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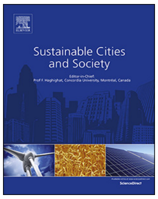

Smart buildings features and key performance indicators: A review

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ABSTRACT

The concept of Smart Buildings was introduced by the Energy Performance Building Directive, with the aim to promote energy flexibility, renewable energy production and user interaction. A wide range of definitions have been introduced in the literature to characterize smart buildings yet, at present, its' concept and features are not clearly and uniquely defined. Simultaneously, building energy retrofit concept has been introduced to facilitate achieving the nearly Zero-Energy Building target and reduce energy consumption in existing buildings. Up to 90 % of the existing European building stock will still be standing and in use in 2050. Thus, there is a need to upgrade the existing retrofitting strategies into Smart Retrofitting, to achieve the nearly Zero Energy Building target and be able to respond to external dynamic conditions such as the weather and the grid. The aim of this research is first to review the concept of smartness in the built environment, highlighting the main features, functions, and technologies of smart buildings, also discussing the possible challenges for smart retrofit applications. The second part of the paper reviews the existing Key Performance Indicators that measure the performance and success in achieving goals in smart buildings. The need to develop a quantified guideline to improve energy and technological innovation is the basis for the increase of the smartness in buildings. Consequently, a set of nine groups of representative performance indicators for smart buildings is developed. This work shows current gaps in the literature and highlights the space for foreseeable future research.

1. Introduction

In the European Union (EU), buildings account for 40 % of total energy consumption (European-Commission., 2019). In 2010, the EPBD recast Recast (2010) introduced the concept of nearly Zero Energy Building (nZEB) target, which has been defined as “a building characterized by a very high-energy performance during its operations, with most of the energy required coming from renewable sources”. The revised EPBD Recast (2010) has recently defined new long-term goals, namely a 80–95 % CO_2 reduction in the EU by 2050 vs. 1990, in order to facilitate a highly energy-efficient and decarbonized building stock, through the renovation of existing buildings into nZEBs. The renovation of buildings is a key action to reach the decarbonization of the building stock by 2050: current renovation rates account for about 1% of existing building stock each year (Dean, Dulac, Petrichenko, & Graham, 2016), while to achieve the 100 % zero-carbon goal by 2050 it is necessary to ensure a renovation rate higher than 3% (Laski & Burrows, 2017). The nZEB retrofitting implies the strong integration of Renewable Energy Sources (RES), as also stated in the Renewable Energy Directive 2009/28/EU (Parliament & Council, 2009); the need to use less fossil fuels and reduce emissions of greenhouse gases is also linked to an increase in the dependency on the electricity produced by RESs. The long-term targets and supporting policy measures in the EU resulted in the growth of renewable energy consumption, from 9% in 2005 to 16.7 % in 2015 (European Commission, 2018). However, its integration had introduced several problems in the management of the electric systems, since renewables that are more easily integrable in buildings have non-programmable energy production profiles and high variable rates (e.g. solar and wind energy) (Smith et al., 2010). Thus, while the RES integration increases in the building sector, the need to properly manage and dispatch energy at the building/district level becomes crucial (Chel & Kaushik, 2018): buildings must be able to balance their own on-site energy generation and consumption. As a result, the traditional grid was enhanced to a Smart Grid (SG), to cope with the increased penetration of solar and wind energy and to control its production.

In parallel, there has been an increasing need for buildings with interactive features, to dynamically respond to users' needs and/or changing boundary conditions (either external, such as climate and grid prices, or internal, such as the occupants' requirements). Wang (2016) highlighted that future buildings are expected to be “grid-responsive“: the building will adapt its usage to time-of-use electricity pricing and to

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Acronyms

EU	European Union
GHG	Greenhouse Gas
EED	Energy Efficiency Directive
EPBD	Energy Performance of Buildings Directive
nZEB	nearly Zero Energy Building
RES	Renewable Energy Sources
HVAC	Heating, Ventilation, and Air Conditioning
SR	Smart Retrofitting
SB	Smart Buildings
SRI	Smart Readiness Indicator
MPC	Model Predictive Control
RNN	Random Neural Network
WSN	Wireless Sensor Network
ESS	Energy Storage System
IEA	International Energy Agency
TOU	Time of Use
DSS	Decision Support System
ANN	Artificial Neural Network
EV	Electric Vehicle
SAIDI	System Average Interruption Duration Index
LOLP	Loss of Load Probability
BAU	Business as Usual
ICT	Information and Communications Technology
KPI	Key Performance Indicators
SC	Smart City
SG	Smart Grid
SM	Smart Meters
BEMS	Building Energy Management Systems
IoT	Internet of Things
DSM	Demand Side Management
DR	Demand Response
SMPC	Stochastic Model Predictive Control
PCDR	Peak Clipping DR Resource
BAS	Building Automation System
BACS	Building Automation and Control System
BMS	Building Management System
EMCS	Energy Management and Control System
HEMS	Home Energy Management System
DHW	Domestic Hot Water
PV	Photovoltaics
PLC	Powerline Carrier
SAIFI	System Average Interruption Frequency Index
DER	Distributed Energy Resources

the users' usage profiles. Similarly, Oldewurtel et al. (2012), emphasized the need to respond to external weather conditions using prediction control strategies, in order to achieve a proper sizing of the mechanical equipment – such as Heating, Ventilation, and Air Conditioning (HVAC) – and the storage systems, as well as to achieve lower energy costs compared to buildings with no weather-prediction strategies. Buildings are going through a transition phase, from being unresponsive to becoming highly efficient, consuming, producing, storing and supplying energy. The concept of Smart Buildings (SB) has been introduced by the EPBD as the main enabler for the future of the building sector. SBs must be nZEBs with a higher flexibility, which is the ability of a building to manage its energy demand and generation based on local climate conditions, users' needs and grid requirements (Costanzo, Zhu, Anjos, & Savard, 2012).

In this sense, the revised EPBD facilitated the development of a voluntary European scheme for rating the smart-readiness of buildings: the "Smart Readiness Indicator" (SRI) (Verbeke et al., 2017). The SRI program is an EU initiative intended to measure the capacity of buildings to adapt their operations to the needs of the grid and occupants (Rochefort, 2019). The limitation in the methodology of the SRI is that it is qualitative and only evaluates the presence of the services and technologies without evaluating their performance. However, quantifying building performance is an essential baseline for assessing the potential savings and validating improvements in retrofitted buildings. To such an aim, the adoption of proper Key Performance Indicators (KPIs) is a crucial step in ensuring energy-saving goals in both new and existing buildings.

In this context, the need for Smart Retrofitting (SR) has become crucial to upgrade the definition of energy-efficient or nZEB retrofitting to reflect the new possibilities into transforming existing buildings into more responsive and efficient buildings and cities. To understand what SR is, it is pivotal to better assess the SB concept, which has not been clarified yet and no clearly defined framework has been set. In fact, the development of SBs calls for the need to add "smart-features" to both new and existing buildings. In this direction, it is important to define the minimum requirements of SBs and develop clear definitions, by addressing the following research questions:

- What are the basic features of a SB and what are the related benefits?
- Which technologies are required to obtain SBs?
- What are the limitations and challenges of achieving SR?

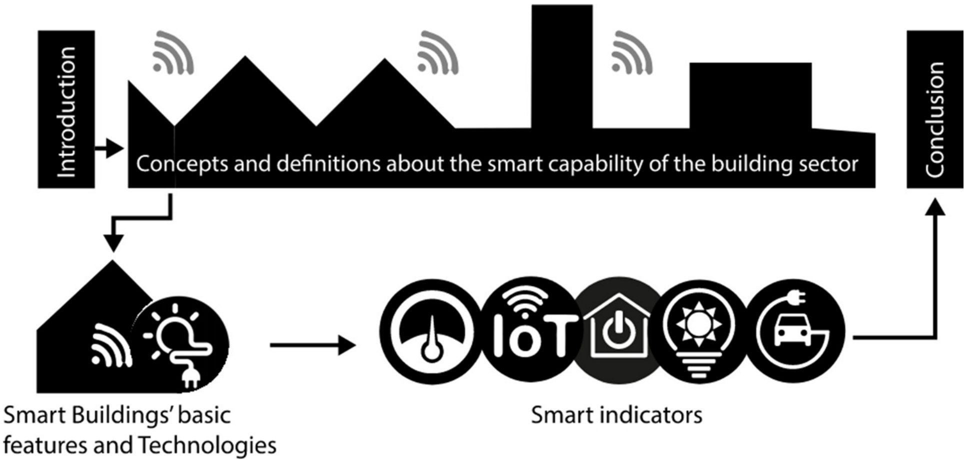

Fig. 1. Framework of the review paper.

- How can “smart-features” be quantified by means of specific Key Performance Indicators (KPIs)?

In such a framework, the aim of this review paper is twofold; first to establish the “basic smart features” and related technologies of SBs, and second, to provide a methodology to quantify the performance of SR. Therefore, the paper firstly reviews the concepts and definitions of SBs, the related features, and technologies, while in the second part the existing KPIs related to SBs are reviewed and the most representative ones are selected. The framework of the paper is summarized in Fig. 1.

2. The smart capability of the building sector: concepts and definitions

The idea of “smartness”, “digitalization” or “intelligence” of a building, a district or a city has gained remarkable popularity over the last few years. However, no internationally agreed definition of such concepts have been established, although the term “intelligence” has been often used in the past (Wong & Li, 2009). The term “smartness” is more recent, and was adopted by the EPBD (Recast, 2010) as a key effort to improve the efficiency of the energy markets. Ghaffarianhoseini et al. (2018), explored the terms “intelligence” and “smartness” in the context of SBs and Smart Cities (SCs) and concluded that the two terms are complementary, as long as they have the mutual aim to optimize the performance and impacts of buildings and cities. Albino, Berardi, and Dangelico (2015), suggested that in the SC context, “intelligence” refers to the diffusion of ICT in the infrastructure, technological development, innovation, electronic and digital technologies, while “smartness” is not only limited to these, but also to the needs of the people and community.

SCs can be identified on several levels, including urban, social, political, transportation or building; in this research, we focus on the relationship between buildings, districts, and city infrastructures. According to Townsend (2013), there are two perspectives on SCs; first, they enable real-time monitoring, efficient management, enforcement of public safety and security using ICT infrastructure; and, second, they allow technology-inspired innovation, creativity, and entrepreneurship on the part of smart people. Several definitions on SCs were reviewed, for instance in Dameri (2013), SC was described as a well-defined geographical area in which ICT, logistics and energy production work together to create benefits for citizens in terms of well-being, environmental quality, and intelligent development. On the contrary, the definition of SC by Caragliu, Del Bo, and Nijkamp (2011), and Morvaj, Lugaric, and Krajcar (2011), focused on the utilization of networked infrastructure, the inclusion of urban residents in public services, high technologies, RES and building automation systems integration, which work together synergistically to improve conveniences, conserve energy and deploy resources effectively and efficiently.

In a smart environment, several components work together, such as Smart Homes, Smart Buildings, Smart Grids and Smart Meters (SM): all these elements are essential in forming a SC (Fig. 2). In this paper, we focus on the SB environment within a SC and its infrastructure. According to the U.S. Department of Energy (Energy, U. D., 2018), SG is described as an advanced electric power grid infrastructure that uses digital technology to improve efficiency and enhance reliability and safety through automated control, sensing and metering technologies through the smooth integration of renewable and alternative energy sources; while SMs are claimed to be advanced energy metering systems that allow bidirectional communication of data and enable the collection of information about the electricity fed to the power grid from customer premises and the execution of control commands remotely and locally (Depuru, Wang, Devabhaktuni, & Gudi, 2011; Zheng, Gao, & Li, 2013).

Although the concept of SBs originated in the’ 80 s (Sinopoli & Sinopoli, 2010), its application and importance were emphasized in the revised EPBD and were identified as a key enabler for the future energy systems, where they allow a larger share of RES, energy flexibility and distributed supply (European-Commission, 2019a). Until now, there is no commonly accepted definition on SB. According to the European-Commission (2019b), and Morvaj et al. (2011), it was claimed that a SB can manage and control RES, adapt to the grid conditions, communicate with other buildings, and actively respond in an efficient manner to any changing conditions in relation to the operativeness of the technical building systems or the external environment and the demands from the building occupants; while De Groote, Volt, and Bean (2017) defined a SB as a highly energy-efficient building that covers its very low energy demand by on-site or district system-driven RES, and is able to (i) stabilize the decarbonization of the energy system through energy storage and demand-side flexibility; (ii) empower its users with control over the energy flows; (iii) recognize and react to the users’ needs in terms of comfort, health and safety, as well as operational requirements. Based on the numerous definitions reviewed on SC, SM, SB, and SG, it is recognized that there is a notable overlap between the reviewed definitions; therefore, the definitions most representative of the objective of this paper have been summarized in Table 1.

Therefore, the SB concept can be classified into four main thematic groups:

1 Achieving the nZEB standard.
2 Buildings’ response to the external condition (grid and climate).
3 Buildings’ response to the user’s needs.
4 Utilization of Building Energy Management Systems (BEMS) to provide monitoring, control, and supervision.

Building retrofit or renovation has been defined by the U.S. Department of Energy (2019), as an opportunity for existing buildings to upgrade their energy performance for their ongoing life. Some attempts to define SR have been made in the literature. In the Amsterdam Institute for Advanced Metropolitan Solution project (van Vliet & de Feijter, 2019), SR has been defined as “restructuring of existing housing stock to increase buildings’ resource efficiency and resource generation capacity involving a structural change in energy and informational flows, actor relations, governance arrangements, and consumer practices”. However, based on the review made previously on “smartness” and SBs’ features, it should be noted that the definition provided by van Vliet & de Feijter (2019) lacks many aspects, such as the building interaction with the grid and the building response to the climate and its occupants’ needs. In the context of this study, we define SR in buildings as the “Process to transform the existing building into a SB, that is a nZEB with the capability to respond to the changing conditions of

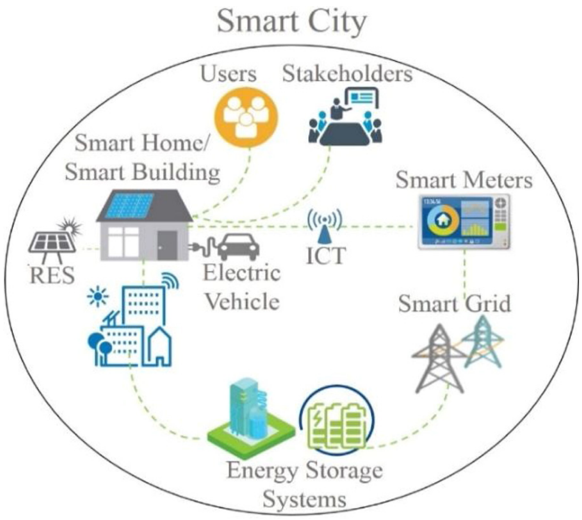

Fig. 2. Smart City Components.

Table 1
Definitions of Smartness in the Built Environment.

Term	Definition
Smart City	Networked infrastructure coupled with high technologies, creative social and environmental industries, that focuses on achieving sustainability. It is composed of ICT, SBs, smart infrastructures (SG and SM), energy storage systems, RES and building automation systems.
Smart Meter	Bidirectional communication that allows to collect data on the electricity fed to the power grid (SG) from customers, to execute control commands and to measure the energy usage, to then provide such data to the providing company for a better monitoring and billing.
Smart Building	A nZEB that is able to manage the amount of RES in the building and the SG, through advanced control systems, SM, energy storage and demand-side flexibility. Also, it reacts to the users' and occupants' needs and is able to diagnose faults in building operations.
Smart Grid	Advanced electric power grid infrastructure for improved efficiency, enhanced reliability and safety, through automated control, sensing, and metering technologies with smooth integration of RES, number of distributed generation and storage resources.

climate and grid, communicate with the user and predict failures in its operations, through the use of ICT, RES, and BEMS".

3. Smart buildings' basic features and technologies

In the context of this study, according to Lê, Nguyen, and Barnett (2012), SBs have the following five fundamental features:

- *Automation:* the ability to accommodate automatic devices or perform automatic functions.
- *Multi-functionality*: the ability to allow the performance of more than one function in a building.
- *Adaptability*: the ability to learn, predict and satisfy the needs of users and the stress from the external environment.
- *Interactivity*: the ability to allow the interaction among users.
- *Efficiency*: the ability to provide energy efficiency and save time and costs.

In an attempt to measure the performance of SBs, the EPBD developed the SRI, that measures the capacity of buildings to adapt their operation to the needs of the grid and the occupants (Rochefort, 2019). The three key functionalities of the smart-readiness indicator in buildings are (Verbeke et al., 2017):

- Readiness to adapt in response to the needs of the occupants and to empower building occupants to take direct control of their energy consumption.
- Readiness to adapt in response to the needs/situation of the grid.
- Readiness to facilitate the maintenance and an efficient operation of the building in a more automated and controlled manner.

Based on the reviewed studies, as a first attempt to identify and describe the SB's key features, the latter were categorized according to four main functions; they represent the macro-categories that describe the mandatory features that a SB must-have, as follows. It is important to note that the four functions work synergistically (Fig. 3).

1. **Climate Response**: the buildings' capability to respond to external climate conditions (actual and expected), according to which the building must identify the best operating profile. Buildings must be able to minimize their energy demand and generate renewable energy, in order to cover their energy consumption. The advancements of the Internet of Things (IoT) and control systems made it easier to obtain weather data (actual and forecasted). For instance, implementing sensors in all the components, such as the building's HVAC, lighting and solar shading system, and connecting them to BEMS will facilitate the connection with the external weather forecast services. Section 3.2.1 elaborates on the application of BEMS for weather forecasts.
2. **Grid Response**: the buildings' action/reaction to signals/information coming from the grid, usually with the aim to maximize the energy/economic efficiency at district/city-scale (e.g. reduce grid overload, consume energy when there is maximum availability thereof and the price is lower, etc.). The key components of a SG are renewable generation, advanced metering infrastructure, and data exchange. The SG emphasizes the maintenance of an interaction with the users, including power consumption and dynamic pricing; that in turn is achieved through the deployment of various Demand Side Management (DSM) strategies (Hussain & Gao, 2018). The complete integration of DSM requires communication systems and sensors, automated metering, intelligent devices and specialized processors (further details about DSM are discussed in Sections 3.1.2 and 3.1.4).
3. **User Response**: the capability of a building to enable a real-time interaction between users and technologies implemented. As claimed by Ponds, Arefi, Sayigh, and Ledwich (2018), the user interacts with the BEMS to automatically create optimal load operation schedules, different priorities and specify their comfort settings. BEMS enable end-users to interact with the automated energy systems and support the switch from energy consumer to an active role, as co-provider (Geelen, Reinders, & Keyson, 2013). In addition, real-time interaction is also achieved through Demand Response (DR) strategies in DSM (Alejandro Gomez Herrera, 2017), which links the price variations (or incentives) to the users' priorities.
4. **Monitoring and Supervision:** the capability to carry out a real-time monitoring of the building operation or, rather, of its technical systems and the users' behaviour; it has the double aim to ease the aforementioned features (1–3) and to also allow an efficient operation (e.g. predictive maintenance, real-time identification of faults/unexpected behaviours, etc.). Granderson (2011) and Erkoreka, Gorse, Fletcher, and Martin (2016) claimed that monitoring and data analyses are essential for an appropriate commissioning and performance tracking, due to the performance gap between predicted (e.g. design phase) and measured energy consumption.

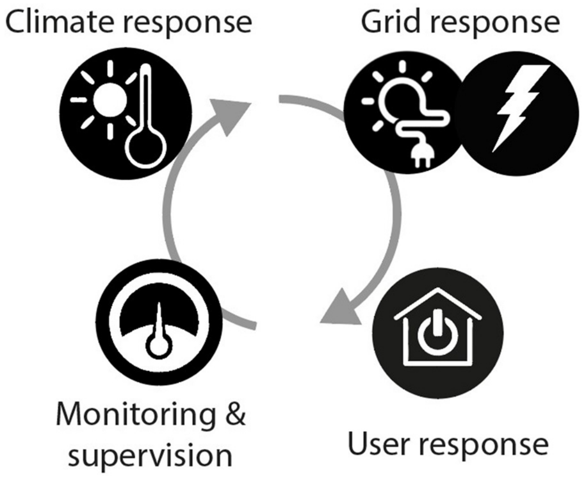

Fig. 3. Smart Buildings basic functions.

Table 2
Smart Buildings features and Characteristics.

Basic Feature	Ref.	Smartness Features/ Technology	Important Characteristics/Functions	Quantified Benefits of Smartness Features
Climate Response	(Oldewurtel et al., 2010)	● Stochastic Model Predictive Control (SMPC) strategy.	● Controller uses weather predictions to select cost-effective energy sources to keep room temperature in the required comfort levels.	● MPC resulted in a theoretical saving of 40 % of the total energy consumption.
	(Zhang, Wan, Ng, & Yang, 2018)	● Online Model Predictive Control (MPC).	● Integrates building thermodynamics, occupancy data, weather forecast and HVAC component for energy reduction and stabilizing temperature.	● 18.2 % energy saving with different temperature regulation settings.
Grid Response	(Halvgaard, Niels Kjølstad, Madsen, & Jørgensen, 2012)	● Real-time electricity pricing and applying Economic Model Predictive Control (MPC).	● Economic MPC for controlling heat pumps using day-ahead electricity prices. ● Load shifting to periods with low electricity prices.	● Optimized operating strategy saves 25 – 35% of the electricity cost compared to the baseline case.
	(Javed et al., 2017)	● Intelligent Sensor Nodes for HVAC. ● Random Neural Network (RNN)-controller.	● Inputs for the RNN model are: 1) heating set point; 2) cooling set point; 3) heating error, 4) cooling error, and 5) CO2 concentrations.	● The total energy saving with the RNN controller is 27.12%.
User Response	(Jazizadeh, Ghahramani, Becerik-Gerber, Kichkaylo, & Orosz, 2014)	● User-BMS communications and fuzzy predictive model.	● HVAC system based on occupants' comfort profiles. ● Sensing approach for user-BMS communications ● Learns user's comfort profiles, using a fuzzy predictive model.	● User control modes showed a 39 % reduction in daily average airflow rates of HVAC (compared to the conventional system).
	(Sembroiz, Careglio, Ricciardi, & Fiore, 2019)	● Wireless Sensor Network (WSN). ● BMS.	● Identify the optimal locations for different sensor types and gateways.	● BEMS increases the overall occupant comfort by 2.2% with respect to the base case and saves 19% of the energy.
Monitoring and Supervision	(Shen, Xue, Newsham, & Dikel, 2017)	● Monitoring, measurement, and verification. ● HVAC system fault detection and diagnostics.	● Fault detection or inappropriate operations of the HVAC system, and reminders to the building operators to address these issues.	● Four pilot buildings showed an average energy saving of 15 %, with a payback of less than 12 months.
	(Liu et al., 2018)	● Distribution system operators in the distribution network. ● Building energy scheduling agents.	● SB coordination and aggregation method reduces building electricity costs and satisfies all distribution system operating constraints.	● Bi-level building load aggregation methodology resulted in an electricity cost reduction of 13% through a price-based MPC algorithm.

Each of these functions is analyzed in detail in the next sections of the work, to set out the basic features and technologies of a SB. In detail, Table 2 reviews some representative studies, with quantified benefits, and categorizes them considering the basic features, elaborates the smartness features, and highlights the achievable results.

Based on the reviewed studies, it should be noted that several technologies need to be implemented as fundamental requirements of SBs, such as BEMS and advanced control strategies, SMs and RES. This table presented the key studies on the characteristics of SBs with quantified benefits; however, many other studies explored the implementation of the aforementioned features without giving quantified results, such as Qureshi and Jones (2018), Xu et al. (2012), Hadri et al. (2019). Therefore, quantifying the benefits of the added smartness features is crucial for a performance evaluation.

According to the review carried out, a schematic representation was developed in Fig. 4 to highlight all the basic features, functions, technologies, and interfaces that define the smartness in a building, based on the four functions previously suggested. Based on the proposed logic, SBs respond to external conditions (climate and the grid) and internal conditions (user) and provide monitoring and supervision in the building. There are four basic features of the SB; the nZEB target, flexibility, real-time interaction and real-time monitoring. Technologies within the nZEB target are connected to flexibility (explained in detail in Section 3.1.2) and to DSM; while flexibility is a feature that takes data from climate, user, and grid and gives an outcome of DSM with different strategies to respond and reduce the in-building demand and load. The Energy Storage System (ESS) (explained in detail in Section 3.2.3) is also a technology connected to the DSM in order to store the energy from RES, and is managed by control systems in the building. Real-time interaction and real-time monitoring are connected to control systems through the internet and through sensors and actuators, respectively, to ensure user interaction, operativeness and the diagnosis of all the technologies and smart features within the building. Control systems (explained in detail in Section 3.2.1) in a SB are local and cloud-based, consisting of classic and computational control systems, respectively. Details on the main components in this schematic illustration are presented in the following sections.

3.1. Basic features

3.1.1. Nearly zero energy buildings target

The EPBD recast had set a target of achieving nZEBs for all new buildings in Europe by the beginning of 2021 (Recast, 2010). The implementation of RES to reach nZEBs has been stressed in several studies to reduce both energy consumption and CO_2 emissions (Pikas, Thalfeldt, & Kurnitski, 2014; Morelli et al., 2012; Aste, Adhikari, Del Pero, & Leonforte, 2017).

Functions: it is agreed that, in order to achieve nZEBs, three main steps must be implemented; application of passive strategies, energy-efficient technologies (efficient heating, cooling, and lighting), and then RES integration J, K. et al. (2011), Kurnitski et al. (2011) and Karlessi et al. (2017) stated that the successful implementation of nZEBs does not focus only on energy-efficient measures and the adoption of RES, but also considers the grid integration, in order to achieve the appropriate balance between consumption and production. Thus, for a proper interaction, the building must be integrated with smartness features to

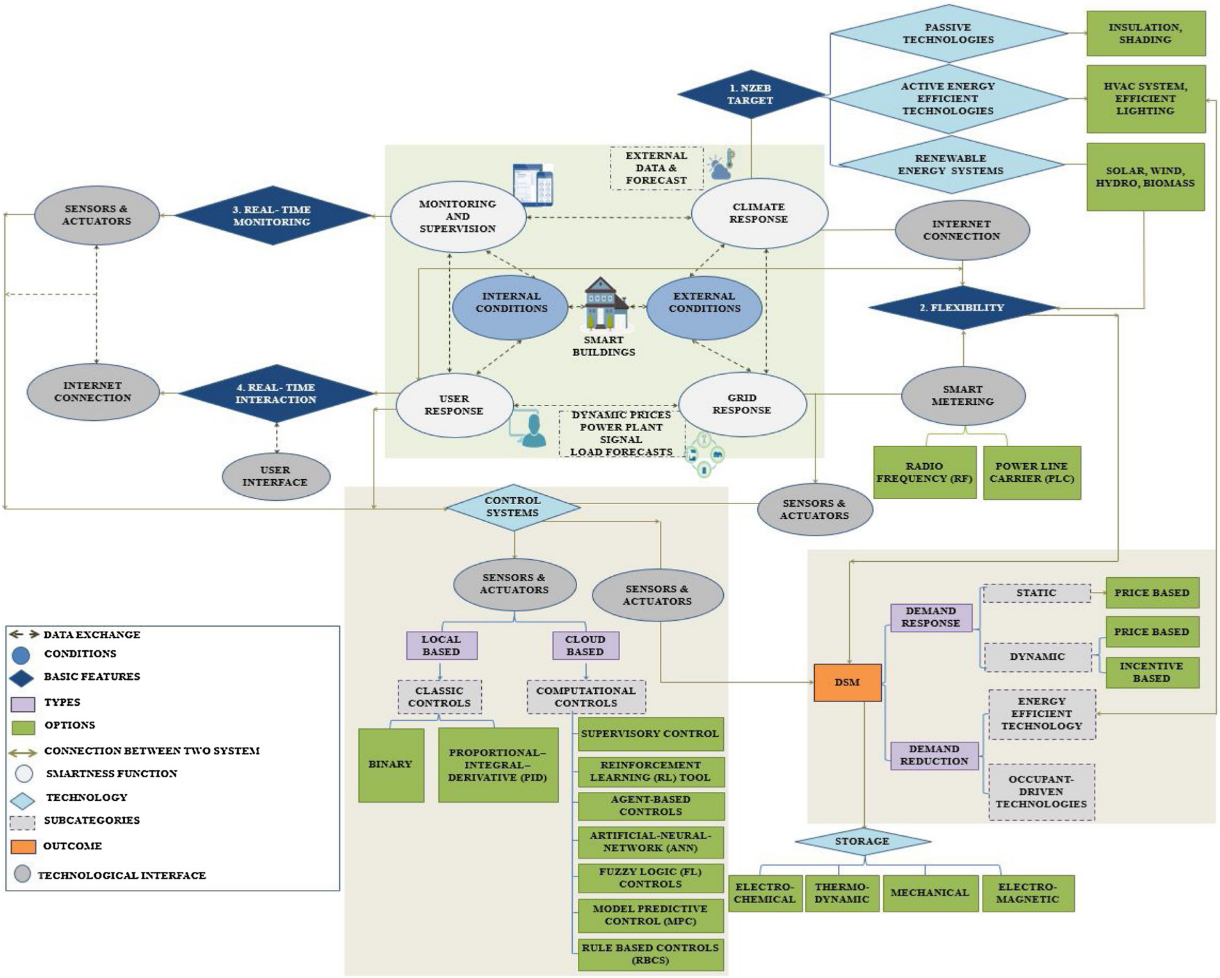

Fig. 4. Smart Buildings features, functions and technologies.

be able to manage and program the surplus amount of RES. The relation between nZEBs, smart features and technologies is a process that requires an integrated design approach, in order to achieve the target of SBs and SCs. Claudi (2018) highlighted that the interaction between nZEBs building and SGs is one of the main aspects of SCs. This target is a fundamental requirement for a SB, since it will ensure energy efficiency in buildings, and prepare the building for the integration with the SG, the response to users and the application of control strategies.

Outcomes: apply cost-optimal solutions to achieve energy efficiency and reduce GHG emissions.

3.1.2. *Flexibility*

The increased share of RES integration in buildings goes in parallel with the electrification goal and the decentralized electricity production. However, this has caused limited controllability of the energy supply and increasing load variations in the course of the day. Therefore, flexible energy systems have been developed as a solution to these issues. The International Energy Agency (IEA) Jensen and Henrik (2017) introduces the concept of ‘Energy Flexible Buildings’ with the project ‘Annex 67’. Building Energy Flexibility is defined by Jensen & Henrik (2017) as, “the capacity of a building to manage its demand and generation according to local climate conditions, user needs, and grid requirements”.

Functions: the building’s ability to provide energy flexibility is influenced by several factors, as suggested by (Reynders, 2015): (1) its physical characteristics, such as thermal mass, insulation, and architectural layout; (2) its technologies, such as ventilation, heating, and storage equipment; (3) its control system, that enables user interactions; the possibility to respond and react to external signals, such as electricity cost or CO_2 factors; and (4) the user’s behaviour and the comfort requirements. The application of energy flexibility in buildings have been studied by several authors. The majority of studies focus on the flexibility of heat pumps, hot water storage, thermal energy storage that contribute to shifting electrical loads (Hewitt, 2012; Arteconi, Hewitt, & Polonara, 2012; Masy, Georges, Verhelst, Lemort, & André, 2015). Other studies have shown that the structural thermal mass can be utilized to achieve flexibility in residential buildings (Le Dréau & Heiselberg, 2016; Reynders, Nuytten, & Saelens, 2013). Moreover, the use of control systems was applied in the majority of studies when addressing the potential of load shifting and achieving flexibility in buildings (Široký, Oldewurtel, Cigler, & Prívara, 2011; Tahersima, Stoustrup, Meybodi, & Rasmussen, 2011).

Outcomes: DSM is the outcome of flexibility and real-time interaction (Section 3.1.4) in SBs. DSM has two main functions; first, to integrate with the user, and second, to integrate with the external environment. In relation to flexibility, it has been claimed by (Gabaldon et al., 2003) that smart grids are based on the use of DSM, which includes the system operation, the minimization of peak demand and planning improvement. As reported by Parrish, Gross, and Heptonstall (2019) and Mahin, Sakib, Zaman, Chowdhury, and Shanto (2017), DSM is categorized into demand reduction and DR. Demand reduction focuses on electricity saving through the implementation of energy-efficient equipment and user behavioural change (achieved through real-time interaction) (Mahin et al., 2017), while DR is the change in electricity use by end-use customers from their regular consumption patterns, in response to price changes (Hussain & Gao, 2018). Therefore, DR can be achieved through flexibility and real-time interaction. The Smart Grid is able to achieve energy measures, peak load shaving, improve the efficiency of the grid, and reduce the need for power investments through DR. According to Hirsch, Parag, and Guerrero (2018), DR facilitates power consumption reduction, saves energy, and maximizes capacity utilization of the distribution system’s infrastructure, by reducing or eliminating the need to build new lines and expand the system. DR strategies could be categorized according to the following three aspects (Sun & Hong, 2017); 1) Peak clipping (explained in Section 3.1.4), 2) Valley filling and 3) Load shifting.

- Valley Filling describes the increase in the demand during off-peak periods, while having the same load peak (Attia, 2010). Its main function is to increase total energy consumption, while the peak demand is kept fixed, and allow off-peak energy consumption through energy storage devices (Deng, Yang, Chow, & Chen, 2015). It can be achieved by reducing the number of operating hours of baseload plants.
- Load Shifting ensures the shifting of part of the demand at the peak period to the off-peak periods without reducing the users’ total energy consumption during any day (Deng et al., 2015). It is achieved through Time of Use (TOU) rates and/or use of storage devices that shift the timing of conventional electric appliances operation (Attia, 2010). It shifts the load to a cheaper billing period if consumption cannot be reduced, and allows to remotely program an appliance, by means of its timer (Law et al., 2012).

3.1.3. *Real-time monitoring*

The real-time monitoring feature is related to the monitoring and supervision function. It is connected to the control systems and uses sensors/actuators to collect, analyze and monitor the data and energy consumption in the building. (Marinakis, Karakosta, Doukas, Androulaki, & Psarras, 2013) defined “real-time monitoring” as a tool that organizes and statistically analyzes data sets on the energy use in buildings and their energy efficiency and economic performance.

Functions: in real-time monitoring, data is collected, analyzed and stored, and then it is ready for the real-time interaction with users and the external building conditions (Marinakis et al., 2013). Thus, real-time monitoring collects information to monitor the behaviour of a building and to allow a predictive maintenance. Yang et al. (2015) stated that the application of real-time monitoring can also be achieved through the Decision Support System (DSS), which has a data-collection module, a data-processing module, and a data-analyzing module. DSS predicts the power demands from consumers, which can allow for the optimization of the scheduling of power supply. The data collected from distributed power grid units and the knowledge of experts in the domain concur to define the measures for evaluating the success of the activities in the power grid (Yang et al., 2015).

Outcomes: real-time monitoring identifies faults and anomalies and puts in place the corresponding actions. Moreover, it determines how much energy is being saved in buildings, and therefore supporting policies could provide subsidies and incentives that are proportional to the energy savings achieved.

3.1.4. *Real-time interaction*

The real-time interaction feature is related to the user’s interaction with external services (weather and grid conditions) and building technologies. Balandin et al., 2014 indicated that real-time interaction allows the collection of users’ feedback through a task-based interaction between the user and the building. Additionally, users can experience real-time interaction with the SB and have an overview of the functionalities of smart technologies.

Functions: real-time interaction includes several components, such as internet connection, sensor/actuators and a direct connection to the users. The collection of real-time data on occupants and weather forecasts was used for prediction in building automation (Stunder, Sebastian, Chube, & Koontz, 2003). Rinaldi et al. (2016) tested the relationship between users and SBs in a project, using a bi-directional interaction via a mobile application. The app is supported by sensors used to monitor and control comfort, indoor air quality, and HVAC parameters. The data is used to create real-time charts on user interaction and to allow easy access to the building status or to allow building automation systems (e.g. lighting systems control, HVAC system control, etc.).

Outcomes: it was suggested by Lertlakkhanakul, Choi, and Kim (2008) that real-time interaction results in shifting the user’s role from being a passive receiver to becoming an active actor. As mentioned earlier, DSM is also the outcome of real-time interaction, through which it allows the planning and implementation of activities designed to impact the customer's use of electricity (Gelazanskas & Gamage, 2014). Mahmood et al. (2014) and Yahia and Pradhan (2018) suggested that in DSM users are encouraged to consume less power during peak times, or shift their energy use to off-peak hours, to flatten the demand curve. Peak Clipping DR Resource (PCDR) strategy in DSM reduces peak energy consumption to stop the load from exceeding the supply capacity of the distribution substations (Sun & Hong, 2017). It supports loads with flexible procedures, such as residential loads and loads with onsite generation units (Behrangrad, Sugihara, & Funaki, 2010). It can be achieved when users shift some of their activities to another time and reduce their electric consumption.

3.2. Technologies

In SBs, several technologies must be present in order to facilitate the application/use of smart features. Based on literature, the main key technologies related to the functions of SBs are classified in Fig. 5.

3.2.1. Control systems

Building automation is a complex, multidisciplinary topic, that in literature has been introduced by several terms, such as Building Automation System (BAS), Building Automation and Control System (BACS); Building Management System (BMS), Building Energy Management System (BEMS); Energy Management and Control System (EMCS); and Home Energy Management System (HEMS). However, it must be noted that, despite the presence of several names and definitions, the main aim of these is to report the building performance, decide actions, and control the decided actions, with the goal of saving energy and costs and reducing environmental impacts. In this paper, to discuss control systems in SBs we selected the acronym BEMS.

The integration of advanced ICTs increases the efficiency of the SB, by providing more automation, a reliable forecast of grid and weather, and a better operation of electrical appliances, resulting in higher energy quality and increased user satisfaction (Lobaccaro, Carlucci, & Löfström, 2016). BEMS is the physical element needed to reach the real-time interaction and flexibility in buildings. It is composed of hardware and software:

- The hardware element in the BEMS consists of technologies such as sensors, actuators, user interface screens, CPU components, connections and monitoring tools.
- The BEMS software provides the CPU operating logic, control system, alarms, user software, and DSS.

As suggested by Levermore (2000), the main communication channel for the operator in the BEMS is the hardware, which allows energy monitoring, integration with utilities and smart grid technologies through DSM, and ensures resilience and security. BEMS is responsible for monitoring and controlling the mechanical and electrical equipment of a building, such as lighting, HVAC, Domestic Hot Water (DHW), shading systems control, fire systems, onsite power generation, security systems and abnormal levels of energy use (Sayed & Gabbar, 2018), (Ock, Issa, & Flood, 2016).

Chen, Chou, Duri, Lei, and Reason (2009) stated that BEMS are integrated into several parts of the building and use dynamic information about the users' activities (e.g. location), ambient conditions (e.g. weather, light), and energy supply conditions (e.g. cost, load). Generally, control systems are classified into; conventional control systems (Kasahara, Matsuba, Kuzuu, & Yamazaki, 1999), (Mathews, Arndt, Piani, & Van Heerden, 2000), and advanced or computational control systems (Oldewurtel et al., 2012). However, in SBs, the use of advanced control systems is more relevant, since they allow the interaction with external and internal conditions. Javed et al. (2017) pointed out that two technical approaches of HVAC control are available: physical model-based techniques (such as model predictive control) and black-box techniques (such as RNNs, artificial neural networks [ANNs], and support vector machines). According to Oldewurtel et al. (2012), Killian and Kozek (2016) and Ma et al. (2012), the most common way to respond to the external climatic condition is through the implementation of MPC. It provides optimal predictions of future disturbances, such as ambient temperature, solar radiation, occupancy, and presents the ideal control strategy to deal with conflicting optimization goals.

3.2.2. Renewable energy systems

The integration of RES in the power system of buildings has been extensively studied to achieve nZEB target to cover a substantial amount of energy, increase energy savings and reduce costs (Attia et al., 2017). The RES contains programmable sources, such as biomass, which can be stored and used anytime, and non-programmable energy sources, such as wind and solar production. Therefore, the RES that can be installed on SBs are Photovoltaics (PV) (Ma et al., 2016), solar thermal collectors (Buker & Riffat, 2015), pumped hydro energy (de Oliveira, Silva, & Hendrick, 2016), mini wind turbines (van Bussel & Mertens, 2005), and biomass (Michopoulos, Skoulou, Voulgari, Tsikaloudaki, & Kyriakis, 2014). It should be noted that high production of PV and wind power must be linked to flexibility and DSM strategies, since their profile must be predetermined with sufficient anticipation in order to ensure the reliability of energy dispatching.

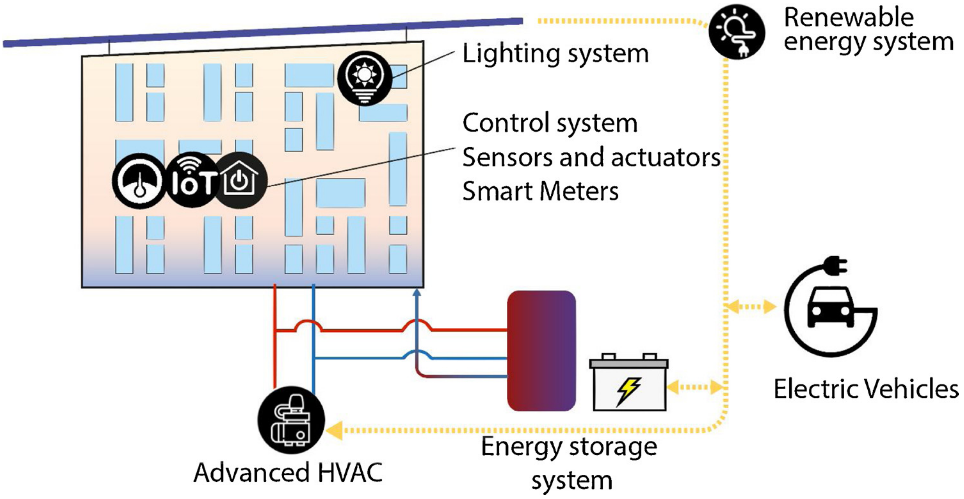

Fig. 5. Key Technologies in Smart Buildings.

3.2.3. *Energy storage systems*

A successful coordination between RESs and power systems plays a vital role in allowing ESSs to improve the reliability, security, and resiliency of micro-grid applications. Storage is identified as the technology that has the ability to capture energy and release it later for consumption (Gupta, Bruce-Konuah, & Howard, 2019). According to Zame, Brehm, Nitica, Richard, and Schweitzer III (2018), ESS provides remarkable opportunities to improve the efficiency and operation of smart buildings. Roberts & Sandberg (2011) wrote that a smart grid, coupled with energy storage systems, increases flexibility. The integration of ESS during peak load periods is also useful to shift electrical demands from on-peak to off-peak (Worighi, Maach, & Hafid, 2015). Moreover, the use of energy storage technologies allows a reduction in the demand side and saves surplus energy in batteries/thermal storages. Lizana, Friedrich, Renaldi, and Chacartegui (2018) stated that energy-flexible buildings which have electric heating, demand-side management, and efficient thermal energy storage represent one of the most promising strategies for carbon reduction. Storage systems are managed based on energy prices; when the price is low, the battery is charged, while when the price is high the battery is discharged (Guo, Pan, Fang, & Khargonekar, 2013). Römer, Reichhart, Kranz, and Picot (2012) pointed out that there is a wide range of storage technologies that have different capacities and speed and time of response. Additionally, energy storage allows energy resilience, through which it can balance and respond to changes in energy demand and supply.

On the other hand, based on the revised EPBD (European-Commission, 2019b), there is an evident link between electric mobility through Electric Vehicles (EVs) and SBs. EVs act as generation/storage devices or an additional element of flexibility to provide energy and capacity to the building and enhance power supply (Guille & Gross, 2009). EVs stay connected to the grid once they are parked, therefore they deliver the energy from their batteries, which can store and release energy in different conditions. The RES can be used to charge the EVs, and when the energy production is higher than the total demand, the EV charges the batteries, while, when the building does not have enough energy, the EV release the stored energy to supply the building (Wang, Wang, Dounis, & Yang, 2012).

3.2.4. *Advanced HVAC and lighting systems*

HVAC systems are considered to be the most demanding systems in the building, with a share of around 50 % of the world total building energy consumption (Korolija, 2011). SBs are able to provide energy-efficient and responsive lighting system that uses ICTs. Energy-efficient HVAC and lighting technologies are fundamental parts of the active strategies to achieve the nZEB target, as illustrated previously in Fig. 4. Unlike conventional HVAC systems, in SBs HVAC systems are integrated with the ESS technology (Fiorentini, Cooper, & Ma, 2015), BEMS (Mirinejad, Sadati, Ghasemian, & Torab, 2008), ICTs (Serra, Pubill, Antonopoulos, & Verikoukis, 2014), and DSM programs (Cai et al., 2018) in order to manage its consumption, reduce peak load and achieve the nZEB target. SBs' HVAC systems also allow building occupants and operators to have more control and are able to adjust and adapt intuitively according to the users' profile, preferences and needs, using real-time weather forecast and grid data through MPC (Bhutta, 2017). Smart Lighting is also claimed to be integrated with the BEMS system to allow information exchange, optimization, and supporting built-in occupancy sensors and logic systems to automatically adjust their luminance with respect to time and occupancy (Bhutta, 2017). Moreover, it is controlled through wireless control units to provide dimming, on/off control, and it changes the intensity of its glow (Delaney, O'Hare, & Ruzzelli, 2009). The integration of smart lighting systems with advanced shading systems and BACS has been also tested and showed higher energy savings, more daylight penetration and increased user satisfaction (Selkowitz, Lee, & Aschehoug, 2003; Martirano, Manganelli, Parise, & Sbordone, 2014).

3.2.5. *Sensors and actuators*

Sensors and actuators are technological interfaces in SBs that are connected to features, functions, and technologies such as DSM, storage systems, real-time monitoring, and BEMS. (Aste, Manfren, & Marenzi, 2017) defined sensors as devices that measure physical quantities and then convert them into digital signals. Conversely, actuators are used in control systems in two ways; first to manage information from sensors and actuate their control function directly, and second to deliver data from sensors to the supervisory control layer. Sensors and actuators have been used for occupancy detection and behavioural modeling in buildings (Jia & Srinivasan, 2015); monitoring data in the SG (Kayastha, Niyato, Hossain, & Han, 2014), lighting control (Labeodan, De Bakker, Rosemann, & Zeiler, 2016), BEMS (Doukas, Patlitzianas, Iatropoulos, & Psarras, 2007), predictive control and energy storage systems (Biyik & Kahraman, 2019), etc. According to (Stankovic, 2008), the use of wireless sensors and actuators for building auditing and controlling presents a viable solution over traditional building monitoring and actuating systems. Sensors and actuators facilitate the application of ICTs in SBs and the connection to the BEMS of all technologies and equipment in the building.

3.2.6. *Smart meters*

SM – another important technological interface connected to the BEMS – promotes communication between the smart grid and the buildings. In particular, between the energy consumer, meter operator, supplier of energy or utility and meter data management systems (Zivic,

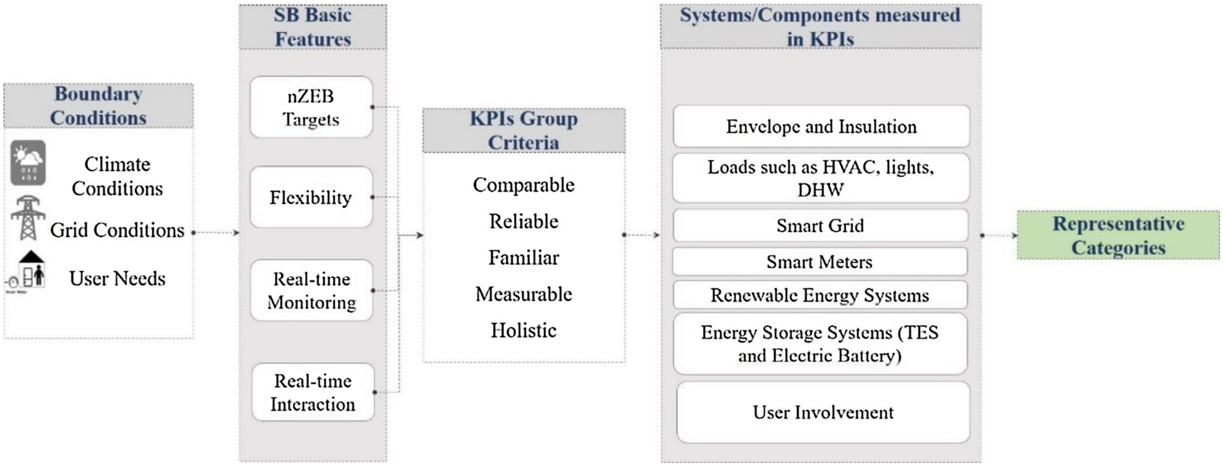

Fig. 6. Smart Buildings Key Performance Indicators Framework.

Table 3
Definitions and References of KPIs in Smart Buildings.

SB Basic Features	Supporting KPIs (Units)	Definitions	References
NZEB target Climate Response, Grid Response	**Primary Energy** (kWh/m^2)	Encompasses all the primary available energy that is consumed in the supply chains of the used energy carriers.	(SCIS, 2017); (European-Commission, 2018a); (Pezzutto, Haas, Exner, & Zambotti, 2018); (Green_Building_Council_Italia, 2019); (Ferrante, Mochi, & Nieboer, 2016); (Pasut, 2019)
	Energy Demand And Consumption (kWh/(m^2.month or year))	Assess the building energy demand and consumption.	(Salom, Marszal, Widén, Candanedo, & Lindberg, 2014); (SCIS, 2017); (Abu Bakar et al., 2015)
	Energy Savings (%)	Percent reduction of energy consumption compared to the baseline case.	(Bosch et al., 2017); (SCIS, 2017); (Liu, W, L., J, L., B, & W., 2010); (Zhang, Shah, & Papageorgiou, 2013)
	Global Energy Performance Indicator (kWh/m^2)	Indicator gives the numeric value, under reference conditions, of the building's energy consumption and refers to the consumption of non-renewable energy sources, like the gas used for heating the building or producing hot water.	(Costanzo, Martino, Varalda, Antinucci, & Federici, 2016); (Attia, 2018); (ENEA, 2017)
	Peak Load Reduction (%)	Compare the baseline peak demand with the peak demand after technology implementation.	(SCIS, 2017); (Chua, Lim, & Morris, 2017); (Kim, Shim, & Won, 2018); (Thanos et al., 2013)
	Degree of Energetic Self-Supply by RES (%)	The ratio of locally produced energy from RES and consumption over a period of time.	(SCIS, 2017); (Quijano, Vasallo, Gallego, Moral, & Egusquiza., 2016);
	Increased RES and Distributed Energy Resources hosting capacity (%)	The additional RES and energy resources that can be installed in the network, when new interventions are applied, and compared to the BAU scenario.	(Hormigo et al., 2014); (Etherden, 2014); (MacEdo, Franco, Romero, Ortega-Vazquez, & Rider, 2017); (Lubośny & Dobrzyński, 2016); (Bissell et al., 2014)
Flexibility Climate Response, Grid Response, User Response	**Storage Capacity** (%)	Available storage capacity of storage technologies integrated into the smart grid.	(Angelakoglou et al., 2019); (Del Pero et al., 2018); (Finck, Li, Kramer, & Zeiler, 2018); (Reynders, Diriken, & Saelens, 2017); (Silva, 2018); (Ibrahim, Ilinca, & Perron, 2007)
	Depth of Discharge (%)	Describes how deeply a storage system can be discharged to provide usable energy with respect to the reference conditions.	(Del Pero et al., 2018); (Cabeza, Galindo, Prieto, Barreneche, & Inés Fernández, 2015); (Haghigat, Tuohy, Fraisse, & Del Pero, 2019)
	Storage Efficiency (%)	The ratio between the discharged energy and the charged energy, typically over a full cycle.	(Reynders, 2015); (Niederhäuser & Rouge, 2017)
	Load Cover Factor (%)	The percentage of electrical demand covered by on-site electric generation.	(Stern, 2013); (Salom et al., 2011); (Tumminia et al., 2020); (Dávi, Castillo-Cagigal, Caamaño-Martín, & Solano, 2016); (Salom et al., 2014); (Verbruggen & Driesen, 2015)
	Maximum Hourly Surplus (kWh)	The maximum hourly ratio between on-site generation and load over the load for each energy type.	(Ala-Juusela, Sepponen, & Crosbie, 2014); (Salom et al., 2013)
	Maximum Hourly Deficit (kWh)	The maximum hourly ratio of the difference between load and on-site renewable energy generation.	(Ala-Juusela et al., 2014); (Salom et al., 2013); (Bosch et al., 2017)
	Demand Response (kWh)	Load shed potential of a device with respect to its rated power consumption during a DR event.	(Hormigo et al., 2014); (IRIS, 2018); (Arteconi & Polonara, 2018); (Yin et al., 2016)
	Load Shifting (%)	Load shifting potential for the considered DSM technology at a certain time step.	(Arteconi & Polonara, 2018); (Märzinger & Österreicher, 2019)
	Flexibility Factor (-)	Instant demand at high/low electricity price periods.	(Li & You, 2018); (Finck et al., 2018)
	Annual Mismatch Ratio (-)	The annual difference between demand and local renewable energy supply.	(Ala-Juusela et al., 2014); (Lund, Marszal, & Heiselberg, 2011)
	Load Matching Index (%)	The on-site energy use: it helps to differentiate between the different timescales.	(Voss et al., 2016); (Salom et al., 2014);(Dávi et al., 2016); (Salom et al., 2011); (Degefa, Lehtonen, McCulloch, & Nixon, 2016)
	Mismatch Compensation Factor (-)	The capacity of the PV or similar RES installation over the capacity of the installation for which the economic value of annual import and export of electricity is the same.	(Ala-Juusela et al., 2014); (Lund et al., 2011); (Athienitis & O'Brien, 2015)
	No Grid Interaction Probability (-)	The probability that the building is acting autonomously of the grid.	(Tumminia et al., 2020); (Salom et al., 2011); (Salom et al., 2014); (Dávi et al., 2016); (Verbruggen & Driesen, 2015)
	RES Self-consumption (Supply Cover Factor) (%)	The degree of instantaneous on-site renewable energy consumption	(Luthander, Widén, Nilsson, & Palm, 2015); (Fachrizal & Munkhammar, 2020); (Salom et al., 2011); (Prasanna, Dorer, & Vetterli, 2017)

(*continued on next page*)

Table 3 (*continued*)

SB Basic Features	Supporting KPIs (Units)	Definitions	References
Real-time monitoring Monitoring and Supervision	**Increased Power Quality and Quality of Supply** (%)	Average time needed for awareness, localization, and isolation of grid fault.	(SCIS, 2017); (Ignatova, Villard, & Hypolite, 2015); (Lubośny & Dobrzyński, 2016)
	Absolute Grid Support Coefficient (-)	Evaluate the grid impact of a building or its heating system	(Li & You, 2018), (Klein, Langner, Kalz, Herkel, & Henning, 2016);
	Relative Grid Support Coefficient (-)	Assesses the optimization potential for heating or cooling system operation.	(Li & You, 2018); (Klein et al., 2016);
	Building Operational Performance KPI (%)	Illustrates the performance of the building by relating the energy consumption, emissions, and geometrical information.	(Ioannidis et al., 2016)
	Reduction of energy price by ICT related technologies (%)	Measures the price of the energy traded by an aggregator, both with baseline and after ICT implementation.	(SCIS, 2017); (IRIS, 2018)
	Smart Ready Built Environment Indicator (-)	Assesses how smart-ready the building is and measures the performance of technologies.	(De Groote, Volt, Bean, Rapf et al., 2017)
	Smart Readiness Indicator (-)	A score that indicates the readiness of a building to adapt operations to the needs of occupant and also to optimize energy efficiency and energy flexibility.	(European-Commission & VITO, 2020); (Verbeke et al., 2017); (Rochefort, 2019)
	EU Energy Label (-)	The energy efficiency of appliances is rated based on a set of energy efficiency classes from A to G on the label, A being the most energy efficient, G the least efficient.	(European Commission, 2010), (European-Commission, 2020); (Provincia Autonoma di Trento, 2010); (European Commission, 2017); (Majcen, Itard, & Visscher, 2013); (van den Brom, Meijer, & Visscher, 2018)
	Reduced Energy Curtailment of RES and DER (%)	Reduction of energy curtailment due to technical and operational problems.	(SCIS, 2017); (IRIS, 2018); (Azpiri et al., 2015);
	Reduction of technical network losses (%)	Compares the technical losses of the baseline scenario against the ones from the smart grid scenario for a period of time.	(Hormigo et al., 2014); (IRIS, 2018)
	Increased reliability (%)	Avoids failures revert on higher reliability, meaning fewer stops on the normal operation of the building and associated systems.	(SCIS, 2017); (IRIS, 2018)
	Grid Interaction Index (%)	Describes the average grid stress, using the standard deviation of the grid interaction over a period of a year.	(Salom et al., 2014); (Voss et al., 2016); (Salom et al., 2011), (, Augus)
Real-time interaction User Response	**Consumer Engagement** (-)	Measures the involvement of users in the control over the energy use in the building.	(SCIS, 2017); (Lubośny & Dobrzyński, 2016)
	System Average Interruption Duration Index System (-)	Estimates the average interruption duration, which leads to disturbance for network users and maintenance costs.	(Hormigo et al., 2014); (Harder & Joosten, 2017); (Putynkowski et al., 2016); (Pramangioulis et al., 2019);
	System Average Interruption Frequency Index (-)	Estimates the average number of service interruptions detected by a typical end user in the network during a defined time.	(Hormigo et al., 2014); (Harder & Joosten, 2017); (Putynkowski et al., 2016); (Pramangioulis et al., 2019)

Ur-Rehman, & Ruland, 2016). According to Gungor et al. (2011), a smart grid system has two types of information infrastructure; first, the information flows from sensors and electrical appliances to smart meters, which is achieved through Powerline Carrier (PLC) or wireless communications (Radio Frequency), such as ZigBee, 6LowPAN, Z-wave; secondly, it flows between SM and the utility's data centers, which is achieved via internet-based solution. Three main benefits are expected from SM systems (Avancini et al., 2019): the availability of energy consumption information to users, which enables them to optimize their consumption, the ability to assess and control meters remotely, and the ability to reduce energy waste, since it can be automated to react to power shortages, failures, and excesses. Moreover, SMs are integrated into the BEMS and automatic functions are enabled when peak use approaches critical price thresholds or system constraints (Förderer, Lösch, Növer, Ronczka, & Schmeck, 2019).

3.3. *Key challenges in smart retrofitting application*

The previous review has shown the fundamental requirements, features and technologies in a SB. The integration of smart technologies in new constructions is always easier than in retrofit cases, since new buildings provide a greenfield and can adapt to the integrated systems. On the other hand, in SR applications it is important to highlight the key challenges that need to be considered. As mentioned earlier, SBs require to achieve nZEB target first, then to ensure a response to the changing conditions of climate, grid and users, and finally to predict failures through the utilization of technologies discussed. Achieving nZEB is a target for new buildings as well as for retrofit solutions; however, it should be noted that for retrofitting cases significant energy efficiency is not achieved only by envelope retrofitting (such as adding thermal insulation and windows replacement), but rather through the integration of these elements with active and renewable energy solutions (such as HVAC, efficient lighting and control systems). Therefore, for SR, the mechanical systems already existing in the building should be optimized in order to integrate properly with the new energy-efficient interventions. Ensuring a proper integration of energy-efficient HVAC is critical, since most building loads are caused by heating and cooling demand. Therefore, the existing heat pumps, fan coils, and thermal storage tanks must be evaluated and optimized properly, in order to integrate the new systems, while keeping the important parts of the systems that can be modified without demolishing the whole systems before retrofit.

Moreover, in SR cases the integration of RES must be accompanied with reliable forecasting methods, to estimate production and exchange profiles of non-programmable sources and facilitate the connection with the SG, SM, storage system through BEMS. The integration of BEMS in SR is very challenging and has many barriers. The first challenge is the technical barrier, due to which there is a lack of standardized solutions for BEMS requirements in existing buildings. Moreover, in SR it is important to install new technologies that must communicate

Table 4
KPIs Analysis.

KPIs	Interpretation
Primary Energy **Global Energy Performance Indicator (EP$_{gl}$)** **Energy Demand and Consumption** **Energy Savings**	● KPIs can be grouped since they measure the "overall building energy performance" (Group 1 - G1). ● These indicators are widely applied in literature, however, the "Primary Energy" can be considered as a more holistic indicator since it achieves the objective of this group of indicators and gives information about the heating/cooling loads and energy savings in the building. Moreover, this indicator has been widely studied in literature.
Demand Response **Peak Load Reduction** **Load Shifting** **Flexibility Factor**	● These indicators are responsible for "DSM assessment in SBs" (G2) and focus on measuring the peak load and the ability of load shifting. ● Among these, the "Demand response", "Load shifting" and "Peak Load Reduction" share common targets by which they measure the load shed potential of a device at a time step with respect to its rated power consumption, however, based on literature the "Demand Response" has been cited more. ● The "Flexibility Factor" measures the flexibility of a building with respect to the Low and high electricity periods and the heating power. However, this indicator has been tested in few studies and requires further investigation.
Degree of Energetic Self-Supply by RES **Increased RES and DER hosting capacity** **Generation** **Load Cover Factor** **RES Self-consumption (Supply Cover Factor)** **Maximum Hourly Surplus** **Maximum Hourly Deficit**	● These KPIs can be grouped since they assess the production, consumption, and installation of "RES in SBs" (G3). ● The KPIs share similar targets, according to literature, the most studied KPI is the "Load cover factor" which represents the percentage of the electrical demand covered by on-site electricity generation. ● Moreover, it is a more holistic indicator since it evaluates the on-site generation with respect to the storage, losses and building loads during the evaluation period.
Annual Mismatch Ratio **Load Matching Index** **Mismatch Compensation Factor**	● This group of KPIs shows the percentage between the onsite RES and the building load profiles which represents the "RES mismatch indicators" (G4). The most applied indicator in literature is the "Load Matching index" which compares the on-site generation with on-site demand, moreover it is considered as a more holistic indicator. ● Measuring the "Mismatch compensation factor" is applied in particular cases only since it considers measuring mismatch at aggregated level and not at each individual building level.
Grid Interaction Index **No Grid Interaction Probability** **Absolute Grid Support Coefficient** **Relative Grid Support Coefficient**	● These indicators monitor the "Grid interaction in SBs" (G5). To achieve this objective several aspects, need to be addressed. The "Grid Interaction Index" is important since it shows the variable amount of purchased or delivered energy for a given time resolution and it has been tested in several researches and thus shows reliability. ● The "No Grid Interaction Probability" is also an important indicator to has been also studied in several research and is important to indicate the time share when the local generation is insufficient to supply the local load. ● The later indicators have been tested in few studies and requires further investigation.
Storage Capacity **Storage Efficiency** **Depth of Discharge**	● These indicators measure the performance of the implemented energy storage system and can be combined as "Storage performance indicators" (G6). ● The most used indicators in literature have been collected such as the storage capacity, efficiency and depth of discharge, however, based on literature, these indicators still have unclear calculation methodologies and their definitions are often oversimplified, and must be further developed to consider the storage energy losses. ● Therefore, based on selected indicators from G3, G4 and G5, it would be better to calculate these indicators with and without storage to assess the obtainable benefit of storage system in buildings.
Smart Readiness Indicator (SRI) **Building Operational Performance KPI** **EU Energy Label** **Smart Ready Built Environment Indicator**	● This group of KPIs represents the attempt for "Building Operational Evaluation" (G7). These KPIs have been developed to evaluate the building performance or the smartness of technologies integrated in the building. ● However, most of these indicators such as the SRI, the Building operational performance, and the smart ready built environment KPI has not been tested yet, and therefore, does not show reliability. ● The Energy Label, which has been cited and used extensively, is a reliable building evaluation process and is fundamental for ensuring the performance of a building. Thus, it can be selected as a representative indicator for this group.
Reduced Energy Curtailment of RES And DER **Reduction of technical network losses** **Increased Power Quality and Quality of Supply** **Increased reliability**	● These KPIs measure the "Technical losses/failures" (G8) in grids and building systems. Based on literature, the most studied indicator is the "Reduced Energy Curtailment of RES and DER". The main purpose of this indicator is to minimize curtailment of the energy supplied by RES/DER generation due to technical and operational problems.
Consumer Engagement **System Average Interruption Duration Index (SAIDI)** **System Average Interruption Frequency Index (SAIFI)**	● These KPIs indicate the "Users' involvement" (G9) and the interruptions caused by them. "SAIDI" and "SAIFI" indicators have been studied extensively in the literature.

with the existing buildings without installing new wires. Therefore, the most optimal solution would be installing advanced control systems that are wireless, such as the ANNs and RNN, which are efficient, since they do not require removing existing structures to install wiring systems.

Furthermore, the application of energy flexibility in SR requires the optimization of systems (such as HVAC systems, storage systems, RES), as well as providing the connections with the SM and SG systems. Upgrading the existing meters with the SM system is challenged by the lack of supporting policies and regulation to set the methods and minimum requirements, and the need to encourage building owners and users to accept this shift.

4. Smartness indicators

Quantifying building energy performance through the development and use of KPIs is an essential step in achieving SB goals in both new and existing buildings. Thus, Specific metrics and KPIs are fundamental to support achieving energy efficiency in buildings. According to (Nelke & Håkansson, 2015), KPIs are a way of measuring the performance in an organization and its success in achieving goals. Jefferson, Hunt, Birchall, and Rogers (2007) claimed that indicator systems can provide measurements of the current performance and give a clear view of achievement in terms of future performance targets and progress.

4.1. Legislations on smartness indicators in buildings and cities

The need to develop policies and standards that enhance energy and technological innovation is a fundamental step for the increase of the smartness in the built environment. In the EU, several legislations, plans and projects have been developed to support and enforce the change towards smarter cities and buildings. At city level, ISO/TC268 for "Sustainable cities and communities" (ISO/IEC, 2015), is responsible for the ISO 37100 series of standards to help cities define their

Table 5
SBs Representative Assessment KPIs.

KPI Group	Most Cited KPI	Timestep	Equation	Remarks
G1. Overall Building Energy Performance	**Primary Energy** [kWh/m^2] (SCIS, 2017); (Pezzutto et al., 2018); (Green_Building_Council_Italia, 2019); (Ferrante et al., 2016); (Pasut, 2019)	Annual	$\sum E_{Ptot} = \sum_i E_{ren,i} + \sum_i (E_{del,i} f_{del,tot,i}) - \sum_i (E_{exp,i} f_{exp,tot,i})$ E_{Ptot} annual total primary energy [kWh/m^2] $E_{ren,i}$ annual renewable energy produced on site or nearby for energy carrier i [kWh/m^2] $E_{del,i}$ annual delivered energy on site or nearby for energy carrier i [kWh/m^2] $f_{del,tot,i}$ total primary energy factor for the delivered energy carrier i, [-] $E_{exp,i}$ annual exported energy on site or nearby for energy carrier I [kWh/m^2 a] $f_{exp,tot,i}$ total primary energy factor of the energy compensated by the exported energy for energy carrier i [-]	An important basic indication of building evaluation is the net primary energy consumed.
G2. DSM Assessment in SBs	**Demand Response** [%] (Hormigo et al., 2014); (IRIS, 2018); (Arteconi & Polonara, 2018); (Yin et al., 2016)	Hourly/ one Season/ one Year	$DR^p = \frac{P_h^{base} - P_h^{LS}}{P_h^{base}}$ DR^p hourly load shedding potential [%] P_h^{base} baseline hourly power consumption [kWh] P_h^{LS} hourly power consumption of a load using the DR profile [kWh] For each load (such as heat pumps, refrigerators, and air conditioners), two consumption profiles are calculated: the baseline setpoint profile, which is the load before DR solution and a DR setpoint profile which is the load after implementation of DR strategy (such as electricity price signal on the load profile or variable temperature set-point, etc.) in order to estimate the change in load within the hour h in which the DR event occurs.	DR is an important indicator for DSM by which positive DR potential refers to a “load shedding” capacity, while negative DR potential refers to an “overloading” capacity. In the case of comparison between two buildings, it must be calculated on one season or one-year basis.
G3. RES Assessment in SBs	**Load Cover Factor** [-] (Stern, 2013); (Salom et al., 2011); (Tumminia et al., 2020); (Dávi et al., 2016); (Salom et al., 2014); (Verbruggen & Driesen, 2015); (Prasanna et al., 2017) **RES Self-consumption**or *Supply cover factor* [-] (Luthander et al., 2015); (Fachrizal & Munkhammar, 2020); (Salom et al., 2011); (Prasanna et al., 2017)	Daily/ Monthly Hourly/ Season/ Year Daily/ Monthly Hourly/ Season/ Year	$y_{load} = \frac{\int_{\tau 1}^{\tau 2} \min[g(t) - S(t) - \zeta(t), l(t)]\,dt}{\int_{\tau 1}^{\tau 2} l(t)\,dt}$ $\mathrm{S(t)} = S_c - S_{dc}$ y_{load} load cover factor [-] $g(t)$ on-site generation [kWh] $S(t)$ storage energy balance [kWh] S_c charging storage energy [kWh] S_{dc} discharging storage energy [kWh] $\zeta(t)$ storage energy losses [kWh] $l(t)$ building load [kWh] t time $\tau 1$ *and* $\tau 2$ are the start and the end of the evaluation period $M(t) = min\{L(t),\ P(t)\}$ $\varphi SC = \frac{\int_{t=t1}^{t2} M(t)d(t)}{\int_{t=t1}^{t2} P(t)d(t)}$ $M(t)$ instantaneously overlapping of the generation and load profiles [kWh] $L(t)$ instantaneous building power consumption [kWh] $P(t)$ instantaneous on-site RES power generation [kWh] ϕSC Self-consumption [-]	Load cover factor represents the percentage of the electrical demand covered by on-site electricity generation; it ranges between 0 − 1 and when it is equal to 1, the system produces more energy than the real needs, while when it is equal to zero it indicates periods with no on-site generation. Moreover, the it is important to calculate the RES consumed instantaneously on-site using the RES self-consumption indicator which has been cited in several studies.
G4. RES Mismatch	**Load Matching Index** [-,%] (Voss et al., 2016); (Salom et al., 2014); (Dávi et al., 2016); (Salom et al., 2011); (Degefa et al., 2016)	Hourly, Daily, Monthly (monthly is most suitable for addressing seasonal effects)	Load match index $f_{load,i} = min\left[1, \frac{onsite\ generation}{load}\right] x\ 100$ $f_{load,i}$ load Matching Index [-] i time interval [hourly, daily, monthly] $f_{load,i} = \frac{\sum_{T1}^{T2} \min[1, \frac{g(t) - S(t) - \zeta(t)}{l(t)}}{N}$ $g(t)$ local renewable energy generation at time step $S(t)$ storage energy balance [kWh] $\zeta(t)$ energy losses (sum of generation energy losses, storage energy losses, building technical systems energy losses (excluding storage) and load energy losses (e.g.: distribution losses)) [kWh] $l(t)$ building load [kWh]	The maximum value is 1 or 100 %. The higher the index is, the better the coincidence between the load and the onsite generation. Moreover, with increasing time interval, excess production decreases.

(*continued on next page*)

Table 5 (*continued*)

KPI Group	Most Cited KPI	Timestep	Equation	Remarks
			N is the number of samples in the evaluation period, from τ1 to τ2. In case that hourly resolution data are used, and the evaluation period is a complete year, the number of samples is 8760.	
G5. Grid Interaction	**Grid Interaction Index [-]** (Salom et al., 2014); (Voss et al., 2016); (Salom et al., 2011), (, Augus) **No grid interaction probability [%]** (Tumminia et al., 2020); (Salom et al., 2011); (Salom et al., 2014); (Dávi et al., 2016); (Verbruggen & Driesen, 2015)	Hourly/ Daily/ Monthly Hourly/ Daily/ Monthly	$f_{grid,i} = \left[\frac{netgrid}{max \mid netgrid\mid}\right] x\,100$ $f_{grid,i}$ grid interaction index [-] *netgrid* net grid metering over a given period (e.g. monthly) compared to the maximum nominal contractual grid power given by contract with the energy company [kWh] $P_{E\sim0} = \frac{\int_{\tau1}^{\tau2} dt_{\mid ne\mid(t)} < 0.001}{\tau2 - \tau1}$ $P_{E\sim o}$ no grid interaction probability [%] *ne(t)* normalized variable for the net exported energy [kWh] *τ1 and τ2* are the start and the end of the evaluation period *t* is the time	Grid interaction index is important to assess the variability of the exchanged energy between the building and the grid within a year normalized on the maximum absolute value. It is also crucial to study the no grid interaction probability to assess the building when it is acting autonomously of the grid and the load is covered by either direct use of renewable energy or by the stored energy.
G6. Storage Performance	**Load Cover Factor [-]** **RES Self-consumption** (*Supply cover factor)* [-] **Load Matching Index [-, %]** **Grid Interaction Index [-]** **No grid interaction probability [%]**	Daily/ Monthly Hourly/ Season/ Year	Indicators equations are described above in G3, G4 and G5	To evaluate the storage performance in buildings, it's interesting to use the load cover/supply factors, load matching and grid interaction indicators selected in G3, G4 and G5, and calculate these indicators with and without the energy storage, to assess the obtainable benefits due to the presence of the storage in a building.
G7. Building Operational Evaluation	**EU Energy Label [-]** (European Commission, 2010), (European-Commission, 2020); (Provincia Autonoma di Trento, 2010); (European Commission, 2017); (Majcen et al., 2013); (van den Brom et al., 2018)	Annual	Compare actual energy consumption with expected one reported by the energy label. EC_a actual energy consumption (measured) [kWh/m^2]. EC_e expected or theoretical energy consumption indicated in the Energy Label of the same building [kWh/m^2].	In order to evaluate the building operational performance, the use of Energy Label is crucial to rate the energy consumption of appliances and devices installed in buildings. The KPI in this category compares the real versus expected energy consumption resulting from energy label.
G8. Technical Losses/ Failures	**Reduced Energy Curtailment of RES and DER [%]** (Azpiri et al., 2015); (Harder & Joosten, 2017)	Annual	$Reduction\ of\ EnI = \frac{EnI_{baseline} - EnI_{R\,\&\,I}}{EnI_{baseline}}\,\mathrm{x}\,100$ *EnI* total energy not injected in network due to network conditions such as overvoltage, over frequency, local congestion, etc. [kWh] *Enl* baseline energy not injected at baseline scenario *EnlR&I* energy not injected after intervention	This indicator can be measured as the percentage of electricity curtailment from DER reduction compared to BAU, for a reference period of time, i.e. a year. The indicator does not consider the losses in RES. It must be also noted that calculating this indicator requires collection of data that can be difficult to access. Thus, further work should be done to improve the indicator.
G9. Users Involvement	**SAIDI/SAIFI [-]** (Hormigo et al., 2014); (Harder & Joosten, 2017); (Putynkowski et al., 2016); (Pramangioulis et al., 2019)	Annual	$SAIDI = \frac{\sum r_i N_i}{N_T}$ *SAIDI* System Average Interruption Duration Index [hours/year and customer] N_i is the number of customers [-] $r_i$total average down time [h/year] N_T total number of customers served [-] $SAIFI = \frac{\sum \lambda_i N_i}{N_i}$ *SAIFI* System Average Interruption Frequency Index [failures/year and customer] λ_i total average failure frequency [failures/year] N_i total number of customers for i [-]	SAIDI and SAIFI indicators have been developed to measure the average number of interruptions and duration of interruptions caused to each customer. It must be underlined that there is a lack of existing indicators to study the user interaction within the technologies integrated in SBs, therefore, further specific KPIs should be developed and tested in this area.

sustainability objectives and put strategies in place to achieve them. ISO/TR 37150 (ISO, 2014) introduced indicators such as Global City Indicators; Green City Index series; and Smart City realized by ICT. Moreover, some legislations are being developed to enhance the existing indicators, such as ISO/NP 37122 (ISO, 2019), "Sustainable Development in Communities- Indicators for Smart Cities", which is still in proposal phase. At building level, the 2010 EPBD recast (Recast, 2010), European Commission (European-Commission, 2019b), and Building Performance Institute Europe (BPIE) (BPIE, 2020) supported the move towards smarter buildings in Europe. The EPBD has introduced the SRI in buildings, to measure the performance of SBs. Moreover, the IEA Annex 67 on energy flexibility and "smartness" of buildings (Jensen & Henrik, 2017) is developing a quantitative methodology to characterize and label energy flexibility that takes into account not only the technical aspects or services at a building level, but also includes its interaction with the energy system, occupants and other boundary conditions.

As seen from the previous claims, some attempts have been made to measure the performance of cities and buildings, however, a clear framework should exist on the fundamental KPIs for SBs and SR cases. These indicators must be able to assess the performance of SBs in terms of its previously discussed functions and basic features.

4.2. Key performance indicators for smart buildings

Several KPIs have been developed in reports and projects, however, some of them have not been always properly tested in research, while others have been tested and reported in more than one study. In the present section, a review on the existing KPIs in literature related to SBs is provided and a list of 36 KPIs that derive from SBs basic features was obtained. The majority of the defined KPIs are quantitative and measure energy and power rate, while few ones are non-energy indicators. The detailed framework of KPI selection and systems/components measured in KPIs are shown in Fig. 6.

Once the available KPIs are assessed, a targeted classification was proposed in order to organize the KPIs based on their priority for SR application. Table 3 classifies these KPIs based on the SB basic functions and shows the definition of each with the references that developed/tested them in literature.

Some of the reviewed KPIs share similar targets/parameters by which they can be grouped and compared to each other. An analysis of the KPIs is presented in Table 4, where the KPIs with similar targets/functions are grouped together. It should be noted that it is challenging to select a representative indicator from each group; however, the designer should decide and select the suitable indicator based on the boundary conditions, such as measurement scale, sampling, unit, time of day, etc. Since some indicators have been studied more than others, they can be considered more reliable than others and, in some situations, can be selected to be more statistically representative (Table 4). To group the indicators, a set of criteria was developed considering CIVITAS framework (Van Rooijen & Nesterova, 2013) using the following requirements:

1) Comparable KPIs, that can be compared to others since they share common targets/parameters.
2) Reliable KPIs, that have been studied frequently in existing studies and researches, which shows the reliability of the KPI.
3) Familiar KPIs, the indicators should be easy to understand.
4) Measurable KPIs, that are capable of being measured quantitatively.
5) Holistic KPI, which covers several aspects based on the aim of the KPI and includes representative parameters.

The theoretical analysis done on KPIs showed that, in order to measure SBs performance, a combination of nine groups of KPIs can be applied. It must be noted that the building designer can choose at least one KPI form each group in order to evaluate the SB performance, depending on the data available and the boundary conditions. After setting the nine KPI groups, a further analysis is carried out to select the representative indicators from each group. The selection is based on the frequency of their citation in literature and on achieving the objective of each group. The following table presents the nine groups that can be applied to test the performance of SBs and shows the 10 most cited KPIs in literature as representative ones for each group (Table 5).

Moreover, the analysis showed a gap within the existing KPIs in addressing climatic conditions and user needs, therefore further KPIs must be developed in these areas.

5. Conclusions

In this work we presented a systematic analysis of the state-of-the-art of smartness in the built environment from the perspective of smart buildings. Particularly, a schematic representation of the basic features and technologies of SBs was presented. The review done showed that the minimum features claiming smartness in buildings lays in the capability of response to external and internal conditions. External factors are mainly represented by variable weather conditions and grid conditions, while the internal ones include the user interaction and the ability of monitoring/supervision of the building systems.

There are significant controversial points regarding the smart retrofitting, including the technical challenges in installing new technologies and the need to optimize the existing systems to interact with such new technologies. Moreover, there is a lack within the current legislation to address the smart retrofitting requirements and steps, as well as the social challenges in user's acceptance for the shift towards smarter buildings and the ability to interact within the building systems.

The second part of the paper proposed a set of 36 KPIs developed in reports/legislations/research, and classified them based on their smartness basic features. An analysis of KPIs with similar targets/aims was made and a set of simplified nine KPI groups was developed. Among these KPIs, some were tested, while others were only mentioned and not tested. The building designer should select at least one KPI form each group, based on the available data and boundary conditions, in order to evaluate the SB performance. In this review, the KPIs that can achieve smart buildings objectives and are most cited in literature were selected as the most representative ones. The analysis showed the top 10 KPIs required for measuring the performance of SBs. Some of these KPIs require further development to be more holistic and achieve the objective of each KPI group. Moreover, the analysis showed a gap within the existing KPIs in addressing climatic conditions and user needs, thus further KPIs must be developed in these areas.

The research also discussed the Smart Readiness Indicator developed by the EPBD and showed the limitation in the proposed methodology, which should be more quantitative to be able to test the performance and progress of smart technologies used in buildings. Thus, the EPBD should consider further development of the current SRI methodology, SBs and SR concept. Therefore, the developed set of KPIs in this study needs further testing to assess the performance of smart retrofitted buildings. Moreover, there is an opportunity for developing new KPIs to address the challenges within the identified representative KPIs. Future works will be done to test the performance of these indicators on real case studies.

Declaration of Competing Interest

The authors declare no conflict of interest.

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