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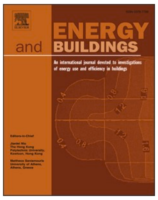

Assessing the performance of smart buildings and smart retrofit interventions through key performance indicators: Defining minimum performance thresholds

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ABSTRACT

Smart technologies play a vital role in facilitating the response of buildings to the external conditions, including climate, grid, and the internal building requirements such as user needs. A salient concern lingers in relation to existing buildings due to their increasing energy consumption. Around 35 % of EU buildings are older than 50 years and 90 % are built before the nineties. In this sense, smart retrofitting represents a key step towards achieving energy-responsive flexible buildings. Quantifying building energy performance with appropriate Key Performance Indicators is a critical step towards achieving decarbonization goals in both existing and new buildings. In this paper a group of five representative indicators has been selected to measure the energy performance of smart features in retrofitted and new buildings, also identifying distinct performance thresholds. Therefore, each threshold defines minimum acceptable and top performing values for the indicators. Accordingly, thresholds are set first based on previous literature and performance data, then a Logical Evaluation Methodology is used to identify suitable range of thresholds. Results of this paper propose a quantified definition for smart retrofitting, which involves transforming an existing building into a Smart Building. A smart building is a nearly Zero Energy Building that achieves primary energy savings of 30 % to 80 % and can adapt to changing climate and grid conditions. It should communicate with users and predict operational failures using a Building Energy Management System. Additionally, it should enable load shifting in response to renewable energy source production and electricity prices by 30 % to 70 % annually, while minimizing grid interaction to 10 % to 30 % on an hourly basis throughout the year. Furthermore, it should allow for RES self-consumption of 30 % to 70 % and cover 20 % to 70 % of the load with RES annually. Finally, the indicators are tested on a case study in Italy within a Horizon 2020 project to validate the thresholds.

1. Introduction

Buildings in the European Union (EU) accounts for 36 % of the European global CO_2 emissions and 40 % of the total energy consumption [1]. These facts highlight an urgency to implement building energy efficiency in the EU. Different targets and standards have been set to achieve the required CO_2 reductions of around 42 % by 2030 and reach net zero by 2050 [2]. Building energy efficiency policies can influence all end uses ranging from lighting, cooling, heating, appliances, and addition of Renewable Energy Systems (RES) to the interaction with the grid systems. These policies may take the form of regulatory control instruments, or, building standards, economic or financial incentives and consumer information campaigns [3]. In 2011 the European Commission (EC) proposed a Roadmap towards a competitive low carbon economy in 2050 and proposed new targets to promote environmental sustainability, energy equity, and energy security [4,5]. In parallel, the concept of nearly Zero Energy Buildings (nZEBs) has been defined to set a minimum energy performance level to be achieved by new buildings [6,7].

In such a framework, it is important to note that by 2050, up to 90 % of the present European building stock will still be standing and in

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Nomenclature

BEMS	Building Energy Management Systems
DHW	Domestic Hot Water
DR	Demand Response
DSM	Demand Side Management
EC	European Commission
EED	Energy Efficiency Directive
EPBD	Energy Performance of Buildings Directive
EU	European Union
EV	Electric Vehicle
GHG	Greenhouse Gas
GII	Grid Interaction Index
HVAC	Heating, Ventilation, and Air Conditioning
ICT	Information and Communications Technology
IEA	International Energy Agency
KPI	Key Performance Indicators
LCF	Load Cover Factor
LEM	Logical Evaluation Methodology
MA	Minimum Achievable
MS	Member State
nZEB	nearly Zero Energy Building
PCM	Phase Change Material
PE	Primary Energy
PE_{nren}	Non-renewable Primary Energy
PV	Photovoltaics
RES	Renewable Energy Sources
SB	Smart Buildings
SC	Self-Consumption
SG	Smart Grid
SR	Smart Retrofitting
SRI	Smart Readiness Indicator
TRNSYS	TRaNsient SYstem Simulation
TP	Top Performing

operation. A major concern remains related to existing EU buildings, in particular, the 2024 Energy Performance of Buildings Directive (EPBD) has highlighted that 85 % of buildings in the EU were built before 2000, and of those, 75 % have poor energy efficiency [2]. Thus, the renovation of buildings is a key action to reach the carbon neutrality, namely decarbonization, of the building stock by 2050. As of 2021, 1 % of existing building stock are renovated annually [8], whereas, to accomplish the 2050 zero-carbon goal of 100 %, it is essential to ensure more than 3 % renovation rate [9]. Deep renovations tend to reduce energy consumption by more than 60 %, yet only 0.2 % of the existing building stock in the EU is deeply renovated annually. Therefore, nZEB retrofitting, which is defined as “Renovation that leads to a building that has high energy performance and the nearly zero or very low amount of energy required should be covered significantly by RES produced on-site or nearby, reaching a primary energy saving of 75 % compared to the pre-renovation status” [10], has gained wide attention lately [11,12,13,14]. The growing renewable energy integration in buildings increases the non-programmable energy at the building/district level. Therefore, buildings should balance their on-site energy generation and consumption in order to properly manage and dispatch the number of renewables [15]. Therefore, to transform existing buildings into nZEBs and smart buildings, to proper manage of RES and to interact with the Smart Grid (SG) have become essential. SGs are electricity networks that influence technologies, smart meters and sensors to enhance real-time balancing of supply/demand and ensure grid stability and reliability. This type of retrofit is identified as Smart Retrofitting (SR), which has been previously introduced in [16]. To achieve this aim, quantifying the building energy performance also in term of smart features and setting minimum thresholds for the smart performance level represent a crucial baseline for evaluating potential savings and reaching the desired GHG emission reductions. In this sense, the revised 2018 and 2024 EPBD [14] facilitated the development of a voluntary European scheme for rating the smart readiness of buildings by means of the Smart Readiness Indicator (SRI) [17]. The SRI was thus introduced as a tool for rating the smart readiness of buildings in terms of technical aspects and the ability to interact with energy networks, occupants, and function more efficiently. It is done through assessing the available services and functionality levels of the technologies in buildings. However, SRIs’ qualitative methodology merely assesses the existence of the technology rather than evaluating its’ performance and contribution. Thus, specific methods should be developed to precisely quantify the smartness of buildings and set reference values for the minimum required performance.

The results of a prior study conducted by the authors of this paper, serves as the foundation of this work [16], where an extensive review was done on existing indicators related to the Smart Buildings (SBs) basic features, namely:

A. *nZEB target and RES integration,* which is related to the implementation of passive and active energy-efficient measures, and to the application of RESs;
B. *flexibility*, which represents the building capability of managing its generation and demand based on local climate conditions, grid requirements, and user requirements;
C. *real-time interaction with the grid and users*, which is related to the capability of interaction with users and external services such as weather and grid conditions;
D. *real-time monitoring*, which is related to the possibility to collect and analyse energy consumption and main operating parameters of the building.

The review identified 36 indicators related to smart building features (Appendix A). After evaluating the most cited, relevant, and representative Key Performance Indicators (KPIs) measuring specific performances, a set of 10 reference KPIs was chosen to measure the smartness of retrofit interventions. To address this, this paper introduces a method to simplify the list of indicators, focusing on those that are both representative and easy to calculate with readily available data. This approach ensures that the KPIs can be widely applied in various contexts.

Additionally, the previous paper did not establish specific thresholds to distinguish between poor and good smart performance. Setting such targets is crucial for determining whether smart and sustainability goals are being met and for assessing the success of new and retrofitted buildings. Currently, the recent EPBD version does not provide clear numeric thresholds or ranges to define nearly Zero Energy Buildings (nZEBs), leading to varied interpretations across EU countries.

In the second part of the present work, a method is developed to propose reliable thresholds for the selected indicators. Lastly, the KPIs are tested and applied on a case-study in Italy within the Horizon 2020 HEART (Holistic Energy and Architectural Retrofit Toolkit) project [18]. In fact, such a project focuses on improving residential buildings sector energy efficiency and aims to develop, test, and validate a holistic system for the deep renovation and the smart upgrade of residential buildings, i.e., to transform them into smart buildings. Considering that the obtained results are promising, the case study of the project can be considered a robust benchmark.

In summary, the aim of this paper is to:

1. Quantify the smartness level of retrofit interventions effectively through refining the previously developed method for KPIs selection by simplifying the list to focus on the most essential and easily calculable indicators.
2. Identify and select representative KPIs for measuring the performance of SB/SR and define SR in buildings.
3. Set reliable thresholds for the selected KPIs.
4. Test/validate the KPIs and the related thresholds on a real smart retrofit project, in order to demonstrate their applicability.

The research methodology includes qualitative methods of thorough literature review, and quantitative validation through testing the KPIs on a real case study.

2. Methodology

With the goal of enhancing energy performance evaluation of smart retrofitting in buildings, an innovative methodology was developed to precisely quantify the smartness level. KPIs have been chosen as means of this quantification and are claimed to establish a set of good practices that should then be adhered during building operation [19].

The research methodology combines mixed research methods, involving qualitative methods such as an extensive critical literature review, and quantitative validation, including testing the KPIs on a real case study. The study followed four stages related to data collection and validation of the proposed framework, as illustrated in Fig. 1. Step 1 began with the critical review carried out based on the previous research by the authors to identify the relevant smartness indicators [16]. In Step 2, a further analyses and classification process was carried out to group the indicators into representative categories and to select the most impactful KPIs and thus excluding some (details in section 3). In Step 3, a threshold identification approach was developed. This began with a critical literature review on building legislations, policies, articles, followed by logical evaluation process to determine two boundary values of thresholds for each KPI. In Step 4, the KPIs were tested on a real smart retrofit project, the demo building of the HEART project. This project, which serves as a benchmark for top-performing smart retrofits, aims to upgrade existing buildings by integrating advanced technologies such as envelope systems, renewable energy sources, high-efficiency heat pumps, smart fan coils, energy storage units, and energy management systems that work together to achieve high levels of energy efficiency and flexibility [20].

3. KPIs selection

Generally, KPIs assess how well a project is progressing towards achieving specific objectives [21]. KPIs should express as accurately as possible to what extent an objective, or a standard has been reached or even surpassed. The selection of representative KPIs is very crucial for measuring the performance of smart buildings/smart retrofits. For instance, Janjua et al. [22] presented a methodology to select KPIs for sustainability assessment of residential buildings based on literature review and the expert panels assessment. While Khorram et al. [23] have used categorization of indicators into groups related to the identified targets for the selection process. In other studies, [24,25,26], literature reviews, interviews with experts, and questionnaires were common methods used for KPIs selection.

As mentioned earlier, a more detailed selection method is developed in this paper to carefully identify the most representative and easy-to-calculate indicators. Thus, the first step was to identify the questions to be addressed by KPIs and the input parameters for each one of the 4 basic features mentioned before, as shown in Fig. 2. This step would help in excluding the KPIs that do not address these questions and thus reduce the list of KPIs.

The nZEB target and RES integration are achieved usually by applying passive or active strategies and RES, while the flexibility feature could be achieved through Demand Response (DR) control, storage systems and RES. Demand response indicates balancing the demand on grids by motivating users to shift electricity demand to lower peak periods. Furthermore, real-time interaction can be attained with user involvement in the demand-response and grid integration, and through smart metering. While the control systems such as Building Energy Management Systems (BEMS) which connects technologies into a single platform could achieve the user interaction as well as the real-time monitoring. This step would make it easier in eliminating the indicators that does not cover these aspects and measure these strategies. The second step was to raise some essential questions that could further narrow down the selection of the indicators. Thus, for the nZEB target and RES integration group, the questions would address the optimal minimum amount of non-renewable primary energy and RES involvement in SB. For the flexibility group, the questions include the definition of the optimal load to be covered from RES and the quantification of

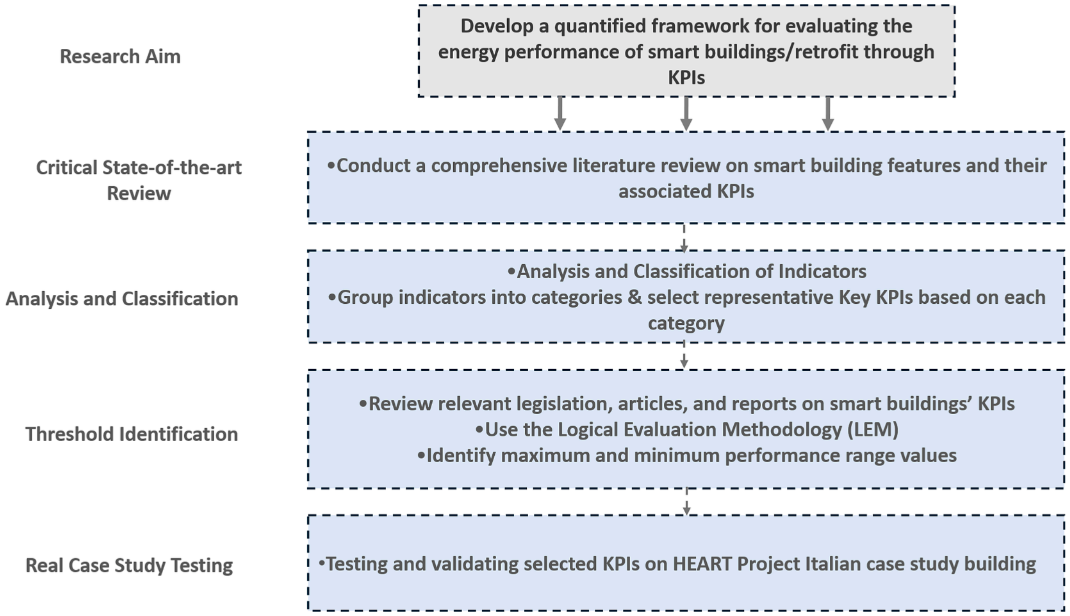

Fig. 1. Representation of the research working phases.

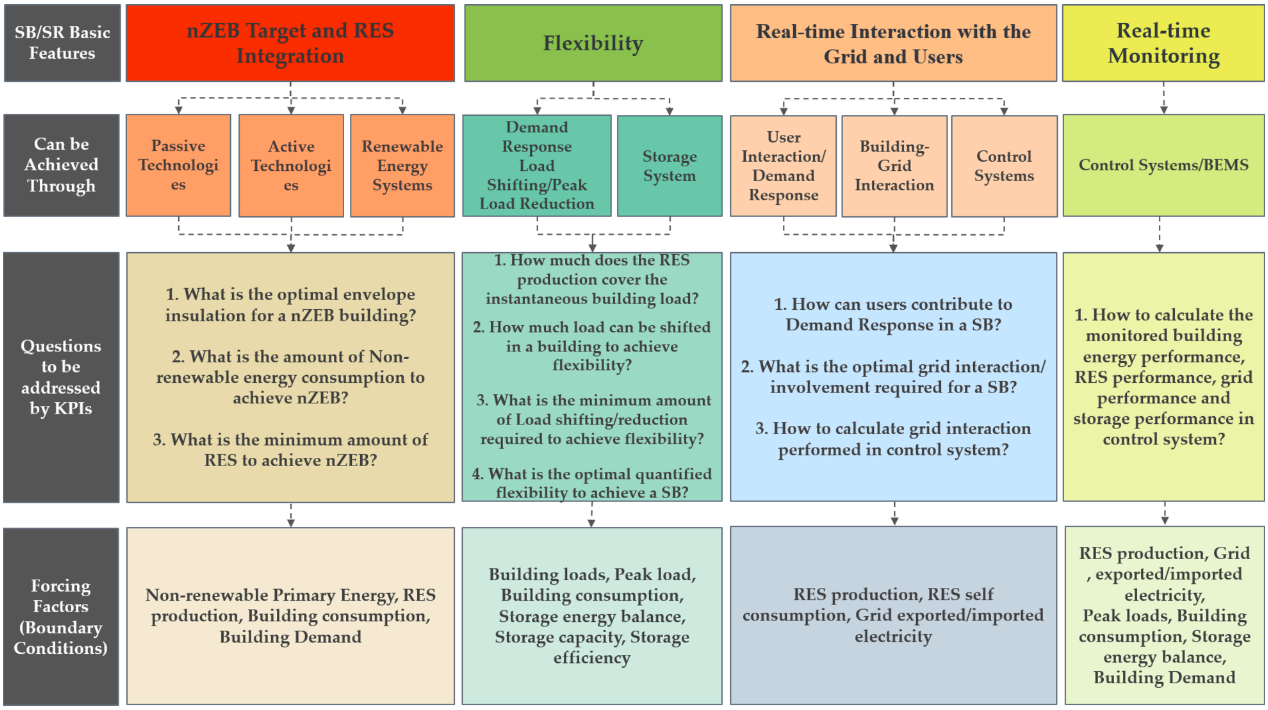

Fig. 2. Questions and Input parameters of KPIs of Smart Buildings/Smart Retrofitting.

shiftable flexible load. While for the real-time interaction group, the questions aimed at defining the optimal grid and user interaction to achieve a SB. Lastly, for the real-time monitoring group, since it involved the building systems evaluation in the building through BEMS, the question was on calculating the energy performance of the buildings systems. Eventually, some important forcing factors or input parameters are suggested. These parameters should help in addressing the raised questions and facilitate the selection of the suitable KPIs. Thus, the indicators presented in the authors' previous paper [16] were subjected to a more thorough examination to re-fine the list. The KPIs were further filtered through a process comprised of three steps. The initial phase involved inspecting the KPIs to eliminate those that were less efficient, redundant, or reliant on inaccessible data. Additionally, KPIs that did not directly address the questions posed in Fig. 2 were also excluded. As a result of this filtration process, the original set of 36 KPIs (Appendix A) was streamlined to a more concise collection of 25 KPIs in this article. In the second phase, as illustrated in Table 1, the KPIs were grouped based on their common objectives and functions, as evident in the "interpretation" column. This step was assumed because several indicators served similar purposes, with the primary goal of simplifying the KPI list and eliminating redundancy. Additionally, the interpretation phase aimed to identify the most representative KPI within each category.

The interpretation presented in Table 1 explains how various KPIs are used to evaluate building energy performance from different perspectives. These KPIs are grouped into categories based on their objectives, such as measuring non-renewable energy consumption, flexibility in load shifting, renewable energy self-consumption, grid interaction, and energy storage. It emphasizes that certain KPIs are well-established and widely used in literature, while others require further testing or refinement. The interpretation also highlights which KPI is the most representative in each group. Selecting representative indicators was based on the following factors:

- **Citation frequency in literature:** the KPI's relevance in existing literature.
- **Ability to achieve objectives:** the KPI's effectiveness in achieving the objectives of its respective group.
- **Ability to measure smart building features:** the extent to which the KPI could accurately gauge the performance of smart buildings, particularly assessing the four basic features of SBs mentioned previously.
- **Ease of data collection:** the feasibility of collecting data for each KPI.

Furthermore, the interpretation suggested eliminating certain generalized KPIs related to storage due to their limitations in assessing losses and thus, the storage indicator will be assessed through calculating the KPIs with and without storage to quantify the obtainable benefit of the storage system in buildings. Eventually, this strategy had reduced the number of indicators from 25 to 5 indicators, which can answer the questions raised previously in Fig. 2 to identify the quantitative way of achieving the SB basic features.

4. Setting thresholds for key performance indicators

Different methods have been discussed in the literature to set thresholds for indicators. In [21], three different scenarios were used for identifying thresholds, based both on experimental data and on literature surveys, while in another study [75] two different approaches were introduced for identifying the threshold of control strategies for reducing energy costs for end-users. In another study [76] that investigated the energy prices, the approach was similar to the methodology presented in [21], which was based on recorded past data in which the thresholds were calculated using the historic price distribution of the two weeks before the calculation time.

However, despite the importance of setting defined thresholds for KPIs, a clear and unified methodology is still not properly defined. For this reason, in the present paper thresholds will be set according to EU building standards, articles, and case studies that have tested the KPIs. This method is illustrated in Fig. 3. First, a review is done on literature, showing the achievable/recommended values of each indicator based on legislations, research articles, and reports that have identified metrics and baselines or a range of acceptable values for these indicators. This helps in identifying the range of possible values of the KPI. Second, an in-

Table 1
KPI Analysis and Interpretation.

KPIs	Interpretation of KPIs	The question addressed by KPI
1. Non-renewable Primary Energy (kWh/m$^{2\cdot}$ y) [27;28;29] 2. Global Energy Performance Indicator (EPgl) (kWh/m^{2}y) [30;31] 3. Energy Demand and Consumption [27;32] (kWh/(m^{2}month or year)) 4. Energy Savings (%) [33;34]	- KPIs can be grouped since they all share the objective of measuring the building energy performance. This group does not assess the smartness of the building; however, it shows if the building is a nZEB; one of the basic features of SBs as identified previously. These indicators are broadly applied in literature; yet the “Non-renewable Primary Energy” indicator is a more complete indicator since it accomplishes the goal of this group and gives data on savings and loads in buildings. Moreover, this indicator has been widely tested in literature.	What is the amount of Non-renewable energy consumption to achieve nZEB?
5. Demand Response [35;36] 6. Peak Load Reduction [37;38] 7. Flexibility Index (FI) [39] 8. Flexibility Factor (FF) [40;41] 9. Flexible Shiftable Load (S_{flex}) [42,43]	- These indicators assess the flexibility of shiftable loads within buildings. “Demand Response” and “Peak Load Reduction” aim to measure the potential for load reduction in buildings. While the “Flexibility Factor” compares load distribution relative to peak load, it does not provide insight into the amount of load that can be shifted. The Flexibility Index evaluates the potential to shift energy demand not met by renewable energy sources. S_{flex} quantifies the shiftable energy based on renewable energy (RES) production and is considered a key metric in flexibility applications, enabling measurement of “Demand Side Management” (DSM) for managing building energy consumption. Furthermore, S_{flex} is widely referenced in literature, as it measures the amount of load adjusted in response to price changes or RES availability.	- How much load can be shifted/Reduced in a building to achieve flexibility? What is the minimum amount of Load shifting required to achieve flexibility? What is the optimal quantified flexibility to achieve a SB?
10. Degree of Energetic Self-Supply by RES [27;44] 11. Increased RES and DER hosting capacity [45;46] 12. Load Cover Factor [47;48] 13. RES Self-consumption (Supply Cover Factor) [49;48] 14. Maximum Hourly Surplus [50;51] 15. Maximum Hourly Deficit [51;52] 16. Annual Mismatch Ratio [50;53] 17. Load Matching Index [54;49] 18. Mismatch Compensation Factor [53;55]	- The KPIs share comparable targets for assessing the production, consumption, and installation of RES. “Load cover factor (Self-generation)” and the “Supply Cover Factor (RES Self-consumption)” are the most used, reflecting the percentage of demand covered by on-site generation and how much of this energy is self-consumed, respectively. While similar to load cover factor, the “Load matching index” gives the same information, however, the load cover factor gives a more accurate result. “Mismatch Compensation Factor” and “Annual Mismatch Ratio” focus on aggregated mismatch rather than building specific performance.	- How much does the RES production cover the building load? What is the minimum amount of RES to achieve nZEB?
19. Grid Interaction Index (GII) [49,56] 20. No Grid Interaction Probability [54;47] 21. Absolute Grid Support Coefficient [40;57] 22. Relative Grid Support Coefficient [40;57]	- The “Grid Interaction Index” and “No Grid Interaction Probability” are important indicators that has been tested in several studies and showing the amount of purchased/delivered energy and when the building is acting autonomously of the grid, respectively. However, the grid interaction index shows the seasonal effect of the grid interaction and thus is more reliable. The other indicators have been tested in a few studies and require further investigation.	- What is the optimal grid interaction/involvement required for a SB?
23. Storage Capacity [58;59] 24. Storage Efficiency [60;61] 25. Depth of Discharge [24;62]	- Based on literature, these indicators measure the storage performance in buildings, however, they tend to be generalized, and further refinement is needed to account for storage losses. Therefore, this group of KPIs calculating storage will be eliminated since the storage effect can be better assessed using the previously selected indicators including RES Self-consumption, Load Cover Factor and Grid Interaction Index. These KPIs will be calculated with and without storage to quantify the obtainable benefit of the storage system in buildings.	- How to calculate energy storage performance?

Table 2
SR Representative KPIs.

Selected KPI	Timestep	Equation	Definition
1. Non-Renewable Primary Energy [27;29;63]	Annual	$PE_{nren} = (\sum_i \left(E_{del,i}.f_{del,nren,i}\right) - \sum_i (E_{exp,i}.f_{exp,nren,i}) PE_P = \frac{E_{P,nren}}{A_{net}}$(Eq.1) [27] $PE_{,nren}$ non-renewable primary energy [kWh/y] PE_P Specific non-renewable primary energy [kWh/m^{2}y] $E_{del,i}$ annual delivered energy on site or nearby for energy carrier i, [kWh/y] $E_{exp,i}$ annual exported energy on site or nearby for energy carrier i, annual [kWh/y] $f_{del,nren,i}$ is the non-renewable primary energy factor (−) for the delivered energy carrier i $f_{exp,nren,i}$ is the non-renewable primary energy factor (−) of the delivered energy compensated by the exported energy for energy carrier *i*, which is by default equal to the factor of the delivered energy, if not nationally defined in other way A_{net} useful floor area (m^2)	Primary energy is the energy that has not been exposed to any conversion or alteration. The indicator adds delivered and exported energy (electricity, district heat/cooling, fuels) into one indicator.
2. Flexible Shiftable Load (Load Shifting) (S_{flex}) [%] [66,67,68,42]	Hourly, Annual	$S_{flex} = \frac{\sum_{i=1}^{n} \max(L_{ref,i} - L_{flex,i}, 0)}{\sum_{i=1}^{n} L_{ref,i}}$(Eq.2) [66] $S_{flex,}$ Shifted flexible load [%] $L_{ref,i}$ Reference load without technologies allowing flexibility [kW/m^2] $L_{flex,i}$ Load with flexible operation [kW/m^2]	The amount of load shifted for the measured flexibility technology at the time step *i*
3. RES Self-consumption [-] [69;70;49;48]	Daily/ Monthly Hourly/ Season/ Year	$M(t) = min\{L(t), P(t)\}\ \varphi_{SC} = \frac{\int_{t=t1}^{t2} M(t)d(t)}{\int_{t=t1}^{t2} P(t)d(t)}$(Eq.3) [69] *M(t)* instantaneously overlapping of the generation and load profiles [kWh] *L(t)* instantaneous building electricity consumption [kWh] *P(t)* instantaneous on-site RES electricity generation [kWh] φSC Self-consumption [-]	The degree of immediate on-site RES consumption.
4. Load Cover Factor [-] [71;49;72;54;73;47;48]	Daily/ Monthly Hourly/ Season/ Year	$y_{load} = \frac{\int_{\tau1}^{\tau2} \min[g(t) - S(t) - \zeta(t), l(t)]dt}{\int_{\tau1}^{\tau2} l(t)dt}$*(Eq.4)* [71] $S(t) = S_c - S_{dc} y_{load}$ 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] *ζ(t)* storage energy losses [kWh] *l(t)* building load [kWh] *t* time *τ1 and τ2* are the start and the end of the evaluation period	Load cover factor characterises the percentage of electricity demand that the on-site electricity generation covers.
5. Grid Interaction Index (GII) [-] [73;74;49,56]	Hourly/ Daily/ Monthly	$f_{grid,i} = STD\left[\frac{netgrid(i)}{max\lvert netgrid(i)\rvert}\right] x100$*(Eq.5)* [73] $f_{grid,i}$ grid interaction index [-] *netgrid* net grid metering over a given duration (e.g., monthly) associated with the maximum nominal contractual grid power provided under the terms of energy company [kW]	Describes the average grid stress, using the standard deviation of the grid interaction over a period of a year.

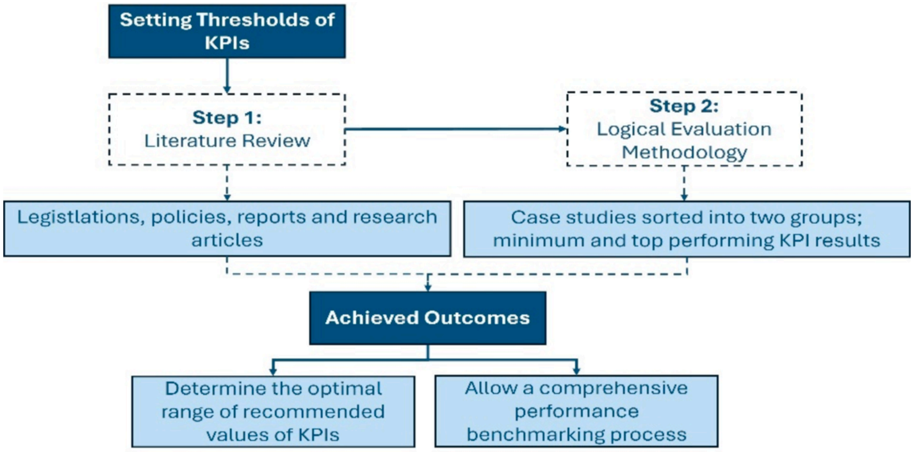

Fig. 3. KPI Threshold Identification Methodology.

depth examination delves into the case studies outlined in the literature, specifically those that have scrutinized the identified KPIs. During this stage, a Logical Evaluation Methodology (LEM) is employed to establish precise thresholds or suitable ranges for each indicator. The LEM, as described in [30], determines indicator thresholds by analyzing the outcomes of case studies reported in literature. The objective is to identify suitable thresholds within the range of the observed outcomes. In the context of this paper, the LEM was employed to identify thresholds based on the calculation parameters of each KPI, on the values specified in legislation and regulations, or on those obtained in case studies. This process entailed the examination of various case studies that assessed the indicators, encompassing both studies involving basic technologies and those employing advanced smart technologies.

In general, Smart Buildings must include a basic set of "smart technologies", which should mainly include RES, energy storage systems, advanced BEMS and Heating, Ventilation, and Air Conditioning (HVAC) systems and smart meters [77–79]. Potential energy savings, lower life cycle costs, simpler decision-making for maintenance management and increased thermal comfort are achieved through the suitable integration of smart systems [78].

In this research, considering the impact of different technological levels, two specific thresholds for each of the above-selected KPI are set, based on different elaborations (Fig. 4):

- For buildings that integrate the basic set of "smart technologies", i.e., only a few of the available smart technologies and with no optimization of the system in terms of sizing and performance, the achieved value represents the Minimum Acceptable threshold (MA). For any achieved value below the MA, the building cannot be considered a smart building.
- For buildings that integrate the complete set of "smart technologies", which include RES, energy storage systems, advanced HVAC systems and BEMS, sized by means of an optimization process (e.g., optimization of size of PV and storage based on the building demand), the achievable value defines the Top Performing Threshold (TP). Thus, any value above the TP means that a smart building reaches an outstanding performance.

The values between the two proposed thresholds identify smart buildings/retrofit interventions with a satisfactory smart performance. This min-top performing KPI methodology has been adopted by several authors [80–82] and proven as a robust method for analyzing KPIs using scenario analysis through allowing variations across extreme scenarios.

Compared to the values found in the literature, the thresholds are defined by taking the mean value of the analyzed standards/case studies, and then each value is rounded down, as described in the following section.

4.1. KPI threshold elaboration

This section describes the definition process for the thresholds of the selected five indicators.

- **Non-renewable Primary Energy Indicator**

Non-renewable Primary Energy indicator ($PE_{,nren}$) is one of the most studied indicators in literature. For setting the threshold of this KPI, a review was done on different studies, national standards and reports [63,83–89], as summarized in Table 3. The table gives information on the parameters considered in the calculation, on the climatic context, and reports the achieved value of the KPI.

According to the previous table, the PE_{nren} is based on general conditions among Member States and non-homogeneous calculation methods. It shows a wide variety of computational results for primary energy. The EU Commission has claimed that the non-renewable primary energy consumption of nZEBs varies between 0 and 160 kWh/m^2.y for residential buildings [91]. This can be expected since all Member States have their specific nZEB definitions in place and different climatic features.

A more robust and common way of measuring Primary Energy performance in building retrofits is assessing the primary energy savings achieved. The EU commission states that between 3 % to 30 % of PE savings can be for very light renovations, 30 % to 60 % PE savings are for medium renovations, and more than 60 % PE savings are for major renovations. In some countries, these energy savings are combined with energy needs and minimum shares of RES [92].

It can be concluded that based on the literature reviewed (reports/legislations and standards), the non-renewable primary energy is an indicator that already has fixed thresholds according to each EU country's defined targets and it can be expressed as follows.

1. A targeted number expressed in kWh/m^2 y, which varies among each country based on its climatic zone and on energy requirements. For new buildings, the PE_{nren} ranges between 0 and 180 kWh/m^2 y and for retrofitted buildings the PE_{nren} ranges between 20 and 200 kWh/m^2 y, showing a wide range due to the different conditions and targets of each country.
2. An easier threshold of Primary Energy (PE) can be expressed in terms of savings, which compares the building to a reference building or the building before the retrofit intervention. For deep retrofit which

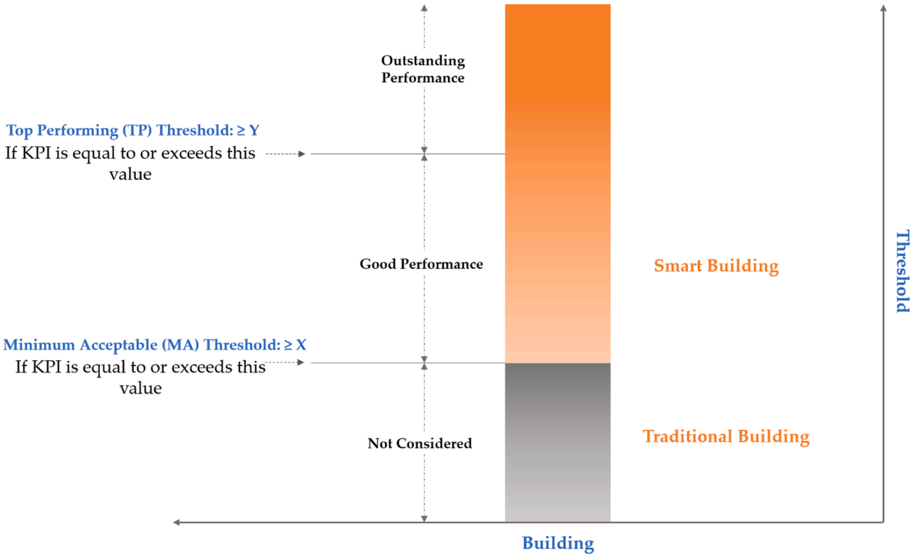

Fig. 4. KPIs Threshold Boundary Logic.

Table 3
Primary Energy Indicator – Review of requirements from standard and reports.

Reference Study	Description	Country/ Climatic Context/ Building Type	Reference values	
[90]	The average non-renewable primary energy demand for new single-family houses	EU level	EU values range between 15 kWh/ (m^2.y) to 95 kWh/ (m^2.y) with an average at EU level of 52 kWh/ (m^2.y).	
[85]	Review on legislations and national nZEB approaches.HVAC, domestic hot water, and auxiliary energy (monthly balancing period) .	Belgium Bulgaria Cyprus Denmark France (Multiple climatic zones) Single-family houses.	Belgium: PE $\leq$ 45 kWh/ m^2. y Bulgaria: PE $\leq$ 50–60 kWh/m^2.y Cyprus: PE $<$ 180 kWh/ m^2.y Denmark: PE $<$ 20 kWh/ m^2.y France: New construction of residential buildings should have a threshold of 50 kWh/ m^2. y, while renovated less than 80 kWh/ m^2.y.	
[88]	Overview on the Directive's requirements linked to nZEBs and the current MS situation. Main parameters includes building category, HVAC energy demand, typology, type and period of balance, physical boundary, RES, metric, normalization, and conversion factors.	Eight MS (non-renewable primary energy) – Residential Buildings	In kWh/ m^2.yBelgium: 30 (Flemish region), 45 (Brussels region), 60 (Walloon region) Cyprus: 180 Denmark: 20 Estonia: 50 France: 50 Ireland: 45 Latavia: 95Slovakia: 32 (apartment buildings) 54 (family houses)	
[89]	Overview on the energy requirements defined by MS for nZEB levels for both new and existing residential buildings (kWh/ m^2.y).Primary Energy consumption defined by EU Member States for nZEB levels of residential buildings (for HVAC and Domestic Hot Water (DHW)).	23 EU Member States (Several climatic zones) – New and existing Residential buildings	**New** kWh/ m^2. y	**Deep Retrofit** kWh/ m^2.y
			Austria: 160	200
			Belgium: 45–60	54
			Bulgaria: 30–50	40–60
			Cyprus: 100	180
			Czech: 75–80	75–80
			Germany: 40	50
			Denmark: 20	20
			Estonia: 50–100	NA
			France: 40–65	80
			Croatia: 33–41	NA
			Hungary: 50–72	NA
			Ireland: 45	75–150
			Italy: Class A1	Class A1
			Latavia: 95	95
			Malta: 40	NA
			Netherlands: 0	NA
			Poland: 60–75	NA
			Romania: 100	NA
			Spain: Class A	NA
			Sweden: 30–75	NA
			Slovenia: 45–50	70–90
			Slovakia: 32–54	NA
			UK: 44	NA

represents the target of SBs and SR the PE savings are typically $>$ 60 %.

According to the proposed methodology, to define MA and TP thresholds a review is done also on studies that have calculated the PE indicator, as reported below (Table 4). This step is done in order to identify the PE indicator in buildings using different simulation and calculation methods. The table shows retrofit examples; thus, the PE saving is compared with the pre-retrofit scenario. Consequently, a threshold value can be advised based on the implemented technologies and the results of previous case studies.

A range can be suggested for the thresholds of the primary energy saving indicator. Top-performing smart retrofit should include envelope and HVAC systems retrofitting, integration of RES and advanced control systems for building energy management. Thus, based on the case studies and literature review, minor renovations strategies achieved PE savings of around 30 % while for the renovation that includes holistic retrofit strategies and integration of RES and storage systems, the PE saving can reach 80 %. Therefore, the MA was set equal to 30 % while the TP has been defined equal to 80 %.

- **Shiftable Flexible Load Indicator**

Several studies have quantified flexibility [98–101]: they describe to which extent a building can respond to the grid's need for flexible behaviour. IEA EBC Annex 67 [102] has indicated that flexibility is defined as "the deviation of a flexible load profile from a baseline not flexible profile". The output is a percentage over time, which is the deviation in energy consumption presented as "*Sflex*". In this paper, the flexibility is calculated using Eq.2 representing the load shifting as the Shiftable Flexible Load indicator. Higher flexibility corresponds to a greater load shifting potential. The above-mentioned studies claim that flexibility can be achieved by recognizing penalty signals or influencing factors such as temperature/humidity set point, Electric Vehicles (EVs) charging profile, electricity price, RES production values, etc., to which the flexibility will respond. The studies also show that storage system, envelope insulation level, installed RES, and the control system play a major role in energy shifting. However, no threshold defines the right flexibility level for smart buildings. Moreover, there is a lack of current legislation and standards on flexibility. Thus, to set thresholds for the load shifting, a review is done in Table 5. The analysis shows the main technologies investigated, methodologies and the achieved result to set the MA and TP performing thresholds.

Based on the reviewed studies, it was observed that building flexibility depends highly on the presence of RES, energy storage systems and control systems. Thus, based on the reviewed studies it is possible to conclude that with some smart technologies integration, a minimum of 30 % (mean of the analyzed case studies with minimum level of smart technologies rounded to the lowest integer value) of load shifting can be achieved, thus such a value was identified as the MA threshold; while for the optimized scenario the TP value for load shifting is set equal to 70 % (mean of case studies integrating a full set of smart technologies and system optimization rounded to the lowest integer value).

- **RES Self-Consumption Indicator**

Table 4
Primary Energy Saving Indicator – Case Studies Review.

Reference Study	Integrated Systems/ Technologies	Methodology	Achieved Annual PE savings values
[93]	Heat Pump powered 100 % by PV electricity, compared to a reference building without PV and with gas boiler.	PE savings calculated by percentage of reduction with pre-retrofit scenario.	PE savings compared to the reference scenario was 80 %
[84]	- High-efficiency HVAC system. - PV system.	Reduction percentage of non-renewable primary energy demand calculated through measurements.	The percentage of reduction of the non-renewable PE demand was 75 %.
[94]	- Milan: building envelope retrofit, high-performance heating and DHW generation systems based on heat pumps and LED lamps with PV and battery storage systems. - Lisbon: External thermal insulation, double glazing windows, LED lamps and PV system.	Primary energy of heating, cooling, DHW, lighting and ventilation simulated before and after retrofit.	Milan PE saving was 77 % after retrofit and Lisbon PE saving was 35 %
[95]	- Renovation of opaque envelope. - Double glazed windows. - Replacing oil-fired boiler with a new natural gas unit for heating.	Assessments through simulation of high-resolution measured data for heating, cooling energy use before and after the refurbishment	PE savings reaches 33.5 %.
[96]	- Residential buildings retrofitted in five EU climatic zones through: - Thermal envelop retrofit (insulation and window refurbishment). - Heat pump and distribution pipes retrofit. Installation of PV systems.	Software simulations used to calculate the PE savings achieved after retrofit.	The PE savings ranges between 41 % and 79 % based on different climatic zones and typologies.
[97]	Single family renovation including thermal insulation of roof and façade, replacing the existing boiler, and PV plant installation.	The primary energy reduction is calculated through TRNSYS simulations.	PE saving of 72 % was achieved.

Table 5
Shifted Flexible Load Indicator – Case Studies Review.

Reference Study	Integrated Systems/ Technologies	Methodology	Achieved Annual Shifted Flexible Load Value
[98]	- Heating systems (radiators and water-based under-floor heating). - Thermal storage system with control strategy based on electricity price. - Phase Change Materials (PCM) wallboards.	- MATLAB-Simulink to model building. - Two different classes of insulation modelled.	- Simulation results showed that integrating thermal storage systems, PCM wallboards and electricity-based control strategy results in an annual load shifting of 42 %.
[103]	- Heat pump. - PCM tank. - Combined Heat and Power (CHP) system. - Model predictive control (Price-based control strategy).	- Flexibility through Shifting of the electrical consumption. - Models of the building systems are implemented in a simulation framework using MATLAB. - Flexibility calculated based on low and high price periods.	- By adding TES tanks and cost-optimal control, the simulation showed annual load shifting is 67 % for PCM tank.
[104]	- Flexible loads such as washing machine, dishwasher, tumble dryer, vacuum cleaner. - PV system. - Multi sensors. - Heat pumps. - Electricity meters.	- Price-Market-based Strategy. - Testing was conducted on different scenarios with varying number of occupants and schedules. - The simulations were developed through Excel environment.	- The monitored results showed that the achieved annual load shifting varied between 53 % to 66 % based on different the scenarios.
[66]	- High thermal insulation. - High thermal mass. - Ground-source heat pump. - PV system. - Heat pump and domestic hot water storage. - Control system. - System optimization.	- Control system was responding to different penalty signals including electricity costs (high/low tariff, spot market prices), CO_2 emissions and self-consumption. - Load management shifts the electricity demand for the heat pump operation to times when CO_2 emission levels in the grid are low.	- Monitored results revealed that annual load shifting was between 40 % and 85 % for the different penalty signals.
[105]	- PCM wallboards - Heating system (convective radiators and under-floor heating system). - High thermal mass. - Control system. - Thermal storage system. - PV system.	- Different scenarios generated with two categories of building envelope (houses from 1980 and passive house), four indoor thermal mass configurations and two heating system types. - MATLAB-Simulink software used to create thermodynamic multi-zone models. - Control system respond to price and RES availability.	- Simulation results showed that houses built in 1980 heated by radiator have annual load shift between 30 % and 40 %. - For passive houses using radiators, annual load shift between 60 % and 90 %.

(*continued on next page*)

RES Self-Consumption (SC) measures the electricity produced from RES, not transferred to the distribution/transmission grid and consumed instantaneously by the building [108]. Maximizing SC leads to minimizing the export of the electricity to achieve an independent building that acts autonomously of the grid. The SC values range between 0 and 1 or can be represented as a percentage, in which the higher value is the better, showing that the building is a high self-consumer of renewable energy. Table 6 presents some quantified requirements of RES SC based on official reports in the EU.

As seen from the previous table still there is a lack of quantified values of the RES SC threshold, thus, to make a logical estimation of the indicator, the thresholds are set according to several case studies. A summary is reported in Table 7 based on different case studies that have tested and quantified the RES SC and categorizes them according to the

Table 5 (*continued*)

Reference Study	Integrated Systems/ Technologies	Methodology	Achieved Annual Shifted Flexible Load Value
[106]	- Control system. - PV system. - Electric heat pumps.	- 751 typical Italian dwellings database (14 dwelling archetypes defined). - Hourly Italian electricity price profile calculated over 2018 and 2019. - Day-ahead market hourly pricing mechanism for load shifting.	- Monitored annual load shifting was found to be 34 %.
[107]	- District heating system. - Optimized thermal storage system. - Building connected with the grid. - Control system. - Electrical boilers.	- Different scenarios of building with varying setpoints, and low and high-cost thresholds. - Shift load to low price periods.	- For the different control scenarios, the monitored annual load shift ranged between 52 % and 79 %.

Table 6
RES Self-consumption Indicator – Review of requirements from standard.

Reference Study	Integrated Systems/ Technologies	Methodology	Achieved RES Self-Consumption Result
[109]	- PV system. - Electric storage system. - Demand-side response strategies.	- EU Commission report on the best practices on RES SC applying Demand-side response strategies	- Between 30 %-65 % of RES SC can be achieved for a household.
[110]	- Self-consumption of PV electricity. - Revenues from excess electricity. - PV System Size Limitations. - Revenues from self-consumed PV. - Maximum timeframe for compensation. - Electricity System Limitations.	- Some countries reported specific targets while others did not identify minimum targets for SC (in this table only countries with quantified targets are reported)	- Germany: minimum requirement of 10 % SC for residential housing. - UK: for small systems with less than 30 kW SC is advised by a export/generation tariff applicable to the electricity fed to the grid.

main influencing technologies, methodology, and achieved results.

Based on the review done, it can be claimed that the self-consumption rate strongly depends on the presence of storage systems and on the optimization of the PV and storage size to meet the building loads. Thus, the typical SC value using only a PV system and without the integration of a storage system is 30 % (rounded to the lower integer value) representing the MA threshold. While by integrating storage systems, heat pumps, control systems, and optimizing the size of PV and storage, the maximum reasonable achievable value is 70 % (mean value rounded to the lower integer), thus representing the TP threshold.

- **Load Cover Factor Indicator**

The Load Cover Factor (LCF or γ_{load}) measures the percentage of the electrical demand instantaneously covered by on-site electricity

Table 7
RES self-consumption indicator – case studies review.

Reference Study	Integrated Systems/ Technologies	Methodology	Achieved Annual RES Self-Consumption Value
[73]	- PV panels. - Optimized storage system. - Heat pump. - Electric chillers (in some buildings). - Smart control (in some buildings).	- Monitored data available for six buildings representing different building typologies, technologies, and PV sizing. - Annual values for the supply cover factor are presented for monitored and simulated case studies.	- The annual SC ranges between 42 % and 59 % in different buildings due to different sizing of on-site generation.
[111]	- Battery storage. - PV system. - Control system.	- Predictive control strategies based on dynamic programming for stationary PV battery systems. - Optimal charge control strategies. - Optimized battery storage sizing.	- SC without storage is 34 %. - SC with optimized storage sizing is 64 %.
[112]	- Battery storage. - PV system. - Control system.	- Meteorological and load demand data sets. - Sensitivity analysis was conducted for different scenarios. - Equation to calculate SC.	- SC is around 35 % with no storage. - SC is around 65 % in the presence of storage.
[113]	- Heat pump. - PV system. - Battery storage system.	- Increase of RES self-consumption by combining PV system with battery storage, controller and an inverter, and hot water storage tank for residential building.	- Based on different battery sizes, SC with storage ranges between 55 % to 88 %.
[114]	- Heat pump. - PV system. - Battery storage system.	- Testing the effect of different battery capacities and heat pump type on the SC assessed for a residential building.	- SC without heat pump, for appliances only is 30 %, - SC with heat pump but without storage is between 30 % and 40 % depending on different heating loads. - SC with heat pump and storage ranges between 45 % and 50 %.
[115]	- Control system. - PV system. - Storage system. - System optimization.	- Optimization for a residential photovoltaic system with storage and control strategy. - Two control algorithms applied: cost reduction based on PV production, and cost reduction without forecast.	- For different storage capacities, and different control algorithms the SC ranged between 30 % and 60 %.
[116]	- Electric vehicle. - PV system. - Control system.	- EV charge–discharge control proposed, and their effects analyzed. - Combining electric vehicle, electricity meter and control system with PV system in a smart house can result in increasing SC.	- SC was 41 %, while combining EV and control strategies SC was 79 %.

generation (i.e., without grid exchange) over a period of time. The factor ranges between 0 and 1 and can be represented as a percentage, in which the higher the indicator the greater is the amount of load covered by RES production. To date, there is no agreed minimum value of LCF for smart buildings or nZEBs. According to the proposed methodology, Table 8 presents several case studies that have calculated the load cover factor indicator in buildings and discuss the main influencing technologies, methods, and achieved values to set thresholds for the indicator.

Thus, based on the reviewed studies it is evident that the LCF mostly depends on the RES production, the presence of a control system, and the optimization of RES and storage sizing. The annual MA of the LCF using a PV system and no system optimization is 20 % (mean value of representing case studies rounded to the lowest integer value), while when the RES sizing is optimized and several technologies are integrated such as storage systems, control systems, heat pumps, etc., the annual LCF can reach 70 %, which has been identified as the TP threshold in smart buildings/retrofits.

Table 8
Load cover factor indicator – case studies review.

Reference Study	Integrated Systems/ Technologies	Methodology	Achieved Annual Load Cover Factor Values (γ_{load})
[73]	- PV system. - Heat pump. - Electric driven chillers.	- Five case studies selected in different climatic zones. - High resolution data used from both monitored and simulated buildings. - Load matching indicators calculated at different time resolutions.	- Annual monitored LCF ranged between 21 % and 56 % according to different case studies based on the variation of onsite production, electricity load profiles as well as the heat load profiles.
[54]	- PV system. - Storage system. - High-efficiency HVAC system. - Control system.	- A house is modeled in Energy Plus based on simulating different PV-battery sizes and high-level battery controller. - Four PV configuration scenarios were tested to improve load match and grid interaction indicators.	- Annual simulated LCF ranged between 25 % and 60 % based on different PV sizing.
[117]	- BIPV system. - Smart control system. - Storage system. - Heat pump.	- Net-zero energy building with BIPV, a heat pump with cooling functionality simulated in dynamic thermohydraulic simulations. - Load shifting strategy of heat pump implemented.	- Annual simulated LCF achieved is 97 %.
[72]	- PV system. - Storage system. - Fuel cell systems.	- nZEB prototype evaluated in terms of energy performances, load match and grid interaction issues. - PV systems and fuel cell systems with different nominal power, electric storage system with varying the nominal storage capacity and.	- Simulated LCF was 30 % when only PV system was used. - When the storage system and the fuel cell systems are used and the sizing of the three systems was optimized, the LCF reached 70 %.
[47]	- Heat pump. - Thermal energy storage (TES). - Control systems. - PV system.	- Building modeling with Modelica software. - Three different control conditions implemented for the storage tank to shift HP electricity consumption to time with higher PV system output.	- Simulated LCF without daytime control is around 20 % and with daytime control is around 30 %.
[118]	- PV system. - High-efficiency HVAC system. - Biomass based co-generation heat and power technologies. - Thermal tracking strategy.	- Single-family house simultion assisted by four conventional heating systems and biomass co-generation heat/ power technologies. - No storage system used.	- Using the CHP-polymer electrolyte membrane fuel cell simulation results could reach the highest LCF of 42 %.

- **Grid interaction index Indicator**

The grid interaction index (GII or f_{Grid}) defines the variable energy exchanged between the building and the grid annually, normalized to the highest absolute value. It is a measure of the variation of energy exchanged between the grid and the building. Thus, the optimal GII value lies in minimizing the load on the grid while ensuring a proper balance in energy and performance. This means that the lower the index the less interaction with the network. No quantified threshold has been set for this indicator, yet different studies have evaluated the GII and quantified its' achievable value. It should be noted that the GII can be calculated according to different time resolutions such as hourly, daily, and monthly. However, the grid interaction must be evaluated according to an hourly time resolution or possibly lower; in fact, hourly values provide quite a good picture of the grid match since hourly data shows the variations in fluctuations of the load. To set a threshold for this indicator, Table 9 reviews different case studies according to their influencing technologies, methods, and achievable values. The GII is calculated at different time resolutions including hourly ($f_{Grid,h}$), daily ($f_{Grid,d}$), and monthly ($f_{Grid,m}$).

The GII depends highly on the RES production, the energy storage capacity and BEMS. Based on the review done in Table 9, a range of thresholds can be suggested for each time step. The values used are the mean values of the representing case studies rounded to the lowest integer. Thus, for the monthly time step, when no optimization is applied and with the use of just the PV system, the MA value (representing the minimum threshold) of $f_{Grid,m}$ is 50 %, while when optimizing the PV capacity/configuration and with the integration of other technologies the TP value of $f_{Grid,m}$ is 30 %. Similarly, for the daily GII, the MA value of $f_{Grid,d}$ is 40 %, while the TP threshold of $f_{Grid,d}$ is 20 %. For the hourly GII, the MA value of $f_{Grid,h}$ is 30 %, and the TP threshold of $f_{Grid,h}$ is 10 %.

4.2. *Summary of threshold evaluation*

A summary of the outcomes reported in the previous section is shown in the graphical representation of Fig. 5, which illustrates the range of the proposed thresholds for residential buildings.

5. Testing KPIs on a smart retrofit case study

To validate the thresholds, KPIs are evaluated on a representative case-study building within the H2020 HEART project. As already introduced, the selected building was retrofitted with a holistic retrofit toolkit that integrates several smart technologies and optimises the building in a systemic way according to its dimensional, functional and performance features. The case-study, located in the city of Bagnolo in Piano (Reggio Emilia, Italy) is a four-storey building, having a total of 12

Table 9
Grid interaction index – case studies review.

Reference Study	Integrated Systems/ Technologies	Methodology	Achieved Grid Interaction Index Values
[119]	- Compression heat pumps. - Heat supply with a CHP unit. - PV system. - Storage system.	- Three buildings monitored: a nZEB and two net plus energy buildings. - PV production exceeds the annual needs. - Load matching and grid interaction tested on three different time intervals: hourly, daily, and monthly.	- Monitored data for building 1, Portugal: - $f_{Grid,m}$ is 37 %, $f_{Grid,d}$ is 25 % and $f_{Grid,h}$ is 31 %. - Monitored data for building 2, USA: - $f_{Grid,m}$ is 55 %, $f_{Grid,d}$ is 29 % and $f_{Grid,h}$ is 29 %. - Monitored data for building 3, Germany: - $f_{Grid,m}$ is 43 %, $f_{Grid,d}$ is 35 % and $f_{Grid,h}$ is 25 %.
[73]	- PV panels. - Optimized storage system. - Heat pump. - Electric chillers (in some buildings). - Smart control (in some buildings). - Battery storage system.	- Monitored data representing different technologies, building typologies, and PV sizing are available for six buildings. - Calculation of Monthly generation of the net exported electricity. - Annual values for the supply cover factor are presented for monitored and simulated case studies.	- $f_{Grid,h}$ varies between 20 % and 30 % for simulated case studies, and between 15 % and 21 % for the monitored case studies.
[120]	- PV system. - Storage system.	- Stochastically generated electricity demand and PV generation. - Simulated model can generate detailed and realistic data down to a 1-min resolution. - Storage system shifts excess generation to times with a net demand.	- f_{Grid} is higher with the monthly resolution. - $f_{Grid,m}$ is 72 % and $f_{Grid,h}$ is 27 %.
[121]	- PV system. - Battery Energy storage. - District heating. - Hot water storage tank. - Solar thermal collectors.	- Simulated data of a residential building with load matching and grid interaction in hourly resolution. - Test different options including changing the slope of solar thermal collectors, battery capacity, and PV installed capacity.	- Based on different options the $f_{Grid,h}$ resolution ranges from 18 % to 23 %. - According to different options the $f_{Grid,d}$ decreases from 44 % to 29 %, and $f_{Grid,m}$ decreases from 70 % to 41 %.
[122]	- Evacuated tube solar collector. - Absorption chiller. - Ground source heat pump. - Air source heat pump. - PV system.	- Investigated buildings in different cities representing low-energy buildings. - Building energy simulation using TRNSYS. - Multi-criteria decision-making optimal models' analysis. - Grid interaction index indicator evaluation using equation.	- $f_{Grid,m}$ variates between 38 % and 77 % depending on the different cities. - $f_{Grid,m}$ of 46 % is achieved when using a biodiesel generator. - $f_{Grid,m}$ of 40 % which achieved when adopting a vertical U-type borehole heat exchanger and ground source heat pump for DHW, and heating/cooling.
[123]	- BIPV. - Control system.	- Analysis of two buildings in different cities to compare monitored electric load data and PV power generation. - Decision-making process for different configuration of BIPV.	- Most efficient typology of BIPV yielded $f_{Grid,d}$ 29 %, and $f_{Grid,h}$ 34 %.
[124]	- PV systems. - Thermal and electrical storage systems.	- The GII was monitored for seven residential building equipped with different technologies and different sizing of PV systems.	- The $f_{Grid,h}$ for the case studies varied between 15 % and 21 %.

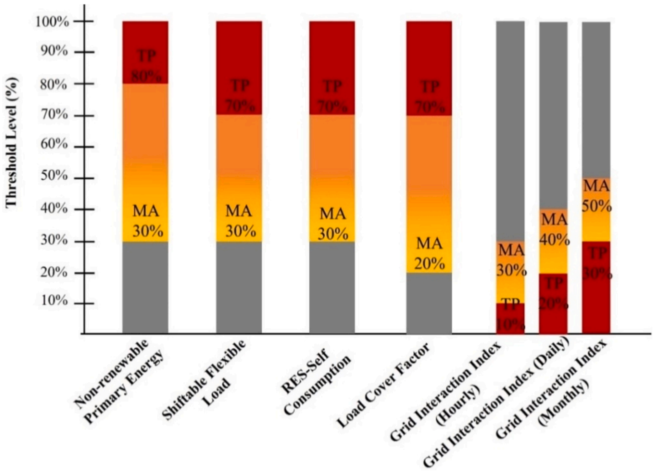

Fig. 5. Summary of the proposed Key Performance Indicators Thresholds.

apartments, with cellars and parking areas located at the ground floor. The total heated area of the building is around 680 [m^2] [125].

In this research, a spreadsheet was developed to calculate the propose KPIs based on input parameters. Hourly data, which has been used as the basis for calculations, was retrieved from the building energy model. The latter has been calibrated and validated on the first available experimental data, which makes it possible to reliably estimate the post-retrofit energy performance of the building, both overall and broken down into subsystems (more details can be found in Deliverable D3.10 of the HEART project [20]). By using the developed spreadsheet, the KPIs were thus calculated based on the implemented technologies in the retrofitted building and the obtained values were compared with the thresholds set in the previous section.

More in detail, the building was numerically modelled using Transient System Simulation Tool (TRNSYS) program which is used to model building technologies together with TRNBuild to implement the building characteristics using Type 65 [126]. A specific yearly weather file was generated from DEXT3R weather dataset of ROLO (Reggio Emilia province) [20]. The building was not equipped with a centralized cooling system before the retrofit, thus only heating demand and DHW were considered. For the building simulation after the retrofit intervention, a rule-based control logic was implemented. The control signals are retrieved for each control rule and are modeled by Type 2d, which is the differential controller. The heating setpoint is set at 20 °C and the cooling setpoint at 26 °C.

The envelope is insulated using pre-formed modular insulation panels that is attached to existing façades, and windows are renovated using new high-performance double-glazed window. The heating system is replaced based on a centralized configuration containing two direct-current air-to-water heat pumps (DC-HPs) used for pre-heating and pre-cooling of the water loop. A TES is also connected to the water loop, in which it keeps sensible/latent heat through water added with Phase Change Materials (PCM) which allows for phase transition to provide useful heat/cooling. A DC smart fan coils connected are mounted in each room and performs as water-to-air decentralized heat pumps used for heating or cooling atmosphere air. The PCM are in the form of balls that are added in 3 water tanks with a total capacity around 120 kWh [127,125]. The PCM phase change occurs at 25 °C. During winter, the temperatures inside the TES unit is around 32–34 °C, while in summer it is around 16–18 °C in order to realize an inlet temperature in the heating system around 25 °C [20]. The TES unit boundary conditions of the heating system are met, by which the ideal water supply temperature going to the fan coils is around 25 °C, while return temperature going to the centralized heat pump is between 15 to 20 °C. For load-shifting, DC-HPs provide heat to the heating system and/or to the TES. This allows the DC-HP to operate at the best conditions (e.g., accessibility of solar energy, higher ambient air temperature, etc.). The control systems' logic which has been further detailed in [127], enables the TES to appropriately shift the load in the presence of PV production. Water-to-water decentralized heat pumps boilers are linked to the DHW system.

The thickness of the thermal insulation and the size of the different components (e.g., PV system and TES) were determined using a decision-support process to identify the cost-optimal option. TRNSYS custom Types for the TES and the air-to-water heat pump were developed by the HEART team, while Type 133 was used in TRNSYS to model the PV system. Constant value of infiltration rate is estimated at 0.27 [1/h], while the U-value after retrofit was 1.2 W/m^{2}K for the glazing, 0.266 W/m^{2}K for the external walls and 0.25 W/m^{2}K for the roof [128]. Furthermore, a battery with a capacity of 14 kWh is also present in the building, with the function to store electricity when the TES is full or the thermal energy is not needed in the building (e.g., mid seasons). The BEMS controls electricity/thermal energy fluxes, as well as coordinates the main devices (e.g., heat pumps, fan coils, etc.) on the basis of different variables (e.g., PV energy production, building load, etc.) [129].

For the KPI calculations, first, *the primary energy saving* was calculated based on the dynamic simulation of the building. The non-renewable primary energy conversion factor adopted is 1.95 [130]. Table 10 and 11 report the non-renewable primary energy calculation before and after the retrofit, respectively. In detail, based on Eq.1 presented previously in Table 2, the non-renewable primary energy before retrofit was estimated equal to 105′210 kWh/y, which corresponds to around 154 kWh/m^{2}y. While after retrofit the non-renewable primary energy was found to be 14′549 kWh/y, which equals 21.4 [kWh/m^{2}y]. Thus, the overall PE$_{nren}$ savings is about 86 %.

To calculate the *Shiftable flexible load indicator*, two scenarios were considered, namely "reference" and "post-retrofit", which correspond to the building before retrofit and after the retrofit, respectively. The flexibility is quantified through load shifting which is achieved with the control system that charges/discharges the energy storage. The load shifting is resembled by Eq.2 shown in Table 2, which considers the overall building load before and after the retrofit intervention. The result showed that the shiftable flexible load of the building is 67 %. Hence, charging the energy storage when there is PV production reduces the peak load demand and improves the energy efficiency of the system.

Table 10
Data for Non-renewable Primary Energy Calculations – Before Retrofit.

$f_{del,nren,i}$ (Delivered energy non-renewable primary energy factor)	1.95
$f_{exp,nren,i}$ (Exported energy non-renewable primary energy factor)	1.95
Non-renewable Primary Energy Before Retrofit (kWh/y)	105′210
Non-renewable Primary Energy Before Retrofit (kWh/m^{2}y)	154,7

Table 11
Data for Primary Energy Calculations – After Retrofit.

$f_{del,nren,i}$ (Delivered energy non-renewable primary energy factor)	1.95
$f_{exp,nren,i}$ (Exported energy non-renewable primary energy factor)	1.95
Non-renewable Primary Energy After Retrofit (kWh/y)	14′549
Non-renewable Primary Energy After Retrofit (kWh/m^{2}y)	21.4

To calculate the *RES Self-consumption*, the PV production is first analyzed. TRNSYS simulations were used to predict the hourly PV production for the building. The power of the installed PV plant is 8.7 kW [128]. The monthly values of the energy generated by the PV plant are reported in Fig. 6.

Outcomes of hourly simulations are summarized in Table 12. The PV SC is calculated considering charging/discharging of the storage system. The annual SC with storage is assessed using Equation 3 and was found to be 47.7 %. This result confirms that the integration of the storage system is very crucial in calculating the RES SC indicator. It must be noted that the summer cooling load is not considered, so this is achieved with a low summer electrical load.

The *Load Cover Factor* (γ_{load} or LCF) for the HEART project was calculated at four different time resolutions: hourly, daily, monthly, and yearly to monitor the seasonal effect of the PV production on the KPI. However, the most reported timestep for the γ_{load} is the annual and it usually gives the best description of the indicator, thus, the threshold was set for the annual timestep only. The values of the load cover factor were calculated using Equation 4 to show the variations throughout the year. The annual load cover factor shows that the PV electricity production covers around 54 % of the electricity demand of the building including heating, cooling, and DHW. As shown in Table 13, as the time resolution increases the LCF decreases. This is because the PV production pattern is more variable at higher time resolutions.

The last calculated indicator is the *Grid Interaction Index* (f_{grid} or GII) which describes the variation of the energy exchange between the grid and the building. It is calculated at three different time resolutions (i.e., hourly, daily, and monthly) using equation 5. It demonstrates that because of the absence of PV output at night hours the hourly resolution has lower values. These results match the GII values discussed in literature on different case studies with similar configuration.

The achieved values of the HEART case-study were compared with the proposed thresholds for each KPI as visualized in Fig. 7. Then, some interpretations and remarks of the results are reported in Table 14.

Results of this research offer a complementary approach to SRI's framework by providing a quantitative assessment of technological performance. While the SRI [17] evaluates smart building capabilities across critical domains such as heating, cooling, domestic hot water,

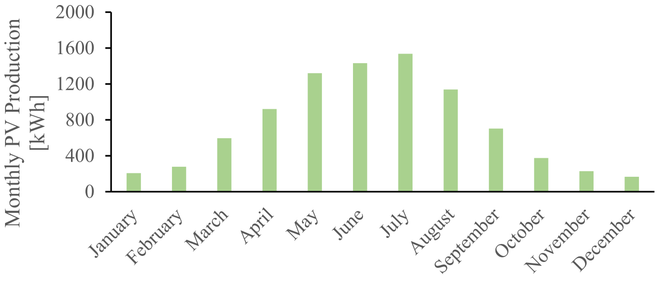

Fig. 6. Monthly Renewable Energy Production of the Installed PV Plant.

Table 12
RES self-consumption indicator calculation variables based on hourly simulations.

RES Self-Consumption Indicator Calculation Based on Equation 3	
Annual PV Production [kWh]	8′900
Annual Building Electricity Consumption [kWh]	16′359
Annual instantaneous self-consumption (Energy used directly in building) [kWh]	4′244

Table 13
Load Cover Factor and Grid Interaction Index calculation at different time steps.

Load Cover Factor and Grid Interaction Index Calculation at different time steps using Equation 4 and 5	
Time step	Value
$\gamma_{load,y}$	54 %
$\gamma_{load,m}$	33 %
$\gamma_{load,d}$	18 %
$f_{grid,m}$	31 %
$f_{grid,d}$	23 %
$f_{grid,h}$	15 %

ventilation, lighting, dynamic building envelope, electricity management, electric vehicle charging, and monitoring and control systems, this study's threshold values enhance the SRI approach. These indicators and thresholds can serve as benchmarks within the SRI framework, providing a more quantitative analysis of each system's efficiency and responsiveness, enabling a more precise evaluation of how technological upgrades align with smart readiness goals.

Furthermore, the findings align with the EPBD and the BPIE, both of which have established key indicators to enhance energy efficiency in buildings across the EU [14]. Where it was stated that the targeted non-renewable primary energy demand for residential buildings to achieve nearly zero-energy status shall be less than 100 kWh/m^2/year [65]. A target of at least 30 % was set for renewable energy self-consumption as well as $\geq$ 20 % for flexible shiftable load.

6. Conclusions, limitations and future recommendations

The pursuit of energy efficiency and smart building readiness presents a formidable challenge in the quest to reduce CO$_2$ emissions and energy consumption, particularly within the context of existing structures. To address this challenge, this paper has introduced a comprehensive framework designed to assess the performance of smart building and retrofit projects, thereby quantifying their advantages. By establishing a group of reference Key Performance Indicators (KPIs) and associated thresholds, minimum acceptable standards were defined. These thresholds were selected through a methodology that incorporates a literature review and a Logical Evaluation approach. Subsequently, these KPIs were rigorously applied to a case-study building, which is a representative case in terms of energy efficiency and smart capabilities, developed as part of a Horizon 2020 initiative. The application of these KPIs to the actual building's performance, leveraging preliminary monitoring data, provided concrete evidence of the thresholds' viability in the context of a real retrofit intervention. Consequently, as a result of the work done in this paper, we propose a quantified definition for smart retrofitting, which is: the process of transforming an existing building into a SB, which is a nZEB with Primary Energy savings between 30 % and 80 % and has the capability of responding to the varying conditions of climate and of the grid, of communicating with the user and of predicting failures in the building operations through the utilization of a BEMS. It shall allow Load Shifting in response to RES production/electricity prices of 30 % to 70 % annually and minimize grid interaction to around 10 % to 30 % at hourly level throughout a year. Moreover, it should allow RES Self-Consumption of 30 % to 70 % and Load covered by RES of 20 % to 70 % annually.

While this study offers valuable insights into KPIs assessing smart retrofitting and having tested them in a real case study, some potential limitations should be acknowledged. One challenge was testing the KPIs across various European smart retrofitting projects, where data collection was hindered by inconsistent time steps, missing pre-retrofit data, or incomplete parameters necessary for KPI evaluation. Consequently, the KPIs were tested only on the Italian case study from the HEART project, rather than a broader range of buildings. This constraint of the selected building types posed a limitation, as the conclusions may not extend to other building categories, such as commercial or industrial buildings, which differ in terms of structure, age, and usage. Additionally, the study focused primarily on measuring energy and grid performance, leaving social and cultural aspects unaddressed. However, the technologies analyzed, such as real-time monitoring and control systems, could have indirect benefits on user satisfaction and social

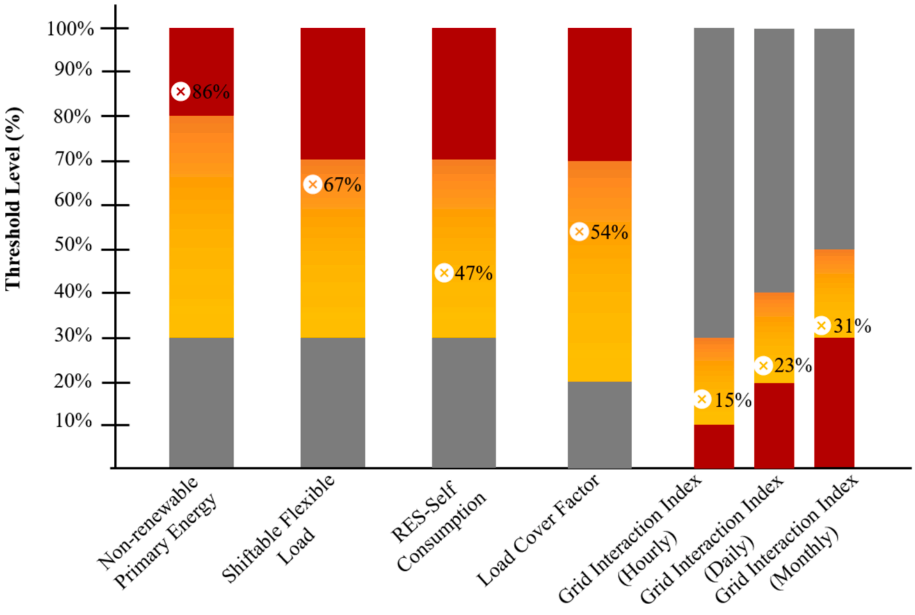

Fig. 7. HEART Project KPI Results in Reference to Elaborated Thresholds.

Table 14
Summary of results of KPIs' tested on the HEART's Italian case study.

Indicator	Achieved Result	Identified Values Based on Literature	Interpretation
1. Non renewable Primary Energy Indicator	Non renewable Primary Energy Saving is **86 %**	Minimum Acceptable Limit:30 % Top Performing Limit: 80 %	Outstanding performance since the building has a compact shape, the envelope was fully insulated with the optimum thickness and high efficiency HVAC system was implemented and supported by RES.
Shiftable Flexible Load	Annual Load Shifting of **67 %**	Minimum Acceptable Limit: 30 % Top Performing Limit: 70 %	The KPI is almost equal to the top performing threshold. It must be noted that the storage size is limited considering the area of the technical room. Thus, the achieved load shifting is based on the maximum allowed storage size.
2. RES Self-Consumption	φ_{SC} with storage **47.7 %**	Minimum Acceptable Limit:30 % Top Performing Limit:70 %	Good value considering that it's a residential building with the peak load not in phase with solar energy availability and the highest consumption is concentrated in the winter season.
Load Cover Factor Indicator	$\gamma_{load,y}$ **54 %**	Minimum Acceptable Limit:20 % Top Performing Limit:70 %	The LCF is within the minimum and top performing threshold; it must be noted that the PV size was limited by the maximum power of the converter.
3. Grid Interaction Index	$f_{grid,h}$ **15 %** $f_{grid,d}$ **23 %** $f_{grid,m}$ **31 %**	Minimum Acceptable Limit: Hourly 30 %, Daily 40 %, Monthly 50 % Top Performing Limit: Hourly 10 %, Daily 20 %, Monthly 30 %	The GII values are close to the top limits thus the obtained result is more than satisfactory.

sustainability by improving comfort, enabling self-consumption, facilitating load shifting, and reducing peak loads during renewable energy production and lower electricity prices.

In order to improve the robustness of the KPIs, the authors are aware of a number of possible avenues for further study. As noted in [80], one important area is dealing with operational and environmental uncertainties, such as user behaviour and climate conditions, which have a big impact on building performance and, in turn, the KPIs. Furthermore, it is necessary to take into consideration the stakeholder interests in these performance evaluations, this has been well highlighted by the results of a recent study on a multi-criteria decision-making framework for building insulation [131]. By performing a balance between a variety of criteria, including cost-effectiveness, energy economy, and thermal comfort, this framework may help increase the KPIs' adaptability, particularly under changeable circumstances.

Additionally, [132] and [133] suggest engaging a metric that quantifies the difference between simulated and actual performance under uncertain scenarios. Such a metric would help clarify the performance gap, and thus aligning predictions with real-world outcomes across a building's entire lifespan. Combining these approaches with the decision-making framework in [131] offers a pathway to strengthen the reliability of building performance assessments, addressing immediate and long-term stakeholder needs effectively.

On the other hand, the broad topics discussed in the paper have drawn attention to many gaps in the literature that can be further emphasized and detailed for future work. One of the key gaps is the lack of testing the indicators and demonstrating their performance in real-world scenarios. For instance, this could be accomplished through monitoring and assessing buildings before and after smart retrofit. Furthermore, studies can be selected in various climate zones to analyze the impact of the SRI thresholds under different energy regulations and energy performances. The defined thresholds of the indicators can be actively communicated and evaluated by architects, designers, and policymakers for the future requirement for Smart Readiness Indicator and smartness labeling. Finally, a detailed cost-benefit analyses and technical–economic evaluations in these case studies would help identify more realistic and affordable thresholds, thereby enhancing the practical applicability of the indicators.

CRediT authorship contribution statement

Joud Aldakheel: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Claudio Del Pero:** Resources, Project administration. **Fabrizio Leonforte:** Writing – review & editing, Resources, Project administration. **Niccolò Aste:** Project administration. **Mohamed El Mankibi:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A1
Original list of smart buildings KPIs definitions and references.

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.	[27;28;29;63;64;65]
	Energy Demand And Consumption (kWh/(m^2.month or year))	Assess the building energy demand and consumption.	[73;27;32]
	Energy Savings (%)	Percent reduction of energy consumption compared to the baseline case.	[52;27;33;34]
	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.	[134;30;31]
	Peak Load Reduction (%)	Compare the baseline peak demand with the peak demand after technology implementation.	[27;135;37;38]
	Degree of Energetic Self-Supply by RES (%)	The ratio of locally produced energy from RES and consumption over a period of time.	[27;44];
	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.	[136–138;45;46]
Flexibility Climate Response, Grid Response, User Response	Storage Capacity (%)	Available storage capacity of storage technologies integrated into the smart grid.	[21;139;41;140;58;59]
	Depth of Discharge (%)	Describes how deeply a storage system can be discharged to provide usable energy with respect to the reference conditions.	[139;24;62]
	Storage Efficiency (%)	The ratio between the discharged energy and the charged energy, typically over a full cycle.	[60;61]
	Load Cover Factor (%)	The percentage of electrical demand covered by on-site electric generation.	[71;49;72;54;73;47]
	Maximum Hourly Surplus (kWh)	The maximum hourly ratio between on-site generation and load over the load for each energy type.	[50;51]
	Maximum Hourly Deficit (kWh)	The maximum hourly ratio of the difference between load and on-site renewable energy generation.	[50;51;52]
	Demand Response (kWh)	Load shed potential of a device with respect to its rated power consumption during a DR event.	[136;141;35;36]
	Load Shifting (%)	Load shifting potential for the considered DSM technology at a certain time step.	[35;142]
	Flexibility Factor (−)	Instant demand at high/low electricity price periods.	[40;41]
	Annual Mismatch Ratio (−)	The annual difference between demand and local renewable energy supply.	[50;53]
	Load Matching Index (%)	The on-site energy use: it helps to differentiate between the different timescales.	[74;73;54;49];
	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.	[50;53;55,72;49;73;54;47,69;70;49;48]
	No Grid Interaction Probability (−)	The probability that the building is acting autonomously of the grid.	
	RES Self-consumption (Supply Cover Factor) (%)	The degree of instantaneous on-site renewable energy consumption	
Real-time monitoring Monitoring and Supervision	Increased Power Quality and Quality of Supply (%)	Average time needed for awareness, localization, and isolation of grid fault.	[27;143;45]
	Absolute Grid Support Coefficient (−)	Evaluate the grid impact of a building or its heating system	[40;57];
	Relative Grid Support Coefficient (−)	Assesses the optimization potential for heating or cooling system operation.	[40;57];
	Building Operational Performance KPI (%)	Illustrates the performance of the building by relating the energy consumption, emissions, and geometrical information.	[144]
	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.	[27;141]
	Smart Ready Built Environment Indicator (−)	Assesses how smart-ready the building is and measures the performance of technologies.	[145]
	Smart Readiness Indicator (−)	A score that indicates the readiness of a building to adapt operations to the needs of occupants and to optimize energy efficiency and energy flexibility.	[146;17;147]
	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.	[148–153]
	Reduced Energy Curtailment of RES and DER (%)	Reduction of energy curtailment due to technical and operational problems.	[27;141;154]
	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.	[136;141]
	Increased reliability (%)	Avoiding failures reverts to higher reliability, meaning fewer stops on the normal operation of the building and associated systems.	[27;141,73;74;49,56]
	Grid Interaction Index (%)	Describes the average grid stress, using the standard deviation of the grid interaction over a period of a year.	

(*continued on next page*)

Table A1 (*continued*)

SB Basic Features	Supporting KPIs (Units)	Definitions	References
Real-time interaction User Response	Consumer Engagement (−)	Measures the involvement of users in control over the energy use in the building.	[27;45]
	System Average Interruption Duration Index System (−)	Estimates the average interruption duration, which leads to disturbance for network users and maintenance costs.	[136;155–157];
	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.	[136;155–157]

Data availability

Data will be made available on request.

References

[1] European Commission, "In focus: Energy efficiency in buildings" Accessed: Sep. 07, 2021. [Online]. Available: https://ec.europa.eu/info/news/focus-energy-efficiency-buildings-2020-feb-17_en.

[2] European Commission, "Energy Performance of Buildings Directive 2024," Energy Performance of Buildings Directive 2024.

[3] C. Camarasa, C. Nägeli, Y. Ostermeyer, M. Klippel, S. Botzler, Diffusion of energy efficiency technologies in European residential buildings: A bibliometric analysis, Energy Build 202 (2019) 109339, https://doi.org/10.1016/J.ENBUILD.2019.109339.

[4] European Commission, "Energy roadmap 2050 Energy," Luxembourg, 2012. doi: 10.2833/10759.

[5] M. da Graça Carvalho, EU energy and climate change strategy, Energy 40 (1) (2012) 19–22, https://doi.org/10.1016/j.energy.2012.01.012.

[6] E. Recast, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast), Off. J. Eur. Union 18 (06) (2010) 2010.

[7] F. Bisegna, L. Evangelisti, P. Gori, C. Guattari, B. Mattoni, From efficient to sustainable and zero energy consumption buildings, in: Handbook of Energy Efficiency in Buildings: A Life Cycle Approach, 2019, pp. 75–205, doi: 10.1016/B978-0-12-812817-6.00038-3.

[8] B. Dean, J. Dulac, K. Petrichenko, P. Graham, Towards zero-emission efficient and resilient buildings: Global Status Report. Global Alliance for Buildings and Construction (GABC), 2016.

[9] J. Laski, V. Burrows, From Thousands to Billions Coordinated Action towards 100% Net Zero Carbon Buildings By 2050, World Green Build. Council (2017).

[10] D. D'Agostino, B. Cuniberti, I. Maschio, Criteria and structure of a harmonised data collection for NZEBs retrofit buildings in Europe, Energy Proc. 140 (2017) 170–181, https://doi.org/10.1016/J.EGYPRO.2017.11.133.

[11] S. Colclough, et al., Post occupancy evaluation of 12 retrofit nZEB dwellings: The impact of occupants and high in-use interior temperatures on the predictive accuracy of the nZEB energy standard, Energy Build 254 (2022) 111563, https://doi.org/10.1016/J.ENBUILD.2021.111563.

[12] P. Moran, J. O'Connell, J. Goggins, Sustainable energy efficiency retrofits as residenial buildings move towards nearly zero energy building (NZEB) standards, Energy Build 211 (2020), https://doi.org/10.1016/j.enbuild.2020.109816.

[13] F. Asdrubali, I. Ballarini, V. Corrado, L. Evangelisti, G. Grazieschi, C. Guattari, Energy and environmental payback times for an NZEB retrofit, Build Environ 147 (2019) 461–472, https://doi.org/10.1016/J.BUILDENV.2018.10.047.

[14] "DIRECTIVE (EU) 2018/844 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency (Text with EEA relevance).".

[15] A. Chel, G. Kaushik, Renewable energy technologies for sustainable development of energy efficient building, Alex. Eng. J. 57 (2) (2018) 655–669, https://doi.org/10.1016/J.AEJ.2017.02.027.

[16] J. Al Dakheel, C. Del Pero, N. Aste, F. Leonforte, Smart buildings features and key performance indicators: A review, Sustain Cities Soc. 61 (2020) 102328, https://doi.org/10.1016/J.SCS.2020.102328.

[17] S. Verbeke *et al.*, "Support for setting up a Smart Readiness Indicator for buildings and related impact assessment Interim report," 2017.

[18] HEART, "HEART Project," European Union Horizon 2020 Research and Innovation Program. Accessed: Feb. 22, 2021. [Online]. Available: https://heartproject.eu/.

[19] A. Kylili, P. A. Fokaides, and P. A. Lopez Jimenez, "Key Performance Indicators (KPIs) approach in buildings renovation for the sustainability of the built environment: A review," Apr. 01, 2016, *Elsevier Ltd.* doi: 10.1016/j.rser.2015.11.096.

[20] European Commission, "Holistic Energy and Architectural Retrofit Toolkit (HEART) Deliverables," 2020.

[21] K. Angelakoglou, et al., A methodological framework for the selection of key performance indicators to assess smart city solutions, Smart Cities 2 (2) (2019) 269–306, https://doi.org/10.3390/smartcities2020018.

[22] S.Y. Janjua, P.K. Sarker, W.K. Biswas, Development of triple bottom line indicators for life cycle sustainability assessment of residential bulidings, J Environ Manage 264 (2020) 110476, https://doi.org/10.1016/J.JENVMAN.2020.110476.

[23] M. Khorram, P. Faria, O. Abrishambaf, Z. Vale, Key performance indicators regarding user comfort for building energy consumption management, Energy Rep. 6 (2020) 87–92, https://doi.org/10.1016/J.EGYR.2020.12.018.

[24] L.F. Cabeza, E. Galindo, C. Prieto, C. Barreneche, A. Inés Fernández, Key performance indicators in thermal energy storage: Survey and assessment, Renew Energy 83 (2015) 820–827, https://doi.org/10.1016/j.renene.2015.05.019.

[25] Y. Li, J. O'Donnell, R. García-Castro, S. Vega-Sánchez, Identifying stakeholders and key performance indicators for district and building energy performance analysis, Energy Build 155 (2017) 1–15, https://doi.org/10.1016/J.ENBUILD.2017.09.003.

[26] M.C. Dejaco, F. Re Cecconi, S. Maltese, Key performance indicators for building condition assessment, J Build Eng 9 (2017) 17–28, https://doi.org/10.1016/J.JOBE.2016.11.004.

[27] SCIS, "MONITORING KPI GUIDE D23.1," 2017.

[28] European-Commission, In-depth analysis in support of the commission communication com (2018) 773, 2018.

[29] S. Pezzutto, F. Haas, D. Exner, S. Zambotti, Europe's building stock and its energy demand: A comparison between Austria and Italy, no. 9783319757735, in: Green Energy and TechnologySpringer Verlag, 2018, pp. 35–47, https://doi.org/10.1007/978-3-319-75774-2_3.

[30] S. Attia, Net Zero Energy Buildings (NZEB): Concepts, frameworks and roadmap for project analysis and implementation, Elsevier, 2018, 10.1016/C2016-0-03166-2.

[31] ENEA, "Annex 2 Italian Energy Efficiency Action Plan," 2017.

[32] N. N. Abu Bakar *et al.*, "Energy efficiency index as an indicator for measuring building energy performance: A review," 2015, *Elsevier Ltd.* doi: 10.1016/j.rser.2014.12.018.

[33] J. Liu, et al., Efficiency of energy recovery ventilator with various weathers and its energy saving performance in a residential apartment, Elsevier 42 (1) (2010) 43–49, https://doi.org/10.1016/j.enbuild.2009.07.009.

[34] D. Zhang, N. Shah, L.G. Papageorgiou, Efficient energy consumption and operation management in a smart building with microgrid, Energy Convers Manag 74 (2013) 209–222, https://doi.org/10.1016/j.enconman.2013.04.038.

[35] A. Arteconi, F. Polonara, Assessing the demand side management potential and the energy flexibility of heat pumps in buildings, Energies (Basel) 11 (7) (2018) 1846.

[36] R. Yin, et al., Quantifying flexibility of commercial and residential loads for demand response using setpoint changes, Appl Energy 177 (2016) 149–164, https://doi.org/10.1016/j.apenergy.2016.05.090.

[37] N.-K. Kim, M.-H. Shim, D. Won, Building energy management strategy using an HVAC system and energy storage system, Energies (Basel) 11 (10) (2018) 2690, https://doi.org/10.3390/en11102690.

[38] G. Thanos, et al., Evaluating demand response programs by means of key performance indicators. 2013 5th International Conference on Communication Systems and Networks, COMSNETS 2013, 2013, 10.1109/COMSNETS.2013.6465597.

[39] S. Yang, et al., Flexibility index for a distributed energy system design optimization, Renew Energy 219 (2023) 119423, https://doi.org/10.1016/J.RENENE.2023.119423.

[40] R. Li, S. You, Exploring potential of energy flexibility in buildings for energy system services, CSEE J Power Energy Syst 4 (4) (2018) 434–443.

[41] C. Finck, R. Li, R. Kramer, W. Zeiler, Quantifying demand flexibility of power-to-heat and thermal energy storage in the control of building heating systems, Appl Energy 209 (2018) 409–425, https://doi.org/10.1016/j.apenergy.2017.11.036.

[42] Y. Ding, Y. Lyu, S. Lu, R. Wang, Load shifting potential assessment of building thermal storage performance for building design, Energy 243 (2022) 123036, https://doi.org/10.1016/J.ENERGY.2021.123036.

[43] R. Brännlund, M. Vesterberg, Peak and off-peak demand for electricity: Is there a potential for load shifting? Energy Econ 102 (2021) 105466 https://doi.org/10.1016/J.ENECO.2021.105466.

[44] Ana Quijano, Ali Vasallo, Marian Gallego, Alberto Moral, and Aitziber Egusquiza, "SmartEnCity: Towards Smart Zero CO2 Cities across Europe," 2016.

[45] Z. Lubośny and K. Dobrzyński, "Real proven solutions to enable active demand and distributed generation flexible integration, through a fully controllable LOW Voltage and medium," 2016.

[46] G. Bissell *et al.*, "Definition and practical application of key performance indicators to support European grid operators to enable the energy policy goals," 2014.

[47] B. Verbruggen, J. Driesen, Grid impact indicators for active building simulations, IEEE Trans Sustain Energy 6 (1) (2015) 43–50, https://doi.org/10.1109/TSTE.2014.2357475.

[48] A. Prasanna, V. Dorer, N. Vetterli, Optimisation of a district energy system with a low temperature network, Energy 137 (2017) 632–648, https://doi.org/10.1016/j.energy.2017.03.137.

[49] J. Salom, J. Widén, J. Candanedo, I. Sartori, K. Voss, A. Marszal, Understanding net zero energy buildings: evaluation of load matching and grid interaction indicators, Proc. Build. Simul. (2011) 2514–2521.

[50] M. Ala-Juusela, M. Sepponen, T. Crosbie, Defining the concept of an Energy positive neighbourhood and related KPIs. Proceedings of Sustainable Places Conference, 2014.

[51] J. Salom, A. Joanna Marszal, J. Candanedo, J. Widén, K. Byskov Lindberg, and I. Sartori, "Analysis Of Load Match and Grid Interaction Indicators in NZEB with High-Resolution Data," 2013.

[52] P. Bosch, S. Jongeneel, V. Rovers, H.-M. Neumann, M. Airaksinen, and A. Huovila, "CITYkeys indicators for smart city projects and smart cities," 2017.

[53] H. Lund, A. Marszal, P. Heiselberg, Zero energy buildings and mismatch compensation factors, Energy Build 43 (7) (2011) 1646–1654, https://doi.org/10.1016/j.enbuild.2011.03.006.

[54] G.A. Dávi, M. Castillo-Cagigal, E. Caamaño-Martín, J. Solano, Evaluation of load matching and grid interaction indexes of a net plus-energy house in Brazil with a hybrid PV system and demand-side management. 32nd European Photovoltaic Solar Energy Conference and Exhibition EVALUATION, 2016.

[55] Andreas, Athienitis, William. O'Brien, Modelling, Design, and Optimization of Net-Zero Energy Buildings, Wiley, 2015, pp. 216–222.

[56] M. Ferraro, F. Sergi, V. Antonucci, F. Guarino, G. Tumminia, M. Cellura, Load match and grid interaction optimization of a net zero energy building through electricity storage: An Italian case-study. EEEIC 2016 - International Conference on Environment and Electrical Engineering, Institute of Electrical and Electronics Engineers Inc., 2016, 10.1109/EEEIC.2016.7555812.

[57] K. Klein, R. Langner, D. Kalz, S. Herkel, H.M. Henning, Grid support coefficients for electricity-based heating and cooling and field data analysis of present-day installations in Germany, Appl Energy 162 (2016) 853–867, https://doi.org/10.1016/j.apenergy.2015.10.107.

[58] F.A. Silva, Electric energy storage systems: flexibility options for smart grids, IEEE Indust. Electron. Mag. 12 (3) (2018) 54–55, https://doi.org/10.1109/mie.2018.2856574.

[59] H. Ibrahim, A. Ilinca, J. Perron, Comparison and analysis of different energy storage techniques based on their performance index, in: 2007 IEEE Canada Electrical Power Conference, EPC 2007, 2007, pp. 393–398, 10.1109/EPC.2007.4520364.

[60] G. Reynders, "Quantifying the impact of building design on the potential of structural storage for active demand response in residential buildings," 2015.

[61] E.-L. Niederhäuser and M. Rouge, "Technical report on best practices for energy storage including both efficiency and adaptability in solar cooling systems," 2017, doi: 10.18777/ieashc-task53-2019-0002.

[62] F. Haghigat, P. Tuohy, G. Fraisse, C. Del Pero, IEA ECES annex 31 final report - energy storage with energy efficient buildings and districts: optimization and automation, Internat. Energy Agency (2019).

[63] Green_Building_Council_Italia, "Energy Efficiency of Buildings in Italy Green Building Council Italia," 2019.

[64] A. Ferrante, G. Mochi, and N. Nieboer, "Energy and architectural renovation towards nZEB The Dutch Scheveningen case in the ABRACADABRA Project," 2016.

[65] W. Pasut, "Key Performance Indicators (KPIs) and needed data ," 2019.

[66] M. Hall, A. Geissler, Comparison of flexibility factors and introduction of a flexibility classification using advanced heat pump control, Energies 14 (24) (2021) 8391, https://doi.org/10.3390/EN14248391.

[67] Z. Luo, et al., Demand flexibility of residential buildings: definitions, flexible loads, and quantification methods, Engineering (2022), https://doi.org/10.1016/J.ENG.2022.01.010.

[68] A. J. Marsza *et al.*, "Characterization of Energy Flexibility in Buildings Energy in Buildings and Communities Programme Annex 67 Energy flexible buildings," Dec. 2019.

[69] R. Luthander, J. Widén, D. Nilsson, and J. Palm, "Photovoltaic self-consumption in buildings: A review," Mar. 05, 2015, *Elsevier Ltd.* doi: 10.1016/j.apenergy.2014.12.028.

[70] R. Fachrizal, J. Munkhammar, Improved photovoltaic self-consumption in residential buildings with distributed and centralized smart charging of electric vehicles, Energies (Basel) 13 (5) (2020), https://doi.org/10.3390/en13051153.

[71] F. Stern, "Peak Demand and Time-Differentiated Energy Savings Cross-Cutting Protocols: The Uniform Methods Project: Methods for Determining Energy Efficiency Savings for Specific Measures," 2013.

[72] G. Tumminia, et al., Grid interaction and environmental impact of a net zero energy building, Energy Convers Manag 203 (2020) 112228, https://doi.org/10.1016/j.enconman.2019.112228.

[73] J. Salom, A.J. Marszal, J. Widén, J. Candanedo, K.B. Lindberg, Analysis of load match and grid interaction indicators in net zero energy buildings with simulated and monitored data, Appl Energy 136 (2014) 119–131, https://doi.org/10.1016/j.apenergy.2014.09.018.

[74] K. Voss, et al., Load matching and grid interaction of net zero energy buildings, Internat. Solar Energy Soc. (ISES) (2016) 1–8, https://doi.org/10.18086/eurosun.2010.06.24.

[75] L. Schibuola, M. Scarpa, C. Tambani, Demand response management by means of heat pumps controlled via real time pricing, Energy Build 90 (2015) 15–28, https://doi.org/10.1016/j.enbuild.2014.12.047.

[76] M.J. Ruá, N. Guadalajara, Estimating a threshold price for CO2 emissions of buildings to improve their energy performance level: case study of a new Spanish home, Energy Effic 8 (2) (2015) 183–203, https://doi.org/10.1007/s12053-014-9286-2.

[77] C. Lamnatou, D. Chemisana, C. Cristofari, Smart grids and smart technologies in relation to photovoltaics, storage systems, buildings and the environment, Renew Energy 185 (2022) 1376–1391, https://doi.org/10.1016/J.RENENE.2021.11.019.

[78] A.O. Windapo, A. Moghayedi, Adoption of smart technologies and circular economy performance of buildings, Built. Environ. Project Asset Manage. 10 (4) (2020) 585–601, https://doi.org/10.1108/BEPAM-04-2019-0041.

[79] T. Karlessi, et al., The concept of smart and NZEB buildings and the integrated design approach, Proc. Eng. 180 (2017) 1316–1325, https://doi.org/10.1016/J.PROENG.2017.04.294.

[80] R. Kotireddy, P.J. Hoes, J.L.M. Hensen, Integrating robustness indicators into multi-objective optimization to find robust optimal low-energy building designs, J. Build Perform Simul. 12 (5) (2019) 546–565, https://doi.org/10.1080/19401493.2018.1526971.

[81] H. Aissi, C. Bazgan, D. Vanderpooten, Min–max and min–max regret versions of combinatorial optimization problems: A survey, Eur. J. Oper. Res. 197 (2) (2009) 427–438, https://doi.org/10.1016/J.EJOR.2008.09.012.

[82] S. Polasky, S.R. Carpenter, C. Folke, B. Keeler, Decision-making under great uncertainty: environmental management in an era of global change, Trends Ecol. Evol. 26 (8) (2011) 398–404, https://doi.org/10.1016/J.TREE.2011.04.007.

[83] A. Dodoo, Primary energy and economic implications of ventilation heat recovery for a multi-family building in a Nordic climate, J. Build. Eng. 31 (2020) 101391, https://doi.org/10.1016/j.jobe.2020.101391.

[84] S. Firląg, M. Piasecki, NZEB renovation definition in a heating dominated climate: case study of Poland, Appl. Sci. 8 (9) (2018) 1605, https://doi.org/10.3390/app8091605.

[85] Buildings Performance Institute Europe, "Collaboration for Housing nearly zero-energy renovation - Intelligent Energy Europe," Netherlands, 2013.

[86] D. D. ' Agostino, P. Zangheri, B. Cuniberti, D. Paci, and P. Bertoldi, "Progress of Member States towards NZEBs Synthesis Report on the National Plans for Nearly Zero Energy Buildings (NZEBs) 2016," 2016, doi: 10.2790/659611.

[87] J. Kurnitski *et al.*, "How to define nearly net zero energy buildings nZEB-REHVA proposal for uniformed national implementation of EPBD recast," 2011.

[88] D. D'Agostino, Assessment of the progress towards the establishment of definitions of Nearly Zero Energy Buildings (nZEBs) in European Member States, J. Build. Eng. 1 (2015) 20–32, https://doi.org/10.1016/j.jobe.2015.01.002.

[89] D. D'Agostino, P. Zangheri, L. Castellazzi, Towards nearly zero energy buildings in Europe: A focus on retrofit in non-residential buildings, Energies (Basel) 10 (1) (2017), https://doi.org/10.3390/en10010117.

[90] European Commission, "REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS State of the Energy Union Report 2023 (pursuant to Regulation (EU) 2018/1999 on the Governance of the Energy Union and Climate Action)," Brussels, Oct. 2023.

[91] EC-Europa, "Nearly zero-energy buildings and their energy performance | Energy." Accessed: Sep. 03, 2021. [Online]. Available: https://ec.europa.eu/energy/eu-buildings-factsheets-topics-tree/nearly-zero-energy-buildings-and-their-energy-performance_en.

[92] D. D'Agostino, P. Zangheri, L. Castellazzi, Towards nearly zero energy buildings in Europe: A focus on retrofit in non-residential buildings, Energies (Basel) 10 (1) (2017) 117, https://doi.org/10.3390/en10010117.

[93] A. Frances Bean Jonathan Volt Vivian Dorizas Eleftherios Bourdakis Dan Staniaszek, M. De Groote Mariangiola Fabbri Oliver Rapf, A. Joyce, E. Michael Villa, and smartEn Stijn Verbeke, "Future-proof buildings for all Europeans a guide to implement the energy performance of buildings directive (2018/844)," *Buildings Performance Institute Europe (BPIE)*, May 2019.

[94] C.S. Monteiro, F. Causone, S. Cunha, A. Pina, S. Erba, Addressing the challenges of public housing retrofits, Energy Proc 134 (2017) 442–451, https://doi.org/10.1016/J.EGYPRO.2017.09.600.

[95] C.A. Balaras, E.G. Dascalaki, K.G. Droutsa, S. Kontoyiannidis, Empirical assessment of calculated and actual heating energy use in Hellenic residential buildings, Appl Energy 164 (2016) 115–132, https://doi.org/10.1016/J.APENERGY.2015.11.027.

[96] E.G. Dascalaki, K.G. Droutsa, C.A. Balaras, S. Kontoyiannidis, Building typologies as a tool for assessing the energy performance of residential buildings – A case study for the Hellenic building stock, Energy Build 43 (12) (2011) 3400–3409, https://doi.org/10.1016/J.ENBUILD.2011.09.002.

[97] M. Beccali, M. Cellura, M. Fontana, S. Longo, M. Mistretta, Energy retrofit of a single-family house: Life cycle net energy saving and environmental benefits, Renew Sustain Energy Rev 27 (2013) 283–293, https://doi.org/10.1016/J.RSER.2013.05.040.

[98] H. Johra, P.K. Heiselberg, J. Le Dréau, numerical analysis of the impact of thermal inertia from the furniture/indoor content and phase change materials on the building energy flexibility, in: Proceedings of the 15th IBPSA Conference, San Francisco, 2017, pp. 35–42, 10.26868/25222708.2017.012.

[99] EBC Annex 67, "Examples of Energy Flexibility in Buildings - Energy in Buildings and Communities Programme Annex 67 Energy Flexible Buildings," Sep. 2019.

[100] H. Tang, S. Wang, Energy flexibility quantification of grid-responsive buildings: Energy flexibility index and assessment of their effectiveness for applications, Energy 221 (2021) 119756, https://doi.org/10.1016/j.energy.2021.119756.

[101] A.K. Athienitis, E. Dumont, N. Morovat, K. Lavigne, J. Date, Development of a dynamic energy flexibility index for buildings and their interaction with smart grids, in: Summer Study on Energy Efficiency in Buildings, California, 2020, pp. 12–31.

[102] T. Weiß, D. Rüdisser, and G. Reynders, "Tool to evaluate the Energy Flexibility in Buildings-A short manual," *Annex 67*, 2019.

[103] C. Finck, R. Li, R. Kramer, W. Z.-A. Energy, and undefined, Quantifying demand flexibility of power-to-heat and thermal energy storage in the control of building heating systems, Elsevier, 2018.

[104] F. Mancini, J. Cimaglia, G. Lo Basso, S. Romano, Implementation and simulation of real load shifting scenarios based on a flexibility price market strategy—the Italian residential sector as a case study, Energies 14 (11) (2021) 3080, https://doi.org/10.3390/EN14113080.

[105] H. Johra, P. Heiselberg, J. Le Dréau, Influence of envelope, structural thermal mass and indoor content on the building heating energy flexibility, Energy Build 183 (2019) 325–339, https://doi.org/10.1016/J.ENBUILD.2018.11.012.

[106] F. Mancini, S. Romano, G. Lo Basso, J. Cimaglia, L. de Santoli, How the Italian residential sector could contribute to load flexibility in demand response activities: A methodology for residential clustering and developing a flexibility strategy, Energies (13) (2020) 3359, https://doi.org/10.3390/EN13133359.

[107] K. Foteinaki, R. Li, T. Péan, C. Rode, J. Salom, Evaluation of energy flexibility of low-energy residential buildings connected to district heating, Energy Build 213 (2020) 109804, https://doi.org/10.1016/J.ENBUILD.2020.109804.

[108] J. Dehler, et al., Self-consumption of electricity from renewable sources, in: Europe's Energy Transition: Insights for Policy Making, 2017, pp. 225–236, 10.1016/B978-0-12-809806-6.00027-4.

[109] European Commission, "Best practices on Renewable Energy Self-consumption," Jul. 2015.

[110] G. Masson, Jose Ignacio Briano, and Maria Jesus Baez, "A Methodology For The Analysis Of PV Self-Consumption Policies," 2016.

[111] J. Li, M.A. Danzer, Optimal charge control strategies for stationary photovoltaic battery systems, J. Power Sources 258 (2014) 365–373, https://doi.org/10.1016/j.jpowsour.2014.02.066.

[112] J. Weniger, T. Tjaden, V. Quaschning, Sizing of residential PV battery systems, Energy Procedia (2014) 78–87, https://doi.org/10.1016/j.egypro.2014.01.160.

[113] R. Thygesen, B. Karlsson, Simulation and analysis of a solar assisted heat pump system with two different storage types for high levels of PV electricity self-consumption, Sol. Energy 103 (2014) 19–27, https://doi.org/10.1016/J.SOLENER.2014.02.013.

[114] C. Williams, J. Binder, T.K. Pes, Demand side management through heat pumps, thermal storage and battery storage to increase local self-consumption and grid compatibility of PV systems, in: 2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe), IEEE, 2012, pp. 1–6.

[115] Y. Riesen, C. Ballif, N. Wyrsch, Control algorithm for a residential photovoltaic system with storage, Appl Energy 202 (2017) 78–87, https://doi.org/10.1016/J.APENERGY.2017.05.016.

[116] M. Osawa, et al., Increase the rate of utilization of Residential photovoltaic generation by EV charge-discharge control. 2012 IEEE Innovative Smart Grid Technologies - Asia, ISGT Asia 2012, 2012, 10.1109/ISGT-ASIA.2012.6303134.

[117] K. Klein, D. E. Kalz, and S. Herkel, "Grid impact of a net-zero energy building with BIPV using different energy management strategies," in *CISBAT*, Lausanne , Sep. 2015, pp. 579–584.

[118] A. Mohamed, A. Hasan, Energy matching analysis for net-zero energy buildings, Sci. Technol. Built Environ. 22 (7) (2016) 885–901, https://doi.org/10.1080/23744731.2016.1176850.

[119] K. Voss, et al., Load matching and grid interaction of net zero energy buildings. EUROSUN 2010 International Conference on Solar Heating, Cooling and Buildings, 2010.

[120] J. Widén, E. Wäckelgård, Net zero energy solar buildings at high latitudes: the mismatch issue. Conference: EASST 2010 Conference: Practicing Science and Technology, Performing the Social, Trento, 2010.

[121] B. Berggren, J. Widen, B. Karlsson, M. Wall, Evaluation and optimization of a Swedish net Zeb-using load matching and grid interaction indicators, IBPSA-England (2012).

[122] F. Harkouss, F. Fardoun, P.H. Biwole, Optimal design of renewable energy solution sets for net zero energy buildings, Energy 179 (2019) 1155–1175, https://doi.org/10.1016/J.ENERGY.2019.05.013.

[123] F. Frontinia, M. Manfren, L.C. Tagliabue, A case study of solar technologies adoption: criteria for BIPV integration in sensitive built environment, Energy Procedia 30 (2012) 1006–1015.

[124] B.-J. Kim, H.-W. Lim, D.-S. Kim, U.-C. Shin, A study of load matching on the net-zero energy house, J. Korean Solar Energy Soc. 38 (4) (2018) 55–66, https://doi.org/10.7836/KSES.2018.38.4.055.

[125] M. Manfren, et al., Parametric energy performance analysis and monitoring of buildings—HEART project platform case study, Sustain. Cities Soc. 61 (2020) 102296, https://doi.org/10.1016/J.SCS.2020.102296.

[126] M. Buzzetti, F. Leonforte, A. Estrada, J. Balest, and R. Fedrizzi, "HEART Deliverable 9.7 Assessment on monitored and simulated results – I," Bolzano, May 2020.

[127] R. Koželj, U. Mlakar, E. Zavrl, U. Stritih, R. Stropnik, An experimental and numerical analysis of an improved thermal storage tank with encapsulated PCM for use in retrofitted buildings for heating, Energy Build. 248 (2021) 111196, https://doi.org/10.1016/J.ENBUILD.2021.111196.

[128] H. Amini Toosi, M. Lavagna, F. Leonforte, C. Del Pero, N. Aste, A novel LCSA-Machine learning based optimization model for sustainable building design-A case study of energy storage systems, Build Environ. 209 (2022) 108656, https://doi.org/10.1016/J.BUILDENV.2021.108656.

[129] D. Ibaseta, et al., Monitoring and control of energy consumption in buildings using WoT: A novel approach for smart retrofit, Sustain. Cities Soc. 65 (2021) 102637, https://doi.org/10.1016/J.SCS.2020.102637.

[130] K. Valančius, M. Grinevičiūtė, G. Streckienė, Heating and cooling primary energy demand and CO2 emissions: Lithuanian A+ buildings and/in different European locations, Buildings (5) (2022) 570, https://doi.org/10.3390/BUILDINGS12050570.

[131] D. D'Agostino, F. De Falco, F. Minelli, F. Minichiello, New robust multi-criteria decision-making framework for thermal insulation of buildings under conflicting stakeholder interests, Appl Energy 376 (2024) 124262, https://doi.org/10.1016/J.APENERGY.2024.124262.

[132] P. De Wilde, The gap between predicted and measured energy performance of buildings: A framework for investigation, Autom Constr 41 (2014) 40–49, https://doi.org/10.1016/J.AUTCON.2014.02.009.

[133] M. Woloszyn, I. Beausoleil-Morrison, Treating uncertainty in building performance simulation, J Build Perform Simul 10 (1) (2017) 1–2, https://doi.org/10.1080/19401493.2017.1261641.

[134] E. Costanzo, A. Martino, G. M. Varalda, M. Antinucci, and A. Federici, "EPBD implementation in Italy," Dec. 2016.

[135] K.H. Chua, Y.S. Lim, S. Morris, Peak reduction for commercial buildings using energy storage. IOP Conference Series: Earth and Environmental Science, Institute of Physics Publishing, 2017, 10.1088/1755-1315/93/1/012008.

[136] M. Hormigo et al., "IDE4L Deliverable D7.1: KPI Definition ," 2014.

[137] N. Etherden, "Increasing the Hosting Capacity of Distributed Energy Resources Using Storage and Communication," 2014.

[138] L. H. MacEdo, J. F. Franco, R. Romero, M. A. Ortega-Vazquez, and M. J. Rider, "Increasing the hosting capacity for renewable energy in distribution networks," in *2017 IEEE Power and Energy Society Innovative Smart Grid Technologies Conference, ISGT 2017*, Institute of Electrical and Electronics Engineers Inc., Oct. 2017. doi: 10.1109/ISGT.2017.8086006.

[139] C. Del Pero, N. Aste, H. Paksoy, F. Haghighat, S. Grillo, F. Leonforte, Energy storage key performance indicators for building application, Sustain Cities Soc 40 (2018) 54–65, https://doi.org/10.1016/J.SCS.2018.01.052.

[140] G. Reynders, J. Diriken, D. Saelens, Generic characterization method for energy flexibility: Applied to structural thermal storage in residential buildings, Appl Energy 198 (2017) 192–202, https://doi.org/10.1016/j.apenergy.2017.04.061.

[141] IRIS, "Deliverable 1.1 Report on the list of selected KPIs for each Transition Track," 2018.

[142] T. Märzinger and D. Österreicher, "Supporting the smart readiness indicator-A methodology to integrate a quantitative assessment of the load shifting potential of smart buildings," *Energies (Basel)*, vol. 12, no. 10, 2019, doi: 10.3390/en12101955.

[143] V. Ignatova, D. Villard, and J. M. Hypolite, "Simple indicators for an effective Power Quality monitoring and analysis," in *2015 IEEE 15th International Conference on Environment and Electrical Engineering, EEEIC 2015 - Conference Proceedings*, Institute of Electrical and Electronics Engineers Inc., Jul. 2015, pp. 1104–1108. doi: 10.1109/EEEIC.2015.7165321.

[144] D. Ioannidis, P. Tropios, S. Krinidis, G. Stavropoulos, D. Tzovaras, S. Likothanasis, Occupancy driven building performance assessment, J. Innov. Digital Ecosyst. 3 (2) (2016) 57–69, https://doi.org/10.1016/J.JIDES.2016.10.008.

[145] M. De Groote *et al.*, *IS EUROPE READY FOR THE SMART BUILDINGS REVOLUTION? MAPPING SMART-READINESS AND INNOVATIVE CASE STUDIES BPIE review and editing team.* 2017.

[146] European-Commission and VITO, "Smart Readiness Indicator for Buildings | Smart Readiness Indicator for Buildings." Accessed: May 20, 2020. [Online]. Available: https://smartreadinessindicator.eu/.

[147] H. C. Rochefort, "EU Smart Readiness Indicator for buildings," 2019.

[148] European Commission, "DIRECTIVE 2010/30/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 May 2010 on the indication by labelling and standard product information of the consumption of energy and other resources by energy-related products," May 2010.

[149] European-Commission, "Energy Label Generator | Energy," Energy Label Generator. Accessed: Jun. 06, 2020. [Online]. Available: https://ec.europa.eu/energy/topics/energy-efficiency/energy-label-and-ecodesign/energy-label-generator_en.

[150] Provincia Autonoma di Trento, "LABELLING AND CERTIFICATION GUIDE," Trento, Jun. 2010.

[151] European Commission, "REGULATION (EU) 2017/ 1369 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL - of 4 July 2017 - setting a framework for energy labelling and repealing Directive 2010/ 30/ EU," 2017.

[152] D. Majcen, L.C.M. Itard, H. Visscher, Theoretical vs. actual energy consumption of labelled dwellings in the Netherlands: Discrepancies and policy implications, Energy Policy 54 (2013) 125–136, https://doi.org/10.1016/j.enpol.2012.11.008.

[153] P. van den Brom, A. Meijer, H. Visscher, Performance gaps in energy consumption: household groups and building characteristics, Build. Res. Inform. 46 (1) (2018) 54–70, https://doi.org/10.1080/09613218.2017.1312897.

[154] I. Azpiri *et al.*, "Best Paths Project - Data set, KPIs, tools & methodologies for impact assessment," 2015.

[155] W.J. Harder, R.A.M.G. Joosten, Key performance indicators for smart grids. Master Thesis on Performance Measurement for Smart Grids", 2017.

[156] G. Putynkowski *et al.*, "A New Model for the Regulation of Distribution System Operators with Quality Elements that Includes the SAIDI/SAIFI/CRP/CPD Indices," 2016.

[157] D. Pramangioulis, K. Atsonios, N. Nikolopoulos, D. Rakopoulos, P. Grammelis, E. Kakaras, A methodology for determination and definition of key performance indicators for smart grids development in island energy systems, Energies (Basel) 12 (2) (2019) 242, https://doi.org/10.3390/en12020242.