Smart Built4EU

The European Smart Buildings Community

D3.1

Co-benefit indicators of Smart Buildings for business case development

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[1] PU = Public
PP = Restricted to other programme participants (including the Commission Services)
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Executive summary

In the context of Energy Performance of Buildings Directive (EPBD), the H2020 SmartBuilt4EU project aims at consolidating and supporting the Smart Building Innovation Community (SBIC), allowing the Smart Building technologies to reach their full potential and to remove those barriers that slow down the improvement of building performances.

The work package 3 of the SmartBuilt4EU project proposes an approach to increase the awareness on the co-benefits of Smart Buildings and introduces technology solution packages. This first deliverable is devoted to the definition of the main co-benefits and key performance indicators (KPIs) to be coupled with the Smart Readiness Indicator (SRI) score. A review of literature sources and other projects was carried out to collect co-benefits of smart technologies and their related KPIs. Their definition and the main associated sources are presented in this deliverable. The objective is to support the SRI assessment value and enable the definition of an effective business case for Smart Buildings.

In this task, the concept of co-benefits needs to be tailored to the project focus which is the smartness of buildings and smart-ready services. The EU delegated act on the SRI defines a set of seven categories in which a smart ready service can provide impacts to the building, its users, and the energy grid. The impact categories are: energy efficiency, maintenance and fault prediction, comfort, convenience, health well-being and accessibility, information to occupants and flexibility for the grid and storage. Therefore, the co-benefits and KPIs analysis has been divided according to these impact categories. The following table shows the 18 identified KPIs.

CATEGORY	KPI
Energy efficiency	Primary energy
	Energy Demand And Consumption
	Degree of Energetic Self- Supply by RES
	Load Cover Factor
Maintenance and fault prediction	-
Comfort	Predicted Mean Vote (PMV)
	Predicted Percentage Dissatisfied (PPD)
	Sum of weighted percentage of hours in class II of comfort
	Room operative temperature
	Indoor relative humidity
	Daylight factor (DF)
	Sound pressure level
Health, well-being and accessibility	CO_2 concentration
	Ventilation rate
	PM2.5 concentration
	Total Volatile Organic Compounds (TVOC)

Energy flexibility and storage	Annual Mismatch Ratio
	Load Matching Index
	Grid Interaction Index
Information to occupants	Consumer engagement
Convenience	-

Furthermore, a consultation process among experts from the Smart Building sector was carried out to collect feedback on the selected KPIs. Participants have been selected from three groups: project partners, experts from other projects which deal with similar topics and ECTP members. Experts who accepted to participate in the consultation process were from VITO, ECTP, R2M, DOWEL Innovation, LIST, Cardiff university, Tecnalia, TABEDE project, CSTB and Empa. The participants received the list of KPIs structured amongst the various impact categories. Each KPI was displayed with its definition, unit of measurements, a more detailed description, quantification method and most relevant sources. Participants were asked to rate each KPI on a scale defined as follows: 1 - not important, 2 - minor importance, 3 – important and 4 - very important. This consultation process enabled to validate the choices made by the consortium and to fine-tune the definitions of co-benefits and KPIs.

This project task is directly connected to Task T3.2, which aims at defining and evaluating the performances of Smart Building technology solution packages. These technology solution packages will be proposed for three representative buildings in four different climatic contexts of the EU and will be assessed in terms of SRI score and their related co-benefits.

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1. Introduction

1.1. Context of the project

The Energy Performance of Buildings Directive (Directive 2018/844/EU) approved by the European Parliament on April 17, 2018 [1] promotes the implementation of building automation and electronic monitoring of technical building systems, supports e-mobility and introduces the Smart Readiness Indicator (SRI), for assessing the technological readiness of the building and the ability to interact with the occupants and the grid.

The aim of the SRI is to raise awareness of the benefits of Smart Building technologies and functionalities and make these benefits more tangible for building users, owners, tenants, and smart service providers. A wider implementation of Smart Building technologies is expected to produce energy savings in a cost-effective manner and to improve indoor comfort, adjusting the indoor environment conditions. Furthermore, in a future energy system with a large share of distributed renewable energy generation, Smart Buildings will be the cornerstone for an efficient demand-side energy flexibility.

In this context, the H2020 SmartBuilt4EU project aims at consolidating and supporting the Smart Building Innovation Community (SBIC), allowing the Smart Building technologies to reach their full potential and to remove those barriers that slow down the improvement of building performances. The project will map and nurture a European Smart Buildings community, with EU projects at its center, while promoting key innovators and innovative solutions for Smart Buildings through its web platform (https://smartbuilt4eu.eu/) and by delivering dedicated brochures. Collaborative open Task Forces involving key stakeholders will identify barriers, opportunities and best practices for the take up of Smart Buildings. These findings will be translated into recommendations to policy makers and a Strategic R&I Agenda that will feed the design of future Horizon Europe calls. In addition, the project will coordinate contributions of the community to the SRI promotion, experimentation and implementation.

1.2. Purpose and structure of the deliverable

Work package 3 (WP3) of the H2020 SmartBuilt4EU project proposes an approach to increase the awareness on the co-benefits of Smart Buildings. In particular, this WP aims to define an approach for setting up the business case of Smart Buildings for different stakeholders, and aims to promote the SRI coupled with the co-benefits as means of assessment of the building smartness. Furthermore, it introduces technology solution packages for Smart Building typologies in different climatic contexts.

This first WP3 deliverable is devoted to the definition of the main co-benefits and key performance indicators (KPIs) to be coupled with the SRI assessment, increasing in this way its value and enabling the **definition of effective business case** for Smart Buildings. The identification of the most important co-benefits is carried out in terms of both quantitative indicators and qualitative information. These results together with the technology solution packages that will be introduced by the following task (T3.2 - "Solution packages for Smart Buildings and SRI evaluations") constitute the approach proposed in WP3 to foster the uptake of Smart Buildings across Europe.

A literature review has been carried out to collect co-benefits of smart-ready technologies and their related KPIs. Hence in chapter 2 and 3, the co-benefits and KPIs definitions and the main associated sources are presented. In chapter 4, a consultation process to collect feedback from experts on the selected KPIs is reported. The objective of the consultation process is to validate the KPIs and understand which are the more important ones.

1.3. Relation to other project activities

The co-benefits and KPIs identified in this task are connected to other project activities:

- Task T3.2 will implement the knowledge here collected in order to evaluate the performances of the Smart Building technology solution packages proposed within the T3.2 activities. This task aims to provide a set of technology solution packages for Smart Buildings for three representative buildings in four different climatic contexts of the EU. These buildings will be assessed in terms of SRI score and their related co-benefits. Furthermore, T3.2 will develop a set of "Smart Building technical sheets" that describe the technological solutions adopted, the relevance in each regional context and the performances in terms of SRI as well as co-benefits for the owners and occupants.
- The technology solution package and technical sheets developed in T3.2 with the relative co-benefits will be part of the dissemination as best practices within the training activities of task T3.3. These activities aim to promote a better understanding of the value of Smart Building technologies and implementation of the SRI instrument.
- Work package 4 "Research, Innovation and Policy roadmap" aims to support the European Commission and the Member States in gaining a better view of the current development state of the Smart Building innovation community, and how to stimulate research, innovation and market uptake in the EU and at national level on Smart Building technologies. At present, standards and research activities focussing on Smart Building technologies often focus mainly on directly quantified impacts such as energy and cost savings. The activities of T3.1 help to highlight the importance of other benefits - often more qualitative in nature - and structure the strategic research and innovation agenda to also take these elements explicitly into account.

2. Definitions and methodology

2.1. Smart Readiness Indicator

Smart technologies in buildings can be cost-effective means to assist in creating healthier and more comfortable buildings with a lower energy use and carbon impact and can also facilitate the integration of renewable energy sources in future energy systems (Figure 1). In the 2018 revision of the EPBD, the potential of smart technologies in the building sector was heavily emphasized.
As part of this focus, the EPBD introduced the concept of SRI, which is a common EU scheme for rating the building smartness. In its final report on the technical support to the development of a smart readiness indicator for buildings [2], VITO and Waide Strategic Efficiency Europe define smartness as follows: "Smartness of a building refers to the ability of a building or its systems to sense, interpret, communicate and actively respond in an efficient manner to changing conditions in relation to the operation of technical building systems or the external environment (including energy grids) and to demands from building occupants".

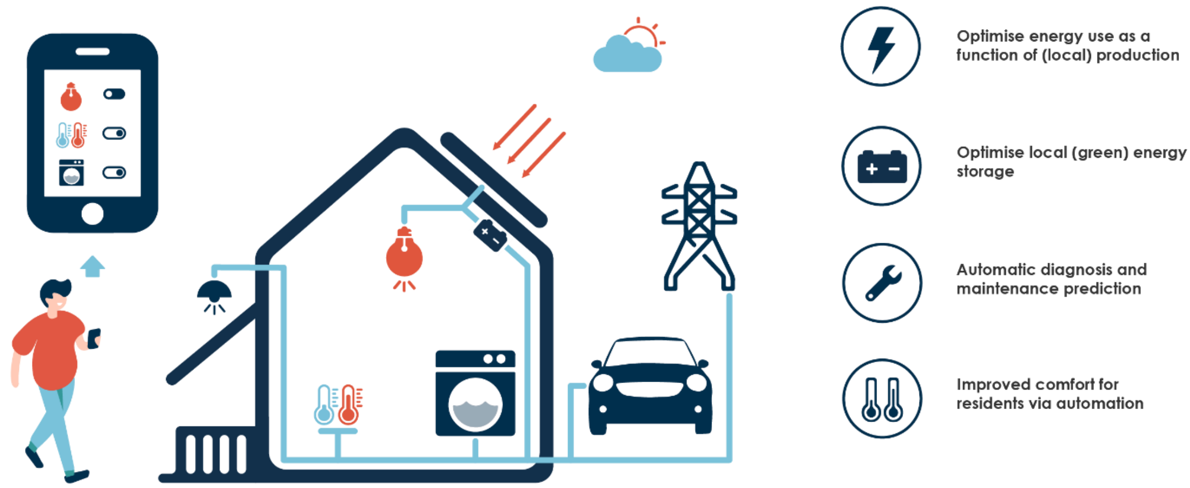

Figure 1. Expected positive impacts of smart technologies.

The SRI builds on three main pillars to assess the technological readiness of buildings in terms of:

1. more (energy-)efficient operation,
2. interaction with their occupants,
3. interaction with connected energy grids.

Figure 2. Three key functionalities of smart readiness in buildings.

The aim of the SRI is to make building occupants, users, designers and smart service providers more aware of the impacts of smart systems and functionalities and make their added value more appreciable. The SRI scheme seeks to support technology innovation in the building sector and create an incentive for the integration of cutting-edge smart technologies in buildings. The methodology for calculating the SRI is based on the assessment of smart-ready services available or planned at design stage in a building or building unit, and of additional smart-ready services that are considered relevant. The three main features have been broken down into 7 impact criteria, as reported in the Figure 3 below.

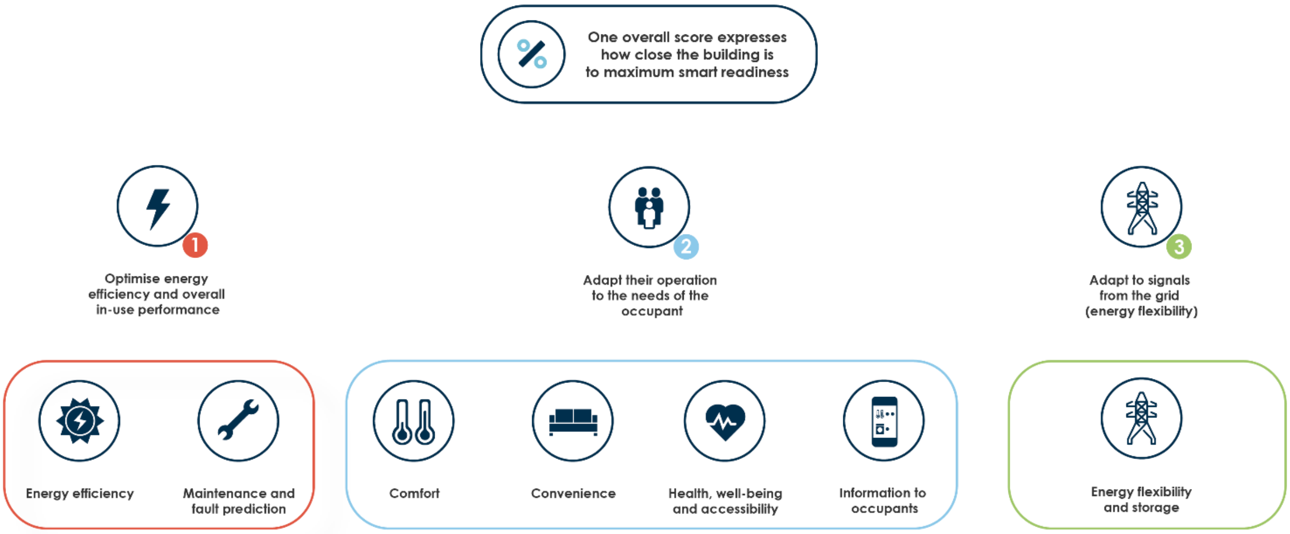

Figure 3. SRI score assessment and impact categories.

2.2. Definitions of co-benefits and methodology

In 2012, the International Energy Agency (IEA), addressed the topic of energy efficiency measures and the benefits that these measures can deliver to the economy and society, beyond energy savings. The term 'Multiple Benefits' was adopted to describe the wider socioeconomic outcomes that can arise from energy efficiency improvement [3]. The same term is used by the US Environmental Protection Agency in the report "Assessing the Multiple Benefits of Clean Energy".
Later, IEA EBC Annex 56 [4] proposed a comprehensive definition of co-benefits in order to develop a new methodology for cost effective renovation of existing buildings. Co-benefits were defined as "***the effects (either positive or negative) beyond the energy savings and the reduction of carbon emissions that may arise from high efficiency energy buildings and from an energy-related building renovation***" [5].

The co-benefits analysis has been placed under the spotlight when the EPBD initiated the principles of cost optimal and nearly zero-energy performance levels. Since all new buildings in the EU are expected to be nearly zero-energy buildings (nZEB) from 2021, these will be a major driver in the construction sector in the coming years. As stated in H2020 CRAVEzero project[1], a broad shift towards nZEBs will require significant adjustments to the existing structures of the building market, which means including added values beyond energy savings and its investment cost. These co-benefits are mainly related to improved indoor comfort and air quality, and to health positive impacts such as reduced sick leaves and increased productivity in office

[1] https://cordis.europa.eu/project/id/741223

buildings. These side impacts improve building quality and users' well-being and offer economic benefits in addition to reducing energy bills. H2020 CoNZEBs project[2] placed the focus on indoor air quality, comfort, building location and low energy costs [6], to inform about experiences, expectations and co-benefits of living in nZEBs.

Moving towards the adoption of smart technologies in buildings, as promoted by the revised EPBD with the introduction of the SRI as a voluntary European scheme for rating the smart-readiness of buildings, a similar approach needs to be applied to evaluate the multiple impacts that these systems and their functionality level have on the built environment, beyond energy efficiency optimization.

As reported in paragraph 2.1, the SRI final report [2] defines a set of seven categories in which a smart ready service can provide several impacts to the building, its users, and the energy grid. The categories are: energy efficiency, maintenance and fault prediction, comfort, convenience, health, well-being and accessibility, information to occupants and energy flexibility and storage. In this task, co-benefits of smart technologies have been identified and divided according to these impact categories. Each category reports the related co-benefits and collects in tables the associated KPIs.

Finally, a consideration concerning the methodology applied in the selection of KPIs to be coupled with the identified co-benefits: scientific literature and projects have produced a large amount of indicators, depending on the specific investigated matter, needs and objectives. Therefore in this task some requirements have been applied in order to filter and select which indicators can effectively be coupled with the SRI assessment and build a business case for Smart Buildings. The requirements are that the indicators have to be transparent, easy to be evaluated and widely adopted, in order to be easily accessible and help the promotion of the SRI assessment.

[2] https://cordis.europa.eu/project/id/754046

3. Smart Building co-benefits and Key Performance Indicators (KPIs)

3.1. Energy efficiency

This category refers to the energy savings impacts of the smart-ready technologies on building energy performances. These impacts can be considered main benefits and not co-benefits as they are considered energy efficiency measures. For instance, a better control of room temperature settings allows to reduce energy waste. A motorized solar shading system with automatic control based on sensor data can better manage solar gains, reducing cooling/heating demand. The European standard EN 15232:2012 [7] introduced a classification of the building control systems and functionalities, providing the methods for a correct assessment of the impact that these systems have on energy performance. On 19 October 2017 the standard was replaced by a new revised version. Indicators which permits to quantify these impacts are:

KPI ID	EE.1
Name	**Primary Energy**
SRI impact category	Energy efficiency
Definition	It represents the energy before any transformation that is consumed in the supply chains of the used energy carriers.
Unit of measurement	kWh/m²a
Formula	$PE = FE * PEf$ • $\mathrm{PE} = \text{primary energy}$ • $\mathrm{FE} = \text{final energy}$ • $PEf = \text{primary energy factor}$
Description/Comments	The primary energy factor (PEf) depends from the calculation method and the inclusion or not of renewable energy.
Sources	Literature: [8]

KPI ID	EE.2
Name	**Energy Demand And Consumption**
SRI impact category	Energy efficiency
Definition	Building energy demand and consumption
Unit of measurement	kWh/ (m²month); kWh/(m²a)
Formula	$$EC = \frac{EC_{tot}}{A_r}$$ • EC_{tot} = Total energy consumption [kWh/month ; kWh/year] • A_r = reference floor area
Description/Comments	It takes into account all the energy delivered to the final consumer in a month or a year. The energy demand refers to calculated or simulated data and the energy consumption refers to monitored one.
Sources	Literature: [8, 9]

KPI ID	EE.3
Name	**Degree of Energetic Self- Supply by Renewable Energy Sources (RES)**
SRI impact category	Energy efficiency
Definition	Ratio of energy produced on site from RES and the energy consumption, over a defined period.
Unit of measurement	%
Formula	$$DE_{E,T} = \frac{LPE_{E,T}}{EC_{E,T}}$$ ● $DE_{E,T}$ = Degree of energy (electrical or thermal) self-supply based on RES ● $LPE_{E,T}$ = Locally produced energy (electrical or thermal) [kWh/month ; kWh/year] ● $EC_{E,T}$ = Energy consumption (monitored) [kWh/(month) ; kWh/(year)]
Description/Comments	The degree of energetic self-supply by RES is defined as a ratio of locally produced energy from RES and the energy consumption over a period of time. This indicator is separately determined for thermal energy and electricity.
Sources	Literature: [8, 10]

KPI ID	EE.4
Name	**Load Cover Factor**
SRI impact category	Energy efficiency
Definition	Load cover factor represents the percentage of the electrical demand covered by on-site electric generation.
Unit of measurement	%
Formula	$$\gamma_{load} = \frac{\int_{t1}^{t2} \min[g(t) - S(t) - \zeta(t), l(t)]\, dt}{\int_{t1}^{t2} l(t) dt}$$ Where: • g(t): on-site generation (kW) • S(t): storage balance (kW) • ζ(t): losses (kW) • l(t): building load (kW)
Description/Comments	Similar to the previous one, this one is focused on electrical energy production.
Sources	Literature: [11]

3.2. Maintenance and fault prediction

Smart functions such as automated fault detection and diagnosis of building equipment operation are strongly connected to an optimized building functioning. These functionalities have the potential to improve operation and maintenance activities of technical building systems, as performances, and device failures are monitored in all systems. In this way, automation systems can reduce building energy and maintenance costs. The main co-benefits which smart ready services can achieve in this category are:

- Lower energy performance gap: building operation presents several inefficiencies compared to project conditions. The gap caused by these inefficiencies can be reduced by installing monitoring and diagnosis systems. Tanking as an example the case of heat pumps (HP), an energy performance gap can be identified with the system performance degradation. This degradation can be visualized as a lower heat pump capacity in terms of kW and a lower coefficient of performance (COP). A study investigated the performance of a split residential heat pump, by imposing faults: compressor valve leakage, outdoor improper air flow, indoor improper air flow, liquid line restriction, refrigerant undercharge, and refrigerant overcharge [12]. These imposed faults led to a performance (capacity and COP) degradation ranging between -5% and -15%. A smart system which can gather data and monitor these conditions can prevent such a performance degradation, allowing a corresponding energy saving.
- Lower maintenance and replacement costs: following the previous example of HP, two studies [10], [11] analyzed 37,000 heat pump faults reported by original equipment manufacturers during the warranty period. Systems involved in the investigation were air/air, air/water, brine/water (geothermal HP) and exhaust air HP. Most common and costliest faults among the 4 categories of HPs are associated with the following components: compressor, fan, control and electronics and shuttle valve. Smart-ready services aim at preventing or early-detecting faults and failures, reducing maintenance and replacement costs.

The corresponding KPIs can be defined as €/year of economic impact, however a general quantification method could not be found as stated by H2020 EEnvest project [13] dealing with de-risking of renovation investments. The project tackled the issue of performance gap and damage quantification, however a rather specific calculation approach is needed to calculate those impacts. For instance, the lower energy performance indicator could be tailored to the evolution of seasonal COP or EER in the case of HP, carrying out a comparison over a time frame to detect degradation of performance.

3.3. Comfort

An improved comfort condition for the occupants is one of the main co-benefits which smart technologies can provide to the built environment. Comfort refers to conscious and unconscious perception of the physical environment, including thermal, acoustic, and visual comfort.
Thermal comfort is defined by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) as 'that state of mind which expresses satisfaction with the thermal environment' [14] and is one of the key design aspects in modern buildings. Smart Building control and operation act on controllable building parameters such as air conditioning setpoint and other environmental conditions in order to improve thermal comfort [15].
With respect to visual comfort, visual contact to nature positively affects concentration and stress as reported in this article [16], which analyses the impact of a view from a window on thermal comfort, emotion, and cognitive performance. In this way visual comfort is also connected to the following impact category, health and well-being.

It is important to underline that the environmental conditions required for comfort are not the same for everyone [17], but differ from person to person, based on its physiological and psychological conditions. Despite that, there are objective metrics to assess them, as reported in the following indicators (e.g. Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD)). Moreover, the achieved comfort is the result of many influencing parameters, including outdoor environmental characteristics, building design features, technical building characteristics and occupant behavior. Consequently, it is very hard to unambiguously attribute the resulting comfort (or lack thereof) to Smart Building services. Dynamic thermal building simulations are likely an essential asset to define the benchmark to compare to.

KPI ID	C.1
Name	**Predicted Mean Vote (PMV)**
SRI impact category	Comfort
Definition	Index that aims to predict the mean value of votes of a group of occupants on a seven-point thermal sensation scale.
Unit of measurement	-
Formula	-
Description/Comments	This indicator, developed by Fanger [18] and reported in the ISO 7730 [19], predicts the mean value of the overall thermal sensation as a function of four environmental parameters (air temperature, air velocity, humidity, mean radiant temperature) and two subjective parameters (metabolic rate and clothing insulation). The result is the mean value of votes assigned on a thermal sensation scale which goes from -3 to +3, where zero represents the state of thermal comfort for a group of building users. The standard ISO 7730 defines comfort ranges based on the combination of different parameters, including PMV: • A Class: -0.2 < PMV < 0.2 • B Class: -0.5 < PMV < 0.5 • C Class: -0.7 < PMV < 0.7
Sources	Literature: [17–21] Certification schemes: Level(s), OsmoZ, BREEAM, KLIMA, ITACA, WELL, NABERS

KPI ID	C.2
Name	**Predicted Percentage Dissatisfied (PPD)**
SRI impact category	Comfort
Definition	PPD establishes a quantitative prediction of the percentage of thermally dissatisfied occupants.
Unit of measurement	%
Formula	-

Description/Comments	The PPD expresses the percentage of dissatisfied people in relation to a PMV value in a given environment. Comfort ranges defined by standard ISO 7730 set the following three categories for PPD: • A Class: < 6% • B Class: < 10% • C Class: < 15%
Sources	Literature: [17–21] Certification schemes: Level(s), OsmoZ, BREEAM, KLIMA, WELL

KPI ID	C.3
Name	**Sum of weighted percentage of hours in class II of comfort**
Impact category	Comfort
Definition	Sum of weighted percentage of hours in class II of comfort (as defined according to the EN 15251
Unit of measurement	h
Formula	-
Description/Comments	-
Sources	Literature: [22]

KPI ID	C.4
Name	**Room operative temperature**
SRI impact category	Comfort
Definition	Operative temperature is defined as the uniform temperature of ambient air and mean temperature of surfaces.
Unit of measurement	°C
Formula	$$t_o = \frac{h_r t_{mr} + h_c t_a}{h_r + h_c}$$ Where: • h_r = linear radiative heat transfer coefficient • h_c = convective heat transfer coefficient • t_a = air temperature • t_{mr} = mean radiant temperature
Description/Comments	-
Sources	Literature: H2020 MOBISTYLE project - Deliverable D3.2 Certification schemes: Level(s), KLIMA, DGNB, BES, WELL, EN 16798

KPI ID	C.5
Name	**Indoor relative humidity**
SRI impact category	Comfort
Definition	Indicates the amount of water vapor that the air contains, compared to the maximum amount that the air could contain under the same temperature conditions.
Unit of measurement	%
Formula	-
Description/Comments	-
Sources	Literature: H2020 MOBISTYLE project - Deliverable D3.2 Certification schemes: KLIMA, DGNB, LiderA, BES, CASBEE, NABERS

KPI ID	C.6
Name	**Daylight factor (DF)**
SRI impact category	Comfort
Definition	Concerning visual comfort, this indicator describes the ratio of outside over inside light level, expressed in percent. The higher the percentage, the more natural light is available in the indoor space.
Unit of measurement	-
Formula	%
Description/Comments	-
Sources	Literature: [23]

KPI ID	C.7
Name	**Sound pressure level**
SRI impact category	Comfort
Definition	The most commonly used indicator of acoustic wave strength.
Unit of measurement	dB
Formula	-
Description/Comments	-
Sources	Literature: [21, 24]

3.4. Health, well-being and accessibility

Well-being in the built environment is a topic that is gaining more and more attention, despite the fact that there are still many questions on how to effectively measure and impact well-being. There are key physical factors of indoor environmental quality (IEQ) that strongly influence occupant perception of indoor spaces, but attention has to be devoted to monitoring and communicating well-being outcomes and their translation into building practice and standards [25].

Smart-ready technologies act on physical parameters (e.g. a control of ventilation systems based on CO_2 sensors) and allow monitoring and better communication with the user. Therefore, these technologies play an important role in determining the IEQ. Some studies tried to determine the connection between IEQ and health and well-being. Few detailed studies have investigated whether a green rating leads to higher occupant satisfaction with indoor environmental quality (IEQ) [26]. Others started from the potential costs of poor IEQ, which can be linked with direct medical costs or indirect costs related to reduced individual performance, which could either be because of higher absenteeism, or reduced effectiveness at work. The benefits of good IEQ are either related to minimizing these negative effects, or creating positive impacts such as improved employee recruiting and retention, and lower cost of building maintenance due to fewer complaints, and enhanced effectiveness at work [27].

Several studies tried to identify indicators specific for office building and related to co-benefits such as increased productivity, reduced sick leaves, reduced employee turnover [28–30]. Although attempts have been made to define this class of indicators, they are hard to calculate, since the figures required should be obtained from the accountability and human resources departments of the companies. For these reasons KPIs related to this kind of co-benefits have not been included in this assessment.

KPI ID	HW.1
Name	**CO_2 concentration**
SRI impact category	Health, well-being and accessibility
Definition	Amount of CO_2 in the air.
Unit of measurement	ppm
Formula	-
Description/Comments	The CO_2 concentration is a commonly used indicator to determine IEQ. The standard EN 16798-2:2019 sets the limits of CO_2 concentration for four different IEQ categories: • Category 1: 550 ppm • Category 2: 800 ppm • Category 3: 1350 ppm • Category 4: 1350 ppm
Sources	Literature: [14, 22, 23]

KPI ID	HW.2
Name	**Ventilation rate**
SRI impact category	Health, well-being and accessibility
Definition	The rate at which external fresh air is delivered into the building.
Unit of measurement	l/(s per person) l/(s m^2)
Formula	-
Description/Comments	Connected to the CO_2 generation rate, the ventilation rate which guarantees a proper IEQ can be obtained.
Sources	Literature: [22, 23]

KPI ID	HW.3
Name	**PM2.5 concentration**
SRI impact category	Health, well-being and accessibility
Definition	Amount of particulate matter 2.5 (PM2.5) in the air. The term PM2.5 (fine particles), refers to tiny particles or droplets in the air that are two and one half microns or less in width.
Unit of measurement	µg/m^3
Formula	-
Description/Comments	WHO guideline value (outdoor): • 8h mean: 15 µg/m^3 • 24h mean: 25 µg/m^3 • Annual mean: 10 µg/m^3
Sources	Literature: [22, 23]

KPI ID	HW.4
Name	**Total Volatile Organic Compounds (TVOC)**
SRI impact category	Health, well-being and accessibility
Definition	The sum of the concentrations of the identified and unidentified volatile organic compounds.
Unit of measurement	µg/m^3
Formula	-
Description/Comments	-
Sources	Literature: [31, 32]

3.5. Energy flexibility and storage

In a grid where the share of intermittent renewable energy sources is growing, smart technologies aim at shifting building energy demand in time to create a better match with energy supply. The SRI scheme does not solely focus on electricity grids, but also includes flexibility offered to district heating and cooling grids. As reported in EBC Annex 67 'Energy Flexible Buildings' [33], the energy flexibility of a building is the ability to manage its energy demand and generation according to local climate conditions, user needs and grid requirements. Factors which play a role in making a building flexible are several as suggested by [34]: its physical characteristics (thermal mass, insulation), services (ventilation, heating, and storage systems), automation and control system, user's behavior and comfort requirements.

Building energy flexibility is a widely investigated topic, therefore many indicators are available to characterize it, depending on the specific needs of the assessed project/case study. According to the reviewed literature, the following KPIs comply with the requirements set within this task of being general and easy to calculate.

KPI ID	FS.1
Name	**Annual Mismatch Ratio**
SRI impact category	Energy flexibility and storage
Definition	The annual difference between demand and local renewable energy supply.
Unit of measurement	-
Formula	$$AMR_x = \frac{\sum_{8760}^{t=1} HMR_x(t)}{8760}$$ Where: • AMR: annual mismatch ratio • HMR: hourly mismatch ratios
Description/Comments	It expresses the annual difference between energy demand and local supply from renewables.
Sources	Literature: [35, 36]

KPI ID	FS.2
Name	**Load Matching Index**
SRI impact category	Energy flexibility and storage
Definition	Load Matching Index, is expressed as the relation of the on-site generation to the load for a specific time interval.
Unit of measurement	%
Formula	$$f_{load,i=min}\left[1, \frac{onsitegeneration}{load}\right] \cdot 100 \quad (8)$$ $$f_{load,i=min}\left[1, \frac{onsitegeneration}{netmetering + onsitegeneration}\right] \cdot 100 \quad (9)$$ $$f_{load,i=min}\left[1, \frac{onsitegeneration + batterybalance}{load}\right] \cdot 100 \quad (10)$$
Description/Comments	The Load Matching Index indicates the amount of energy that can be generated by RES and stored with batteries in comparison to the load. The higher the index is, the better the coincidence between the load and the onsite generation.
Sources	Literature: [35, 37]

KPI ID	FS.3
Name	**Grid Interaction Index**
SRI impact category	Energy flexibility and storage
Definition	Describes the average grid stress, using the standard deviation of the grid interaction over a period of a year.
Unit of measurement	%
Formula	$f_{grid,i} = \frac{netgrid}{max\lvert netgrid\rvert} \cdot 100$
Description/Comments	The grid interaction index is the ratio of the net grid metering in a given period compared to the maximum/minimum within an annual cycle. A positive value indicates a net exporting building.
Sources	Literature: [35, 37]

Further than the selected KPIs, it is interesting to mention that IEA EBC Annex 67 has developed two KPIs to quantify energy flexibility, namely efficiency of flexible operation Eflex [%] and shifted flexible load Sflex [%] [38]. These KPIs have different focus areas: shifted flexible load focuses on the load shifting ability, while efficiency of flexible operation focuses on the related costs/savings.

3.6. *Information to occupants*

This category refers to the ability of Smart Building services to provide information on building operation to occupants or to facility managers, such as indoor air quality, production from renewables, storage capacity and other building performances with the objective of positively influencing their interaction with the building.

As stated in the H2020 PEAKapp[3] project, occupant behavior in buildings is one of six influencing factors of energy-related building performance [39]. Therefore, it is key to understand and model occupant behavior to reduce energy consumption and improve comfort while promoting a behavioral change of energy end-users. According to H2020 MOBISTYLE[4] project which dealt with users behavior's motivation to change habits by providing information on energy use, indoor environment, health and well-being, the impact of user awareness and information to occupants (both energy, comfort, IEQ and well-being) could be taken into account in two ways:

1. Information services leading to a measurable impact on long-lasting positive behavior such as lowering of the indoor temperature settings.
2. Information services focused on actual building performance to prevent the energy performance gap discussed in the maintenance and fault prediction section.

[3] https://cordis.europa.eu/project/id/695945
[4] https://cordis.europa.eu/project/id/723032

In many cases, users are not aware of incorrect behaviors, for instance excessive ventilation of some rooms, wrong use of the thermostatic valves or domestic appliances. [40] analyzed IoT technologies[5] as a tool to enhance user awareness on energy consumption in residential buildings. Frequent feedback contributes significantly to motivating and supporting change in occupant behavior. Several studies reviewed by [41] show that feedback to end-users can reduce a household's final energy consumption between 5% and 10%. In addition, confirming that direct feedbacks are more effective than the indirect ones.

One of the objectives of H2020 HOLISDER[6] project is to provide recommendations on energy efficiency and demand response to occupants. The project aims at measuring how often occupants open the mobile app and whether they follow the recommendation received or they discard them. Therefore, indicators such as "User acceptance", "% of Acceptance of DR suggestions", "Use (in time and in users) of the developed APP", "No. of downloaded and in use apps among occupants" were defined. Drawing from this experience the following KPI is proposed:

KPI ID	CE.1
Name	**Consumer engagement**
Impact category	Information to occupants
Definition	This indicator measures the user involvement in the building control thanks to the feedback received from metering systems.
Unit of measurement	-
Formula	-
Description/Comments	-
Sources	Literature: [8, 10]

3.7. Convenience

This category aims at collecting those impacts which "make life easier" for the occupant. It can be defined as the ability to facilitate the user's life, alternatively as the ease with which the user accesses the services.

This impact category is not easy to be assessed in terms of co-benefits and indicators, due to the rather qualitative approach to the topic and the lack of literature references. To better understand convenience, some characteristics can be identified which in turn can lead to co-benefits definition:

- Ability to interact with building services that are always updated, without the user having to deal with it.
- Level of digitalization of the building's control.
- Features and functionalities that adapt to the user's changing needs.
- Ability to access information and controls from a single point or at least with uniformity of approach, even not at home (user experience).
- Reporting / summary of monitored data and suggestions to the user.

[5] Definition by Oracle (https://www.oracle.com/it/internet-of-things/what-is-iot/): "The Internet of Things (IoT) describes the network of physical objects—"things"—that are embedded with sensors, software, and other technologies for the purpose of connecting and exchanging data with other devices and systems over the internet. These devices range from ordinary household objects to sophisticated industrial tools."

[6] https://cordis.europa.eu/project/id/768614

- The reusability / convertibility / flexibility of the available spaces.
- The sharing of common infrastructures, such as the energy community
- From the user's point of view, it expresses a relative concept, and tends to decrease over time
- From the system point of view, it expresses the ability to identify a potential need in advance for the user, and then provide a facility or directly the solution, to facilitate / perform maintenance and operate the building systems efficiently.

For instance, taking the case of commercial buildings, smart services can control parking systems, elevators, escalators and conference rooms. The related co-benefit is the resulting user experience. As a consequence, this may impact on employees productivity levels, reduced lease turnover, energy savings and improved space management.

3.8. Summary of KPIs

This deep literature review had the purpose of putting together knowledge that is scattered in many studies, sources and project results. Besides the identification of Smart Building co-benefits and KPIs, this global overview allowed to determine which are the most widely adopted ones and where the investigation is moving the focus. Table 1 collects the KPIs identified in the literature and project review, divided in the SRI impact categories. In order to verify the KPIs selected, this list was submitted to a consultation process among Smart Building experts.

Table 1. Summary of the identified KPIs.

CATEGORY	KPI
Energy efficiency	Primary energy
	Energy Demand And Consumption
	Degree of Energetic Self- Supply by RES
	Load Cover Factor
Maintenance and fault prediction	-
Comfort	Predicted Mean Vote (PMV)
	Predicted Percentage Dissatisfied (PPD)
	Sum of weighted percentage of hours in class II of comfort
	Room operative temperature
	Indoor relative humidity
	Daylight factor (DF)
	Sound pressure level
Health, well-being and accessibility	CO_2 concentration
	Ventilation rate
	PM2.5 concentration
	Total Volatile Organic Compounds (TVOC)

Energy flexibility and storage	Annual Mismatch Ratio
	Load Matching Index
	Grid Interaction Index
Information to occupants	Consumer engagement
Convenience	-

4. Consultation process on the KPIs

The analysis of indicators is the starting point of most of the research activities performed in this sector. Therefore thanks to a deep literature and projects review, a list of KPIs (see Table 1) was defined. At this point, a consultation process was introduced with the objective of cross-check and validate the obtained KPIs with experts either directly involved in the project or focused on the Smart Building topic. As a result of the consultation, on the one hand, a feedback on the research methodology was gathered. On the other hand, the most relevant KPIs related to Smart Buildings could be identified.

4.1. *Method*

As mentioned above, experts from the Smart Building sector have been involved in the consultation process. Participants have been selected from three groups:

1. Project partners – Experience and accessibility due to direct involvement in the project made this group the first choice for the consultation process.
2. Experts from other projects dealing with similar topics – Tasks T1.1 aimed at mapping the EU-funded Smart Building projects, collecting them in a brochure providing a synthetic factsheet for each identified project (https://smartbuilt4eu.eu/1st-brochure-on-eu-funded-smart-building-innovations-released/). Thanks to this activity relevant projects have been selected to participate to the consultation process.
3. ECTP members - The European Construction, built environment and energy efficient building Technology Platform (ECTP), coordinator of SmartBuilt4EU project, is a membership organization promoting and influencing the future of the Built Environment.

Experts who accepted to participate in the consultation process were from VITO, ECTP, R2M, DOWEL, LIST, Cardiff university, Tecnalia, TABEDE project, CSTB and Empa. Participants received the list of KPIs divided in impact categories as reported in section 3. Each KPI was displayed with its definition, unit of measurements, a more detailed description, quantification method and most relevant sources. Participants were asked to rate each KPI on a scale defined as follows:

- 1: not important
- 2: minor importance
- 3: Important
- 4: Very important

Furthermore, there was the possibility to provide extra information such as suggestions and additional sources.

4.2. *Results*

Table 2 reports the results collected from the consultation process. Each column represents a single consultation and for each KPI the corresponding score is reported. In order to better display the consensus that each KPI has reached among consulted experts a column with the mean vote and one with the calculated standard deviation are reported.

Table 2. Consultation results.

Key Performance Indicators	1	2	3	4	5	6	7	8	9	10	11	12	Mean vote	St. Dev.
Primary Energy	3	4	4	3	4	4	3	3	4	4	1	4	3.42	0.86
Energy Demand And Consumption	3	4	3	4	4	3	4	1	4	2	1	4	3.08	1.11
Degree of Energetic Self-Supply by RES	4	3	3	2	3	2	3	4	2	2	1	3	2.67	0.85
Load Cover Factor	4	2	1	3	3	2	3	4	3	4	1	3	2.75	1.01
Lower energy performance gap*	3	3	3	2	1	3	4	2	3	4	-	3	2.82	0.83
Lower maintenance and replacement costs*	3	3	3	4	2	3	-	3	2	4	-	4	3.10	0.70
Predicted Mean Vote (PMV)	4	4	1	3	-	4	3	2	3	3	1	3	2.82	1.03
Predicted Percentage Dissatisfied (PPD)	3	3	2	2	-	3	3	2	4	2	2	3	2.64	0.64
Sum of weighted percentage of hours in class II of comfort	2	2	2	3	3	2	3	2	2	2	-	3	2.36	0.48
Daylight factor	3	3	3	2	3	3	2	1	2	1	2	3	2.33	0.75
Room operative temperature	4	4	3	4	4	4	2	4	2	4	3	4	3.50	0.76
Indoor relative humidity	4	4	3	3	3	3	2	4	2	4	3	4	3.25	0.72
CO_2 concentration	3	4	3	4	3	4	2	3	4	4	2	4	3.33	0.75
Ventilation rate	4	4	3	3	3	3	2	1	3	4	2	5	3.08	1.04
PM2.5 concentration	3	4	3	3	2	3	2	1	3	4	2	3	2.75	0.83
Increased productivity (office building)*	3	2	2	1	2	2	3	3	-	2	-	4	2.40	0.80
Reduced sick leaves (office building)*	3	3	2	1	2	3	3	2	-	2	-	5	2.60	1.02
Reduced employee turnover (office building)*	2	2	2	1	2	2	3	2	-	2	-	5	2.30	1.00
Annual Mismatch Ratio	2	4	2	2	2	3	2	2	3	3	3	5	2.75	0.92
Load Matching Index	3	3	2	2	3	4	2	3	3	4	3	5	3.08	0.86
Grid Interaction Index	3	3	3	3	2	4	3	3	2	2	3	5	3.00	0.82
Consumer Engagement	-	-	-	-	-	-	-	-	4	-	-	3	-	-

Five KPIs have been marked (*): lower energy performance gap, lower maintenance and replacement costs, increased productivity, reduced sick leaves and reduced employee turnover. These have been submitted for consultation as possible indicators in the first place, however they have not been included among the KPIs in the end, due to the difficult calculation and the lack of literature on those topics. They can be seen as co-benefits for which still clear and reliable KPIs need to be investigated.

Figure 4 collects the KPIs which in the consultation process obtained a mean vote higher than 3.00 (“important”), divided into the three SRI main pillars.

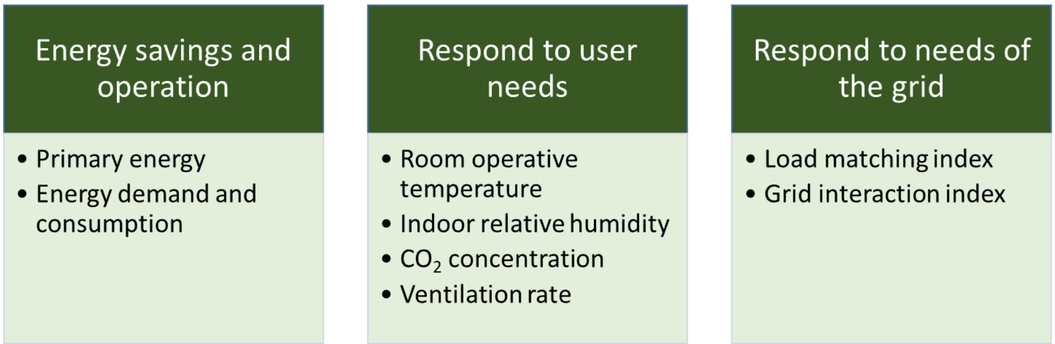

Figure 4. Relevant KPIs, emerging from the consultation process, divided into SRI main pillars.

5. Conclusion and future developments

The identification of co-benefits and definition of Key Performance Indicators associated with Smart Buildings have been displayed as a result WP3 activities. From the literature and projects review carried out in this task it emerges that there are categories in which the impacts of smart ready technologies are already widely investigated and therefore, can be easily assessed (e.g. energy efficiency, energy flexibility and storage). Nevertheless, there are other categories whose associated co-benefits still are at an early stage in terms of identification and quantification (e.g. health, well-being and accessibility, convenience). As a result, widely adopted indicators are not available yet. A broader diffusion of smart technologies and a growing attention to all those aspects that go even beyond energy efficiency – which is actually one of the pillars behind the SmartBuilt4EU project – will allow to deeper understand their mechanisms and the impacts that they have on the built environment.

As mentioned at the beginning of this deliverable, the objective of work package 3 is to support the SRI assessment value and enable the definition of an effective business case for Smart Buildings, promoting the SRI score coupled with the co-benefits as means of assessment of the building smartness. Therefore, an interesting development of this work is the definition of an approach for integrating this co-benefits analysis in the SRI methodology and even providing resources to update the scoring tables of the SRI. Moreover, it is interesting to set up and analyze in detail a Smart Building business case and how to come from the definition of KPIs to better insights on the value of Smart Buildings and how these typically perform better.

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