et al., 2018a) it was applied the "K-means" algorithm in the daily averaged heat consumption profiles in a DH Danish case constituted of 8293 single-family households. Both studies revealed that the clustering methods are a great tool to assess the building's heat consumption in terms of its intensity and its daily pattern. Concerning the selection of the most suitable methodology, more research must be made, as it is stated in (Wang et al., 2019), it is very difficult to find the optimal clustering algorithm on a dataset because this selection depends on the parameters evaluated and the time-resolution of the data. Therefore, if the DH variables and the distance measures are selected correctly, the clustering method will achieve good results.

From the DH data collected by the smart energy meters, it is also possible to create different types of models to perform several calculations to assess the performance of the building and of the DH network where they are connected. As seen in (Guelpa et al., 2019), with the historical data from the DH system measured in Turin, Italy it was developed a multi-level approach to predict the building's demand profiles and to model the thermal request on the different network levels, i.e., distribution network, group of distribution networks and the plant level. In (Kristensen et al., 2020) it was created a model with DH data from detached single-houses in Aarhus, Denmark, to forecast the buildings' heat load regarding their archetype distinction using a hierarchical stochastic archetype calibration approach. In both research studies, it is presented promising methodologies to predict the heat demands in the different urban levels, which allows its application in the DH urban-scale design and optimisation, where it is possible to predict and assess the impact of different management decisions and energy solutions in the network, e.g., heat pumps, energy storage, etc. Other methodologies that can be used to extract meaningful information regarding the district heating given by the data from the installed meters is through various Machine Learning (ML) algorithms. In (Maljkovic and Basic, 2020) it was applied three different ML algorithms to test their forecasting ability by using the billing data of 260 buildings in Zagreb, Croatia. In the same study, it was also assessed the influence of several technical, building and behavioural parameters on the heat consumption, showing that the variables dependent on the building's refurbishment and the consumer's behaviour have the most impact on the energy performance.

Regarding ML, it can also be applied to detect faults in district heating, as seen in (Månsson et al., 2018). In this study, it was used a ML algorithm to develop a model that forecasts the mass flow, using hourly-basis measurements, on the primary side of the DH system's substations in Sweden during a year. As a conclusion of this study, the chosen model, "Gradient Boosting Regressor", was considered a promising model to be used as a forecasting and fault detection methodology for the DH network.

With the application of all the different existing methodologies to handle the data from the smart meters installed in the DH network, it can be presented all the results in an interface page to be available for consulting. In **Fejl! Henvisningskilde ikke fundet.**, it is seen a web-interface page developed in *Aalborg University*, to present the DH data from a small village in Denmark. For this case, it can be consulted the average measurements of the buildings connected to the network, the number of detected faults by the meters, clustering results and estimated building characteristics.

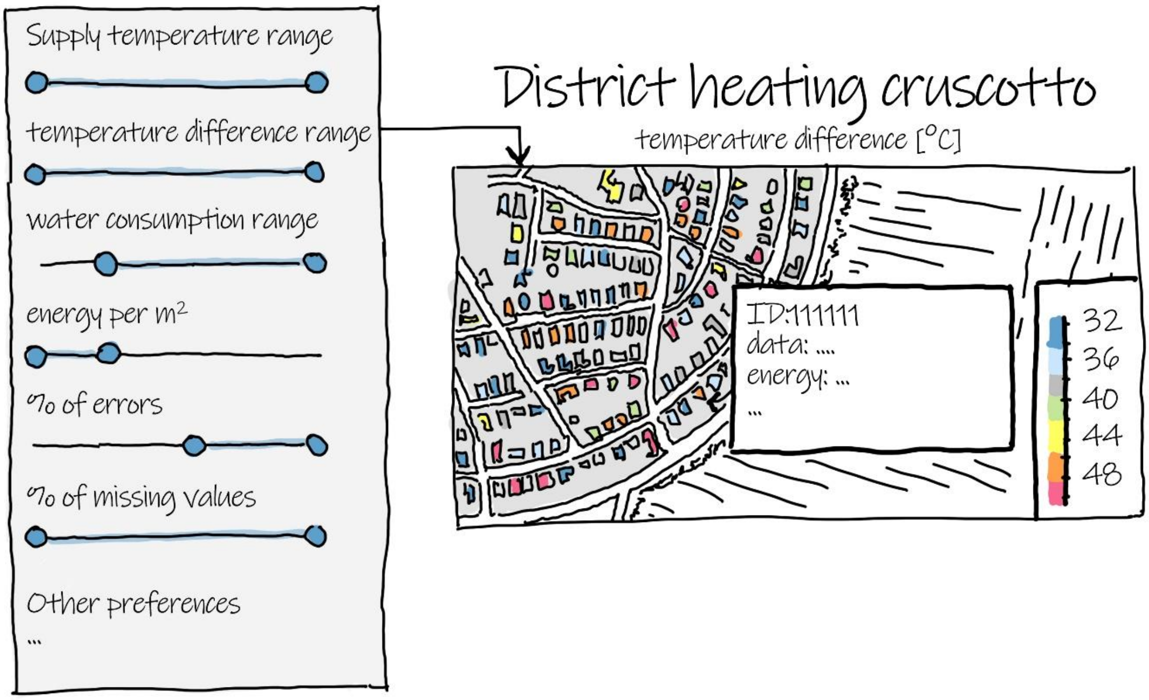

Figure 16: Web-interface to display the District heating data

2.5 *Hourly dynamic models and performance gap*

A well-known challenge connected to building energy performance estimation is the need to minimize and manage the "performance-gap". Even if different definitions of what it is a performance-gap and which are its correlated causes are underlined in literature (Jain et al., 2020; Jradi et al., 2018; Zou et al., 2018), it can be stated that it defines the gap between an expected (simulated) energy consumption and the real (monitored) consumption. It is a common procedure to use simulation programs to predict or to define the expected building energy performance, nevertheless the real counterpart of the simulated standard building-model was demonstrated in several occasions to react in a different way. This discrepancy opens a great challenge in energy performance simulations, especially when simulations are used to label a building defining its expected standardized performance, or when they are used to evaluate retrofitting scenarios including the definition of optimal costs and a payback time of the investments. Finally, this is also connected to great challenges in the user-information and user-behaviour optimisation to support energy efficiency management. Focussing on EPC, it is possible to underline that on the one side, there is the need to "standardise operating conditions under the EPBD" (supporting national approaches and comparisons), nevertheless, on the other side, this open to the risk that "energy-related procurement issues go unnoticed" and all EPG (Energy Performance Gap) discrepancies will be solely justified by mentioning differences between standard and real operational conditions. "This can seriously compromise energy efficiency in building stock in the EU" (Burman et al., 2014).

Main performance gap effects may be defined by the terms "prebound" and "rebound". The prebound effect refers to the under-consumption in real conditions of old, not efficient, and low label buildings in respect to their simulated energy needs. This effect defines a negative energy performance gap (EPG) – meaning that energy services in old and low energy quality buildings consumes less than simulated – and, consequently, retrofitting scenarios result in an overestimation of potential energy need reductions. On the contrary, the rebound effect defines a positive EPG that arrives in high quality, retrofitted, high energy rating buildings. This increase in real consumption in respect to simulated energy needs is correlated to several causes, including the fact that the marginal cost for energy services is reduced under energy-efficiency actions, supporting users in consuming more energy (Cozza et al., 2020a).

From a general point of view, the building energy performance gap is generally linked to several issues and causes:

- The adoption of simplified simulation approaches (like steady-state ones)(Carbon Trust, 2011; Frei et al., 2017; Menezes et al., 2012; Oduyemi and Okoroh, 2016; Raslan et al., 2009; van Dronkelaar et al., 2016);
- Potential errors (model operators) in model data inputting (Herrando et al., 2016; Khoury et al., 2017; Mørck et al., 2012);
- The use of common and standardized data in simulation, like for example:
    - The accuracy of input variables (e.g., the building U-value, the airtight and air change – ACH) (Ahern and Norton, 2019; Burman et al., 2014; Cozza et al., 2020a; Cuerda et al., 2020; Herrando et al., 2016; Menezes et al., 2012; Mørck et al., 2012);
    - The adoption of standard climate conditions (Cuerda et al., 2020; Mørck et al., 2012);
    - The adoption of user standard profiles and behaviours (Ahn et al., 2017; Cuerda et al., 2020; Herrando et al., 2016; Robinson et al., 2016);
    - The adoption of standard set-points or the definition of inaccurate expected indoor temperatures (Cozza et al., 2020a; Flourentzou et al., 2019; Frei et al., 2017; Gaetani et al., 2016; Mørck et al., 2012);

- The interaction between occupants and technologies (Al Dakheel et al., 2020; Dasgupta et al., 2012; Flourentzou et al., 2019; Herrando et al., 2016; Jradi et al., 2018; Menezes et al., 2012; Pappalardo and Reverdy, 2020; Robinson et al., 2016; van Dronkelaar et al., 2016).

An interesting focus on operational management and occupant/technology interactions is reported in (Liu et al., 2019), underlining the importance of supporting communications with users to obtain large reductions in EPG thanks to an enhancement of their ability in energy-saving. User information is hence an essential aspect to be considered in reducing EPG during operational phases and this is a topic that is faced within E-DYCE.

Additionally, it is also possible to classify performance-gap causes according to different building phases, assuming 3 classes (Frei et al., 2017; Jradi et al., 2018; Zou and Alam, 2020) – see also the discussion on S-curve scenarios introduced in (Bunn and Burman, 2015):

- Design-phase correlated causes;
- Construction-phase correlated causes (e.g., quality of finished building (Bordass, 2004; de Wit, 1995; Herrando et al., 2016; Wong et al., 2020));
- And operational-phase correlated causes.

This classification underlines performance-gap causes that base in the design choices and in the correct interpretation of design impacts on energy needs, on construction issues, e.g., insulation gaps, bad positioning/installation of services or components, and on operational causes correlated to an optimisation of energy service management, user activation, and behaviours. The last, may also be connected to unexpected changes in building fabric behaviours (e.g., internal temperature variations during unheated periods) (Cozza et al., 2020a; Love, 2014).

From a general point of view at least 3 types of building performance gaps exist (Bruman, 2016; van Dronkelaar et al., 2016):

i. Regulatory performance gap;
ii. Static performance gap;
iii. and dynamic performance gap.

Where, the regulatory PG (performance gap) refers to the discrepancies between results from compliance energy modelling tools and measured energy consumptions, the static PG compares performance simulation predictions (potentially including unregulated loads) and measured data, and the dynamic performance gap analyses differences between calibrated dynamic energy models and actual energy consumptions (Jradi et al., 2018). Clearly, the first two mainly refer to differences between design and asset rating analyses and real building behaviours – focussing the first on design stages and the second on design, construction and first operational years before the introduction of energy-management optimisation (if any). In particular, if the first relies on compliance modelling approaches, the second allows to tailor operational conditions generally based on dynamic energy simulations – see also CIBSE TM54 (CIBSE, 2013) and (Jain et al., 2020). Differently, the third is a comparison between tuned-simulated and real operational behaviours and may be defined and improved by calibrating models and systems, especially from the second building operational year (supporting energy-technical optimisation processes). The latter has in fact the possibility to analyse operational inefficiencies supporting operational optimisations. Figure 17 schematically represents these 3-types of PG. Similarly, (Jain et al., 2020) define a perceived gap, which corresponds to the above-mentioned regulatory performance gap, an actual gap, correlated to the static performance gap, and two additional gaps: the first defining operational changes in simulations, and the second referring to remaining operation gap due to technical issues.

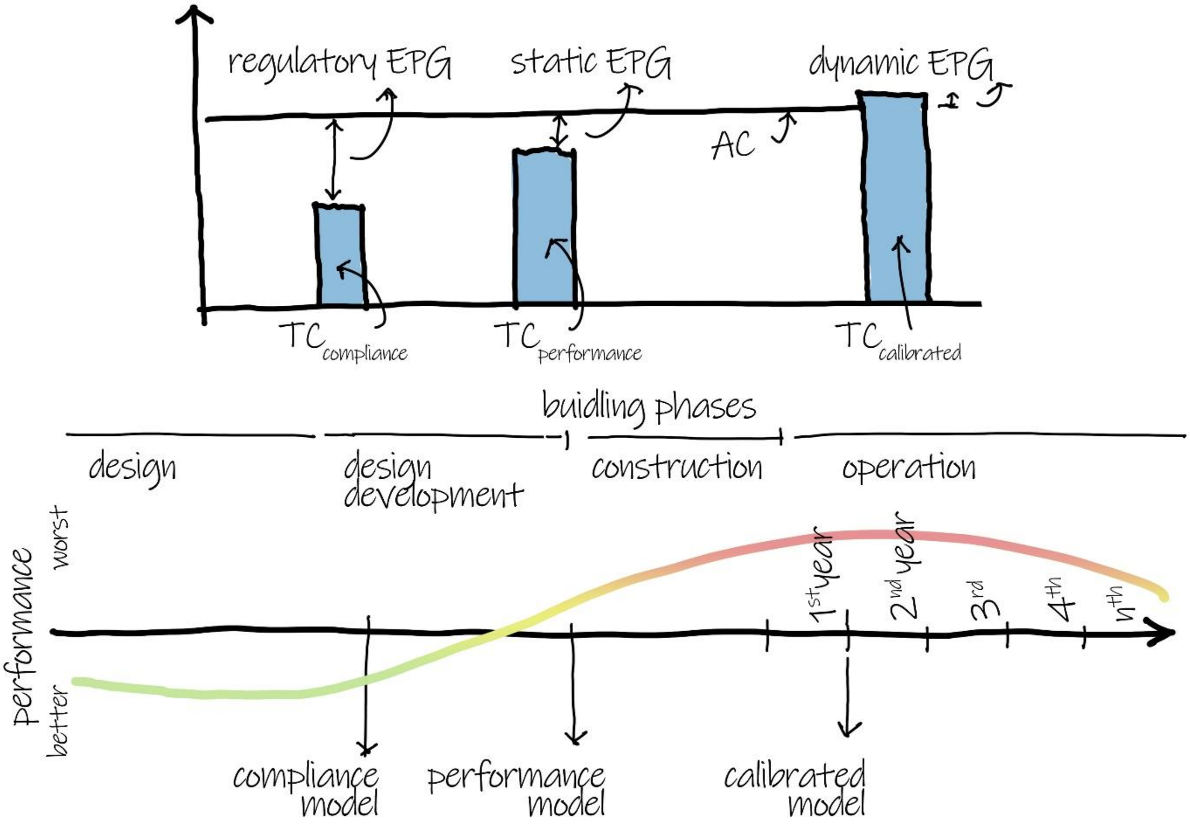

***Figure 17: Compliance modelling, performance modelling, and actual modelling EPG, including building phases and expected performance of TC (theoretical consumptions) vs AC (actual consumptions) – elaboration from* (Bunn and Burman, 2015; Jradi et al., 2018; van Dronkelaar et al., 2016).**

As mentioned in several works, the "simple post commissioning optimisation actions, like adaptation of the heating control, installation of smart heating control systems, contracting performance optimisation service immediate after refurbishment and continuous monitoring of the building, may provide a significant reduction of the performance gap" (Flourentzou et al., 2019). For these reasons, the possibility to support additional actions toward an operational EPC in parallel to the design and asset rating methodologies is very important, especially bearing in mind the increase in ICT and IT solutions devoted to building operational control and optimisation.

In addition to energy performance gap, it is also possible to refer to additional building performance issues, such as the thermal comfort conditions. Studies on IEQ (Indoor Environmental Quality) performance gaps are limited, but examples may be underlined. The paper of (Shrubsole et al., 2019) identifies common factors correlated to a "total performance gap", including energy and IEQ, and considering building regulations and the balance between costs and performances comparing UK and Chinese contexts. Similarly, the work of (Jain et al., 2020) focusses on the interrelation between energy and IEQ in performance gap considering four case studies in UK. Previous studies focussed on the uncertainty aspects of building thermal models, e.g., referring to thermal comfort conditions (de Wit, 1995).

Considering the aforementioned references, it is possible to underline the main issues connected to building EPG:

i. the adoption of more reliable simulation models and tools (e.g., dynamic), able in including phenomena like Free-running operation in summer;
ii. the inclusion of more realistic input conditions, including a data input inspection to feed dynamic simulations; and
iii. the definition of real-adapted simulation including real boundary conditions to verify dynamic operational gaps, including minimal monitoring specifications.

E-DYCE will work on all of these mentioned issues.

2.5.1 Correlated PG indicators

A general indicator to calculate the energy performance gap (EPG%) is defined in the following equation, adapted from (Galvin, 2014) – see also (Cozza et al., 2020b; Cuerda et al., 2020; Grossmann et al., 2016):

$$EPG\% = \frac{AC - TC}{TC} 100$$

Where AC are actual consumptions (monitored), TC are theoretical consumptions (simulated/calculated). In this equation, positive performance gap refers to overconsumptions in respect to TC, and negative to under-consumptions.

Nevertheless, recent studies have implemented interesting additional indicators to define performance gaps for specific conditions. In particular, it is possible to mention the PG indicators defined by (Cozza et al., 2020a) and referring to prebound and rebound effects. If a prebound effect is the case – i.e., non-retrofitted buildings are behaving better (consume less) than expected by simulations/certifications – the potential savings of a retrofitting action are limited in respect to simulated ones. This limitation has an impact on economic and energy analyses, defining a performance gap that may be defined as ESD (Energy Saving Deficit) – see also (Filippidou et al., 2019; Galvin, 2014). On a simulation level, the expected energy benefit from a retrofitting scenario (theoretical savings) may be defined as the difference between the simulated (expected) energy needs before the intervention and the simulated energy needs after the retrofitting – e.g., expressed in kWh/m^2 year. In line with (Cozza et al., 2020a), it is also possible to introduce an anticipated saving [kWh/m^{2}y] indicator based on the difference between the real actual consumption and the expected energy needs after the retrofitting (theoretical consumptions). Both are defined as follows:

$$theoretical\ saving\ (TS_{retrofit}) = TC_{actual} - TC_{retrofit}$$

$$anticipated\ savings\ (AntS_{retrofit}) = AC_{actual} - TC_{retrofit}$$

Assuming that consumption refers to final energy usage for thermal purposes (e.g., heating and DHW), it is possible to define two KPIs to evaluate the retrofitting action (Cozza et al., 2020a):

$$ESD_R = \frac{TS_{retrofit} - AS_{retrofit}}{TS_{retrofit}} 100$$

$$ESD_A = \frac{AntS_{retrofit} - AS_{retrofit}}{AntS_{retrofit}} 100$$

Where $AS_{retrofit}$ is the retrofit actual saving, given by the difference between real energy consumptions before and after the intervention, ESD_R is the Energy Saving Deficit Regulatory – based on compliance building simulation analyses, and ESD_A is the Energy Saving Deficit Anticipated, including the anticipated saving (AntS) indicator. As mentioned in the referenced work, ESD_R may support policy definitions, while ESD_A may also support, in addition to policy makers, also owners and designers to base retrofitting design choices on a more reliable indicator able in reducing the final performance gap. Hence, it is important to underline the need to define optimized refurbishment actions after investigating the operational conditions of buildings in order to predict and minimize performance gaps on both energy and economic points of view. See also Figure 18.

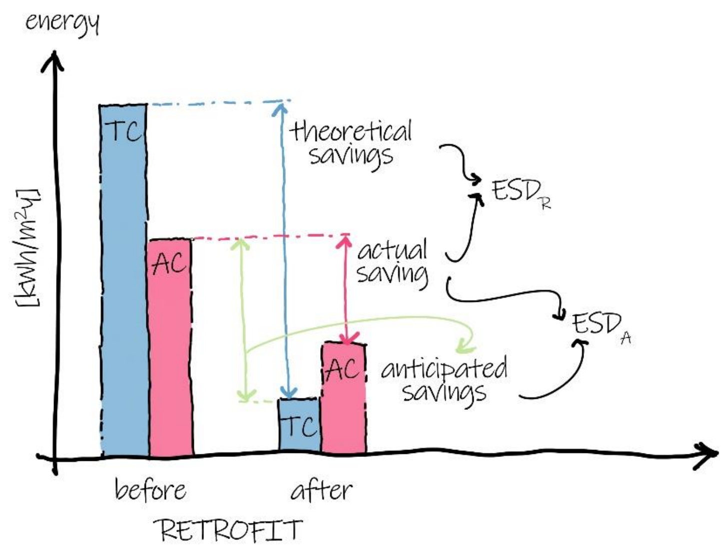

***Figure 18: ESD_R and ESD_A main parameters – redrawn from* (Cozza et al., 2020a).**

Furthermore, the work of (Zou and Alam, 2020) proposes a method to subdivide the total EPG% in sub-systems, underlining that differences in building service behaviours (positive and negative EPG%) may support a better comprehension of global performance gaps, supporting the devoted actions. In particular, authors define both the total level and the component level EPG% according to the following expressions (positive results represent overconsumption in respect to simulated needs, negative results under-consumption), which differs from the previous given ones in the denominator:

$$EPG\% = \frac{AC - TC}{AC} 100$$

Nevertheless, in the same study it is presented an expression to define the single component (building service) contribution to the global EPG%:

$$single\ component\ contribution\ to\ global\ EPG\% = \frac{AC_{component} - TC_{component}}{AC_{global} - TC_{global}} EPG\%_{global}$$

The adoption of a double analysis level (global and partial) is an important aspect for defining building performance KPIs, which may be classified into system-level KPIs (whole building) and in component-correlated KPIs (partial KPIs).

In order to reduce the performance gap, measured data are included as inputs to adjust building simulation models in order to couple expected results with monitored performances. A methodological exploration on real-data inputting in simulation tools to reduce performance gap and support energy retrofitting is discussed in (Cuerda et al., 2020). The paper focusses mainly on the potential reduction in EPG due to the adoption of real weather data and on an adapted users' behavioural definition, furthermore authors also studied the impact of building envelope constructive data defining respectively, outdoor, indoor and envelope factors. This study defines some aspects to be considered to adjust simulations combining data to be directly adopted in simulation models (to perform calculations to be compared with standardized building outputs) and data to be processed in mixed-method applications, which are used to identify user profiles to further feed simulations. The investigated factors and data are listed in Figure 19.

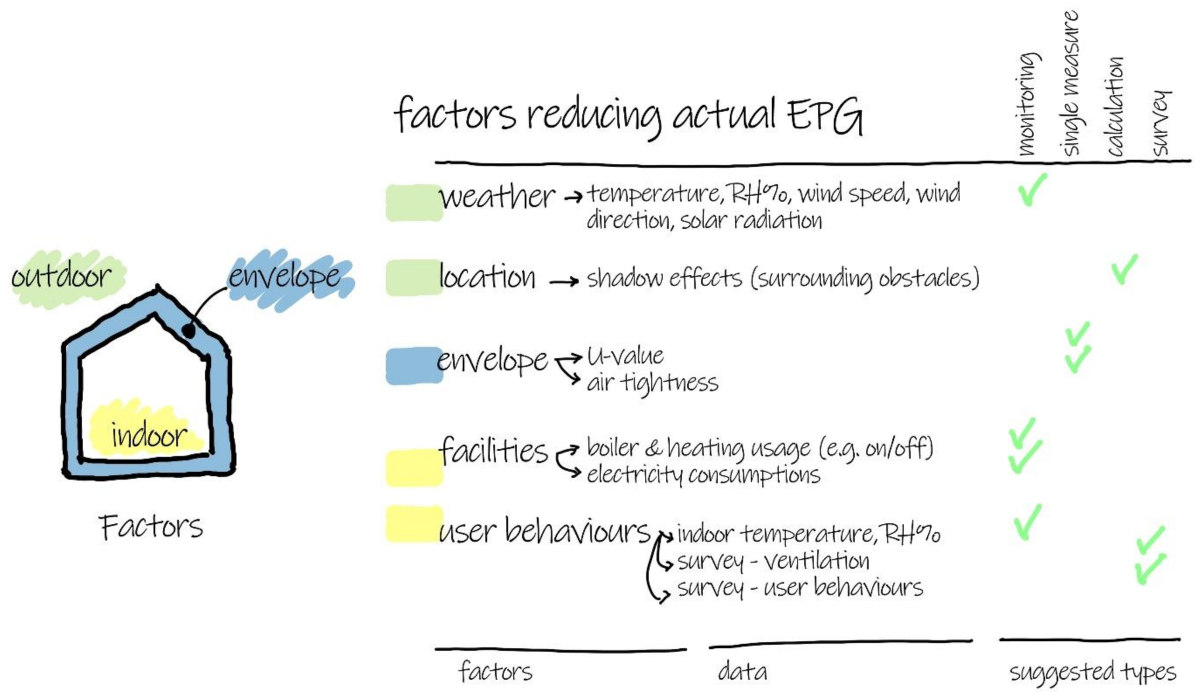

***Figure 19: Monitored/collected data suggested to feed simulation models reducing and investigating performance gaps – re-elaboration from* (Cuerda et al., 2020).**

Other studies analyse the need to adopt model calibrations implementing validation and verification and better forecasting, e.g., (de Wilde, 2014). The mentioned example identifies three performance gap types in buildings: i. between early-assessed energy models and measurement data; ii. between machine learning results and measurements; and iii. between energy ratings considering on the one side the EPC (compliance) and on the other side the display energy certificates (DEC). Focusing on the certification level, it was underlined that compliance EPCs are higher than the obtained rating from display energy certificates. A potential critical issue is underlined between regulation-background and design/engineering research background.

2.5.2 EPG and EPC

Considering literature outcomes, it is possible to agree that buildings characterized by a high energy rating (expected high thermal performances) are operating with a positive performance gap (consume more than expected), while buildings with a low energy rating (expected low thermal performances) are operating with a negative performance gap (consume less than expected) – see for example (Cozza et al., 2020b, 2020a; Ramallo-González, 2013; Risholt and Berker, 2013). This result was demonstrated to be valid along Europe – see for example the studies for Austria (Haas and Biermayr, 2000), Belgium (Hens et al., 2010), Denmark (Gram-Hanssen et al., 2017; Gram-Hanssen and Hansen, 2016), France (Cayre et al., 2011), Germany (Galvin and Sunikka-Blank, 2013; Sunikka-Blank and Galvin, 2012), Nederland (Tigchelaar et al., 2011), Switzerland (Cozza et al., 2020b; Flourentzou et al., 2019; Thaler and Kellenberger, 2017), and UK (Kelly, 2011). It is clear that methodologies to better predict and define the expected performance gap and the energy saving deficit are essential to support and increase the success of energy policies and building retrofitting actions. Here below two focuses are detailed considering one MS sample (Denmark) and one non-EU Member State (Switzerland).

Focusing on the Danish situation, several studies have analysed the performance gap between the current energy labels and the actual measured energy uses of buildings defining a well-documented situation. The mentioned studies by (Gram-Hanssen et al., 2017; Gram-Hanssen and Hansen, 2016) analysed a large database, composed by 230 233 detached houses – a building typology very representative of Denmark dwelling building stock with 48.7 % – with an energy labels (theoretical energy use) and 135 443 houses with actual-energy uses. Focussing on TC (theoretical consumptions), it may be underlined that buildings labelled in class “A” theoretically consume only 15% of houses with an energy label in class “G” – see Figure 20. Nevertheless, if focussing on AC (actual consumption), A-labelled buildings are only consuming 50% less than G-labelled houses. On a theoretical level, it is underlined the great impact of energy efficiency in reducing energy use. Nevertheless, focusing on real consumption, a shift is underlined. In particular, buildings with inefficient energy classes {E,F,G} are consuming less than expected, while buildings characterized by high energy labels {A,B,C} are consuming more than predicted. As mentioned before, this discrepancy will have an impact on the expected energy saving under retrofitting and renovation actions, limiting the actual energy saving potential in respect to the theoretical saving. One of the mentioned issues is correlated to the fact that theoretical energy use are defined by using steady-state regulatory approach in line with current EPC label calculations. During E-DYCE project, specific analyses will be conducted to check and manage dynamic simulations and real data to reduce performance gaps.

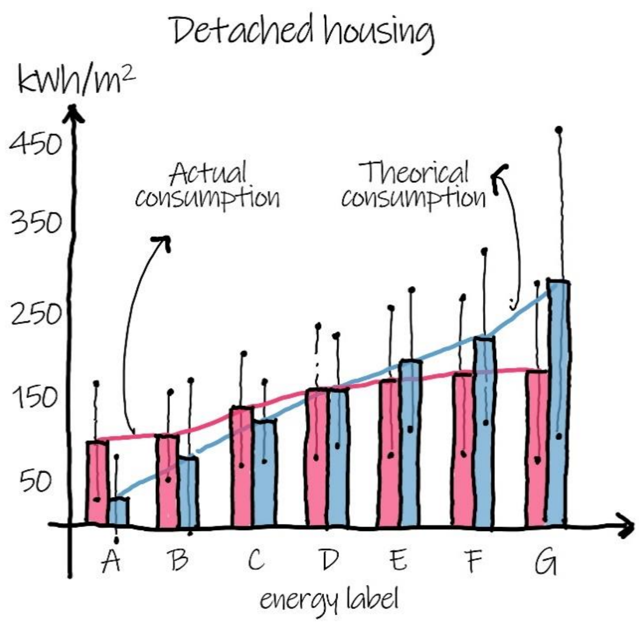

Figure 20: Detached houses in Denmark – TC and AC EPG – re-elaboration from **(Gram-Hanssen and Hansen, 2016)**

Considering the Swiss territory, a LARGE number of studies on building EPG are reported – see also the previously mentioned works. The EPG topic is well-analysed and also described thanks to the collection of specific cadastre data including energy bill consumptions. Focussing on multifamily residential buildings – that is a very representative building typology, representing about 60% of the building stock in some countries – it was underlined that TC reduction for refurbishment averaged to about 60-70% of energy savings. Nevertheless, the reduction in AC due to the same refurbishment action averaged to only about 30-40%, with a consistent EPG. Considering nearly zero energy buildings, real post-occupancy analysis on AC shows that instead of 30 kWh/m^{2}y, consumptions arrive to a mean of about 50-60 kWh/m^{2}y. The majority of the mentioned EPG% was defined to be correlated to some of the above discussed causes: static simulation models for EPC, unrealistic operational scheduling and assumptions, and a lack in optimisation of services under operational stages. Different professional and research experiences have, although, demonstrated that this gap might be significantly reduced when attentive control of services and building spaces is conceived, such by adopting control systems and correctly activating and allowing passive strategies. Focussing on the first 59 nearly zero refurbished buildings in the Geneva Canton, it was demonstrated that their actual energy labels (AC-based) are performing significantly worse than expected – see Figure 21. Several of them are in fact performing in Class D instead of the predicted Class B using steady-state approaches. Nevertheless, in order to minimize their actual performance gap, a combination of actions on operational conditions reduced the gap by about 1 energy label class. A correct combination of monitoring and evaluations in dynamic modelling labels may, in fact, increase building performances by about one-EPC class without additional retrofitting actions. Furthermore, it may be envisaged that the dynamic modelling and the user-information approach of E-DYCE will define a more standard approach for these technical management actions by even reducing the time needed to reach optimal operational conditions, which at present may be estimated to be about 4 years.

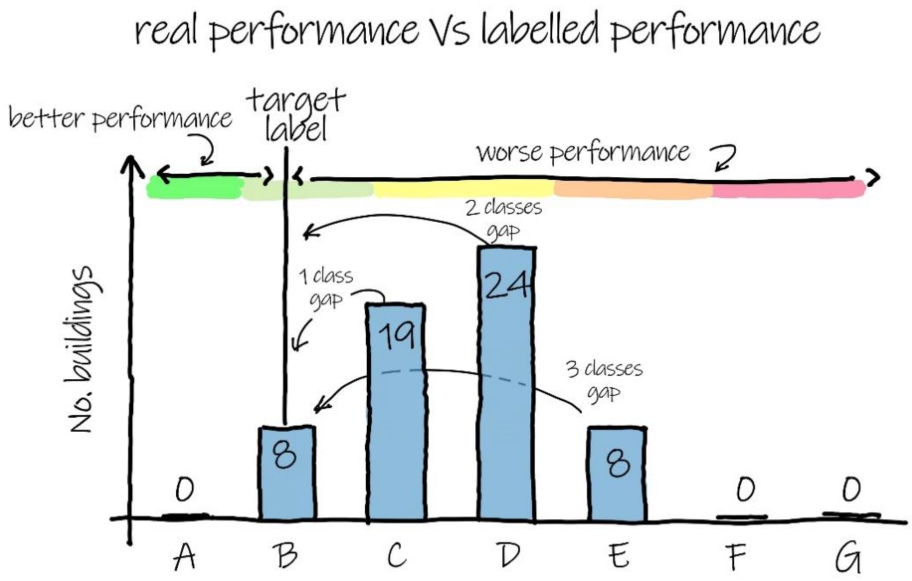

Figure 21: Real performance of first 59 nearly-zero refurbishment buildings in the Geneva Canton – re-elaboration from **(Gram-Hanssen and Hansen, 2016)**

2.5.3 Post-design simulation approaches

A growing interest is underlined in literature to usage of simulation in post-design applications, especially to support building commissioning. These usages mainly refer to the adoption of calibrated simulations including monitored data for testing building management. Different EMCS (Energy Management Control System) testing approaches are underlined, e.g., by adopting "passive" and "active" testing. The first refer to the adoption of standard-condition operational data, while the second supports the adoption of specific control sequences extending the standard range of operating variables (Visier, 2004). Nevertheless, such as underlined by (Claridge and Paulus, 2019), it is possible to identify at least five categories of post-design usages of simulation engines:

i. Post-construction commissioning for new building considering design simulation;
ii. Calibrated simulation to support existing building commissioning actions;
iii. Adoption of simulation approaches to define/optimise control procedures;
iv. Calibrated simulation to support building performance diagnosis and identify fault detection;
v. Calibrated simulation to define potential energy savings.

The usage of calibrated simulations is underlined by specific guidelines such as the calibration criteria defined in the ASHRAE Guide 14 (ASHRAE, 2014) and the CIBSE Technical Memorandum TM63 devoted to "Operational performance: Building performance modelling" (CIBSE, 2020).

In order to tune simulation models and increase the matching between simulation and measured data different approaches may be adopted. Among them, a simple process defined in literature may be reported (Claridge and Paulus, 2019; Wei et al., 1998). This simple approach bases on the definition of "calibration signatures" that are describe by the following expression:

Where the numerator may be defined as "Residual". The obtained values are hence plotted as function of temperatures and regression lines defined to evaluate the signature. Fully calibrated models will result in horizontal lines at 0%. Different statistical indices may be adopted to evaluate the accuracy – e.g., mean bias differences (MBD), root mean square differences (RMSD) or mean absolute differences (MAD) or combinations defining total error analyses. In order to simple calibrate a simulation, the calibration signature and statistical errors may be used to graphically compare results, additionally another parameter may be considered to help in the identification of most impactful changes in simulation inputs. This latter is defined as the "characteristic signature" and is similar of the calibration signature, but able in comparing two simulation outputs. In this case the previous ratio is based on changes in energy usages (numerator) and in maximum energy usage (denominator).

Balancing simulated and measured data on a plot by comparing at the same time calibration signature and statistical errors may support the identification of best input parameters to reduce, when possible, RMSD to less than 10%. Characteristic signature may also help, if plotted on the same graph, to identify those input variations, for different given outside air temperatures (e.g., daily mean), that better tune simulation results. Figure 22 shows a potential representation of the process.

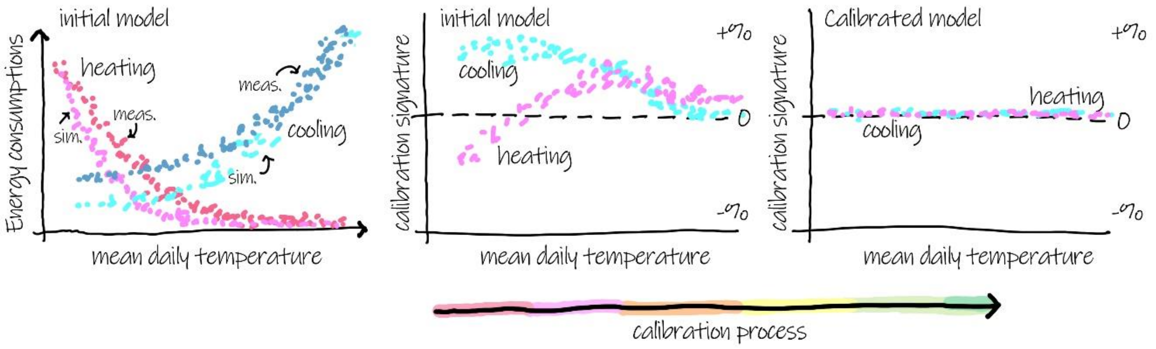

Figure 22 – Sample representation of the mentioned simple calibration process. Elaborated from (Claridge and Paulus, 2019).

2.5.4 E-DYCE implications

Current energy labelling based on steady-state approaches have some strengths, such as reducing simulation efforts and needed inputs in respect to other more detailed approaches, as well as encouraging the performance comparison of building belonging to the same category, through the introduction of standardised operating conditions. Several shortcomings however, apply, typically the current labelling systems are not able to accurately reflect the dynamic behaviour of buildings, the changing environment and use conditions. The mentioned EPG phenomenon is partially connected with this aspect, reducing the ability in providing timely decisions and the economical exploitation of building retrofitting choices. Furthermore, the adoption of a steady-state approach is restricting the potential of several climate and FR technologies – especially in the cooling seasons – not allowing for a correct analysis of their potential and not reflecting building dynamics.

Nevertheless, the adoption of hourly approaches for energy labelling is generally connected with an increase in complexity and in required computational capacities, while the diffusion of smartness solutions (BEMS or even smartphone-based) and the diffusion of higher computational capacities of standard working computers have at least overpassed several of these issues. Additionally, the rise of cooling energy uses depending on: global and local climate change, as well as the excessive heat and air insulation of new and high-energy standard renovated buildings (Kranzl, 2018; Murano et al., 2017) is calling to the improvement of feasibility of building performance analyses toward a dynamic background to also reduce the increased EPG of nZEB buildings (Gram-Hanssen et al., 2017). In order to support the transition toward dynamic calculations it is underlined the need for an efficient approach supporting input data acquisition, data storage and interoperability of data bridges, including transparent communication and information processes adopting different Key Performance Indicators (KPIs) to analyse main results. The additional computational time due to switching from steady state to hourly should not be considered as a barrier and additional disqualifying cost, but need to be translated including the possibility to increase efficiency and adopt current knowledge on airflows and dynamic building behaviours supporting an increase in feasibility and in the possibility to connected additional services to a DEPC (Dynamic Energy Performance Certification). One of these potential benefits is, as an example, connected to the possibility to rate and valorise untapped cooling potential due to passive, natural and low-energy technologies, like ventilative cooling (Artmann et al., 2007; Chiesa, 2019b). Finally, a dynamic approach allows to integrate potential predictive control methodologies – e.g., machine learning algorithms or filters like Kalman filter – and compensation techniques to support smart operations of buildings (Afram and Janabi-Sharifi, 2014), potentially feeding operational ratings including standardisation actions, and user information for self-optimisation. The performance potential of these aspects, however, is not yet reflected in current compliance and certification calculations. The E-DYCE methodology for Dynamic Certification (DEPC) will address the quality and energy flexibility of the buildings by their free running performance and by the ability in reducing EPG. As remembered DEPC in E-DYCE refers to hourly/sub-hourly simulation engines.

Focussing on EPG, E-DYCE will include not only the intrinsic performance of envelope and systems, but also extend the assessment to building operation. The proposed approach promotes low-cost and low-tech technologies and strategies and support the optimisation of building/system operations acting on the inclusion of monitoring plans and data storage, supporting ESCOs and different users in acting to reduce EPG in a short time. The E-DYCE system proposes, in its services, operational corrections based on building's real energy performance and communication with the building users. The monitoring of change in user behaviour may potentially allow to correct standard user profiles and create updated user behaviour database. The outcome could be statistical and measurable user awareness due to continues dialog between E-DYCE (applications) and tenants. In E-DYCE different levels are defined:

i. the first level is to adjust the calculation approach to the hourly one;
ii. the second level is to optimize the building, based on its real operation under current boundary condition;
iii. the third level is to be able to predict performance when applying renovation strategies; and
iv. the fourth level is to be able to take account for predictive control of the building by using statistical data and weather forecasts.

2.6 *EDYCE –renovation and operation roadmaps*

Among key E-DYCE additional features should be mentioned rational composition of energy retrofitting actions so called "renovation roadmaps". By rational energy retrofitting actions authors understand actions taking into account multiple specific project objectives and least-cost approach. One of the major factors that hinders building owner from executing retrofitting actions is unclear expectations to the outcome of the renovation. The values highly prioritized by building owners include: indoor climate improvement, energy savings and monetary savings, not necessarily prioritized in the given order. All these aspects become unclear especially when aiming for the deep energy renovations that are composed of multiple single actions.

In E-DYCE work on renovation actions will be based on the currently ongoing method developed in RECO2ST project (Antonov et al., 2020). The method starts with the project definition, continues with evaluation of the contribution of single actions and finally, evaluation of selected renovation packages (scenarios). Method encompasses a very important aspect of cost efficiency and reduction of energy demand while at the same time weighing share of (i) investment to energy saving renovation to the building and (ii) investment to renewable energy production. In EDYCE, the method will be enriched by simulations in dynamic environment and with respect to realistic distribution of variable input parameters. In that manner evidence or lack of evidence of advantages due to transfer from stead-state to dynamic calculations will be reflected. Special attention will be paid to package solutions with the best NPV and least primary energy demand. Fine-tuning of these will be performed. The inclusion of a parametric approach to dynamic hourly building simulation, will support the hybridisation between the above-mentioned approach and E-DYCE simulation models. For example, the latter will support the potential variations of single and multiple parameters in give ranges supporting automatic massive runs of hourly simulations (e.g., EnergyPlus based) to statistically analyse outputs and suggest retrofitting scenario choices (Chiesa et al., 2019a; Grosso et al., 2018). The analysis allows to also define heat maps to define EPBD energy usage voices (heating, cooling, lighting, ventilation, DHW, ...) as a function of chosen retrofitting scenario inputs. The approach is potentially open to the inclusion of incertitude in the definition of variables, e.g., by introducing random Gaussian distribution of the occupancy, or a cost-economical risk dimension. Figure 23 shows sample early-stage potential outputs of parametric python-coded Energy-Plus simulations.

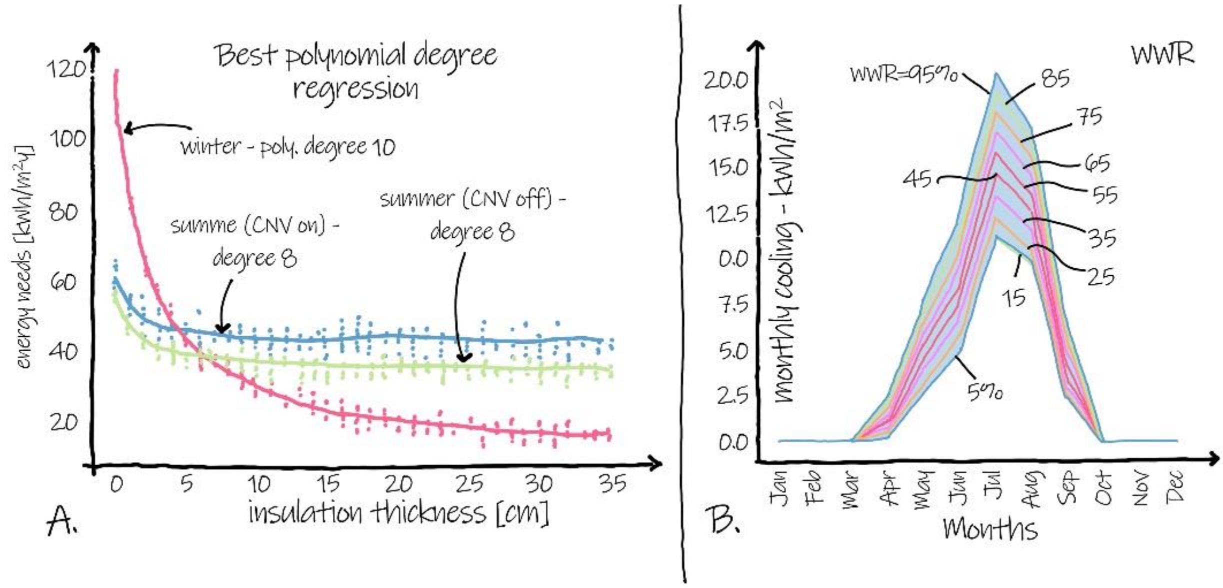

Figure 23 – (a) Energy needs for space heating and cooling as a function of different envelope U-values to optimise insulation thickness, including random Gaussian occupancy values; (b) Monthly cooling energy needs as a function of different window-to-wall ratio. The two samples refer to different buildings and locations.

What is more, method will be applied to estimate operational savings based on the operational improvements "operation roadmaps", for example, tuning towards free running operation, more natural ventilation, reduction of set points, active use of solar shadings, etc. In this approach investment costs are related to diagnosis of the building and improvement interventions. Retrofitting actions as such are not to be implemented. Energy and cost savings will be weather corrected for actual boundary condition. The NPV will be investigated for shorter periods (1 year) for tracking and comparing actual NPV and Primary Energy Demand with respect to calculated to monitor the performance gap. Method will identify required simulation and measured energy inputs to perform NPV calculations.

In Figure 24 is presented example of calculation of approx. 350 different renovation packages applied to specific residential buildings. Renovation packages are evaluated based on building theoretical primary energy demand and NPV. Various renovation solutions are monitored with respect to renovation goals: renovation classes and NZEB and with reference cases (building before renovation actions).

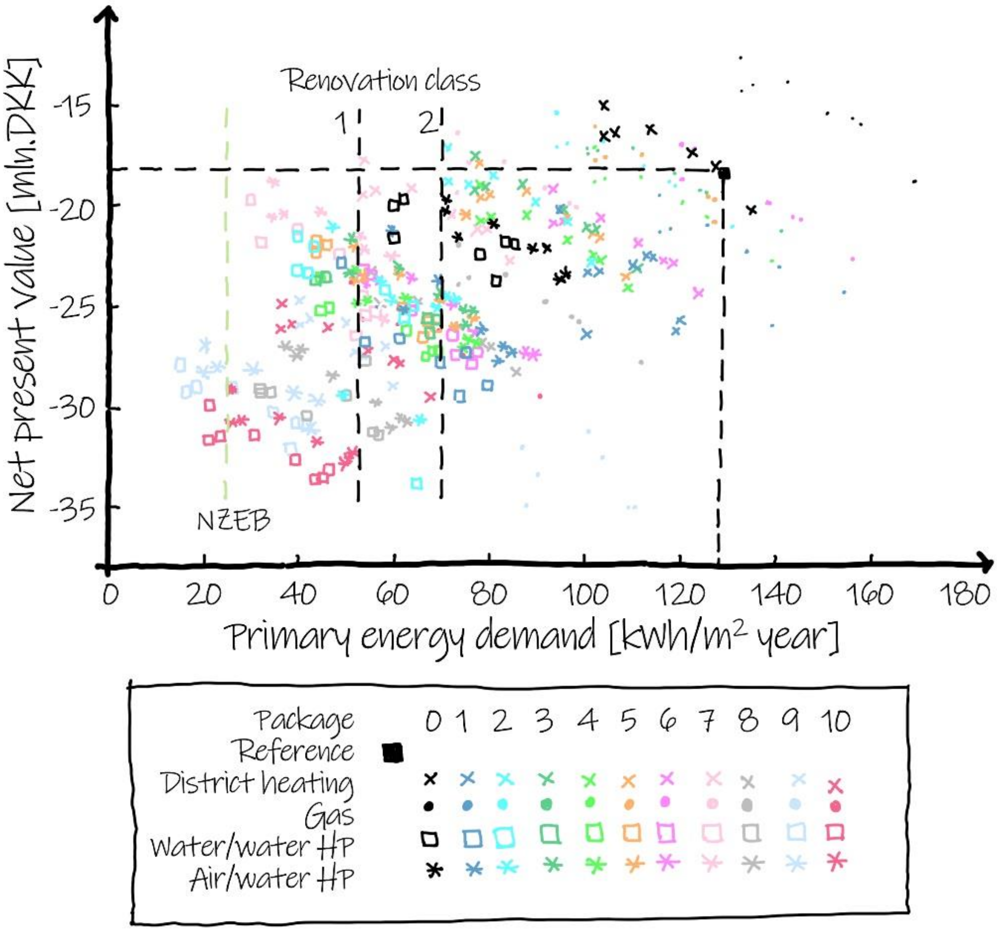

Figure 24 - Primary energy demand as a function of Net Present Value for investigated packages.

3 Suggested specifications for E-DYCE DEPC

This section will introduce the E-DYCE proposed logical definition focussing on data flows including different functionalities and issues connected to previously mentioned innovations and backgrounds.

3.1 *Definition of logical design*

3.1.1 E-DYCE logical approach

Giving the main issues faced in E-DYCE discussed in Section 2, the dynamic building certification (DEPC) that will be defined in E-DYCE is intended to contribute to the gradual phasing out of steady-state models. This will be achieved by an approach focusing on generating all the associated advantages of dynamic certification while reducing the complexity of the correlated-calculation process itself.
In line with outcomes coming from international energy researches – such as IEA EBC Annex 62 on Ventilative Cooling – steady-state calculation approaches are not able in representing with sufficient precision the behaviour of several passive and low-energy technologies and approaches, with special regards to those referring to heat gain dissipation and to energy balances in the cooling season. These technologies are in fact based on daily cycles taking advantage, for example, of the day-night variations in environmental air temperatures. Ventilative Cooling potential, for example, requires a deeper time-step calculation – at least hourly-defined – in respect to average monthly values in order to define its ability in cooling a space and prevent overheating – see also the Deliveries of the mentioned Annex and connected works (Flourentzou and Bonvin, 2017; Heiselberg, 2018; Kolokotroni and Heiselberg, 2015).

The rationale behind the EDYCE project is shown in Figure 25. Input data from existing sources (CAD, BIM cadastre or other sources) are supplemented by an inspection process that will be detailed during the project according to different levels of required inputs to define a cost-effective approach. Data acquisition will be based on criteria definition sets to reduce the amount of data to the minimal ones needed to run simulations and calculate the expected indicators at chosen EPB level (design, asset, and/or operational rating). Data are used to generate a building model that is classified according to building clustering with regard to baseline operation. The building model definition includes the first simulation run, based on standardised conditions for the selected EPB assessment type supporting design and asset ratings.

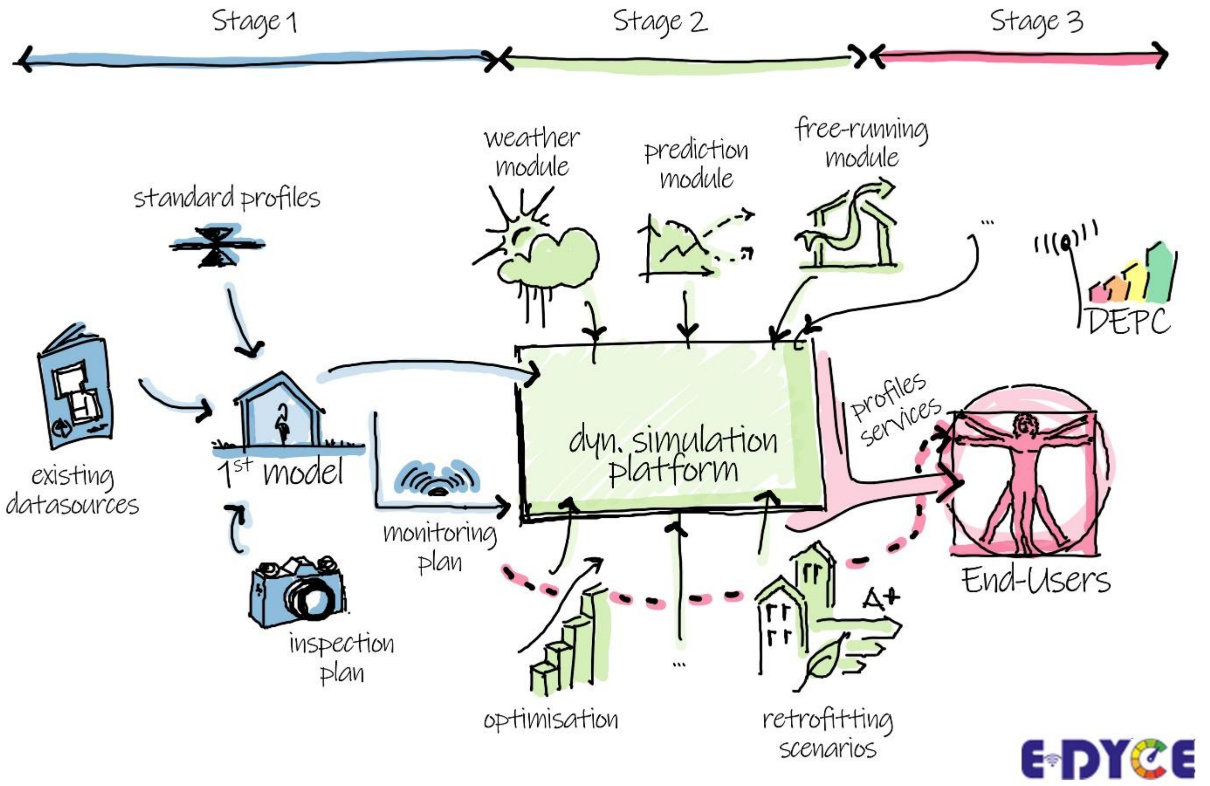

Figure 25: E-DYCE rationale

Based on the results of this process, a monitoring plan (including required data frequency) is decided and implemented to develop the full application of the E-DYCE approach supporting operational specifications and optimisation. During the monitoring plan definition, spatial and time aggregations will also be defined in order to support the calculation of the E-DYCE selected KPIs. Furthermore, data collection will be optimised, supporting data processing and defining the number of probes needed to increase building/system efficiency. By adopting existing inputs and sensor outputs, a dynamic (hourly) model is constructed and implemented to be able to be fed by additional standard and dynamic real data (e.g., weather) inputs. The dynamic model is part of an integration framework that features modularity and multiple functionalities, enabling the addition of functions such as weather monitoring, demand prediction and free running operation. This opens the possibility to conduct future optimizations to generate building operation scenarios to increase performance. A first implementation level will include the possibility to define an operational monitoring-driven DEPB label. Furthermore, an additional level will work in informing different potential end-user profiles on the monitored behaviour of the building in almost real-time combining data-acquisition and operational/hybrid rating with user information. Furthermore, an additional step is envisaged defining the usage of these data to support optimisation strategies to improve the building's operation. These scenarios constitute the base to define feedback for the users to both suggest actions to improve building performances in operation, and/or support renovation roadmaps for long-term actions. Building operation data is uploaded to the cloud, where they contribute to the refinement and updating of the clusters, closing the data-collection-treatment-transmission circle. The possibility to feed the simulation engine with additional data or with variation domain of data to optimise the expected (or real) impact of actions (e.g., renovation scenarios) supports the optimisation of design and operational EPB. In E-DYCE EPB labelling scheme, KPIs, main integration framework logic, and user information alerts will be developed, while further implementations and additional projects will support optimisation and intelligent decision processes.

In particular, the E-DYCE process can be divided into three stages that are ideally connected and managed by an integration framework:

- Stage 1: inputs and data collection;
- Stage 2: Monitoring and implementation of dynamic certification methodology; and
- Stage 3: User feedback and actuation.

In the first stage the necessary building related resources are collected and processed. Main outputs of this stage are the Building Model, able to be processed in dynamic hourly simulation tools, and the Monitoring Plan. The second stage will yield the Dynamic Building Simulation and the verification of actual building energy consumptions. The final stage provides the users with operational feedback information and Renovation Roadmaps. Data visualisation, Feedback and Renovation Roadmaps will be scaled in term of services and information according to different user profiles.

3.1.1.1 Stage 1: Inputs – data collection

E-DYCE will be open to a large set of potential input data, including the possibility to use existing building related resources as well as a collection and process of additional specific data. Available data across Member States and beyond Europe are not homogeneous and large variances were envisaged, especially for data not included in EPC data exchange formats, i.e., *.xml. Hence, the E-DYCE data collection processing stage needs to be adaptable, smart and efficient, allowing to collect and adapt data from heterogeneous sources. Data collection needs to discard not useful, inconsistent or redundant information to provide streamlined outputs including the identification of missing data to be acquired through efficient and smart building inspection protocols.

The complexity to be faced during the data collection step is also referring to the significant discrepancies between similar buildings, even when located in the same country, considering that not all buildings have an EPC and that current EPCs are generally provided using steady-state models with a high risk in facing performance gaps or inhomogeneity evaluation being building regulations and codes not uniform. E-DYCE will support a multifaceted approach based on simple data inputting, e.g., including geo-tags, building typologies and correlated information, building age, refurbishment information, and architectural data. Different additional data information sources will be adopted for defining basic E-DYCE inputs, including cadastre, BIM models, typological data (e.g., typological-connected envelope definitions from existing databases, such as the TABULA (Loga et al., 2012) and EPISCOPE (Stein et al., 2016) projects co-funded by EU), existing geometrical models and maps. Existing EPC data will also be implemented. Reference standards will be considered to define standard load profiles and set points, including dynamic load definitions. Related standards will be adopted in the design and asset rating steps considering for example related ones in M3 through M11 (M/480) and building occupancy and operational conditions, e.g., by EN 16798-1 (European Committee for Standardization, 2019) and ISO 17772-1 (International Standardization Organization, 2017) (M1-6). Finally, missing information will be defined based on an inspection process with the double aim of finalizing missing data inputs, and of verifying the accuracy of information collected from existing data sources. This process needs to be based on functions and libraries that may define databases to be accessed by owners and by other end-users with the possibility to feature additional capacities, such as a streamlined data processing that will be very useful in the process of regional building energy efficiency assessments. Furthermore, focussing on the monitoring input needed to feed an operational rating vision, existing data from different sources – if available – will be considered to potentially define different levels of KPIs, while additional data collection will be based on the definition of specific monitoring plan.

The main output of Stage 1 is a structured information database to feed further E-DYCE steps. Sample information included in the database will refer, among others, to location, site, building typology, geometry, schedules, thermal and other specifications of elements, lighting and HVAC. This will require the development of processing methodologies to treat input data that are collected during Stage 1 and compile files for dynamic energy simulations and clustering according to typology and performance as main parameters. In addition to information coding into a defined format, Stage 1 will also define the updated DEPC vision. Thirdly, Stage 1 will also include the definition of the baseline model of considered building or building space unit. Finally, in this stage will be assessed the monitoring plan allowing additional E-DYCE functionalities, including a check with end-users to define correct spatial and time granularities and a consistent definition of expected outcomes, from very low-cost and low-tech applications till advance SR levels.

The definition of a DEPC requires a clear and smart definition of inputs needed to feed hourly dynamic models. Furthermore, considering additional E-DYCE main-faced issues, a logical definition of inputs and of the first (reference) model is essential to support additional features that the project will consider in respect to the current EPC.

3.1.1.2 Stage 2: Monitoring and implementation of dynamic certification methodology

This second stage of the E-DYCE logic will focus on additional usage and expansion of the defined building models, compiled data files and sensor outputs. Simulation inputs will be modified to run hourly dynamic energy simulator tools (e.g., EnergyPlus (DOE and NREL, 2020) and other relevant tools such as DIAL$^+$ (ESTIA, 2017)) in order to generate parametric variations of the building able in featuring additional E-DYCE functionalities. Apart from the stand-alone simulations of Stage 1, which is used to define design ratings by adopting indicative standard values, additional functions will be considered to face some of the issues mentioned in Section 2. In particular, they will be included in this stage the following topics:

a. Free running operation: A variation of the model will be used to calculate the potential of the building for free running operation, mainly considering thermal comfort issues, and the potential of the building in exploiting local free-running potential – see also first KPIs definition in Section 4.

b. Sensor inputs: sensor data will be collected by demo cases according to the data time/spatial frequency selected by the end user in order to define operational KPIs and building performances.

c. Real time weather data: A connection will be established between the system (monitoring data and simulation tools) and weather stations or other weather data sources. Weather monitored data will be used to feed real-weather-based simulations to compare predicted (standard profiles) and real behaviours of buildings. A method will be analysed to identify the connected building performance gaps and an evaluation of the quality in operation of building management actions, in order to support optimisation processes and operational rating visions.

d. Prediction: A prediction module combining weather information and cluster outputs (profiles) to anticipate a sample energy demand will be early-introduced. This predictive module will help in combining DEPC functionalities with smart solutions supporting a theoretical future implementation of the approach toward smart grid management and innovative prosumer services considering multiple energy vectors.

E-DYCE will be based on a modular structure supporting optimisations and correct definitions of different building performance aspects focussing on energy-efficiency and feasible dynamic simulations. The E-DYCE approach needs to be user-friendly and technology neutral allowing it to be potentially implemented with different simulation software, including a multi-utility and multi-services vision open to smart conception. E-DYCE will mainly define a methodological vision toward DEPC defining a scalable and flexible approach. Finally, a retrofitting supporting module will be developed coupling "realistic" inputs, simulation, and polynomial correlations.

3.1.1.3 Stage 3: User feedback and actuation

The logic of the E-DYCE's approach toward DEPC and above identified issues bases on a new methodology to input definition including inspection plan (Stage 1) and the development of a scalable, modular, open, and multi-service vision of DEPC outputs' definition (Stage 2). Furthermore, this approach allows for additional features and large future implementations at different levels. Nevertheless, a third essential pillar of E-DYCE is at the base of Stage 3: the communication of outputs and suggestions to end-users in order to support them to perform the appropriate actions. User feedbacks will work following different profiles and based on different potential service aggregations, including local and cloud elaborations. Main interaction methodologies will be:

a. tenant/user or building owner/operator – feedback including information and optional recommendations at building and service levels differentiated for profiles;
b. energy certification party – information on dynamic building usage supporting operational energy certification analyses;
c. actuation (potential) – optional integration of building automation systems supporting monitor/actuation automatic controls of buildings and services.

Feedbacks will be scaled according to a set of different end-users and specific services following an implementation/scalable and modular approach, e.g., supporting comfort, energy and economic information. Furthermore, the E-DYCE approach will optionally support, via appropriate simulation modules and methods, the definition of optimised renovation roadmaps, supporting priority lists and the definition of most impactful and cost-efficient approaches to building retrofit.

3.1.1.4 Integration Framework

E-DYCE methodology will include an integration framework aiming at integrating data and services from different mentioned sources to provide applications (at different level of module integration) to dynamically control/optimise and certify building performances. The theoretical definition of the E-DYCE framework is based on 4 main parts:

a. The information model – formal high-level definition of collected data and references for local and external data storages;
b. Bridging agents – to connect different serves/devices, to capture data and store information. They will support data exchanges and requests by implementing different protocols for data access;

c. Intelligence agents – data usage being registered to the information model to perform higher-level functions (e.g., calculations, filtering/resampling, control, decision supports, ...);
d. Repository – to facilitate different resource data collection and storage.

All of these features are part of the theoretical logic definition of the E-DYCE platform, nevertheless during current E-DYCE project implementation, the development of Bridging and Intelligence agents will be used to notify users, while further projects will be in charge to develop and optimise the whole system to support optimisation and intelligent decision processes.

Considering E-DYCE methodology and focussing on the implementation concept that will be tested during the project, the mentioned E-DYCE framework will be here prototyped to some extent on FusiX integration platform, which will foster in return the bilateral communication with involved entities to produce a dynamic flow of information across ends. Using its integrated features:

- SCADA
- Monitoring
- Alerting
- Scheduling
- DB
- GUI

will organize and streamline procedures according to projects' requirements and deliver notifications to the end user for better exploitation of the building's potential.

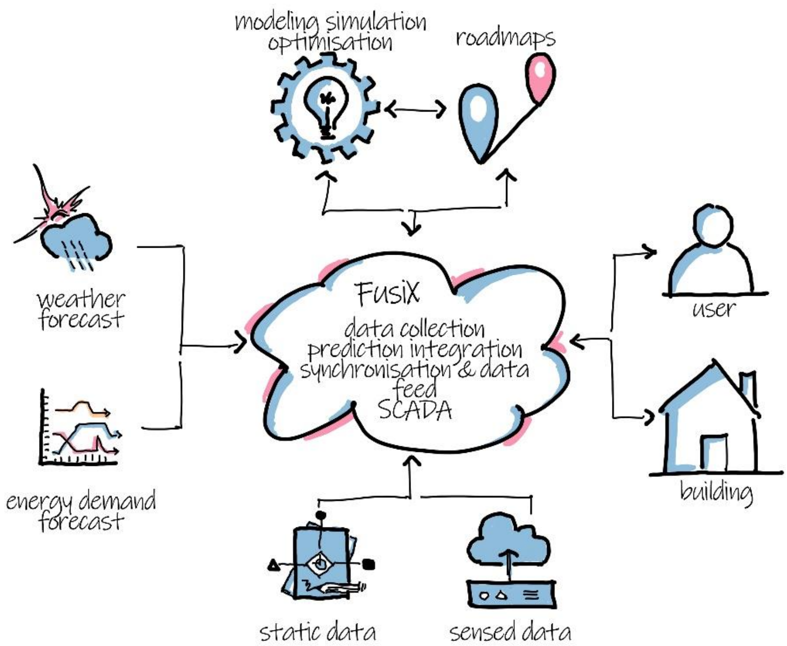

Figure 26: Potential sample representation of an E-DYCE integration framework

Data collection: As soon as the data frequency acquisition is set, scheduling events will be created and data will be collected from the gathering points of the demo buildings. The storage could begin in a raw form or even in a predefined format. Further statistical analysis of the stored data is always available.

Static data, which describe a specific building will be also packed together with the real time measurements and kept as input for the simulation activities.

Predictions Integration: Predictions are always an integral part of simulation and modelling, therefore the relative mechanisms could be constructed inside an integration platform, so that a REST API could always await for data retrieval. Those predictions could also be stored in the E-DYCE repository that resides in the platform.

Synchronization and data feed: Several scheduled activities could be set in order to trigger simulations and optimizations and feed simultaneously the corresponding pre-collected or real time data. This way a real time loop of data gathering, modelling, simulation and optimization is conceivable to be always feasible in an autonomous way.

Interaction: Suggestions and improvement scenarios produced from the respective roadmaps, could be potentially presented to the end user, together with some relative hints for improved building's efficiency. Users can take advantage of a comprehensive user interface that presents in an informative way the real state of energy efficiency and the respective energy classification. Using the alerting functionality of the platform (e.g., the one of FusiX) in collaboration with the real time simulations, we can detect anomalous behaviours aborning. The user can then be informed to check conditions or resolve the problems arising by taking simple actions.

SCADA: Having as ultimate monitoring tool the Supervisory Control and Data Acquisition, the platform will let direct control and regulation to controllable assets in the demo-buildings. Whether the action is implied from a user or directly from a simulation model, the consuming devices could always be under supervision and hence under the platform's management ability. This idea shows the way towards building's automation.

The E-DYCE integration framework logic is scalable and open to be adopted at different integration levels according to specific user-requirements and implementation scenarios.

3.1.2 EPB Assessment Types

Standard EN ISO 52000-1:2017 (EN ISO, 2017c) defines different EPC assessments based on two main types, i.e., Calculated and Measured, and four sub-types for each main type. In particular, the mentioned EPC assessment types are defined in the following table:

Table 9: Assessment types for EPC according to (EN ISO, 2017c)

Type	Sub-type	Input data			applications
		Building	Climate	Use	
Calculated / asset	Design	Design	Standard	Standard	Building permission / under condition EPC
	As built	Actual	Standard	Standard	EPC, regulation
	Actual	Actual	Actual	Actual	Validation
	Tailored	Purpose-based			Optimisation, retrofitting, validation, planning, energy audit
Measured / operational	Actual (*)	Actual	Actual	Actual	Monitoring (not EP)
	Climate corrected	Actual	Corrected to standard	Actual	Monitoring, energy audit
	Use corrected	Actual	Actual	Corrected to standard	Monitoring
	Standard	Actual	Corrected to standard	Corrected to standard	EPC, regulation

(*) not adapted for energy performance definitions being missing essential corrections.

Considering the table, it is important to underline that in E-DYCE measured EPB will be defined at different levels of smartness and will allow to identify also from actual operational data a support for retrofitting actions' definition. Actual use evaluations will be considered to reduce retrofitting EPG by adopting the above-mentioned approach to the energy saving deficit ESD_A.

It is important to remember that the standard EPB and the measured EPB may be compared when the measured is corrected to cover the same building services and assumed conditions, nevertheless not all of these features will be coverable in E-DYCE practice (e.g., User profile).

According to EN ISO 52000-1 it is possible to compare calculated energy performance and measured energy performance if both are tailored to reflect the same climate and use conditions:

a. By assuming measured data and modifying calculated performances for climate and use;
b. By assuming calculated and modifying the measured data using standardisation for climate and use.

Assuming this concept, it is potentially possible to compare, for analysing the user behaviour, a simulated object (e.g., building) under standard use and real climate and building definitions and a monitored object (real data) to verify differences between standard and real uses – see also Figure 27. Potentially (optional future service) standard use may be modified to optimise expected (calculated) building comfort or energy consumptions by maximising the exploitation of local FR potential. This optimisation may be used to suggest (future optional service) users' behaviours.

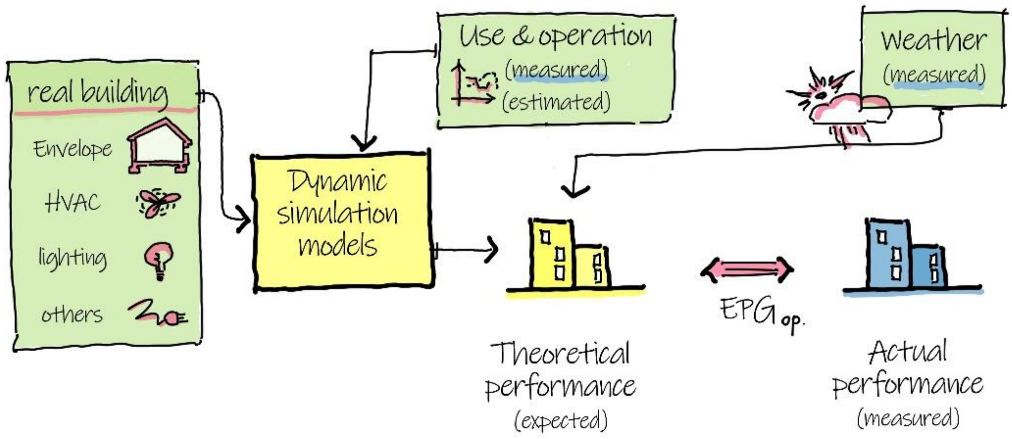

Figure 27: Sample schematic restitution of building energy performance evaluation via calibrated models – Elaborated from* (Borgstein et al., 2016)*.

Concerning the operational rating, E-DYCE includes the definition of a monitoring plan for evaluating buildings to perform different levels of services. The definition of demo cases will help in refining the E-DYCE approach to operational rating by supporting a cost-effective approach to data acquisition. During E-DYCE, different monitoring levels will be considered, in addition to research long-term spread monitoring, a series of monitoring specifications for E-DYCE platform applications concerning main correlated services will be defined. Long-term simple monitoring actions (continuous monitoring, e.g., centralized heater, or simple temperature sensors for domestic users) will be described supporting different end-user information. Short-term specific monitoring campaigns will be carried out to support building performance evaluations in given representative periods to collect specific data and evaluate EPG risks, causes, and needed optimisation actions. The latter will be particularly important in supporting energy service companies and technical services in system optimisations during first operational periods (1 to 3 years) of a building after retrofitting and renovation.

3.1.3 Technologically versatile approach

3.1.3.1 Definition of technological versatile approach on data and communication protocols

The E-DYCE demonstrations will make the best of open data collection and data exchange protocols.

For data collection, sensor communication will be based on open metering standards (OMS) for building management systems (BMS) and internet of things (IoT). The most common examples of these protocols are Modbus, Bacnet, LoRa, Mbus and wireless MBus. This use of open protocols makes the E-DYCE approach technology-agnostic on the metering side.

Regarding data exchange, E-DYCE promotes the use of APIs for communication between actors to break the traditional silos. These APIs are based upon open protocols, such as JSON-based RESTful web services, with interfaces in standard formats defined in the project and available in a public documentation. The generic structure of these services makes it possible to access them from a variety of systems and programming languages, which allows the user side to be technology-agnostic. Privacy and security of these services is ensured via encryption and authentication between actors.

3.1.3.2 Application regimes for different user profiles

The E-DYCE methodology is scalable to different end-user profiles, by changing specific services and outputs to be communicated. Furthermore, E-DYCE will focus on its related logic and data analysis according to specific profiles. Two are considered the main users' categories of the E-DYCE approach:

a. The energy certification party – who materially performs energy certification analyses. This category varies across Member States and need to be adapted following local processes. Usually, certifiers are private companies and use certified tools. The E-DYCE framework will augment certifier capabilities to perform dynamic analyses on the energy behaviour of buildings.
b. Tenants/users, operators or owners of the building. These end-user profiles will use the E-DYCE framework for informative and operative purposes in order to monitor the building and receive push notifications on real-time operational suggestions and/or recommendations about planning and renovations according to specific profiles.

Tenants/users and building operators will benefit from receiving specific feedback on the building performance, related for example to energy efficiency, comfort levels (thermal, indoor air quality, visual, ...) supported by monitoring and/or dynamic EPC.

In particular, the following list of main potential end-users is defined, even if the platform is open to different requests and user-profiles.

Tenants and users

> *Armo wakes up at 5:30 a.m. in a room at 20° and is ready to go to work at 6:20 a.m. being working far from home, Amaia, his wife, wakes up at 7:00 in a 21°C environment and go to work at 8:00. When both are coming back at 18:00 pm the house is at 21°C, but remained at 17°C during unoccupied period to reduce energy consumptions and the family energy bill. Similarly, room balance temperatures are adapted to their general schedules, with the possibility to be controlled pushed by specific requests. For example, yesterday, Armo left his office earlier and arrived at home at 14:00, but thanks to a smart home control he was able to modify his house thermal performance in remote and enter a thermally comfortable environment.*

Armo and Amaia are tenants, they live in a rent dwelling unit and are passionate in managing their house energy consumptions according to routines and life organisation, and to their personal comfort expectations. They are attentive to operational aspects and may be happy to control and reduce their operative consumption while guarantee comfort levels, this may have positive impact on the environment and on their bills.

> *Nour and Marco are working in the same open-office space, nevertheless, Nour is waking up earlier and start working 2 hours before Marco to have the possibility to go home in the early afternoon. Fortunately, they may control trough an App and personal controllers the illuminance levels at their desk and the shading opening position of the nearer window. The company has also recently installed small innovative devices supporting personal thermal comfort variations. These systems are very appreciated by them, being Nour requiring higher*

illuminance values than Marco, but aiming at opening the window oftener to increase air quality, while Marco feels cold in winter. Similarly, in summer Marco activates a personal fan, while Nour does not like air draught.

Nour and Marco are users, they share the same space (e.g., a working space), but may have different personal comfort expectations. They love to control certain parameters, and to use a space that is providing the right quality. As users they are mainly interested in managing comfort sensations rather than controlling energy consumptions, but they may like to pursue sustainable objectives when expressed. At general level their satisfaction and wellbeing are reflected on their productivity, and may also be an interest of other end-users (e.g., their company) to support them.

Monitoring the energy consumption, adjusting it with the aim of having a more efficient building, and in general promoting an energy-efficiency culture, could improve the living standards for tenants and/or occupants of a building, as they are directly connected with the operation of systems and services in the building, be it residential or non-residential. Tenants and users may benefit from simple (e.g., colour scale) infographics supporting early evaluation and suggestions (potential) on their behaviours supporting building operation. Given KPIs will be limited and represented by simple and clear definitions. They may be interested, if passionate on energy and comfort, on main thermal comfort parameters (temperatures and RH%, with special regards to be or not in the expected conditions) and in indoor air quality (in or above thresholds). Potentially, they may be interested in controlling building technical elements devoted to users (e.g., set points, personal light, personal fan/cooling devices, window openings, etc.) and in managing their personal energy bills.

Owners

Katharine and Benoit have just finished a long meeting defining strategies to support the economic growth of the rent of their building portfolio. They represent a family holding and manage their buildings in order to increase their renting values and appeal to avoid vacancies. They need to discuss economic, financial and technical issues with their consultants, just now they are starting a new meeting for the refurbishment of a large office area.

Katharine and Benoit are professional building owners, they are interested in increasing revenues and the value of their building portfolio.

Energy labelling of buildings can be perceived as an added market value and is beneficial to the property owners for whom the buildings are often perceived as a long-term investment. Nevertheless, as defined in E-DYCE D1.1., this connection is not homogeneous. In retrofit projects, for instance, a holistic energy assessment of the systems especially those of HVAC and lighting can be beneficial for building owners as it can lead to the reduction of maintenance costs. In addition, energy-efficiency is associated with increased tenant satisfaction and higher levels of occupancy. This could have a potentially large financial impact on building owners. Furthermore, owners of energy-efficient buildings could benefit from various climate action tax benefits, such as carbon tax credits.

Professional owners that have in their society an internal energy service staff may be interested in services and analyses like the one proposed by E-DYCE connecting energy consumptions and building performance with different scenarios supporting retrofitting choices on a multi-dimension vision. Methodologies able in defining, in a dynamic way, energy performances may support a higher reliability in results helping in feed their economical optimisation implementations. Professional owners that do not have an internal energy service staff may clearly benefit not only from specific E-DYCE services, but also from potential support in choices implementing additional elements and specific processes in the platform. Furthermore, the possibility to integrate future indicators, directly connected to the building market, like the SRI, or to dynamic EPC will define a benefit for owners supporting users' decisions. They may be interested in optimisation analyses and in standard profiling supporting tenants'/users' choices by increasing building quality and by the possibility to integrate the approach to a wide building portfolio supporting information choices and optimisation at different scales and for different profiles, KPIs and KPIs' domains.

Individual owners – e.g., the ones living in their proper house –, especially when energy passionate, may benefit from E-DYCE supporting retrofitting choices and the definition of main aspect to be improved in buildings in order to increase, without losing the economical dimension, building energy performances. E-DYCE may support the implementation of dynamic simulations and optimisation enablers to give access to information that an individual owner will rarely have.

Technical Managers/Energy service companies

> *Cedric is going to check sensors in a multi-family building that is under his energy management. It looks that the central heater is not balancing well the power curve. A few months before, Amelia was looking for causes of the electricity performance gap stated from a nearer hotel building during summer due to bad regulation of chillers. Their ESCO is very active in supporting energy services and correct management of buildings, with special regards to post-renovation optimisation.*

Cedric and Amelia are technical managers providing energy services. They are interested in maximising the energy efficiency of the buildings that their ESCO is managing to also increase their incomes, which are given, at least under the first contract years, by their ability to reduce energy bills and keep differences.

Technical managers and energy service companies will benefit from E-DYCE considering the scalable approach, the possibility to include different modules and the ability to connect different type of data sources and data analysis, including dynamic energy simulations and performance evaluations that, at present, are not connected. These evaluations require the development of a proper platform – which is a difficult issue to be faced – or the adoption of implicit actions based on their experience. Nevertheless, the proposed logic may reduce the calculation and managing time, may connect different services in a whole platform ranging from EPC to DEPC, to performance gap reduction and retrofitting suggestions.

Assessing building energy performance, periodic inspection of building systems and components and their optimisation necessitate a more active contribution of technical energy managers and can promote the industry and job market in the fields related to the energy management in buildings e.g., energy service providers and certifiers and technology providers.

Other actors receiving benefits from E-DYCE DEPC

> *Svetlana and Noah are working on updating and analysing data of the public authority cadastre. In past years, in addition to maps and building geometries (2D or 3D) the PA started collecting consumption data of buildings. This helps to verify the impact of medium-term energy policies. A GIS comparison on past and current data is supporting the definition of priorities and the distribution of incentives. Svetlana thinks that having access to energy consumption data will really support the adoption of more reliable choices and Noah agrees, looking to make additional long-term analyses when a sufficient number of data will be collected in future years.*

Svetlana and Noah are working in a public administration working on energy policies and analysis on a territorial scale. The possibility to have access to new and diffused data with different spatial and time granularities will considerably support their work. Even if a PA is not directly an end-user for DEPC and operational analyses, they will benefit from having access to a part of these data to verify policies, supporting new incentives, or identifies challenges. Additional actors that may potentially receive benefits from E-DYCE may also include other PA, district heating and cooling providers and energy providers supporting analyses and potential optimisations on different scales.

Monitoring the energy performance and DEPC of existing buildings could be a means for public administrators or government to encourage property owners to invest in energy efficiency retrofits. Assessment of building energy performance could provide accurate statistical data for governments and could be beneficial for them in their plans to comply with different energy-efficiency targets.

3.2 *Common verification methodology (KPIs)*

E-DYCE faces different open issues connected to EPBD – see Section 2 – and defines a scalable methodology including different services and service-levels. All of these aspects are connected to the definition of verification instruments, that considering the performance-driven mentioned approach to design, asset and operational levels, directly relates to the assumption and the definition of Key Performance Indicators (KPIs). E-DYCE will analyse and include in DEPC new KPIs, including comfort and free-running and passive potential exploitation. Furthermore, the given attention to the operational rating and to the end-user behavioural changes due to feedback on real building performance requires the adoption of specific KPIs. KPIs may be used to analyse the performance at building (or system) level or at sub-levels (e.g., sub-systems, zones, components, etc.). In the first case, indices directly define a whole building or system behaviour, while, in the second case, the whole level is reached by summing or aggregating sub-levels KPIs. Large efforts will be defined in E-DYCE to support simplification processes in building simulations (calculated) and monitoring (measured) to reduce efforts and computational times without losing the possibility to analyse building/unit performances. Reflections on how to average data and scale from sub- to whole performances will be supported in spatial and time domains. Additionally, a reflection on data properties and on data granularity will be developed and connected to specific KPIs definition, including also the potential delay in data transmission from local storage to cloud analysis domains. In some cases, data transfer domains are connected to privacy or specific requests and may require for specific adaptation in KPIs (e.g., may reduce the validity of hourly or sub-hourly analyses for user suggestions if delays overpass specific domains, but may support weakly-based analyses such as the energy signature of buildings). Furthermore, attentions will be given during the monitoring plan definitions for different levels of smartness and services considering the usage of long- and short-term monitoring of specific variables – and connected KPIs' definitions and calculations – to adapt to specific aims, e.g., analysing in details local performance gaps, or supporting user informed actions. Similarly, total and partial data set analyses will be adopted considering for example the adaptation of simulation weather files to real ones and the parallel computation of KPIs.

Focussing on KPIs' definition and classification, a large set of references on KPIs focussing on energy, temperature efficiency and comfort is available in literature. From the passive and ventilative point of view, it is possible for example to refer to IEA EBC Annex 62 KPIs (Heiselberg, 2018; Kolokotroni and Heiselberg, 2015) and to several additional references, e.g. (Artmann et al., 2007; Chiesa, 2019b; Guo et al., 2019; Sameron et al., 2012; Santamouris and Asimakopolous, 1996). Considering the long-term it is possible to classify KPIs able in defining building thermal discomfort conditions on the base of the calculation typology of indices (Carlucci and Pagliano, 2012a): i. percentage indices – defining the percentage of discomfort hours with respect to the total number of hours/occupied hours –, ii. cumulative indices – defining the cumulative discomfort intensity in a given calculation period –, iii. risk indices – mainly defining the risk of the occurrence of a discomfort phenomenon, e.g., overheating –, and iv. averaging indices – defining the average value of a discomfort index in the given calculation period. Differently, it is possible to classify the effect of low-energy elements, e.g., ventilative cooling, by considering the potential impact on: i. temperature performance, including heat removal effectiveness; ii. energy efficiency, including the ability to reduce the cooling/heating/... energy use; iii. thermal comfort evaluation, including the improvement in thermal comfort conditions during occupied hours (Guo et al., 2019). Referring to free-running and passive elements, main KPIs will concern comfort/discomfort, both focussing on Boolean or intensity indices, temperatures, and cooling/heating/... loads – see for example the recent discussion on energy performance standards' elaborations like the Brazilian ABNT NBR 15575-1:2020.

In particular, the following categories of KPIs are considered in the early-definition of E-DYCE DEPC logic to verify the additional proposed building performance features.

1. Energy and energy efficiency (including reduction in energy needs);
2. Free running Operation and potential exploitation (including temperature performances);
3. Comfort/quality (including thermal comfort improvement);
4. Smartness readiness and smartness of end-users (including user ability in optimising real building behaviours);
5. Correlated indicators

Energy-correlated KPIs will focus on:

- Building energy performances;
- Energy savings including reduction in energy needs;
- Percentage of energy saving due to taken actions

Free-running-correlated KPIs will consider in particular:

- Exploitation of the climatic free-running potential;
- Free-running activation hours;
- Temperature performance

Comfort/quality KPIs will include:

- Climate-comfort correlations (thermal comfort);
- Thermal Discomfort (Boolean or intensity);
- Thermal Discomfort reduction and improvements in comfort conditions
- Indoor air quality
- Lighting requirements

Smart-correlated KPIs will focus on:

- Operational detachment from standard building performances and performance gap;
- End-user ability in maintain standard optimised building behaviours;
- Smart-technology levels and activations - SRI
- Quantitative/qualitative indicators for data collection

Correlated indicators will consider in particular:

- Energy demand forecast (including performance GAP dimension);
- Economic efficiency indicators (potentially including cost optimal calculation; operational cost; Pay-Back period; cost benefit; embodied energy, LCC);
- climate change impact

Note 1: In E-DYCE, only some specific correlated indicators will be directly faced, in line with project objectives. Further comfort domains (e.g., acoustic comfort) or additional correlated indicators that are not included in present version, may be further included being the E-DYCE approach scalable and based on a neutral technology vision opened to the implementation of additional features.

Note 2: It is important to remember that the main open issue faced in E-DYCE (free-running, smartness, ...) are not only directly correlated with their additional KPI family, but have direct influences on the others. For example, to evaluate the thermal performance of a free-running building will be not only considered

Note 3: Not all mentioned KPIs families and KPIs will be defined in further Section 4, mainly referring to a first reflection on KPIs directly connected with main E-DYCE faced issues.

Note 4: KPIs priority levels and combinations may varies according to specific end-users and activated E-DYCE services. Furthermore, not all buildings may benefit from the whole set of KPIs and the definition of main KPIs to be considered (with the possibility to be further updated) will be part of the E-DYCE inspection plan process.

The mentioned classification of KPIs in families may support the development of simple graphical representations to be, for example, adopted for presenting the same to end-users during setting phases of the E-DYCE implementation in a specific building – see Figure 28.

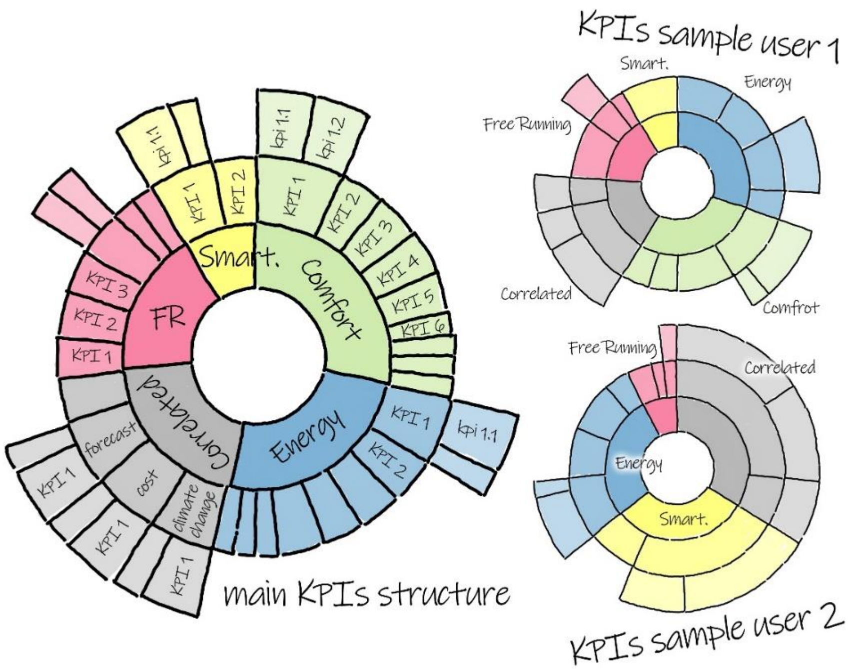

Figure 28:: Main KPIs structure and potential sample adaptation to different end-user profiles.

3.3 *E-DYCE demo cases*

E-DYCE development process will benefit by testing actions on demo cases. Demo buildings in five locations and a territorial demo are provided, in order to: on the one side implement and optimise the abovementioned E-DYCE rationale supporting simplification actions and applicability plans, and on the other side to support first DEPCs' definition. Demos are:

- Geneva (Switzerland) - 4 multi-store and multi-apartment buildings (residential) mixing EPG analyses, retrofitting plans, and operational rating;
- Torre Pellice (Italy) - 1 school building (kindergarten and Middle school), 1 single residential house, and 2 residential units in small residential houses. All are not renovated (retrofitting plans) and may benefit from IEQ evaluation and user information;
- Nicosia (Cyprus) - 1 office buildings (municipal building), NZEB post-design evaluation in a warm climate, high passive and FR autonomy;
- Hånbæk Frederikshavn (Denmark) - multi-apartment residential building already renovated in 2011;
- Aalborg (Denmark) - two multi-apartment residential buildings renovated between 2010-12 representative of other local buildings. Calculation of DEPC using standard and operative conditions scaling up implementations to multi-apartment.

- Geneva (Switzerland) - territorial scale, implementing E-DYCE functionalities to support local authorities and checking real-time data implementations in the existing large database that includes building consumptions. The action supports E-DYCE potentialities in reducing the needed time to support optimisation strategies after building implementation actions.

Figure 29 represents demos and their locations. Differences among selected test-cases allow to test E-DYCE functionalities in different climates, building typologies and for different aims.

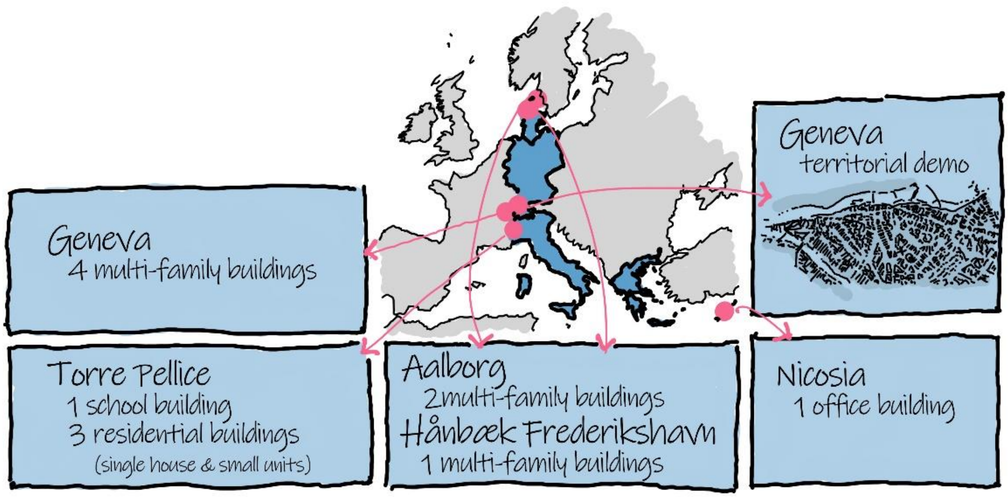

Figure 29 – Territorial distribution of demos.

Furthermore, these cases will also help in tuning different part of the E-DYCE methodology, including the inspection plan, the minimal spatial and temporal distribution of data acquisition for the implementation of both the simulation model and the monitoring plan.

4 KPIs definition

4.1 *Introduction*

Such as mentioned before, Section 4 is devoted to introduce a first set of KPIs that may be adopted in E-DYCE supporting verification methodologies and different levels of information and decision logics. Assuming the classification defined in Section 3.2, the following analysis is subdivided into KPIs categories. Additional KPIs may be included or developed during the project or in future updates focussing and taking advantage of E-DYCE data analysis and platform development. Although, not all the KPIs mentioned here below will be included in the E-DYCE prototype developed during the project time, while the proposed open and scalable methodology will allow for their future integration.

In order to simplify the KPIs description, they are presented adopting a two-table description methodology, on the base of the following table formats:

a. The first table is dedicated to the definition of the KPI, containing, when relevant, possible equations for its calculation, a short overview of the KPI possibly with some examples of use or some expected values/thresholds. The references, including standards, in which the KPI was either defined or mentioned. Finally, a level of importance of the KPI for the E-DYCE building performance analysis is tentatively defined.
b. The second table correlates each KPI with its input parameters in order to define a list of needed inputs to calculate and/or measure the chosen list of KPI. These inputs are extracted from the equations that define the KPI or are correlated to its description. Additionally, this table provides information on whether that KPI can be calculated via dynamic simulation and/or it can be monitored using various measurement techniques, including on-site and continuous detecting approaches.

A sample of both tables is reported here below – see Table 10 and Table 11.

Table 10: Definition of Table a.

KPIs	Expression/Method	Short description	Ref.	importance
KPI 1				
KPI 2				
….				
KPI n				

Table 11: Definition of Table b.

Inputs → KPIs ↓	simulated	monitored	input 1	input 2	…..	input n
KPI 1	yes/no	yes/no		x		

KPI 2	yes/no	yes/no	x		x	
….	yes/no	yes/no			x	x
KPI n	yes/no	yes/no	x	x		

.

4.2 *Energy operation KPIs*

Table 12: KPIs definition and calculation

KPIs	Expression/Method	Short description	Ref.	importance
EP	The calculation of Energy needs (e.g., primary/specific energy) and energy performance indicators refers to current standards (ISO 52000-1:2017)(EN ISO 52016-1:2017)(EN ISO 52017-1:2017) and to current national standards. Energy Performance indices that will potentially be considered are: - EP_H winter heating; - EP_W sanitary hot water production; - EP_C summer cooling; - EP_L artificial lighting; - EP_T people and goods transportation (e.g., elevators, movable stairs, ...); - EP_{gl} global building index. They are generally expressed in kWh/m^2 year or month (or eventually kWh/m^3). Global energy performance index of the building $$EP_{gl,tot} = EP_H + EP_W + EP_V + EP_C + EP_L + EP_T$$ Where $EP_{gl,tot}$ [kWh/m2.year] is the global energy performance index of the building corresponding to the total primary energy requirement per unit area for services.	In line with current standards and national/regional requirements may be expressed in final energy, primary energy, not renewable energy, ... The calculation of these indices will follow a dynamic calculation approach (EN ISO 52016-1:2017). Results will be compared with steady-state results and national standards.	(ISO 52000-1:2017)(EN ISO 52016-1:2017)(EN ISO 52017-1:2017)	1st

	The same is also assumed as KPI in several IEQ evaluation approaches – e.g. (Green Building Council Italia, 2019)			
PE_{pet} OR EP_P	primary energy indicator [kWh/m^2.year] e.g., for non-renewable primary energy (Kurnitski, 2013): $$EP_P = \frac{E_{P,nren}}{A_{net}}$$ $$E_{P,nren} = \sum_i (E_{del,i} f_{del,nren,i}) - \sum_i (E_{exp,i} f_{exp,nren,i})$$ where $E_{P,nren}$ is the non-renewable primary energy [kWh/year], $E_{del,i}$ is the delivered energy on site or nearby for energy carrier i, $E_{exp,i}$ is the exported energy on site or nearby for energy carrier i, $f_{del,nren,i}$ is the non-renewable primary energy factor [-] for the delivered energy carrier i, $f_{exp,nren,i}$ is the non-renewable primary energy factor of the delivered energy compensated by the exported energy for energy carrier i, which is by default equal to the factor of the delivered energy, if not nationally defined in other way, and A_{net} is the useful floor area [m²] calculated according to national definition. e.g. of calculation in Sweden (Zuhaib, 2020b): $$PE_{pet} = \frac{\sum_{i=1}^{6} \left(\frac{E_{uppv,i}}{F_{geo}} + E_{kyl,i} + E_{tvv,i} + E_{f,i} \right) . PE_i}{A_{temp}}$$ where E_{uppv} is the delivered energy for heating [kWh], F_{geo} is the geographical factor to account for climatic variation [-], E_{kyl} is delivered energy for cooling, E_{tvv} is delivered	<u>Building-level KPI</u> Primary energy indicator is defined by summing all delivered and exported energy (electricity, district heat/cooling, fuels). And is calculated by dividing the delivered and exported energy with national primary energy factors to the net floor area. In Sweden, for instance, the primary energy indicator is calculated using the yearly sum of 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. And finally the	(Kurnitski, 2013; Zuhaib, 2020b)	

	energy for domestic hot water, E_f is electricity delivered for other than heating, A_{temp} is the heated floor area [m²], and PE_i is primary energy factor per energy carrier i (electricity, district heating, district cooling, biofuel, oil and gas).	total consumption is recalculated to primary energy and divided by the heated floor area.		
RER	Renewable Energy Ratio $$RER = \frac{E_{Pren;RER}}{E_{Ptot}}$$ where E_{Ptot} is the total primary energy and $E_{Pren;RER}$ is the renewable primary energy calculated with the following formula and using total primary energy conversion factors $f_{Ptot;del;cr,i}$ and $f_{Ptot;exp;cr,i}$: $$E_{we} = E_{we;del;an} - E_{we;exp;an}$$ $E_{we;del;an}$ and $E_{we;exp;an}$ are respectively the annual weighted delivered and exported energies.	<u>Building-level KPI</u> Share of primary renewable energy from the total primary energy.	(ISO 52000-1:2017)	
RER_P	It is the renewable energy ratio based on the total primary energy $$RER_p = \frac{\sum_i E_{ren,i} + \sum_i\left(\left(f_{del,tot,i} - f_{del,nren,i}\right)E_{del,i}\right)}{\sum_i E_{reni,i} + \sum_i\left(E_{del,i}f_{del,tot,i}\right) + \sum_i\left(E_{exp,i}f_{exp,tot,i}\right)}$$ where $E_{ren,i}$ is the renewable energy produced on site or nearby for energy carrier i [kWh/year], $f_{del,tot,i}$ is the total primary energy factor [-] for the delivered energy carrier i, $f_{del,nren,i}$ is the non-renewable primary energy factor for the delivered energy carrier i, $f_{exp,tot,i}$ is the total primary energy factor of the delivered energy compensated by the	<u>Building-level KPI</u> For nZEB buildings, RER_P is calculated relative to all primary energy consumption in a building considering that the exported energy compensates the grid mix or in the case of thermal energy, the district heating or cooling network mix. For on-site and nearby	(Kurnitski, 2013)	

	exported energy for energy carrier i, $E_{del,i}$ is the delivered energy on site or nearby for energy carrier i, and $E_{exp,i}$ is the exported energy on site or nearby for energy carrier i.	renewable energy the total primary energy factor is 1.0 and the non-renewable primary energy factor is 0.		
E_iso	ISO weighted energy use $$E_{ISO} = \sum_{ci} E_{IS,del,ci} - \sum_{ci} E_{ISO,exp,ci} = \sum_{ci} E_{EPdel,ci} f_{ISO,del,ci} - \sum_{ci} E_{exp,ci} f_{ISO,exp,ci}$$ with $E_{EPdel,ci} = E_{EPus,ci} - E_{pr,EPus,ci}$	Building-level KPI Due to different primary energy sources, different climatic conditions, and different operation assumptions in the world, primary energy factors are not identical internationally. Therefore, for an international comparison of building performances, the ISO energy performance indicator is used.	(ISO 16346:2013) (Antonucci and Pasut, 2019)	
EPCoef.	Energy Performance Coefficient based on standard NEN 5128 addressing the energy performance of dwellings: $$EPCoef. = \frac{Q_{total:EPC}}{C_1 \times A_{gs;EPC} + C_2 \times A_{ts;EPC}} \times \frac{1}{C_{EPC}}$$ in which $Q_{total:EPC}$ is the characteristic yearly energy use [MJ] of the new house, $A_{gs;EPC}$ is the total ground surface [m^2], $A_{ts;EPC}$ is the total thermal transmission surface, C_1 and C_2 are correction factors equal to 330 and 65 MJ/m^2	Building-level KPI The EPCoef. for new buildings developed by Netherlands Normalisation Institute (NNI).	(Entrop et al., 2010)	

	respectively, and C_{EPC} is another correction factor to fit past EPC results. The $Q_{total:EPC}$ comprises energies for 1-heating, 2-additional auxiliary electric for heating system operation, 3-heating water, 4-fans, 5-lighting, 6-summer comfort, 7-cooling, 8-moisturising, in addition to energy generations by 9-photovoltaic systems, and 10-combined heat and power systems			
FE_{FR}	See Section 2 of this report for potential calculation methodologies.	Fictitious Energy Needs for Free-Running mode. The calculation of this KPI will be defined in line with the methodologies introduced in section 2 of this document by translating residual discomfort intensities into virtual energy needs.	See Section 2	1st
COP	Coefficient of performance $$COP = \frac{h_h}{P_e}$$	Component-level KPI The ratio of rate of heat production h_h to the electrical power P_e (e.g., of a heat pump)	e.g. (Baglivo et al., 2018; Li et al., 2020)	
EER	energy efficiency ratio $$EER = \frac{h_c}{P_e}$$	Component-level KPI The ratio of rate of heat removal h_c to the electrical	e.g. (Baglivo et al., 2018)	

		power P_e (e.g., of a heat pump)		
SEER	Seasonal Energy Efficiency Ratio $$SEER = \frac{Q_C}{Q_{CE}}$$ in which Q_{CE} is the annual electricity consumption for cooling and Q_C is the representative annual cooling demand, $P_{design,c}$ is the design load for cooling, and HCE are the equivalent active mode hours for cooling	Component-level KPI SEER is defined as the ratio between the reference annual cooling demand and annual electricity consumption considering the varied outdoor air temperature Similarly, may be calculated the SCOP index - Seasonal coefficient of performance (heating).	(EN 14825:2018) Delegate Regulation (EU) No. 626/2011	
SCOP	seasonal coefficient of performance $$SCOP = \frac{Q_H}{Q_{HE}}$$ in which Q_{HE} is the annual electricity consumption for heating and Q_H is the representative annual heating demand	Component-level KPI SCOP is defined as the ratio between the reference annual heating demand and annual electricity consumption. For heat pumps it is called HSPF or heating seasonal performance factor.	(EN 14825:2018) Delegate Regulation (EU) No. 626/2011	
ESEER	European seasonal energy efficiency ratio $$ESEER = A \times EER_A + B \times EER_B + C \times EER_C + D \times EER_D$$ where:	Component-level KPI Since the energy labels and standard efficiency of the chillers were defined	(Marinhas, 2013)	

	for conditions A, B, C, and D, the load ratio, weighing coefficient, air temperature at condenser inlet (air cooled chiller), and water temperature at condenser inlet (water cooled chiller) are: • A 100% 0.03 35 30 • B 75% 0.33 30 26 • C 50% 0.41 25 22 • D 25% 0.23 20 18	under standard conditions at full load, ESEER was therefore designed as a weighed formula that enables to consider the variation of EER with the load rate and the variation of air or water inlet condenser temperature.		
$SEER_{VC}$	$$SEER_{VC} = \frac{Q_C^{Ref} - Q_C^{Scen}}{E_{VC}}$$ Where: $_{VC}$ refers to ventilative cooling, Q^{Ref} is the cooling/heating need of the standard reference scenario, and Q^{Scen} is the cooling/heating need of the analysed case adopting the considered ventilative cooling strategy. E_{VC} is the electricity energy need for activating the analysed VC strategy (e.g., fan energy needs for mechanical ventilative cooling)	Component-level KPI Ventilative Cooling Seasonal Energy Efficiency Ratio	(Flourentzou and Bonvin, 2017)	
ADV	$$ADV_{VC} = \frac{Q_{el,c}^{Ref} - Q_{el,c}^{Scen}}{Q_{el,v}}$$ Where: $Q_{el,c}^{Ref}$ is the reference-standard-case electrical energy need of the cooling system, $Q_{el,c}^{Scen}$ is the electrical energy need of the considered ventilative cooling scenario, and $Q_{el,v}$ is the electrical energy need of ventilation systems.	System-level KPI Advantage of the given technology, e.g., ADV_{VC} (Advantage of Ventilative Cooling)	(Heiselberg, 2018)	

xRR	e.g. for cooling: $$CRR = \frac{Q_c^{Ref} - Q_c^{Scen}}{Q_c^{Ref}} = 1 - \frac{Q_c^{Scen}}{Q_c^{Ref}}$$ Where: Q_c^{Ref} is the cooling need of the standard reference scenario and Q_c^{Scen} is the cooling need for the analysed case (e.g., with ventilative cooling) Output domain [-1;+1]	System-level KPI Energy Requirement Reduction, e.g., CRR – cooling requirement reduction In order to be calculated it requires the definition of a reference scenario (standard energy needs) adopting current standards (e.g., Swiss SIA 2024)	(Flourentzou and Bonvin, 2017; Heiselberg, 2018)	
Energy signature	Plotting average power versus the average external temperature or versus Degree-Days for heating, cooling and neutral seasons by using linear regression lines. $$\Phi = \Phi_0 - H\vartheta_e$$ Where: Φ is the average power, Φ_0 is the characteristic power at 0°C, H is the line slope, and ϑ_e is the average external temperature. $$H = \frac{\Phi_0 - \Phi_b}{\vartheta_L}$$ Where: Φ_b is the building base power independent by the external temperature and ϑ_L is the external temperature limit for heating. Note: Additional definitions may include solar radiations.	Building-level KPI Operational rating method. Correlation between heating and cooling needs to climatic data over a sufficient period. Used to perform fast detection of buildings EP and malfunctions. May be used for: - Diagnosis of consumptions - Analyse drift - Find malfunctions - Optimise system management	(EN 15603:2008)*, Annex B (Acquaviva et al., 2015; Eriksson et al., 2020; Hitchin and Knight, 2016)	1st

		Using the signature it is possible to estimate seasonal energy use (e.g., for heating) $Q_h = (\Phi_0 - H\overline{\vartheta_e})t$		
H-m method	Heat loss coefficient of a building may be estimated using: $$H = \frac{\Phi - \Phi_a}{\Delta\vartheta} = H_0 - \eta A_e m$$ Where $\Delta\vartheta = (\overline{\vartheta_i} - \overline{\vartheta_e})$ and $m = \frac{I_{sol}}{\Delta\vartheta}$ is a *meteorological* variable. The slope is modified considering an equivalent area of solar collection including a utilisation factor and assuming the effective heat loss coefficient as the ordinate at x=0.	Building-level KPI Operational passive solar building. Adaptation of the energy signature for passive solar buildings.	(EN 15603:2008)*, Annex B	
**$EP_{gl,nren}$	non-renewable global energy performance index $$EP_{gl,nren} = EP_{H,nren} + EP_{W,nren} + EP_{V,nren} + EP_{C,nren} + EP_{L,nren} + EP_{T,nren}$$ $$index = \frac{EP_{gl,nren}}{EP_{gl,nren,ref,standard\ 2019/21}} \times 100$$ where $EP_{gl,nren}$ is the non-renewable energy performance index of the real building [kWh/m^2.year], and $EP_{gl,nren,ref,standard\ 2019/21}$ is the non-renewable energy performance index for the reference building according to the minimum requirements established by the Ministerial Decree of 26 June 2015	Building-level KPI • negative points >100% -1 • sufficient points 100% 0 • good points 64% 3 • great points 40% 5	(UNI/PdR 13.2:2019, 2019)	
**$EP_{H,nd}$	Performance index for winter heating $$index = \frac{EP_{H,nd}}{EP_{H,nd,limit}} \times 100$$	System-level KPI	(UNI/PdR 13.2:2019, 2019)	

	Where $EP_{H,nd}$ [kWh/m^2.year] is the thermal performance index useful for winter heating of the building, $EP_{H,nd,limit}$ [kWh/m^2.year] is thermal performance index useful for winter heating of the reference building	• negative >100% -1 points • sufficient 100% 0 points • good 80% 3 points • great 66.7% 5 points		
**$EP_{C,nd}$	Performance index for summer cooling $$index = \frac{EP_{C,nd}}{EP_{C,nd,limit}} \times 100$$ Where $EP_{C,nd}$ [kWh/m^2.year] is the thermal performance index useful for summer cooling of the building, $EP_{C,nd,limit}$ [kWh/m^2.year] is thermal performance index useful for winter heating of the reference building	System-level KPI • negative >100% -1 points • sufficient 100% 0 points • good 80% 3 points • great 66.7% 5 points	(UNI/PdR 13.2:2019)	
η_H	Average seasonal efficiency of the heating system $$\eta_H > \eta_{H,limit}$$ where η_H is the average seasonal efficiency of the heating system, $\eta_{H,limit}$ is the minimum value of the average seasonal efficiency of the heating system	System-level KPI	e.g.,(Green Building Council Italia, 2019)	
η_C	Average seasonal efficiency of the cooling system $$\eta_C > \eta_{C,limit}$$	System-level KPI	e.g.,(Green Building Council Italia, 2019)	

η_W	Average seasonal efficiency of the DHW system $\eta_W > \eta_{W,limit}$	System-level KPI	e.g.,(Green Building Council Italia, 2019)	

*This standard was substituted by ISO EN 52000-1:2018

** This is a translation of EPBD indices into the ITACA protocol: an environmental impact and sustainable evaluation criteria tool.

Table 13: KPIs input (S=simulation/M=monitoring)

Inputs → KPIs ↓	Simulated KPI	Monitored KPI	simulated electrical energy	simulated thermal energy	energy smart meter electrical	energy smart meter thermal	system on/off		area/volume	time	ϑ_e	$\vartheta_{air,i}$	$\vartheta_{set.i}$
			s	s	m	m	s/m		s/m	s/m	s/m	s/m	s/m
EP	yes	yes[1]	x	x	x	x			x	x			
PE_{pet} OR EP_P	yes	yes	x	x	x	x			x	x			
RER	yes	yes	x		x								
RER_P	yes	yes	x		x								
E_iso	yes	yes	x	x	x	x							
EPCoef.	yes	yes	x	x	x	x			x				
COP	yes	yes	x	x	x	x							
EER	yes	yes	x	x	x	x							

SEER	yes	yes	x	x	x	x				x			
SCOP	yes	yes	x	x	x	x				x			
ESEER	yes	yes	x	x	x	x				x			
$SEER_{VC}$	yes	yes	x	x	x	x	x			x			
ADV	yes	yes	x		x								
xRR	yes	yes		x		x							
Energy signature	yes	yes	x		x						x	(x)	x
H-m method	yes	yes		x		x							
$EP_{gl,nren}$	yes	yes	x	x	x	x							
$EP_{H,nd}$	yes	yes	x	x	x	x							
$EP_{C,nd}$	yes	yes	x	x	x	x							
η_H	yes	yes	x	x	x	x							
η_C	yes	yes	x	x	x	x							
η_W	yes	yes	x	x	x	x							

4.3 *Free running operation KPIs*

Table 14: KPIs definition and calculation

<table>
<tr><th>KPIs</th><th>Expression/Method</th><th>Short description</th><th>Ref.</th><th>importance</th></tr>
<tr><td>FRh</td><td>Free Running hours
$$FRh = \frac{\sum_{i=1}^{Hrs} \begin{Bmatrix} h_i = 1 \Leftarrow FR\ active \\ h_i = 0 \Leftarrow MS\ active \end{Bmatrix}}{\sum Hrs} \quad [\%]$$
Hrs is the No. of hours in the calculation period. The index may be defined for occupied hours only (Hrs = Oh) assuming that the positive potential effect of FR in non-occupied hours is indirectly translated in a reduced need for additional cooling, or based on all hours in the calculation period. FR = free-running mode; MS= mechanical system activation mode.
For building in FR mode A (without a system) this index is substituted by:
$$FRh = \frac{\sum_{i=1}^{Hrs} \begin{Bmatrix} h_i = 1 \Leftarrow \vartheta_i \le \vartheta_{c,upper} \wedge \vartheta_i \ge \vartheta_{c,lower} \\ h_i = 0 \Leftarrow \vartheta_i > \vartheta_{c,upper} \vee \vartheta_i < \vartheta_{c,lower} \end{Bmatrix}}{No.Hrs} \quad [\%]$$
where ϑ_i is the internal air temperature (operative), $\vartheta_{c,upper}$ and $\vartheta_{c,lower}$ are respectively the adopted upper and lower comfort temperature thresholds.</td><td>The No. of hours in which the building is operating in free-running. The index may be expressed using both absolute or percentage values (see sample).
For buildings without systems (FR mode A), the activation hours are considered those hours in which internal temperature is maintained in the given comfort range.</td><td>Adapted for E-DYCE</td><td>1st</td></tr>
<tr><td>MSh</td><td>$$MSh = \frac{\sum_{i=1}^{Oh} \begin{Bmatrix} h_i = 1 \Leftarrow MS\ active \\ h_i = 0 \Leftarrow MS\ off \end{Bmatrix}}{\sum Oh} \quad [\%]$$
Where Oh is the No. of hours in the calculation period. MS= mechanical system activation mode.</td><td>The No. of hours in which the building is operated mechanically to reach thermal comfort. The index may be expressed using both absolute or</td><td>Adapted for E-DYCE</td><td></td></tr>
</table>

		percentage values (see sample). Potentially the index may be adapted to classify the number of hours according to MS power %.		
PAER	passive air-conditioning efficiency ratio $$PAER = {FRh}/{SPh}$$ Where: FRh is the Free-Running hour indicator and SPh is the number of hours in the simulation period – both may refer to occupation hours.	PAER is defined as the number of hours in which the building is in free-running mode and air-conditioning is not required, divided by the total number of hours of the simulation period	(Bourgeois et al., 2000)	
$f_{se}(t, T_o)$	frequency distribution of degree-hour of stack-effect $$f_{se}(t,T_o) = N.T_{bin}.P_{df}(T_o).(T_{cu} - T_o).\delta_{fc}$$ $$with\ \delta_{fc} = \begin{cases} 1, when\ T_o \leq T_{cu}\ and\ T_{fr} > T_{cu} \\ 0, otherwise \end{cases}$$ Where: T_{cl} lower limit of comfort temperature, T_{cu} upper limit of comfort temperature, T_{fr} free running temperature, T_o outdoor temperature, $NT_{bin}P_{df}(To)$ is the probable frequency of the daily variation of T_{fr} as a function of T_o	This index gives an indication of the applicability of buoyancy driven natural ventilation	(Ghiaus, 2003)	
$CIBSE_A$	CIBSE overheating indices Dry bulb resultant temperature in designed building under Design Summer Year (DSY) conditions will:	Overheating performance indices introduced in CIBSE Guides – Guide J: $CIBSE_J$	(Chartered Institution of	

$CIBSE_J$ overheating indices	$CIBSE_J$ = not exceed 25°C for more than 5% of occupied time; $CIBSE_A$ = not exceed 28°C for more than 1% of hours in naturally ventilated buildings – not exceed 26°C in bedrooms $$CIBSE_{A,J} \equiv \frac{\sum_{i=1}^{Oh}\left(wf_i^{A,J} h_i\right)}{\sum_{i=1}^{Oh} h_i} \in [0,1]$$ $$CIBSE_J = f\left(wf_i^J\right): \begin{cases} wf_i^J = 1 \Leftarrow (\theta_{res} > 25°C \\ wf_i^J = 0 \Leftarrow (\theta_{res} \leq 25°C \end{cases}$$ $$CIBSE_J \leq 0.05$$ $$CIBSE_A = f\left(wf_i^A\right): \begin{cases} wf_i^A = 1 \Leftarrow (\theta_{res}^{bedrooms} > 26°C \\ wf_i^A = 0 \Leftarrow (\theta_{res}^{bedrooms} \leq 26°C \\ wf_i^A = 1 \Leftarrow (\theta_{res}^{otherrooms} > 28°C \\ wf_i^A = 0 \Leftarrow (\theta_{res}^{otherrooms} \leq 28°C \end{cases}$$ $$CIBSE_A \leq 0.01$$	and Guide – A: $CIBSE_A$. They define the percentage of occupied hours above (below) a reference temperature.	Building Services Engineers, 2002) (Butcher et al., 2015) (Carlucci and Pagliano, 2012b)	
Overheating indicator I_{OH}	Overheating indicator (I_{OH}) for thermal zone $_{tz}$: $$I_{OH;tz;an} = \sum_{m=1}^{12} T_{OH;tz;m} \qquad [Kh]$$ Where $_{an}$ refers to annual time granularity, $_m$ to month and T_{OH} to monthly accumulated over-temperature [Kh] defined as follows: $$T_{OH;tz;m} = 1000 \cdot \frac{Q_{OH;gn;tz;m} - Q_{OH;ht;tz;m}}{H_{OH;tr;tz;m} + H_{OH;ve;tz;m}} \qquad [Kh]$$ Where Q_{gn} refers to heat gains, Q_{ht} refers to the total heat transfer by transmission and ventilation, H is an overall heat transfer coefficient for $_{tr}$ transmission and for $_{ve}$ ventilation.	Considered in case of absence of mechanical cooling and defined at an annual base. It is correlated to the accumulated over-temperature monthly indices. This indicator is assessed only at thermal zone level. Attention need to be given if in the same zone spaces with different thermal loads or properties are present to not	(EN ISO 52016-1:2017)	

	ISO 52016-1:2017 sets the cooling set point in thermal zone for T_{OH} equal to 26°C.	underestimate the indicator.		
%Ohnat-vent.comf.	Percentage of occupied hours with natural ventilation within a temperature range. A potential expression to calculate this indicator for upper cooling comfort limits is: $$\%Oh_{nat-vent,comf.} = \frac{\sum_{i=1}^{Oh} \begin{cases} h_i = 1 \Leftarrow \vartheta_i \leq \vartheta_{c,upper} \wedge natural\ ventilation\ on \\ h_i = 0 \Leftarrow \vartheta_i > \vartheta_{c,upper} \vee natural\ ventilation\ off \end{cases}}{No.Oh} \quad [\%]$$	The index may be adapted to define the occupied hours adopting a specific passive/low-energy technique maintaining indoor comfort temperature ranges.	ABNT NBR 15575-1: 2013 (new 2020)	
CCP CCP_d	Climate cooling potential $$CCP = \frac{1}{N}\sum_{n=1}^{N}\sum_{h=h_i}^{h_f} m_{n,h}\left(T_{b,n,h} - T_{e,n,h}\right) \begin{cases} m = 1h & if \quad T_b - T_e \geq \Delta T_{crit} \\ m = 0 & if \quad T_b - T_e < \Delta T_{crit} \end{cases}$$ where $T_b - T_e$ is the building/external air temperature difference, h is the time of the day (0-24h), h_i and h_f are initial and final time of night-time ventilation, and ΔT_{crit} is the threshold value of temperature difference the daily climate cooling potential [for ventilative night cooling] $$CCP_d = \sum_{t=t_i}^{t_f} m_{d,t}\left(\vartheta_{b_{(d,t)}} - \vartheta_{e_{(d,t)}}\right) \begin{cases} m_{d,t} = 1h \Leftarrow \vartheta_b - \vartheta_e \geq \Delta\vartheta_{crit} \\ m_{d,t} = 0 \Leftarrow \vartheta_b - \vartheta_e < \Delta\vartheta_{crit} \end{cases}$$ Where m_t is an activation mode, $\vartheta_{b_{(t)}}$ is the building temperature at time *t* and $\vartheta_{e_{(t)}}$ is the environmental air temperature at the same moment. t_i and t_f are respectively the initial and ending hours of ventilative cooling activation	CCP is defined to assess the mean climate potential for ventilative cooling during a given time period of N nights. It is defined as the summation of products between building/external air temperature-difference and time interval.	(Artmann et al., 2008; Kolokotroni and Heiselberg, 2015)	1st

	(e.g., natural free-running ventilation or fan-assisted ventilation), while $\Delta\vartheta_{crit}$ is a minimal activation threshold representing a minimal difference in temperature to assure an effective ventilation, e.g. 3K. According to (Artmann et al., 2007) when internal temperatures are not known they may be estimated (e.g., design rating) assuming an harmonic floating temperature around a 24.5°C considering ±2.5K → $\vartheta_{b_{(t)}} = 24.5 + 2.5 \cdot cos\left(2\pi \frac{t-t_i}{24}\right)$ In operational and in dynamic simulated building, internal temperatures may be measured or simulated without ventilative cooling. This index was originally conceived for office buildings mechanically cooled during daytime, assuming a t_i = 19:00 h and a t_f = 7:00 h am.			
CCP_{usage}	$$CCP_{d,usage} = 1 - \frac{CCP_d^A}{CCP_d^{ref}}$$ Where A is the real scenario (or the evaluated scenario) and ref is the reference scenarios assuming that the building is operated without ventilative cooling. In the first case $\vartheta_{b_{(d,t)}}$ is the internal monitored/simulated temperature while, in the reference case, $\vartheta_{b_{(d,t)}}$ is the simulated temperature (e.g., FR building without ventilation). Both are calculated adopting the same external temperature (real/typical) conditions.	This new indicator is defining the percentage of exploitation of climatic cooling/heating potential (e.g., ventilative cooling) The index may be adapted to define the percentage of usage of the local potential dissipation due to ventilative cooling according to external conditions. This analysis may be performed both in design rating and in operational rating.	New for E-DYCE	

xDD_{res} xDH_{res}	Residual Heating/Cooling degree-days or degree-hours A sample definition of this index (e.g. CDH_{res}) bases on: $$CDH_{res,\vartheta_b} = \sum_{h=1}^{n} \begin{cases} 0 & \Rightarrow \vartheta_h \leq \vartheta_b \vee \vartheta_{treat} \leq \vartheta_b \\ \vartheta_{treat} - \vartheta_b & \Rightarrow \vartheta_h > \vartheta_b \wedge \vartheta_{treat} > \vartheta_b \\ \vartheta_h - \vartheta_b & \Rightarrow \vartheta_h > \vartheta_b \wedge \vartheta_{treat} < \vartheta_b \end{cases}$$ Where ϑ_{in} is the environmental temperature (e.g., hourly defined), ϑ_b is the reference base temperature, and ϑ_{treat} is the adapted air temperature after a "virtual" or "real" treatment effect by a passive cooling dissipative system or technology (for CDH). This value may be adapted by introducing an activation threshold of the system *k* – see below. $$\vartheta_{treat} = \begin{cases} \vartheta_{tr} \Rightarrow \Delta\vartheta_{h-tr} \geq k \\ \vartheta_h \Rightarrow \Delta\vartheta_{h-tr} < k \end{cases}$$ Where ϑ_{tr} is the treated air temperature after the passive system treatment. The same approach is adapted for defining residual heating degree-days or degree-hours (e.g., considering the effect of a sun space – see early introduction (Chiesa et al., 2017b)). Given the xDD_{res} xDH_{res} it is possible to define the absolute difference or the percentage of the reduction (or of the residual) climate-driven energy need after passive-system fluid (e.g., air) treatment. For example $$red.xDH\% = \left\| \frac{xDH_{res} - xDH}{xDH} \right\|$$	The index may be defined using both percentage or absolute values, considering residual Dh or DD or reduction in Dh/DD. The residual degree-hours/day index is adaptable to different technologies by adapting the expression. In fact, the definition of the "virtual" ϑ_{tr} may be adapted for each considered passive system. Focussing on ventilative cooling some expressions were developed in (Chiesa and Grosso, 2015a), similarly for evaporative cooling (Chiesa et al., 2019c, 2017a), and for ground cooling and pre-heating (Chiesa, 2018, 2017c).	(Chiesa, 2019b; Chiesa and Grosso, 2015a)	1st
$xDD_{res,CCres}$ $xDH_{res,CCres}$	The residual heating/cooling degree-days or degree-hours indices are able to be used to define the climate resilience of technologies under perturbance events – short (e.g. heat waves) and long term (e.g. climate changes) ones.	Building or system resilience to climate changes or different events.	(Chiesa and Zajch, 2020; Zajch et al., 2020)	

	$\Delta red.xDH\% = red.xDH_{future}\% - red.xDH_{base}\%$ Where $_{future}$ is referring to future or different climate scenario and $_{base}$ to the assumed climate-reference scenario.			
$xDD_{res,usage}$ $xDH_{res\ usage}$	Percentage of exploitation of climatic cooling/heating potential (e.g., ventilative cooling) $$\%xDD_{res,usage} = \frac{xDD^{Ref.} - xDD^{Act.}}{xDD^{Ref.} - xDD_{res}}$$ Where $^{Ref.}$ is the reference case without the activation of passive/low-energy technologies, $^{Act.}$ is the xDD index calculated on actual data (e.g., monitored ones). The same may be calculated for xDH indices. Considering the potential operational usage of the index, the same may be referred to internal conditions (xIDH – see below).	Adaptation of xDD_{res} indices to define their exploitation (e.g., in operational phases). It defines the usage of xDD_{res}	New indicator for E-DYCE	
CIDH HIDH	Cooling Internal Degree Hours $$CIDH = \sum (T_{in,op} - T_c)$$ where $T_{in,op}$ is indoor operative temperature and T_c is the comfort temperature Heating Internal Degree Hours $$HIDH = \sum (T_c - T_{in,op})$$	Internal cooling degree-hour indices allow to analyse the discomfort intensity in a building (FR especially) and to compare different scenarios. Internal heating degree-hour indices allow to analyse the discomfort intensity in a building (FR especially) and to compare different scenarios.	(Pellegrino et al., 2016)	

TE	Temperature efficiency [of night-time ventilation] $$TE = \frac{\vartheta_{outlet} - \vartheta_{inlet}}{\vartheta_{surface} - \vartheta_{inlet}}$$	The temperature efficiency in general decreases with higher air change rates, however, this decrease is bigger in displacement ventilation compared to mixing ventilation. In a perfectly mixed room the value of temperature efficiency is limited to 1, while in displacement ventilation the efficiency exceeds 1 due to temperature stratification.	(Guo et al., 2019) (Artmann et al., 2010)	
TDR	temperature difference ratio $$TDR = \frac{\vartheta_{e,max} - \vartheta_{i,max}}{\vartheta_{e,max} - \vartheta_{e,min}}$$	used in assessing the heat removal effectiveness in night cooling, a higher TDR means a larger difference between the indoor and outdoor temperatures	(Guo et al., 2019)	
DF	decrement factor $$DF = \frac{A_i}{A_e} = \frac{\vartheta_{e,max} - \vartheta_{i,min}}{\vartheta_{e,max} - \vartheta_{i,min}}$$ where Ai and Ae are the amplitudes of the heat wave measured at the inner and the outer surface of the wall	The Decrement Factor defines the ratio of indoor air temperature variations to the environmental air temperature fluctuations	(Gagliano et al., 2014; Guo et al., 2019)	
φ	time lag for thermal inertia effect of envelope $$\varphi = \tau(T_{i,max}) - \tau(T_{e,max})$$	time difference between the peak temperatures of	(Gagliano et al., 2014)	

	where $\tau(T_{i,max})$ and $\tau(T_{e,max})$ represent the time when the outer and the inner surface temperatures reach their peak value, respectively, within a period of 24 h.	outdoor and indoor surfaces		
DI	weighted Discomfort temperature Index $DI = \sum w_i(\vartheta_a(i) - \vartheta_{comf,sup})$ $w_i = \vartheta_a(i) - \vartheta_{comf,sup}$ $DI = \sum (\vartheta_a(i) - \vartheta_{comf,sup})^2$ Where ϑ_a is the indoor air temperature, w_i is the weight factor, and $\vartheta_{comf,sup}$ is the upper comfort limit temperature	Distance of discomfort from upper operative limit (e.g., fixed at 28°C in literature). A lower DI means night ventilation can better improve thermal comfort.	(Corgnati and Kindinis, 2007)	
DTP	Discomfort over-temperature Time Percentage $DTP = \frac{\sum_{i=1}^{Oh} \left\{ \begin{matrix} h_i = 1 \Leftarrow \vartheta_i > 28°C \\ h_i = 0 \Leftarrow \vartheta_i \leq 28°C \end{matrix} \right\}}{\sum Oh} \quad [\%]$	Percentage of occupied hours where indoor temperature is higher than a fixed upper temperature limit set to 28°C	(Corgnati and Kindinis, 2007)	
%TtC-Oh	Percentage of discomfort hours Turned to Comfort by passive/bioclimatic technologies. This approach allows to calculate the % of exploitation of bioclimatic technologies discomfort coverage: $BP = 1 - \frac{\sum_{i=1}^{Oh} m_i}{\sum_{i=1}^{Oh} m_{BC,i}}$ $\begin{cases} m_i = 1 \; if \in comfort \\ m_i = 0 \; if \notin comfort \end{cases}$ $\begin{cases} m_{BD,i} = 1 \; if \; ext. \in bioc. comfort \\ m_{BD,i} = 0 \; if \; ext. \notin bioc. comfort \end{cases}$	Number of environmental or internal discomfort hours (e.g., occupied hours) translated to comfort by the activation /usage of passive and bioclimatic technologies.	Early definition from (Chiesa et al., 2019c)	

$\vartheta_{i,MAX}$ $\vartheta_{i,MIN}$	summer thermal performance: $\theta_{i,max} \leq \theta_{e,max}$ winter thermal performance: $\theta_{i,min} \geq \theta_{e,min} + 3°C$	According to the Brazilian standards, the maximum daily indoor temperature in rooms with long-terms use, in absence of internal heat sources, must always be less than the maximum daily outdoor values in shade. Similarly, in winter the minimum indoor temperature must be always 3°C higher than the outdoor values.	ABNT NBR 15575-1: 2013	

Table 15: KPIs input (S=simulation/M=monitoring)

Inputs → KPIs ↓	Simulated KPI	Monitored KPI	$\vartheta_{external}$	$\vartheta_{air,internal}$	$\vartheta_{surface,internal}$	$\vartheta_{surface,external}$	MRT_i	$\vartheta_{uppercomfort}$	$\vartheta_{lowercomfort}$	$\vartheta_{comfort}$	$\vartheta_{indoor,operative}$	wind velocity	FR on	$\vartheta_{resultant}$	time
			s/m	s/m	s/m	s/m	s/m	s/m	s/m	s/m	s/c	s/m		s/m	s/m
FRh	Yes	Yes		x				x	x						x
MSh	yes	yes		x											x
PAER	yes	yes		x				x	x						x

$f_{se}(t, T_o)$	yes	yes	x	x				x	x						x
$CIBSE_A$ / $CIBSE_J$ overheating indices	yes	yes								x				x	
I_{OH} overheating indicator	yes	yes		x											
$\%Oh_{nat\text{-}vent.comf.}$	yes	yes		x				x	x				x		x
CCP	yes	yes	x	x											x
CCP_d	yes	yes	x	x											x
CCP_{usage}	yes	yes	x	x											x
*xDD_{res} / xDH_{res}	yes	yes	x	x						x	x	(x)			x
* $xDD_{res,CCres}$ / $xDH_{res,CCres}$	yes	yes	x	x						x	x	(x)			x
*xDD_{res} / $xDH_{res\ usage}$	yes	yes	x	x						x	x	(x)			x
CIDH	yes	yes								x	x				x
HIDH	yes	yes								x	x				x
TE	yes	yes	x	x	x										
TDR	yes	yes	x	x											
DF	yes	yes			x	x									
φ	yes	yes			x	x									x
DI	yes	yes		x				x							
%TtC-Oh	yes	Yes													

* Inputs may vary according to the evaluated low energy technology (e.g., wind-driven ventilation, evaporative cooling, EAHE)

4.4 *Comfort/quality KPIs*

4.4.1 Thermal comfort

Thermal comfort is a huge topic and here we are refereeing partially to the state-of-the-art. Fixed the two approaches to define thermal comfort in adaptive free-running buildings (BS EN 15251:2007, BS EN 16798-1:2019, SIA 180) and in mechanical controlled ones (BS EN ISO 7730:2005, SIA 180) – see Section 2 – the following list of indicators will be analysed toward the early-definition of a potential comfort labelling specification.

Table 16: KPIs definition and calculation

KPIs	Expression/Method	Short description	Ref.	importance
PPD	Predicted Percentage of Dissatisfied $PPD = 100 - 95e^{[-(0.03353PMV^4+0.2197PMV^2)]}$	The PPD index (Predicted Percentage of Dissatisfied) defines a quantitative prediction of the percentage of people that are thermally dissatisfied, feeling too cool or too warm. It is expressed in percentage [0-100] and is function of the Predicted Mean Vote. Being thermal sensation a personal voice, when PMV is 0 (comfort) the PPD is reaching a value of 5% that statistically means that a minimal percentage of dissatisfied is expected in all cases. According to ASHRAE-55:2017 standard, this index is only applicable to healthy individuals. This standard does not apply to occupants: a) whose clothing insulation exceeds 1.5 clo; b) whose clothing is highly impermeable; or c) who are sleeping, reclining in contact with bedding, or able to adjust blankets or bedding.	(ASHRAE, 2017; ASHRAE and CBE, n.d.; Ruz et al., 2018) (BS EN ISO 7730:2005)	1st
PMV	Predicted Mean Vote *PMV = f (*ϑ_{air}*, MRT, RH%,* v_{air}*, clo, met)*	The Predicted Mean Vote (PMV) forecasts the average thermal sensation response of a large set of people in given thermal conditions for a sufficient long time. It is organised	(ASHRAE, 2017a; Castilla et al., 2014; EN	1st

	See mentioned standards and literature Ref.s, e.g. (Ruz et al., 2018; Silva, 2013)	according to a 7-point scale from -3 (too cold) to +3 (too hot) fixing a 0 point for comfort. Comfort range is generally assumed in the domain [-0.5 … +0.5] even if larger thresholds may be defined for specific scopes. Potentially, corrected PMV may be assumed for given climatic regions and seasons – e.g., for India, the Singh expressions may be adopted (Singh et al., 2011): I. winter cPMV=PMV/(1-1.68PMV); II. spring cPMV=PMV/(1-0.6PMV); III. monsoon cPMV=PMV/(1+0.2PMV); autumn cPMV=/(1-0.4PMV)	ISO, 2005; Fanger, 1970, 1970)	
Adaptive comfort model	According to (BS EN 16798-1:2019): optimal operative temperature θ_c [°C] for running mean outdoor temperature of $10 < \theta_{rm} < 30$: $\theta_c = 0.33\theta_{rm} + 18.8$ where θ_{rm} is calculated as: $\theta_{rm} = (1-\alpha).\{\theta_{ed-1} + \alpha\theta_{ed-2} + \alpha^2\theta_{ed-3}\}$ in which θ_{ed-i} is the daily mean outdoor air temperature for the i-th previous day, and α is a constant between 0 and 1 (recommended 0.8) allowable operative mean temperatures for the three occupant classes according to (BS EN 16798-1:2019): • category I upper limit: $\theta_o = 0.33\theta_{rm} + 18.8 + 2$ lower limit: $\theta_o = 0.33\theta_{rm} + 18.8 - 3$ • category II upper limit: $\theta_o = 0.33\theta_{rm} + 18.8 + 3$	Adaptive comfort model applicable to naturally ventilated buildings defines the optimal operative temperature based on the [running mean] outdoor temperature with a general formula of $\theta_c = a\theta_{rm} + b$ where a and b can be adapted based on different climatic conditions, cultural backgrounds and contextual factors. See also report Section 2.	(EN 16798-1:2019) (Carlucci et al., 2018b)	1st

	lower limit: $\theta_o = 0.33\theta_{rm} + 18.8 - 4$ • category III upper limit: $\theta_o = 0.33\theta_{rm} + 18.8 + 4$ lower limit: $\theta_o = 0.33\theta_{rm} + 18.8 - 5$			
Adaptive model discomfort	No./% of hours in assumed upper/lower comfort boundary (on the base of classes I, II, III).	Time aggregated approaches to describe Oh distributions in adaptive comfort classes defined in the (BS EN 16798-1:2019) standard. See also Section 2 of this Report.	(EN 16798-1:2019)	
Bioclimatic Charts	Bioclimatic charts and comfort boundaries	Distribution of Oh on psychometric bioclimatic charts to analyse thermal comfort and verify potential passive strategies to increase comfort boundaries. See also Section 2	(Givoni, 1969; Olgyay et al., 2015; Watson and Labs, 1983)	1st
Accumulated PPD	$Sum_{PPD} = \sum_{i=1}^{Oh} PPD_i \in [0, +\infty[$ Oh = occupied hours	This is in line with Method E of (BS EN ISO 7730:2005) Appendix H to define the global thermal comfort over long periods. This index can only be applied to Fanger comfort model.	(Carlucci and Pagliano, 2012; Kolokotroni and Heiselberg, 2015) (BS EN ISO 7730:2005)	2nd
PPD-weighted criterion	$PPD_w C = \sum_{i=1}^{Oh} wf_i \cdot h_i \in [0, +\infty[$ Calculation is seasonally based: $\begin{cases} PPD_w C_{summer} = f(PPD) \Leftrightarrow PMV > PMV_{upper} \\ PPD_w C_{winter} = f(PPD) \Leftrightarrow PMV < PMV_{low} \end{cases}$	This indicator is used **only** for mechanically heated/cooled buildings. This is in line with Method C of (BS EN ISO 7730:2005) Appendix H to define the global thermal comfort over long periods.	(Carlucci and Pagliano, 2012; Kolokotroni and Heiselberg, 2015) (BS EN ISO 7730:2005)	

Average PPD		This is in line with Method D of (BS EN ISO 7730:2005) Appendix H to define the global thermal comfort over long periods. This index can only be applied to Fanger comfort model.	(Carlucci and Pagliano, 2012) (BS EN ISO 7730:2005)	2nd
Exceeding PMV		Number of hours or percentage of hours in the chosen interval in which the PMV (or the operative temperature) is not in the defined comfort interval. This is in line with Method A of (BS EN ISO 7730:2005) Appendix H to define the global thermal comfort over long periods.	(EN ISO 7730:2005)	
wf	Weighing index Summer : $\sum wf \cdot t \quad if \quad \vartheta_o > \vartheta_{o,\text{limit}}$ [No. Hours] Winter: $\sum wf \cdot t \quad if \quad \vartheta_o < \vartheta_{o,\text{limit}}$ [No. Hours] Where *t* is the time (hour), *wf* is the weighting coefficient, ϑ_o is the operative temperature and $\vartheta_{o,\text{limit}}$ is the operative temperature limit (upper or lower) according to the chosen thermal comfort class. E.g., for Fanger see Appendix A of EN ISO 7730. The *wf* coefficient is defined as follows: $$wf = \begin{cases} 1 \Leftarrow \vartheta_o = \vartheta_{o,limit} \\ 1 + \frac{\lvert\vartheta_o - \vartheta_{o,limit}\rvert}{\lvert\vartheta_{o,opt.} - \vartheta_{o,limit}\rvert} \Leftarrow \lvert\vartheta_o\rvert > \lvert\vartheta_{o,limit}\rvert \end{cases}$$	Weighing index (occupation hours only). The time in which the operative temperature is in the given domain is weighted by adopting a coefficient that is function of how much this domain was overpassed. This is in line with Method B of (BS EN ISO 7730:2005) Appendix H to define the global thermal comfort over long periods. The same approach may be used for adaptive thermal comfort approaches by assuming the related thermal comfort classes and operative temperature limits.	(EN ISO 7730:2005)	2nd

DhC	Degree-hours criterion $$DhC = \sum_{i=1}^{Oh}(wf_i . h_i) \in [0, +\infty[$$ $$DhC_{warm\ period} = f(wf_i): \begin{cases} wf_i > 0 \Leftarrow \theta_{op,i} > \theta_{op,upper\ limit} \\ wf_i = 0 \Leftarrow \theta_{op,i} \leq \theta_{op,upper\ limit} \end{cases}$$ $$DhC_{cold\ period} = f(wf_i): \begin{cases} wf_i > 0 \Leftarrow \theta_{op,i} < \theta_{op,lower\ limit} \\ wf_i = 0 \Leftarrow \theta_{op,i} \geq \theta_{op,lower\ limit} \end{cases}$$	The time during which the actual operative temperature exceeds the specified range during the occupied time is weighted by a factor which is a function depending on by how many degrees the range has been exceeded.	(EN 15251:2007) (Carlucci and Pagliano, 2012b)	
Exceedance$_M$	$$Exceedance_M = \sum_{i=0}^{all\ hours} \begin{matrix} n_i & if\ discomfort_M > 20\% \\ 0 & if\ discomfort_M \leq 20\% \end{matrix} \bigg/ \sum_{i=0}^{all\ hours} n_i$$ where n_i is the number of occupants present for a given hour, and $discomfort_M$ is the estimated percentage of people dissatisfied according to comfort model *M*.	Represents the percentage of occupied hours with conditions over the 20% dissatisfied threshold on warm side, weighted by the time varying occupancy. It can be calculated based on PMV/PPD and adaptive comfort models and its unit is percentage of occupant-hour. The formula can be eventually changed by considering specific comfort categories (Masterton and Richardson, 1979a) (Kolokotroni and Heiselberg, 2015)	(Borgeson and Brager, 2011)	2nd
LPD	long-term percentage of dissatisfied $$LPD = \frac{\sum_{t=1}^{T}\sum_{z=1}^{Z}(p_{z,t} . LD_{z,t} . h_t)}{\sum_{t=1}^{T}\sum_{z=1}^{Z}(p_{z,t} . h_t)}$$ where T is the calculation period, Z is the total building zones, $p_{z,t}$ is the zone occupancy rate at certain time step, h_t is the duration of the calculation time step, and	Carlucci's LDP (Carlucci, 2013) is a symmetric index for assessing overheating and overcooling in buildings normalised over the number of occupants, over all zones, and over all calculation periods.	(Péan et al., 2017)	

	$LD_{z,t}$ is te likelihood of dissatisfied inside zone z at time step t depending in the chosen comfort model			
POR	percentage outside range $$POR = \frac{\sum_{i=1}^{Oh} wf_i \cdot h_i}{\sum_{i=1}^{Oh} h_i} \in [0,1]$$ Oh = No. hours or % of hours May be applied to Fanger or adaptive comfort models*.	percentage of hours of occupancy when the PMV or indoor operative temperature are outside the comfort range specified in the chosen comfort category	(EN, 2019, 2007; EN ISO, 2005) (Carlucci and Pagliano, 2012b)	1st
Top	Operative temperature	See Section 2 of the Report		1st
WBGT	Wet Bulb Globe Temperature without solar load: $$WBGT = 0.7t_{nw} + 0.3t_g$$ with solar load: $$WBGT = 0.7t_{nw} + 0.2t_g + 0.1t_a$$ where t_{nw} is the natural wet bulb temperature, t_g is the globe temperature and t_a is the air temperature	WBGT is an environmental index which assesses the heat stress in hot conditions along with metabolic rate	(EN ISO 7243:2017)	
WBDT	wet-bulb dry temperature $$WBDT = 0.4T_{nw} + 0.6T_a$$ where T_{nw} is natural wet-bulb temperature and T_a is the dry-bulb temperature		(Wallace et al., 2005; Zare et al., 2019)	
TSI	tropical summer index $$TSI = 0.308T_{nw} + 0.745T_g - 2.06\sqrt{V + 0.841}$$ where T_{nw} is natural wet-bulb temperature and T_g is radiation temperature and V is the air velocity	TSI is the air temperature of still air with an RH of 50% generating the same thermal sensation as the considered environment	(Zare et al., 2019) (Sharma and Ali, 1986b)	

Humidex	Humidex $$Humidex = \vartheta_a + 5/9 \times (e - 10)$$ with ϑ_a as the air temperature in Celsius and e as the water vapour pressure in hPA • Humidex <25 state of comfort • Humidex >35 starts discomfort • Humidex >45 unbearable restlessness • Humidex >54 danger zone for human body Other expressions are available (e.g., under Canadian Government, Atmospheric Environment Service): $$Humidex = \vartheta_a + 0.5555\left(6.11e^{5417.7530\left(\frac{1}{273.16}-\frac{1}{\vartheta_{dew.point[K]}}\right)} - 10\right)$$ Different scale may be defined. For example, the same source suggests: • Humidex< 29: No discomfort • 30 < Humidex < 39: Some discomfort • 40 < Humidex < 45: Great discomfort; avoid exertion • Humidex > 46: Dangerous; possible heat stroke Humidex may also be defined according to RH% (e.g., under Canadian Government, Atmospheric Environment Service):	aims at measuring the level of discomfort associated with conditions of high humidity and temperature based on the dew point.	(Teodoreanu, 2016) (Masterton and Richardson, 1979b)	

	$$Humidex = \vartheta_a + \frac{5}{9}\left(6.112 \cdot 10^{7.5\frac{T}{237.16+T}} \cdot \frac{RH\%}{100} - 10\right)$$			
*ITS	Index of Thermal Stress $$ITS = E\frac{1}{f}$$ Where E is the cooling rate [W] produce by sweat required for thermal equilibrium – see below – and f is the cooling efficiency of sweating. $$E = (M - W) \pm R_n \pm C$$ Where M is the body metabolic rate, W is the mechanical work, R_n and C are environmental exchanges for radiation and convection redefined for body surface area. This index may be adopted to evaluate both indoor and outdoor conditions, with a change in ITS comfort limits for output classification. For example, for indoor ITS classes may be defined as: 0 → about 160 W 1 → about 280 W 2 → about 400 W	ITS is the most complete outdoor thermal comfort indices for the evaluation of environmental heat stress (Vogt et al., 1981). It expresses the overall thermal exchange between the human body and its surroundings. It is mainly conceived to work under warm conditions, including evaporation aspects. This index was early developed by Givoni.	(Erell et al., 2015; Givoni, 1963; Pearlmutter et al., 2007)	
*DI	Thom's discomfort index $$DI(°F) = 0.4(T_{dry} + T_{wet}) + 15$$ or	indicator for assessing outdoor thermal comfort based on dry bulb and wet bulb temperatures	(Stathopoulou et al., 2005)	

	$DI(°C) = T_a - 0.55(1 - 0.01RH).(T_a - 14.5)$ Thom's DI classification: - DI<21° no discomfort - 21°≤DI<24° under 50% population feels discomfort - 24°≤DI<27° over 50% population feels discomfort - 27°≤DI<29° most of population suffers discomfort - 29°≤DI<32° everyone feels severe stress - 32°≤DI state of medical emergency			
*MOCI	Mediterranean Outdoor Comfort Index $MOCI = -4.068 - 0.272.WS + 0.005.RH + 0.083.T_{MR} + 0.058.T_A + 0.264.I_{CL}$ where I_{CL} is clothing insulation, T_{MR} is mean radiant temperature, T_A is the air temperature, RH is the relative humidity, and WS is the wind speed	MOCI (as the PMV) predicts the Mediterranean people's mean vote values judging the thermal qualities of an outdoor environment, and is defined based on the ASHRAE's seven-point scale.	(Salata et al., 2016)	
*UTCI	Universal Thermal Climate Index $UTCI = f(Ta, Tmrt, va, vp) = Ta + Ofsset(Ta, Tmrt, va, vp)$	Used to measure outdoor heat stress based on air temperature (Ta), mean radiant temperature (Tmrt), wind speed (va) and humidity expressed as water vapour pressure (vp).	(Zare et al., 2019) (COST Action 730) (Fiala et al., 2012)	
*WCI	wind chill index $WCI = (10.45 + 10 \times V^{1/2} - V) \times (33 - T_a)$ where WCI [kcal/m^{2}hr] is the wind chill index, V is the wind velocity [m/s], 33 [°C] is the thermo-neutral exposed skin surface temperature, and T_a is the air temperature.	WCI expresses the cooling power of subfreezing atmosphere in absence of shade and evaporation.	(Shitzer, 2006)	

*WCET	wind chill equivalent temperature method 1 by Siple and Passel: $$WCET = 33 + (T - 33) \times (0.474 + 0.454 \times \sqrt{W} - 0.454 \times W)$$ where T is the air temperature [°C] at 1.5 meters, W is wind speed [m/s] at 10 m method 2 by Steadman: $$WCET = 1.41 - 1.162 \times W + 0.98 \times T + 0.0124 \times W^2 + 0.0185 \times W \times T$$ method 3 by Joint Action Group on Temperature Indices: $$WCET = 13.12 + 0.6215 \times T - (11.37 - 0.3965 \times T) \times (W \times 3.6)^{0.16}$$	WCET is the equivalent colder air temperature without wind when the same skin heat loss happens as in the actual windy condition.	(Groen, 2009)	

*Outdoor comfort indices are not directly considered in basic E-DYCE functionalities, but they may be included in advanced services. For simplicity, only few indices are here reported to evaluate outdoor thermal comfort, nevertheless a deep review on this topic was reported in (Coccolo et al., 2016).

Table 17: KPIs input (S=simulation/M=monitoring)

Inputs → **KPIs ↓**	calculated KPI	measured KPI	$\vartheta_{e,wetbulb}$	$\vartheta_{e,\ drybulb}$	$\vartheta_{air,i}$	$\vartheta_{surf,i}$	MRT_i	MRT_e	water vapour pressure	$RH\%_e$	$RH\%_i$	P_{atm}	$Vel_{air,e}$	$Vel_{air,i}$	$Dir._{wind}$	clo	met	PMV	$\vartheta_{op,i}$	no. occupants	occupancy time
	yes	yes[1]	s/m/c	s/m	s/m	s/m	s/m*	s/m*	s/c	s/m	s/m	s/m	s/m	s/m	s/m	s**	s**	c	s/c	s/m	s/m

PPD	yes	yes																x			
PMV	yes	yes			x		x				x			x		x	x				
Adaptive model discomfort	yes	yes		x_{rm}															x		x
Adative comfort model				x_{rm}															x		
Accumulated PPD	yes	yes																x			x
PPD-weighted criterion	yes	yes																x			x
Average PPD	yes	yes																x			x
Exceeding PMV	yes	yes																x	x		x
wf	yes	yes																	x		x
DhC	yes	yes																	x		x
$Exceedance_M$	yes	yes																x	x	x	x
LPD	yes	yes																x	x	x	x
POR	yes	yes																x	x		x
Top	yes	yes																	x		
ITS***	yes	yes		x	(x)	x	(x)	x	x	x	(x)		x	(x)		x	x				
DI	yes	yes	x	x						x											
MOCI	yes	yes		x				x		x			x			x					
UTCI	yes	yes		x				x	x				x								
WBDT	yes	yes	x	x																	
TSI	yes	yes	x					x					x								
Humidex	yes	yes		x					x												

WCI	yes	yes		x									x								
WCET	yes	yes		x									x								

*requires specific sensors (e.g., globothermometers, …) no generally available for end users. May be eventually assumed equal to the air temperature in spaces characterized by almost homogeneous surface temperatures.
**may be defined in operational using typical values or defining a user interface for manual inputs. On-site survey may also be adopted for focussed analyses.

[1]with certain limitations.

***ITS requires the development of the short and long wave radiation balance both incident and emitted (long wave) from the body, the emissivity of the body and the body's surface temperature.

4.4.2 Indoor Air Quality

Table 18: KPIs definition and calculation

KPIs	Expression/Method	Short description	Ref.	importance
AQI	[Outdoor] Air Quality Index For each pollutant: $$I_p = (C_p - BP_{LO}) \times \frac{I_{Hi} - I_{Lo}}{BP_{Hi} - BP_{Lo}} + I_{Lo}$$ For CO the following breakpoint values have been considered: - AQI 0-50 Good 0.0-4.4 ppm - AQI 51-100 Moderate 4.5-9.4 ppm - AQI 101-150 Unhealthy for sensitive people 9.5-12.4 ppm - AQI 151-200 Unhealthy 12.5-15.4 ppm	Air Quality Index (AQI) was developed in 2006 for outdoor spaces by the US EPA. It is a numerical scale with colour codes and allows to make measurements of different pollutants directly understandable and readably by end-users without a specific technical background by adopting intuitive categories (good, moderate, unhealthy, and hazardous). This index may be applied to a large series of different outdoor pollutants (e.g., VOC, CO, O_3, NO_2, SO_2, $PM_{2.5}$, PM_{10}, Cl_2, NH_x, H_2, etc.) requiring to adapt for	(Mintz, 2006; Saad et al., 2017)	

	- AQI 201-300 Very unhealthy 15.5-30.4 ppm - AQI 301-500 Hazardous 30.5-50.4 For all pollutants 6 classes were defined and connected with a correlated colour scale: Good – Green; Moderate – Yellow; Unhealthy for sensitive groups – Orange; Unhealthy – Red; Very unhealthy – Purple; Hazardous – Maroon. Colours are also referred with specific RGB and CMYK definitions. Additionally, different pollutant-specific sub-indices (thresholds) are suggested for different time-granularity according to specific pollutant (e.g., 1-hour; 8-hour for Ozone, or 24-hour for PM10)	each pollutant the classification scale based on the thresholds suggested by reference standards.		
IAQI	Indoor Air Quality Index For CO_2 the following classification has been applied, even if different thresholds may be assumed in line with reference standards: - IAQI 100-76 Good 340-600[a,b] ppm - IAQI 75-51 Moderate 601-1000[a,c] ppm - IAQI 50-26 Unhealthy 1001-1500[a] ppm - IAQI 25-0 Hazardous 1501-5000[g,h] ppm The numerical scale is further translated to a colour scale defining potential risks (e.g., good, moderate, unhealthy, hazardous). The use of colours allows to communicate with not-technical end-users.	Based on the AQI by US EPA, IAQI is defined as a numerical classification scale [0-100] for indoor air quality, where 0 is the worst and 100 the perfect condition. This index similar to AQI can be used with different pollutants e.g., CO, O_3, PM_{10}, NO_2, H_2, CO, CO_2, VOC and also temperature and humidity.	(Chiesa et al., 2019b; Saad et al., 2017)	1st

$\%HCO_2$-risk	No. of hours/percentage of hours outside CO_2 limits $\%CO_{2\,risk,lim.} = \frac{\sum_{i=1}^{Oh} m_i}{\sum Oh} \begin{cases} m_i = 1 \Leftarrow av_i\ CO_2[ppm] > limit \\ m_i = 0 \Leftarrow av_i CO_2[ppm] < limit \end{cases}$ Where *i* is the calculation timestep (e.g., 1 hour), *Oh* is the number of occupied hours, limit is the assumed threshold for CO_2 concentration that varies according to standards and local recommendations. It may be assumed to 800 ppm or to 1000ppm.	Additional thresholds may be assumed subdividing the index in classes (e.g., assuming a m_i value in range [0-1], or defining different percentages on the base of classes of limits).		
%HCO2-Hrisk	No./percentage of hours outside maximum healthy CO2 concentration limits. Sub-hourly time granularity is suggested. CO2 concentration higher than 2000 ppm.			
	percentage of days at or above a given CO2 level	the amount of time during the occupied period that the CO2 level exceeds the predefined levels.	(Daniels, 2016)	
	Hours with bad air quality (%)	percentage of occupied hours with CO_2 concentration above a certain limit, e.g. higher than IDA2 in the standards.	(Bres, 2018)	
$I_t^{CO2(av)}$	index of air quality based on CO2 $I_t^{CO2(av)} = \frac{\sum_{i=1}^{N} I_{t,i}^{CO2}}{N}$ $I_{t,i}^{CO2} = \begin{cases} 1 \quad if \quad (CO2^{real})_{i,t} \leq CO2^{threshold} \\ otherwise \qquad \frac{(CO2^{real})_{i,t}}{CO2^{threshold}} \end{cases}$	Average value of CO2 level indexes in the monitored ventilated space at the time t. N is the number of measurement points and $I_{t,i}^{CO2}$ is the index of CO2 for sensor I at time t.	(Antonucci and Pasut, 2019)	

		$(CO2^{real})_{i,t}$ is the CO2 level in zone I at time t, and $CO2^{threshold}$ is the CO2 limit varying according to national standards.		
$LT\_KPI^{i}_{CO2}$	long term CO2 evaluation vector $$LT\_KPI^{i}_{co2} = \begin{pmatrix} T^{i}_{I}/T^{i}_{occ} \\ T^{i}_{II}/T^{i}_{occ} \\ T^{i}_{III}/T^{i}_{occ} \\ T^{i}_{IV}/T^{i}_{occ} \end{pmatrix} * 100\%$$	The long term IAQ evaluation of CO2 concentrations KPI for a monitored space I for a time-period T, is performed by evaluating the specific percentage of time the space was in each of the four categories during occupied time.	(Biosca et al., 2016)	
A_S	Air change rate $$A_S = \frac{6x10^4 nC_p}{\{V(C_S - C_R)\}}$$	The air change rate is calculated using the average CO2 generation rates per person C_p (generally 0.46 $l.min^{-1}.person^{-1}$), number of occupants n, volume of the space V, the steady state indoor CO2 concentration C_S and the steady state outdoor CO2 concentration C_R.	(Zuhaib, 2020b)	
S	Stale air indicator $$S = \frac{\sum_{t=1}^{n} o_t\,(c(t) - c_{max})\,\mathbb{1}_{c(t) > c_{max}}}{\sum_{t=1}^{n} o_t}$$ o_t indicates occupancy (1) o not (0). $\mathbb{1}_{c(t) > c_{max}}$ is the characteristic function equal to 1 when $c(t) > c_{max}$ and 0 otherwise. For c_{max} one uses the higher limit of category IDA2 in the standards.	Ratio between the occupied hours with CO2 concentrations above a certain value, and total occupied hours.	(Bres, 2018)	

According to the standards (BS EN 16798-1:2019) and (PD CEN/TR 16798-2:2019), the ventilation requirement for indoor air quality are defined for residential and non-residential buildings, for four different categories, under three different methods:

a) based on perceived air quality: in this method the ventilation rates are defined so as to remove/dilute pollutants from adapted and non-adapted occupants and the pollutants from the very-low-, low- and non-low-polluting buildings;

$$q_{tot} = n \times q_p + A_R \times q_B$$

b) using limit values of gas concentration: in this method the limit CO2 concentration above outdoor are given for the four categories of non-adapted persons; corresponding CO2 concentration above outdoors in ppm for non-adapted persons are:
   - IDA I 550 ppm CO2
   - IDA II 800 ppm CO2
   - IDA III 1350 ppm CO2
   - IDA IV 1350 ppm CO2

$$Q_h = \frac{G_h}{C_{h,i} - C_{h,o}} \times \frac{1}{\varepsilon_v}$$

c) based on pre-defined ventilation flow rates: in this method ventilation flow rates are given both per person and per square meter, and the higher value must be used for design.

WHO has a guideline for some common pollutants (benzene, carbon monoxide, formaldehyde, naphthalene, nitrogen dioxide, polycyclic aromatic hydrocarbons, radon, trichloroethylene, and tetrachloroethylene) that often have worrying concentrations in indoor spaces (World Health Organization, 2010).

Note: In inspecting ventilation effectiveness in a building, indicators such as contaminant removal effectiveness, contaminant removal efficiency, ventilation effectiveness, local air quality index, air change efficiency and local air change index are used, too (Mundt, 2004). These indicators are, however, assessed using various tracer gas techniques. Therefore, despite the fact that they are suitable indicators for assessing the operation of a ventilation system, they cannot be continuously monitored as in this project. They can be assessed for in-situ short-term monitoring.

Table 19: KPIs input (S=simulation/M=monitoring)

Inputs → KPIs ↓	simulated KPI	monitored KPI	$T_{drybulb}$	RH%		$CO_{2,i}$	$CO_{2,e}$	area/volume	time	No. occupants		SO_x	PM_x	VOC	NO_x
			s/m	s/m		s/m	s/m	s/m	s/m	s/m		s/m	s/m	s/m	s/m
AQI	Yes	Yes		x			x		x			x	x	x	x

IAQI	Yes	Yes	x	x		x		x	x			x	x	x	x
$\%HCO_2$-Hrisk	yes	yes				x		x							
% of days at or above a given CO2 level	yes	yes				x			x						
hours with bad air quality	yes	yes				x		x	x						
$I_t^{CO2(av)}$	yes	yes				x		x	x						
$LT\_KPI^i_{co2}$	yes	yes				x		x	x						
A_S	yes	yes				x	x	x	x	x					
S	yes	yes				x		x	x						

4.4.3 Lighting requirements

Table 20: KPIs definition and calculation

KPIs	Expression/Method	Short description	Ref.	importance
LENI	Lighting Energy Numeric Indicator LENI = W/A [kWh/m^{2}y] Where A is the net floor area (it is also possible to calculate LENI factor using the space total volume [kWh/m^{3}y], and W is the energy need for artificial lighting defined as follows: $W = W_L + W_P$ [kWh/year] (BS EN 15193:2007) Where W_L is the energy need for guarantee the designed illuminance requirements (BS EN 12464-1:2011) and W_P is the energy need for emergency lighting systems and lighting control systems.	LENI is part of the EP_{gl} calculation (Energy global performance index) and represents the energy voice correlated to artificial lighting uses in the EPC balance.	(EN 15193-1:2017) (PD CEN/TR 15193-2:2017)	1st

	LENI can be calculated for existing and new buildings using difference methods: - Real electrical consumption data; - Quick method (annual calculation) using standard values; - Comprehensive method (annual calc. or shorter periods) based on analytical calculation of all parameters In the new standards LENI is defined using the following equation: $$LENI = \{F_C \times (P_j/1000) \times F_O[(t_D \times F_D) + t_N]\} + 1 + 1.5$$ annual energy required for electric lighting within the building: $$W = LENI \ \times A$$	Lighting Energy Numeric Indicator (LENI) is also known as normalized annual energy demand for lighting W_L [kWh/m^{2}year]		
DA	Daylight Autonomy $$DA = \frac{\sum_i (wf_i\ t_i)}{\sum_i t_i} \in [0, 1] \quad with \quad wf_i \begin{cases} 1 \ if \ E_{daylight} \geq E_{limit} \\ 0 \ if \ E_{daylight} < E_{limit} \end{cases}$$	**DA** represents the percentage of annual hours that a given point in a space receives daylight above a specified illumination level. For instance DA300 represents the percentage of the floor area that receives more than 300 lux for at least 50% of the yearly occupancy time.	(Reinhart et al., 2006) (Dutra de Vasconcellos, 2017)	

sDA	Spatial daylight autonomy (sDA300/50%) $sDA = \frac{\sum_i (wf_i\ t_i)}{\sum_i t_i} \in [0,1]\ \ with\ \ wf_i \begin{cases} 1\ if\ \ E_{daylight} \geq E_{limit} \\ 0\ if\ \ E_{daylight} < E_{limit} \end{cases}$ This indicator may be calculated by assuming the simulations approach defined in the LM-83's methodology. A potential classification of results may be: sDA < 55%: failed 55% ≤ sDA ≤ 74%: "nominally accepted" by occupants sDA ≥ 75%: is welcome	sDA, also known as minimum daylight autonomy mDA, measures the sufficiency of daylight illuminance for a given floor area at a specified illuminance level for a specified amount of annual hours. For instance, sDA300/50% requires that at least 55% of the space receives at least 300 lux of daylight for at least 50% of the operating hours each year.	(Zuhaib, 2020b) Illuminating Engineering Society (IES) 2013 Lighting Measurement 83 (LM-83)	2nd
ASE	Annual sunlight exposure (ASE1000, 250) ≥10% area unsatisfactory visual comfort, 7% neutral visual comfort 3% clearly acceptable visual comfort	ASE measures the percentage of floor area that exceeds a specified direct sunlight illuminance level	Illuminating Engineering Society (IES) 2013 *Lighting Measurement 83 (LM-83)*	2nd

		for a specified number of hours, with any blinds or shades left in the fully retracted position. This can cause visual discomfort (glare) or increase cooling loads. For example, ASE1000/250 requires that no more than 10% of the area receive more than 1000 lux for 250 hours each year.	(Dutra de Vasconcellos, 2017)	
UDI	Useful daylight illuminance $UDI = \frac{\sum_i (wf_i\, t_i)}{\sum_i t_i} \in [0,1]\ with$ $\begin{cases} UDI_{overlit}\ with\ wf_i \begin{cases} 1\ if\ E_{daylight} > E_{upper\ limit} \\ 0\ \ if\ E_{daylight} \leq E_{upper\ limit} \end{cases} \\ UDI_{useful}\ with\ wf_i \begin{cases} 1\ if\ E_{lower\ limit} \leq E_{daylight} \leq E_{upper\ limit} \\ 0\ \ if\ E_{daylight} < E_{lower\ limit} \vee E_{daylight} > E_{upper\ limit} \end{cases} \\ UDI_{underlit}\ with\ wf_i \begin{cases} 1\ if\ E_{daylight} < E_{lower\ limit} \\ 0\ \ if\ E_{daylight} \geq E_{lower\ limit} \end{cases} \end{cases}$	UDI calculates the percentage of annual hours that a given point falls in the specific range of illuminance. This range was defined to encompass “useful illuminances for occupants” from a	(Dutra de Vasconcellos, 2017) (Nabil and Mardaljevic, 2006) (Mardaljevic et al., 2009)	2nd

	UDI thresholds by (Nabil and Mardaljevic, 2006): - UDI fell short of useful range [0-100 lux] - UDI is within the range defined as useful [100-2000 lux] - UDI exceeds the useful range [>2000 lux] UDI thresholds by (Mardaljevic et al., 2009): - UDI fell short [0-100 lux] insufficient illumination - UDI supplementary [100–500 lux] integrate with electric light - UDI autonomous [500–2,500 lux] no electric light required - UDI exceeded [>2,500 lux] bad situation: glare, overheating, etc.	comprehensive review of occupant's behaviour with artificial lighting, dimming and blinds.		
DSP	Daylight Saturation Percentage $DSP = \frac{\sum_i (wf_i\, t_i)}{\sum_i t_i} \in [0,1]\ with$ $\begin{cases} DSP_{overlit}\ with\ wf_i \begin{cases} 1\ if\ E_{daylight} > E_{upper\ limit} \\ 0\ \ if\ E_{daylight} \le E_{upper\ limit} \end{cases} \\ DSP_{useful}\ with\ wf_i \begin{cases} 1\ if\ E_{lower\ limit} \le E_{daylight} \le E_{upper\ limit} \\ 0\ \ if\ E_{daylight} < E_{lower\ limit}\ \vee\ E_{daylight} > E_{upper\ limit} \end{cases} \\ DSP_{underlit}\ with\ wf_i \begin{cases} 1\ if\ E_{daylight} < E_{lower\ limit} \\ 0\ \ if\ E_{daylight} \ge E_{lower\ limit} \end{cases} \end{cases}$	DSP is a modification of UDI with increased lower and upper limits of 430 lux and 4300 lux respectively. It also penalizes the grid points receiving more than 4300 lux by subtracting the annual hour values within the range of 430-4300 lux.	("Daylight Saturation Percentage | Daylighting Pattern Guide," n.d.)	
DAcon or cDA	Continuous Daylight Autonomy $DAcon = \frac{\sum_i (wf_i\, t_i)}{\sum_i t_i} \in [0,1]\quad with\quad wf_i \begin{cases} 1\ if\ E_{daylight} \ge E_{limit} \\ \frac{E_{daylight}}{E_{limit}}\ if\ E_{daylight} < E_{limit} \end{cases}$	Compared to DA, DAcon awards partial credit to the time steps when	(Reinhart et al., 2006) (Dutra de Vasconcellos, 2017)	

		the daylight illuminance is lower than the defined threshold. For example, if DA500 gives 0 credit to an interior grid point receiving 400 lux of daylight at a given time step, DAcon500 will give that point 400/500=0.8 credit. DAcon in fact acknowledges that "even a partial contribution of daylight to illuminate a space is beneficial."		
	Annual Light Exposure recommended illuminance limit and total exposure limits in terms of illuminance hours per year: type of material — max illuminance — exposure time highly sensitive to light — 50 lux — 50000 lux.hr/year low sensitivity to light — 200 lux — 100000 lux.hr/year	**Annual Light Exposure** which is measured in lux hours per year defines the amount of annual visible light incident on a point. This indicator is majorly used for	(Reinhart et al., 2006) (Al-Sallal et al., 2018)	

	no sensitivity to light 1000 lux 300000 lux.hr/year $$T_M = E/L$$ Where, E = Estimated cumulative lux hours to a just noticeable fade (based on Michalski's ISO 1–8 recommendations. See table 1 for values).L = Measured incident lux (in a given lighting scenario).TM = Total hours (before a JNF occurs).	designing spaces where light-sensitive artworks are displayed.		
FVC	Frequency of visual comfort $$FVC = \frac{\sum_i (wf_i . t_i)}{\sum_i t_i} \in [0, 1]$$ with $wf_i = \begin{cases} 1 \; if \; E_{Under} \le E_{Daylight} \le E_{Over} \\ 0 \; if \; E_{Daylight} < E_{Under} \vee E_{Daylight} > E_{Over} \end{cases}$ E_{under} assumed as 150 lux E_{Over} assumed as 750 lux According to (Sicurella et al., 2012) depending on the design requirements, the actual use of the building and the visual task, the threshold values may vary.	VFC is defined as the percentage of the time during which daylight's average illuminance level stays in the range between two threshold values so as to guarantee the visual. The difference between UDI and FVC is that the UDI deals with spatial distribution of illuminance values, but FVC deals with the spatial-average values.	(Carlucci et al., 2015) (Sicurella et al., 2012)	
IVD	intensity of visual discomfort $$IVD = \int_P \Delta E(t)dt \; with$$	IVD is the time integral of the difference between	(Carlucci et al., 2015) (Sicurella et al., 2012)	

	$\begin{cases} IVD_{over}\ with\ \Delta E(t) = \begin{cases} E(t) - E_{over}\ if\ E(t) \geq E_{over} \\ 0\ if\ E(t) < E_{over} \end{cases} \\ IVD_{under}\ with\ \Delta E(t) = \begin{cases} E_{under} - E(t)\ if\ E(t) > E_{under} \\ 0\ if\ E(t) \leq E_{over} \end{cases} \end{cases}$	the spatial-average daylight illuminance and the upper and lower limits of visual comfort.		
DGI	discomfort glare index $DGI = 10\ \log_{10}\left[0.478 \sum_{i=1}^{n}\left(\frac{L_{s,i}^{1.6}\ .\ \omega_{s,i}^{0.8}}{L_b + 0.07\omega^{0.5}\ .\ L_{win}\ .\ P_i^{1.6}}\right)\right]$ DGI generally varies between 18 and 31, corresponding respectively to barely perceptible glare and intolerable glare.	DGI aims at predicting glare from large sources, such as a window, described by its luminance.	(Carlucci et al., 2015) (Zuhaib, 2020b)	
DGP	Daylight glare probability $DGP = 5.87 * 10^{-5} * E_v + 9.18 * 10^{-2} * \log\left(1 + \sum_i \frac{L_{s,i}^2 * \omega_{s,i}}{E_v^{1.87} * P_i^2}\right) + 0.16$ Recommended threshold in (Wienold, 2009): DGP > 0.45 intolerable glare 0.45 > DGP > 0.40 disturbing glare 0.40 > DGP > 0.35 perceptible glare DGP < 0.35 imperceptible glare Recommended threshold in (Van Den Wymelenberg et al., 2010): DGP > 0.25 likely to be uncomfortable 0.25 > DGP > 0.23 bounded between comfort and discomfort DGP < 0.23 likely to be comfortable	DGP is an approach that considers both the illuminance at eye level and individual glare sources of high luminance to estimate the fraction of dissatisfied persons. DGP is developed under real daylight conditions in a side-lit space.	EN 17037:2018 (Motamed et al., 2020, 2017) (Dutra de Vasconcellos, 2017)	

DGPs	simplified daylight glare probability $DGPs = 6.22 * 10^{-5} E_v + 0.184$ (Wienold, 2007) $DGPs = 587 * 10^{-5} E_v + 0.16$ (Hviid et al., 2008)	Relates likelihood of glare only to vertical eye illuminance E_v. DGPs ignores the individual glare sources, therefore it has to be used in the absence of direct sun.	(Jones, 2017)	
DF	Daylight factor $$DF = \frac{E_{P,obs}}{E_{P,unobs}}$$	ratio of the illuminance at a point on a given plane due to the light received directly and indirectly from a sky of assumed or known luminance distribution, to the illuminance on a horizontal plane due to an unobstructed hemisphere of this sky, where the contribution of direct sunlight to bot illuminances is excluded.	(Carlucci et al., 2015) EN 12665:2018 EN 17037:2018	1st

Other indicators able in defining specific aspects of the visual comfort domain may be included in the methodology in future. Nevertheless, this first definition bases on energy-correlated and overheating-connected indicators. For this reason, only glare is mentioned outside these specific categories, while chromatic restitution, contrast, dazzling are not directly described. Additionally, there are many other indicators related to specific technological elements (sub-systems), e.g. artificial lighting characteristics, glazing properties, etc., that are not considered here as they are not focussed on energy uses or on main visual comfort, and/or for reducing redundancy. Some of them, however, are listed below. Furthermore, the point-in-time metrics such as Illuminance, luminance, and other glare indexes such as CGI glare index are not included in the table either. Last but not least, (EN 17037:2018, 2019) includes rankings based on different levels of daylight provision defined as the median and minimum values of daylight on work plane, sunshine exposure as the duration of sunshine from each opening, and horizontal view angle, which are all excluded from this this project.

- Daylight Effectiveness Indicator (DEI) is a metric that reflects monthly lighting energy use density considering daylight hours (Li et al., 2020)
- Lighting Power Density (LPD) is lighting power per unit building floor area (Li et al., 2020)
- Flicker is noticeable rapid fluctuations in light level (Biosca et al., 2016)
- Contrast Rendering Factor (CRF) is a lighting effectiveness indicator that determines how well a task contrast is rendered (Biosca et al., 2016). Ideally, it is measured by comparing the contrast of the object under the actual ambient lighting with its contrast under reference lighting (completely diffuse, unpolarised illumination) (Levy, 1978).

$$CRF = \frac{C_{eff}}{C_{ref}}$$

- Glazing's light transmittance is the fraction of the incident light that is transmitted by the glass. For a single glass the following formula is applied (BS EN 410:2011):

$$\tau_v = \frac{\sum_{\lambda=380\,nm}^{780\,nm} D_\lambda\, \tau(\lambda)\, V(\lambda)\, \Delta\lambda}{\sum_{\lambda=380\,nm}^{780\,nm} D_\lambda\, V(\lambda)\, \Delta\lambda}$$

- Glazing's light reflectance is the fraction of the incident light that is reflected by the glass. For a single glass the following formula is applied (BS EN 410:2011):

$$\rho_v = \frac{\sum_{\lambda=380\,nm}^{780\,nm} D_\lambda\, \rho(\lambda)\, V(\lambda)\, \Delta\lambda}{\sum_{\lambda=380\,nm}^{780\,nm} D_\lambda\, V(\lambda)\, \Delta\lambda}$$

- Glazing's colour rendering index is the change in colour of an object as a result of the light being transmitted by the glass (BS EN 410:2011)

$$R_a = \frac{1}{8}\sum_{i=1}^{8} R_i$$

$$R_i = 100 - 4.6\,\Delta E_i$$

Table 21: KPIs input (S=simulation/M=monitoring)

Inputs → KPIs ↓	simulated KPI	monitored KPI	static	dynamic							Area/Volume		lighting illuminance E	daylight illuminance E	luminance L	time	sky conditions		
											s/m		s/m	s/m	s/m	s/m	s/m		
LENI	yes	yes	x	x							x		x	x		x			
DA	yes	yes		x										x		x			
sDA	yes	yes		x										x		x			
ASE	yes	yes		x										x		x			
UDI	yes	yes		x										x		x			
DSP	yes	yes		x										x		x			
DAcon	yes	yes		x										x		x			
annual light exposure	yes	yes		x									x	x		x			
FVC	yes	yes		x										x		x			
IVD	yes	yes		x										x		x			

DGI	yes	no (yes*)													x				
DGP	yes	no (yes*)												x	x				
DGPs	yes	no (yes*)												x					
DF	yes	no	x											x			x		

*Monitoring glare indices may be difficult, few examples are referred in literature, like the ones from EPFL-LESO using a vertical adapted camera, e.g. the adoption of a HDR vision sensor for DGP index assessment (Motamed et al., 2020, 2017).

4.5 *Smartness readiness and smartness of end-users*

Table 22: KPIs definition and calculation

KPIs	Expression/Method	Short description	importance
SRI (A) - simplified	See Section 2	Smart Readiness Indicator See Section 2	1st
SRI (B) – expert assessment	See Section 2	Smart Readiness Indicator See Section 2	
SRI (C) – in-use smart building performance	See Section 2	Smart Readiness Indicator See Section 2	1st

In addition to SRI indicators, a further set of indices will be included in further E-DYCE steps to define the user awareness of GUI and actuator/sensing interfaces.

4.6 *Correlated KPIs*

Several additional performance evaluation domains and correlated KPIs may be included in sustainable and energy/environmental building design, assessment and operational rating. In this section, some of additional correlated-KPIs' domains are shortly introduced, although the E-DYCE approach is open for further inclusions.

4.6.1 Energy demand forecast KPIs

Predicting the energy performance of a building can be done based on white-, grey- and black-box models, with varying degrees of *mechanistic* complexities.

White-box models are physics-based approaches in which detailed physical information about the building operation with a high level of accuracy is required. They entail rather computationally expensive simulations (Wei et al., 2018) and may be prone to errors associated with uncertainty and simplification of variables whose values cannot be known (such as random ventilation due to window openings) (Amara et al., 2015). White-box models are based on static, dynamic, linear, non-linear, differentiable, continuous, and non-continuous models (Amara et al., 2015). The E-DYCE used tools to support hourly simulations (EnergyPlus and Dial^{+}) are based on white-box models.

Black-box models are statistical data-driven approaches (Wei et al., 2018), in which, despite the automatic adjustment of parameters and rapid automated identification of outputs – e.g., of building's thermal energy consumption –, the lack of detailed knowledge of the physical information – the model is non-transparent – and the implicit relationship of the parameters with fundamental principles of physics are big disadvantages compared to the white-box approaches. In fact, being data-driven, black-box models can be inconsistent with physical reality where little building system data is available. Similar to white-box models, black-box models can have static or dynamic, linear or nonlinear internal structures.

Grey-box models are a hybrid of white-box and black-box models. Grey-box parameters are, fully or partly, determined based on measured data of the real system. Grey-box models can be useful where the detailed thermal mass characteristics of building are missing and where the occupants' behaviours are uncertain (Amara et al., 2015).

Different statistical error analyses may be developed to define the ability of a model in representing monitored conditions (or specific simulation conditions), using methods such as the Mean Bias Error (MBE), the Root Mean Square Error (RMSE), the expanded uncertainty U95, the T-statistical test (TT), and the coefficient of determination R^2 (when relevant). Potential aggregation of them can be done by adopting potential Global Performance Indices – see for example the following expression, which determines with values closer to zero the most performant cases.

$$GPI = MBE \times RMSE \times U95 \times TT \times (1 - R2)$$

Other statistical verification models may be adopted, see for example the approaches used in (Chiesa and Grosso, 2015b) (Behar et al., 2015) for passive-heating/cooling model verifications.

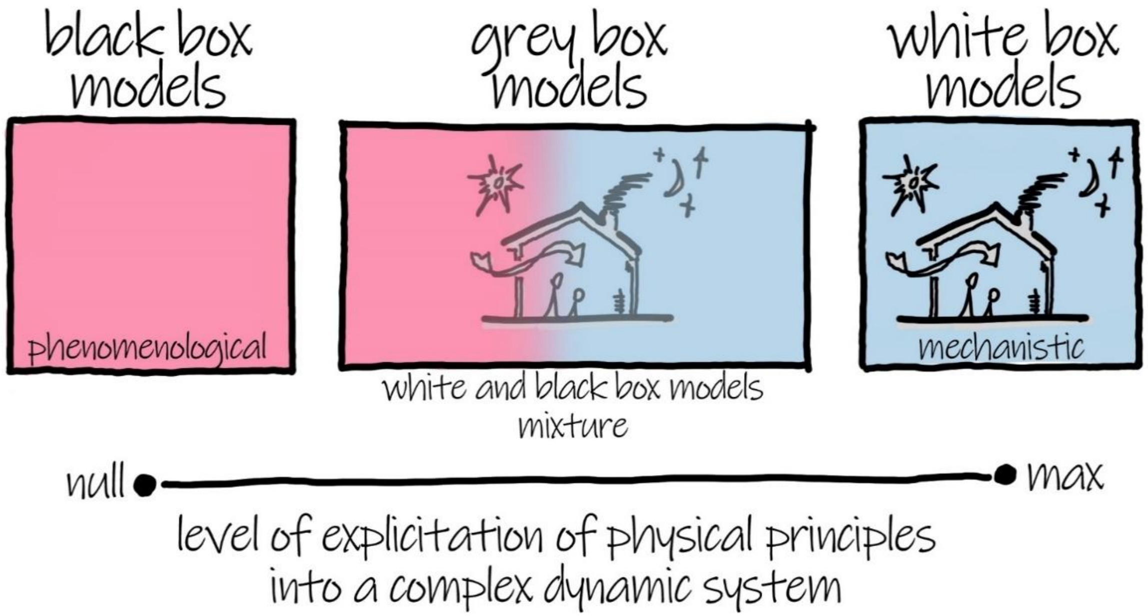

Figure 30 – Schematic representation of mechanistic insight into black, grey and white box models – Elaborated from (Kalmykov and Kalmykov, 2015).

4.6.2 economic KPIs

Several economic KPIs are connected to building energy and environmental performances, and/or are correlated to the NZEB and EPC definition. It is possible to mention the adoption of *Global Cost* indicator for which a sequential search-optimization technique was developed by (Corrado et al., 2014). This indicator may be defined by the following expression from (EN 15459:2007, 2007) which takes into account the initial investment costs, and the relevant cost items during the building's life cycle:

$$C_G(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} \left(C_{a,i}(j).R_d(i) \right) - V_{f,\tau}(j) \right]$$

Where $C_G(\tau)$ is the global cost referred to the starting year τ_0, C_I is the initial investment cost, $C_{a,i}(j)$ is the annual cost during year i of component j including the annual running costs (energy costs, operational costs, maintenance costs) and periodic replacement costs, $R_d(i)$ is the discount factor during the year i, and $V_{f,\tau}(j)$ is the residual value of the component j at the end of the calculation period referred to the starting year.

In addition to the previously mentioned calculation methodology, it is also possible to refer to the Global cost simplified version (Fregonara et al., 2017) (Chiesa and Fregonara, 2020)– see below – assuming that the initial investment costs are summed to heating, cooling, electric lighting and DHW systems' consumption costs, and excluding the residual values and disposal costs (Fregonara et al., 2017).

$$C_G = C_I + \sum_{t=0}^{N} \frac{C_o + C_m}{(1+r)^t}$$

Where C_G is the global cost, C_I is the initial investment cost, C_o is the operating and energy costs, C_m is the maintenance costs, t is the year in which the costs occurred and N is the number of years within the timespan considered for the application, and r is the discount rate.

Finally, a series of studies have introduced uncertainty in the simulation of energy needs and global cost calculations, suggesting a stochastic approach – see the adaptation of previous expression into its stochastic version – to support energy retrofitting design choices – see in particular (Fregonara et al., 2018).

$$\hat{G}_C = \hat{C}_I \sum_{t=0}^{N} \frac{\hat{C}_o + \hat{C}_m}{(1+\hat{r})^t}$$

Where $\hat{C}_G$ is the stochastic global cost, $\hat{C}_I$ is the stochastic initial investment cost, $\hat{C}_o$ is the stochastic operating and energy costs, $\hat{C}_m$ is the stochastic maintenance costs, t is the year in which the costs occurred and N is the number of years within the timespan considered for the application, and $\hat{r}$ is the stochastic discount rate.

Following the calculation of the primary energy consumption and global costs for different packages applied to the reference building, the cost curve could be developed, from which the cost-optimal scenario can be selected (Boermans et al., 2011).

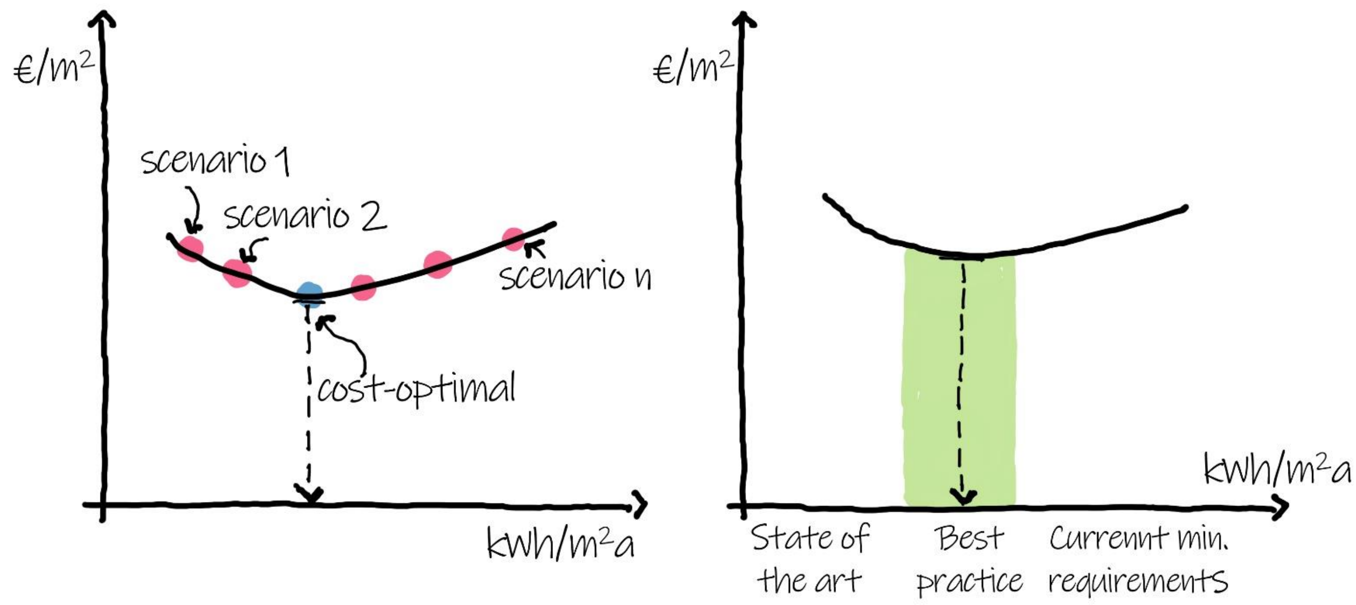

Figure 31 – The optimal cost for different packages applied to a reference building (left) and the cost-optimal range for minimum performance requirements (right) (Boermans et al., 2011).

Additional economic KPIs are connected to the Life Cycle Assessment approach applied jointly with LCC analysis. These KPIs and connected environmental LCA KPIs – e.g., the embodied energy of buildings – are considered of great importance, nevertheless they are not directly faced in the E-DYCE project, while the proposed methodology may be compatible with their inclusion in a future development step.

4.6.3 Climate-change-connected KPIs

Several indicators can assess the correlation between buildings, their surroundings and climate. Such as:

- Urban heat island degree-hours (UHIdh) and urban cool island degree-hours (UCIdh) which compare the outdoor temperature in rural and urban areas. A graphic representation of UHIdh bases on the area define by diurnal temperature between the lower urban and higher rural air temperatures, and UCIdh represents the area of diurnal temperature between the higher urban and lower rural air temperatures (Yang et al., 2017).

$$UHIdh = \int_{0}^{24} |\Delta T_{r-u}(t)| dt - \int_{t_{min(\Delta T_{r-u} \geq 0)}}^{t_{max(\Delta T_{r-u} \geq 0)}} \Delta T_{r-u}(t) dt$$

$$UCIdh = \int_{t_{min(\Delta T_{r-u} \geq 0)}}^{t_{max(\Delta T_{r-u} \geq 0)}} \Delta T_{r-u}(t) dt$$

Where $\Delta T_{r-u}(t)$ is the temperature difference between the rural and urban air temperature.

- The impact of building on the external spaces has been assessed in Italian standards UNI/PdR 13.1:2015 by evaluating the ratio between the overall surface area of the lot capable of reducing the heat island effect [S_{reif}] to the total intervention area of the lot [S_l].

$$index = \frac{S_{reif}}{S_l} \times 100$$

The surfaces to be considered in the S_{reif} are the greeneries, the surfaces that are shaded in 21st of June at noontime, and the surfaces with high solar reflection values.

- According to ISO 16745-1:2017 the GHG emissions associated with energy use of a building is calculated as follows:
$m.co_{2eqv} = \sum\left(\left(E_{del,ci} \times K_{del,ci}\right) + \left(E_{site,ci} \times K_{site,ci}\right)\right)$
where $E_{del,ci}$ is the delivered energy for energy carrier del, ci, $E_{site,ci}$ is the energy produced on-site for the energy carrier $site, ci$, $K_{del,ci}$ is the GHG emission coefficient for delivered energy carrier del, ci, and $K_{site,ci}$ is the GHG emission coefficient for on-site energy carrier $site, ci$.

- To calculate the carbon emissions based on the electricity and natural gas consumptions in a building (Mousa et al., 2016), the following formulas can be utilized:

$$C_{electricity} = \left(\sum_{i=1}^{n} E_{consumed,i}\right) \times Y_{carbon,ave}$$
$$C_{natural\ gas} = G_{consumed,i} \times 5 \times 10^{-8}$$

where $C_{electricity}$ is the total carbon emissions due to electricity use [$kgCO_2$], $E_{consumed,i}$ is the electricity consumed of type i [kW or kWh], $Y_{carbon,ave}$ is the average carbon density of electricity which depends on the location and generation time of electricity, $C_{natural\ gas}$ is the total carbon emissions due to natural gas consumption, $G_{consumed,i}$ is the amount of natural gas consumed [J], and 5×10^{-8} is the carbon density of natural gas [$kgCO_2$/J].

- carbon intensity of an asset based on final energy consumption can be calculated using following formula based on French studies (ICADE, 2020):

$$CI_{asset} = \frac{(EC_{f,asset,elec} \times EF_{elect}) + (EC_{f,asset,gas} \times EF_{gas}) + (EC_{f,asset,fuel\ oil} \times EF_{fuel\ oil}) + (EC_{f,asset,heat} \times EF_{heat}) + (EC_{f,asset,cold} \times EF_{cold})}{floor\ area}$$

where CI_{asset} is the asset's carbon intensity [$kgCO_{2e}$/NLAsq.m/year], $floor\ area$ is the asset's floor area [NLAsq.m], $EC_{f,asset}$ is the annual final energy consumption of asset [kWh/year], EF is the emission factor [$kgCO_{2e}$/kWh] for$elect$ =electricity, gas=natural gas, $fuel\ oil$=domestic fuel oil, $heat$=heating from a district network, and $cold$ is the cooling from a district network.

- Using renewable energy sources can contribute in GHG savings which can be quantified as (Pereira et al., 2020):

$$GHG_{savings} = \sum_{y=1}^{n}(GHG_{reference,y} - GHG_{project,y})$$

where $GHG_{savings}$ is the annual GHG emissions avoided due to the energy generation from renewable energy sources during the period n, $GHG_{reference,y}$ is the annual GHG emissions for the generation of the same energy using a reference technology, $GHG_{project,y}$ is the annual GHG emissions from the renewable energy production, and n is the last year of operation of the project (Pereira et al., 2020). Under a sensible simplification approach for different projects the GHG saving can be calculated as:
  - $GHG_{savings} = EG_y \times EF_{grid,y,y} - 0$ grid-connected electricity from solar/wind/ocean

- $GHG_{savings} = EG_y \times EF_f - 0$ heat generation from solar/wind/ocean
  where EG_y is the Energy Generated by the project in year y, in MWh, $EF_{grid,y}$ is the average grid emissions factor for year y, in tCO_{2e}/MWh, and EF_f is the emission factor for the supply and combustion of the reference fuel type f (i.e., "typical emissions" from REDII), in tCO_{2e}/MWh.

Except for the above-mentioned indicators for GHG emissions, there are others such as Carbon Emission Intensity* that identifies emission consumption and is measured in tons of carbon dioxide per year. It determines which facilities have good or poor emissions and uses time trend analyses to compare seasonal peaks, anomalies, or trends. Carbon Emission Intensity per Occupant* gives the normalised value of the previous indicator by the number of occupants [tons CO_2]. See the work of Customer Focus Group, EPA, Architecture 2030, EO 13423.

***see also the calculation approaches for U.S. like https://www.ibm.com/support/knowledgecenter/SSFCZ3_10.5.2/com.ibm.tri.doc/overview/c_prod_overview.html**

5 Conclusions

E-DYCE will support a natural evolution of convention EPC into real time optimisation of building performance and comfort including building hourly behaviours including clear feedbacks using simple and intuitive GUI. The mentioned E-DYCE aspects aim at increasing the reliability of the assessment process to building energy performance calculation and monitoring post-elaboration. Furthermore, the E-DYCE framework will allow and increase communication processes between involved users, from labelling professionals, to building owners and tenants providing higher indoor comfort and energy savings.

In this report, updated backgrounds, logics and methodologies of E-DYCE's considered issues are introduced and described. Furthermore, the main conceptualisation of the E-DYCE approach, including potential services, end-users, and verification KPIs, is given. Further WPs will support the implementation of mentioned issues and parts, from inputs, data modelling and project design, to simulation/optimisation enables, till extended functionalities, including demonstrations and dissemination actions.

Main abbreviations

E-DYCE	Energy flexible DYnamic building Certification	**EPC**	Energy Performance Certification
EPBD	Energy Performance of Buildings	**DEPC**	Dynamic (hourly*) Energy Performance Certification
FR	Free-Running	**KPI**	Key Performance Indicator
MS	Member State	**IEQ**	Indoor Environmental Quality
PMV	Predicted mean vote	**PPD**	Predicted percentage of dissatisfied
IAQ	Indoor Air Quality	**IoT**	Internet of Things
ICT	Information and Communication Technologies	**IB**	Intelligent building
RES	Renewable Energy Source	**SRI**	Smart Readiness Indicator
DHW	Domestic hor water	**DEC**	Display energy certificate
EPG	Energy Performance Gap	**EMCS**	Energy Management Control System
BIM	Building Information Model	**BMS**	Building Management System
nZEB	Nearly-zero energy building	**GUI**	Graphic User Interface

***NOTE: in E-DYCE DEPC is assumed as hourly EPC.**

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