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ASSESSING SMART RETROFITTING IN RESIDENTIAL BUILDINGS THROUGH KEY PERFORMANCE INDICATORS

Doctoral Dissertation of:
Joud Aljumaa Aldakheel

Supervisor: Professor Claudio Del Pero

Tutor: Professor Paola Caputo

Head of Doctoral Program: Professor Marco Scaioni

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ABSTRACT

In the European Union, buildings account for 40% of the total energy consumption. New buildings can achieve high-performance levels, however, up to 90% of the existing European building stock will still be standing and in use in 2050. Thus, the renovation of buildings is a key action to reach the decarbonization of the building stock in the next 30 years. In such a context there has been an increasing necessity to have buildings with interactive features, to dynamically respond to users' needs and/or changing boundary conditions such as climate and grid prices. As a result, the concept of Smart Buildings has been introduced by the Energy Performance Building Directive (EPBD) as the main enabler for the future of the building sector. In this sense, Smart Retrofitting has become crucial to upgrade the definition of energy efficient or Nearly Zero Energy Building retrofitting and reflect the new possibilities of transforming existing buildings into more responsive/efficient buildings and cities. To understand Smart Retrofitting, it is very important to clarify the concept of Smart Buildings. The revised EPBD has developed a voluntary European scheme for rating the smart readiness of buildings: the "Smart Readiness Indicator", to measure the capability of smart buildings to adapt their operation to the needs of the grid, and occupants. Yet, its' methodology is qualitative and only assesses the presence of the services and technologies without evaluating their performance. Hence, this thesis develops a framework for Smart Retrofitting and the achievable quantified benefits. Particularly, the proposed methodology evaluates the energy performance of smart retrofitted buildings by identifying specific Key Performance Indicators (KPIs) that provide a quantitative performance assessment of the building operation. The implemented KPIs measure the energy performance of the technologies integrated into the building as well as its' grid interaction. Moreover, the thesis elaborates on quantified thresholds for the indicators by reflecting on existing case studies from the literature. It identifies "Minimum Acceptable Thresholds" for the KPIs which define the basic performance level for a smart building/retrofit, and "Top-performing Thresholds", which indicate a smart building/retrofit with outstanding performances. Furthermore, the proposed evaluation methodology is tested on a case study of the Holistic Energy and Architectural Retrofit Toolkit (HEART) project, part of the Horizon 2020 program, and aims at smart retrofitting existing buildings. The final part of the thesis normalizes the indicators to have common units that facilitate comparison at a wider building scale. The outcomes of the present work are expected to quantify the Smart Readiness level and give guidelines on smart retrofitting. The proposed Smart Retrofitting framework will thus allow building designers, users, and policymakers to estimate the energy performance of smart retrofit projects and measure their success.

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LIST OF ABBREVIATIONS

ANN	Artificial neural network
BACS	Building Automation and Control System
BAS	Building Automation System
BEMS	Building Energy Management Systems
BMS	Building Management System
CO_2	Carbon Dioxide
DHW	Domestic Hot Water
DR	Demand Response
DSM	Demand Side Management
DSS	Decision Support System
EC	European Commission
EEAP	Energy Efficiency Action Plan
EED	Energy Efficiency Directive
EMCS	Energy Management and Control System
EPBD	Energy Performance of Buildings Directive
ESS	Energy Storage System
EU	European Union
EV	Electric Vehicle
FI	Flexibility Index
GHG	Greenhouse Gas
GII	Grid Interaction Index
HEMS	Home Energy Management System
HVAC	Heating, Ventilation, and Air Conditioning
IEA	International Energy Agency
ICT	Information and Communications Technology
IoT	Internet of Things
KPI	Key Performance Indicators
LCF	Load Cover Factor
LEM	Logical Evaluation Method
LFA	Logical Framework Approach
MPC	Model Predictive Control
MS	Member States
NET ZEB/NZEB	Net Zero Energy Building
nZEB	Nearly Zero Energy Building
PE	Primary Energy
PCDR	Peak Clipping DR Resource
PV	Photovoltaics

RES	Renewable Energy Sources
RES SC	Renewable Energy Systems Self-Consumption
RNN	Random Neural Network
SB	Smart Buildings
SC	Smart City
SDG	Sustainable Development Goals
SG	Smart Grid
SR	Smart Retrofitting
SRI	Smart Readiness Indicator
SM	Smart Meters
SMPC	Stochastic Model Predictive Control
TES	Thermal Energy Storage
TRNSYS	TRaNsient SYstem Simulation
TOU	Time of Use
WSN	Wireless Sensor Network

1. INTRODUCTION

According to the U.S Energy Information Administration [1], energy in buildings accounts for about one-third of the total primary energy consumption worldwide. It has been claimed that existing buildings in the European Union (EU) are responsible for 40% of the total energy consumption and 36% of the European global CO_2 emissions [2]. The most significant proportion of building energy consumption goes for heating and cooling, accounting for 70% of the energy consumption of residential building stocks [3]. This highlights the great potential of buildings with respect to energy consumption reduction and Greenhouse Gas GHG emissions. The EU aims at drastic reductions in domestic GHG by 80% in 2050 compared to the 1990 level [4]. According to the Paris Agreement, urgent actions are required to reduce GHGs emissions in all sectors to keep global warming below 2 °C (ideally under 1.5 °C) above the pre-industrial levels [5]. Setting sustainable and robust energy solutions plays an important role in enhancing climate change mitigation and adaptation in cities. The EU has put in place a comprehensive legislative and regulatory framework for the construction sector. Stringent policies have nurtured to support sustainable energy which aims to move towards cleaner energy use. Mainly bioenergy and renewable energy (i.e. incentives and tax mechanisms for renewables development, energy planning procedures, network connections, carbon pricing, and monitoring) have been implemented [6]. This has led to doubling the share of Renewable Energy Systems (RES) in the EU gross energy consumption from 6% to 12% by 2010 [7]. Initially, several targets were set for 2010 including 135 Mtoe of energy production for biomass; 40 GW installed capacity for wind energy; 3 GWp for photovoltaic energy; 5 GWth for geothermal heat; 1 GW for geothermal electricity, and 105 GW for hydro [8], [7]. In fact, the targets of 2010 have been achieved or even exceeded by some RES such as wind energy which reached an installed capacity of 80 GW at the end of 2010, and the Photovoltaic Systems (PV) installed capacity has reached 29 GW.

These RES achievements in the building sector were accomplished due to key European regulatory frameworks; the Energy Performance of Buildings Directive 2002/91/EC (EPBD) [9] which is the EU's main legislative instrument aiming to promote the energy performance of buildings within the EU, and its recast [10]. In this framework, the European Commission (EC) which is the executive body of the EU and operates as a cabinet government with the 27 European member countries, has promoted a new paradigm for building energy efficiency. It has introduced several targets and concepts such as the Nearly Zero Energy Buildings (nZEBs) [10] which is "a building characterized by a very high-energy performance during the operation and most of the energy required is covered by energy from renewable sources" as a minimum energy performance level to be reached in new buildings in 2020. A minimum performance level based on the national condition was required to be defined by each Member State (MS) of the EU specifying a quantitative range of minimum performance levels. Today, the reduction of the environmental impact determined by building technologies and services is fundamental for global sustainability. Different targets and minimum performance thresholds have been set to achieve the required CO_2 reductions. Energy efficiency policies for buildings can impact all end uses ranging from heating and cooling to lighting and appliances, and integration of RES to the interaction with the grid systems. These can take the form of regulatory or control instruments, building codes, consumer information campaigns, and economic or financial incentives [11].

Quantifying building energy performance and setting thresholds represent an essential baseline for assessing any potential savings and achieving the targeted GHG emission and CO_2 reductions. The next sections explore the building energy efficiency legislations developed and imposed by the EU to determine the minimum energy standards and targets in the MS. Subsequently, the implications of these policies and regulations are evaluated setting the gap in the literature and defining the objective and aim of this thesis.

1.1 Buildings Energy Efficiency Legislations and Regulatory Framework in the European Union

The EU has adopted several policies and programs to promote energy efficiency in the building sector. Following the first oil crisis in 1973–1974, energy efficiency started to emerge as an important plan in response to enhance oil security. Different targets and policies have emerged to support this movement. This section explores the main implemented EU energy efficiency policies and initiatives in the building sector that has evolved through the years.

1.1.1 Overview of Main EU Energy Efficiency Targets and Actions Plans

Several ambitious targets have been developed by the EC aiming at reducing GHG emissions and improving energy efficiency in European buildings. The first major EU action plan on energy efficiency was on heating and hot water boilers which were the first building technical equipment to be covered by EU legislation in 1978, by the Council Directive 78/170/EEC on the performance of heat generators for space heating and the production of hot water [12]. Later in 1992 [13] and 1996 [14], similar directives were developed on the heating and hot water boilers introducing efficiency requirements also for domestic refrigerators and freezers. Afterward, in 1993, the "SAVE"

Directive (93/76/EEC) was initiated [15], [16]. In this directive, the building insulation requirements (minimum U-value) were a priority national matter to be implemented in all MS, in line with the principle of subsidy [17]. The SAVE Directive, therefore, called for all MS to implement programs introducing sufficient thermal insulation provisions in new buildings. The SAVE Directive was reinforced in the 2000 Action Plan [18]. In this action plan, more concrete measures were defined and strengthened reporting and compliance procedures directive provisions on buildings were mandated. This Action Plan has nonetheless served as a key trigger that shaped the policy cycle leading to the development of the EPBD in 2002 (Details in Section 1.1.2).

Later in 2006, the EC published its second Energy Efficiency Action Plan (EEAP) [19], [20]. The 2006 action plan proposed a set of energy efficiency policies at the EU level to reach a 20% energy saving target by 2020 through new measures, and the strengthening of existing policies. This objective resembled achieving approximately a 1.5% saving per year up to 2020. The policy debate that followed this action plan led to the 2010 revision of the EPBD. Following the 2006 Action Plan in March 2007, the EU leaders committed to Europe to become a highly energy-efficient, low carbon economy and agreed on the targets, known as the "20-20-20" targets, by 2020 [21]. This target stipulates a 20% reduction in GHG emissions compared to 1990 levels; an increase in the share of energy from RES to 20% and improvements in energy efficiency that lead to 20% EU primary energy savings. As a result, there was a need for a directive on the penetration of RES, thus in 2009, the EC developed the Renewable Energy Directive (2009/28/EC) [22]. The directive had established an overall policy for the production and promotion of energy from renewable sources in the EU. It requires the EU to fulfill at least 20% of its total energy needs with renewable energy by 2020, to be achieved through the attainment of individual national targets. Moreover, it mandated all EU countries to ensure at least 10% of their transport fuels from renewable sources by 2020.

In 2011 the EC proposed the Roadmap for moving to a competitive low carbon economy in 2050 and proposed new targets to promote energy security, energy equity, and environmental sustainability: a cut in GHG emissions of 40% in 2030, 60% in 2040, and 80–95% in 2050 compared to 1990 levels [23], [24]. Moreover, in 2011, the Commission adopted a new EEAP [25]. The plan stressed the need for further energy renovations in private and public sectors in the EU and introduced energy efficiency criteria for public buildings. In 2012, the Energy Efficiency Directive (EED) [26] was developed and presented as a set of binding measures to assist the EU policy to reach the 20% energy efficiency target by 2020. According to this directive, all EU countries should be energy efficient at all stages of the energy chain, from production to final consumption [27]. The directive reinforced the policy measures to achieve energy savings equivalent to an annual reduction of 1.5% in national energy. The RES target was increased in the 2030 Climate and Energy Framework presented by the EU Commission in 2014 [28], [29]. A framework for EU climate and energy policies in the 2020-2030 period has been set in this plan in which the share of renewable energy target was set to at least 27% of energy consumption.

In 2016, the EC proposed the "Clean Energy For All Europeans" package of measures boosting the clean energy transition in line with its commitment to cut GHG emissions by at least 40% by 2030 [30]. In 2019 the package was released by the commission and consisted of eight legislative acts to ensure a clean and fair energy transition at all levels of the economy starting from energy generation and reaching people's homes, such as increasing renewable electricity and encouraging the use of smart meters. The Strategic Energy Technology (SET) Plan was developed aiming at achieving two major timelines [31]. The first was set for 2020 in which the plan provided a framework to accelerate the development and deployment of cost-effective low-carbon technologies. This has come in line with the 20-20-20 goals. The second plan is for 2050, which targets limiting climate change to a global temperature rise of no more than 2°C, by matching the vision to reduce EU GHG emissions by 80 - 95%. In December 2018, the recast of Renewable Energy Directive 2018/2001/EU [32] entered into force, as part of the Clean Energy for All Europeans package. The recast directive focused on the 2030 EU target and had set a new binding renewable energy target of at least 32% with a clause for a possible upwards revision by 2023. The directive also urged for an increase to 14 % for the share of renewable fuels in transport by 2030 and strengthened the criteria for ensuring bioenergy sustainability.

In parallel to these plans, the European Green Deal was introduced in 2019 as a strategic road map to tackle climate change effects in the EU by 2050 [33]. It enforces achieving carbon neutral and carbon negative regions to tackle the climate crisis. One of its' main objectives is renovating both public and private buildings to drive energy efficiency in the building sector and help pave the way for a decarbonized and clean energy system [34]. Up to 90% of the existing European building stock will still be standing and in use in 2050. Thus, the renovation of buildings is a key action to reach the decarbonization of the building stock by 2050. The Renovation Wave has been established by the EC aiming at doubling the annual energy renovation rates in the next 10 years [34]. It supports developing stronger regulations and standards on the building energy performance of public and private sector renovations**.** Furthermore**,** ensuring that renovations will enhance the quality of life for people living in and using the buildings, reduce Europe's greenhouse gas emissions, foster digitalization, and improve the reuse and recycling of materials. Consequently, the New European Bauhaus initiative was developed by the EC as a part of the EU Green Deal to support the renovation wave and ensure connecting technological advancements to the social and cultural aspects [35]. In particular, it is developed to support the movements of society along with sustainability (including climate goals, circular economy, zero pollution, and biodiversity), aesthetics (quality of experience and style, beyond functionality), and inclusion (from valuing diversity, to securing accessibility and affordability) [35].

1.1.2 The EPBD

The Energy Performance of Buildings Directive is the EU's main legislative instrument that aims at promoting the improvement of the energy performance of buildings within the Community [36]. The EPBD was inspired by the Kyoto Protocol signed in 1997 that was imposed on the EU countries and all its parties by setting binding emission reduction targets following agreed individual targets [37]. The first version of the EPBD was published in 2002 introducing the 2002/91/EC Directive [9]. The Directive required that the MS strengthen its building regulations and introduce energy performance certifications. The directive aimed to tap into the large cost-effective saving potential of the building sector namely 22% in 10 years [38]. The Energy Performance Certificate (EPC) was introduced by the EPBD in 2002 as a mandatory requirement for the EU MS [39]. The EPC is a document recognized by MS which indicates the energy performance of a building or building unit, calculated according to a stipulated methodology [39].

Directive 2002/91/EC was replaced by the "EPBD recast" (Directive 2010/31/EU) introduced in 2010 [10]. With this directive, the concept of nZEB target was introduced. New long-term goals for CO_2 reduction by 80-95% reduction in 2050 compared to 1990 have been defined in the EU by the revised EPBD [10], to facilitate a highly energy-efficient and decarbonized building stock through the renovation of existing buildings into nZEBs. The recast directive mandated that by 2020 all new buildings constructed within the EU should reach nearly zero energy levels. Moreover, their low energy needs should be significantly covered by RES. A requirement of a general framework for a methodology of calculating the integrated energy performance of buildings was mandated, as well as minimum energy requirements of the newly built buildings as well as large existing buildings under major renovation. Additionally, energy performance requirements were introduced for technical building systems (heating, hot water, ventilation, cooling, and air conditioning). The provisions related to the EPC and inspection of heating and air-conditioning systems were reinforced to make them more effective. With the 2010 EPBD directive, the EPC has been re-introduced and added a set of new requirements to improve the quality, usability, and public acceptance of EPC. The EPC sets an energy efficiency scale, selected energy indicators calculated based on the adopted methodology, general information about the building (e.g., location and climate), and an extensive attachment with comprehensive information about the building in terms of components and energy systems. Energy indicators are displayed both as quantitative values (e.g., in $kWh/m^2/y$) and as rating results such as A, B, C, and so on (A being the most efficient and G being the least efficient), thus allowing the easy comparison between buildings in terms of energy performance [40].

The latest version of the EPBD revision was Directive 2018/844/EU [41]. It had introduced targeted amendments to the EPBD aiming at accelerating the cost-effective renovation of existing buildings for a decarbonized building stock by 2050 and mobilization of investments to reach this goal. It also states that MS shall establish more effective long-term renovation strategies to identify an adequate set of financial measures and consult stakeholders in the preparation and implementation of their strategies [41]. As well as introducing new provisions to foster smart technologies and technical building systems, including building automation. As a result, the concept of Smart Buildings has been introduced in the EPBD. However, there was no clear definition of it, instead, the integration of smart grid, smart vehicles, and smart technologies was emphasized as a part of the smart building. Furthermore, the Commission developed common European schemes for rating the smart readiness of buildings, which will be optional for MS. This was done by introducing the Smart Readiness Indicator (SRI) [42] (in article 31 of the Directive) which should be used to measure the capacity of buildings to use Information and Communication Technologies (ICTs) and electronic systems to adapt the operation of buildings to the needs of the occupants and the grid and to improve the energy efficiency and overall performance of buildings. The SRI is expected to raise awareness amongst building owners and occupants of the importance of using building automation and electronic monitoring of technical building systems and should give confidence to occupants about the actual savings of those new enhanced functionalities. However, the use and rating of the smart readiness of buildings are optional for MS. The main purpose of the EPBD recast was to make sure that national minimum energy performances standards adopted by MS under the EPBD were of a similar ambition level in relation to energy consumption (in kWh/m^{2}y).

1.1.3 Summary and Timeline of Main EU Building Energy Efficiency Regulations and Plans

The previous sections have briefly discussed the ongoing legislation and energy efficiency policies on buildings and retrofitting. The main EU regulations were discussed however, it should be noted that many more directives, and policies were developed in between to support the development of these policies. Thus, in this thesis, only the main ones were mentioned. The policies adopted started more than five decades ago and have achieved considerable strides in terms of scope, scale, and ambition. The main goals that triggered these standards were the reduction of CO_2 emissions and the GHG effect, thus the target started by setting some requirements for the insulation and boilers and gradually improved to encompass energy performance for the entire building. Building requirements and policies have been in continuous update and improvement to cope with the advancements of technology and the move toward supporting ICT systems offering flexibility to designers, architects, and engineers for cost-optimized solutions. The diversification of instruments and tools deployed in energy efficiency policy has varied through the years. Starting with the SAVE Directive developed in 1993 as a major step to energy efficiency, then moving into more detailed directives by setting guidelines for different technical systems in the buildings such as the EPBD which has been updated throughout the years. Moreover, the targets of CO_2 and GHG emissions reductions have been increased through the years through enforcing more stringent regulations which were also supported by different regulations and resolutions. A graphical representation of the timeline of major EU directives is exemplified in Figure 1.

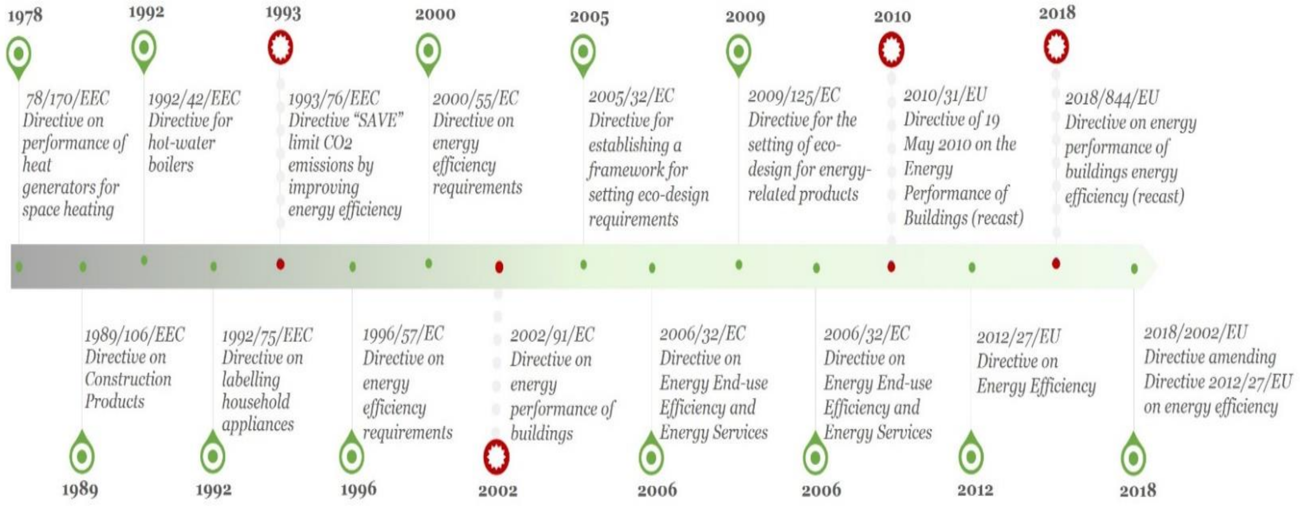

Figure 1. *EU Energy Efficiency Directives Timeline*

Along with energy requirements, the building concept has been also in continuous evolution during the last decades. Starting from energy-efficient buildings with high insulation to implementing advanced technological systems, several terminologies have been developed such as Energy Efficient Buildings [43], High-Performance Buildings [44], Zero Emission Building [45], Zero Carbon Buildings [46], Net Zero Buildings [47] and others. According to this context, the most significant terminology is the nZEB concept which has been officially introduced and defined in the EU EPBD recast in 2010 [10]. The concept of nZEBs reinforced the use of RES to cover building loads, adopt cost-optimal technology choices, and guarantee a healthy and sustainable environment. As a result, several legislations have been also developed to support the implementation of RES in buildings and achieve the targets. With the shift towards the smarter grid and smart metering in buildings and the ongoing technological advancements, the concept of Smart Buildings has been established in the latest version of the EPBD [41].

The previous analysis of building energy efficiency regulations has stressed the importance of setting targets and ambitions to measure the performance of improvements and energy savings achieved by these legislations and directives. Thus, this calls for establishing proper methodologies and indicators to measure the performance of improvements of smart buildings and setting thresholds that can quantify the targets to be achieved by these buildings. These targets and thresholds can have short- or long-term benefits and can be implemented on various scales, ranging from the national level down to individual buildings.

1.2 Research Background and Problem Statement

New residential buildings in Europe are estimated to consume about 60% less energy on average than those buildings constructed before the mid-1970s [48]. A major concern remains related to existing buildings and their related high energy consumption. Around 35% of EU buildings are over 50 years old and 90% are built before 1990 [34]. Thus, the renovation of buildings is a key action to reach the decarbonization of the building stock by 2050: current renovation rates account for about 1% of existing building stock each year [49], while to achieve a 100% zero-carbon goal by 2050 it is necessary to ensure a renovation rate higher than 3% [50]. Moreover, across the EU, deep renovations that reduce energy consumption by at least 60% are carried out only in 0.2% of the building stock per year [51].

On the other hand, the implementation of RES to reach nZEBs has introduced several problems in electric systems' management, since renewables that are more easily integrable in buildings have non-programmable energy production profiles and high variable rates (e.g. solar and wind energy) [52]. Thus, as the RES integration increases in the building sector, the need to properly manage and dispatch energy at the building/district level becomes very crucial [53]: buildings must be able to balance their on-site energy generation and consumption. As a result, the traditional grid should be enhanced to Smart Grid to cope with the increased penetration of solar and wind energy and control its production.

With the new paradigms in building regulations and moving towards smarter buildings, in parallel, there has been an increasing necessity to have buildings with interactive features, to dynamically respond to users' needs and/or changing boundary conditions either external, such as climate, and grid prices or internal, such as occupants' requirements. In [54], it was highlighted that future buildings are expected to be "grid-responsive", where the building adopts its usage to time-of-use electricity pricing and users usage profiles. Similarly, in [55], the need to respond to external weather conditions using prediction control strategies was emphasized to achieve proper sizing of mechanical equipment such as Heating, Ventilation, and Air Conditioning (HVAC) and storage systems and achieve lower energy costs compared to buildings with no weather predictive strategies. Buildings are going through a transition phase from being unresponsive to becoming highly efficient, consuming, producing, storing, and supplying energy. Thus, the need for Smart Retrofitting (SR) has become crucial to upgrade the definition of energy-efficient or nZEB retrofitting to reflect the new possibilities of transforming existing buildings into more responsive and efficient buildings and cities.

To understand what SR is, it is very important to clarify the concept of an SB which has been re-introduced by the EPBD as the main enabler for the future of the building sector. A SB must be nZEB with higher flexibility, which presents the ability of a building to manage its demand and generation based on local climatic conditions, user needs, and grid requirements [56]. Quantifying the value of smart buildings is very important to understand how it functions and the minimum performance of achieving smartness in buildings. In this sense, the revised EPBD facilitated the development of a voluntary European scheme for rating the smart readiness of buildings in the SRI [42]. The limitation in the methodology of the SRI lies in being qualitative and only evaluates the presence of the services and technologies rather than evaluating their performance. Thus, quantified methods should be developed to test the smartness of buildings and set a threshold for the minimum performance criteria, and claim the building smartness.

The concept of smart buildings is a new part of the EPBD; thus, it is important to set a definition and identify the "smart features" of smart buildings to give a clear framework for people designing new buildings and retrofit interventions. Hence, there is a need for a better understanding of smart buildings, and their minimum performance features. As well as the indicators that measure their features and technologies, and the minimum thresholds that identify the targets of smart buildings. Eventually to define the gained benefits of smart buildings for users and stakeholders such as legislation and policymakers.

This thesis sets the definition of SBs, the related features, and technologies, intending to describe the "basic smart features" and define the smart retrofit concept. Then identifies the Key Performance Indicators (KPIs) related to SBs and sets a defined quantified threshold for each indicator and finally tests them on an existing case study.

1.3 Research Aim and Questions

The aforementioned gaps are the starting point of the thesis. Until now there is a lack of research done on SBs, SR, and the methodology for measuring their performance. It is essential to define the main features and functions that characterize a SB and the guidelines to achieve SR in buildings. The aim of this thesis is twofold; first to develop a framework for smart retrofitting by describing the minimum features, technologies, and steps, and second to provide a measuring guideline for the progress of smart retrofitting and the main metrics required to measure its performance through identifying the appropriate KPIs and their thresholds. The guideline is intended for policymakers, building designers, and other smart building service providers. The work focuses mainly on residential buildings since they greatly contribute to global energy consumption. The Eurostat has claimed that in 2018 the residential sector, represented 26.1% of final energy consumption (total energy consumed by end-users) or 16.6% of gross inland energy consumption (total energy demand of a country) in the EU [57].

Hence, this work aims to develop an approach that quantifies the smartness of retrofitted buildings and tests it on a selected case study. To achieve this aim, several targets should be attained:

- Define the smart retrofitting requirements in buildings.
- Identify the main KPIs for quantifying the performance of smart buildings.
- Identify the threshold of each KPI.
- Identify the benefits of smart buildings for users (occupants) and stakeholders (designers of new buildings and retrofit interventions and policymakers).
- Add quantification method to the Smart Readiness Indicator methodology.

Quantifying the performance of smart retrofitting is challenging and there is currently no comprehensive overview of how to quantify the benefits of smart retrofitting. To overcome this research gap and achieve the research objectives, the main research question is therefore formulated as:

"What are the most representative Key Performance Indicators for measuring Smart Retrofitting, and what are the quantified performance thresholds?"

Three main aspects are embedded in this question. First, a scheme should be established to illustrate the basic features and technologies that define a SB to understand the concept of SR. Second, the basic KPIs for measuring the performance of the features and technologies integrated into a SB/SR should be evaluated. Thus, a methodology should be set to define the basic indicators for measuring the "smart-functions" performance. Third, the minimum thresholds for achieving smartness in buildings must be set for every KPI.

The other research questions that need to be assessed in the thesis are:

- What are the basic technologies in a smart building/ smart retrofit?
- What is the smart readiness indicator and how can we measure it in buildings?
- Which measures shall be taken to ensure that the renovation delivers the most positive results?

1.4 Research Methodology

To achieve the objectives of assessing the performance of smart retrofitting and identifying its' framework, the methodology combines both the analytical-qualitative part and application part. The overall methodology in relation to the thesis structure and chapters is illustrated in Figure 2. The methodology was tailored and defined based on the thesis's main objectives which can be summarized as five basic Phases:

- Identification of smart building features, technologies, and related measuring KPIs.
- Selection of smart retrofitting representative KPIs.
- Setting Thresholds for the KPIs that define the minimum performance criteria for each.
- Validate the KPIs on a real case study.
- Identify a framework for measuring the performance of smart retrofitted buildings.

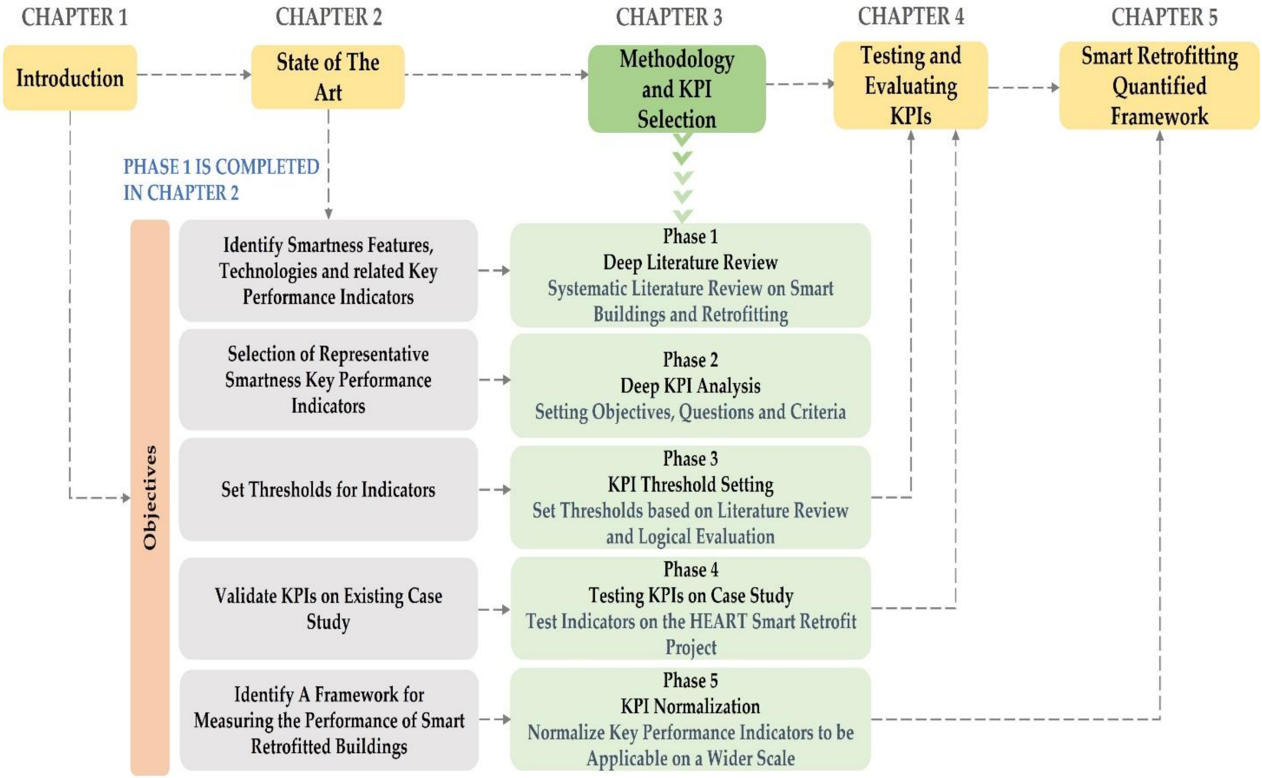

Figure 2. *Methodological Framework of the Thesis*

Particularly, the first part of the methodology lies in carrying out a systematic literature review that provides answers to pre-defined research questions or hypotheses. A systematic review has been defined as a way to synthesize research findings systematically by identifying and critically evaluating relevant research, in addition to collecting and analyzing data from previous research [58]. The systematic review in this thesis answers some of the research questions and objectives identified previously. The first research objective and question that will be answered through a structured systematic literature review is identifying the minimum features and technologies of smart buildings as well as identifying the smart retrofitting requirements in buildings. This part of the methodology is shown in Chapter 2 which shows the state of the art of smartness in the built environment and is explained later.

To achieve the second objective and research question of the thesis and measure the performance of smart retrofitting, Key Performance Indicators have been chosen as means of quantifying this measurement. KPIs are claimed to be quantifiable measurements, that provide a framework or a set of good practices that should then be followed within the operation of the building [59]. This approach is suitable since building renovation is affected by a list of aspects by which KPIs can measure them. It is claimed that indicator systems allow measuring current performance, give a clear statement of future performance targets, and measurement of progress [60]. Moreover, in this thesis, the use of KPIs identifies the current gaps that exist in the field and indicate the suitable measuring metrics for smart retrofit. An extensive literature review is carried out first to identify the relevant KPIs related to smartness features and technologies in SB and SR. Then a coherent selection criterion and analysis are set to choose the most representative ones.

The analysis done on the European regulations and legislations developed on energy efficiency in Section 1.1 has shown that setting targets and thresholds is very crucial for understanding if the goals are met and to determine the level of success of new and retrofitted buildings. In the EPBD, numeric thresholds or ranges are not clearly defined to identify the nearly and net ZEBs characteristics, this had caused several interpretations both for the definition and limits across the EU Countries. The different limitations are affected by specific climate conditions, local targets, or building traditions, that allow different national targets. This makes it difficult to specify the thresholds and targets for smart buildings and smart retrofits. This gap should be addressed to allow a robust design for Smart buildings and Retrofitting. Despite the importance of setting defined thresholds to define nZEBs and Smart buildings, a clear methodology is still not discussed in the literature. Therefore, in this thesis, a threshold for each indicator is set based on an extensive literature review done first on the legislations and reports to identify the desirable range of possible values for each indicator. Then, a Logical Evaluation Methodology is applied to find the correlations between different indicators, and their influencing parameters and be able to set a specified threshold or range for each. The Logical Evaluation Methodology has been referred to as a method that links the objectives with the components and their respective inputs, activities, and outputs at different implementation stages [61]. This method is also referred to as the Logical Framework Approach (LFA) which is a systematic approach to designing, executing, and assessing projects which encourage users to consider the relationships between available resources, planned activities, and desired changes or results [62]. In this thesis, this method is used to identify thresholds for the defined KPIs. This method is done through reviewing the existing case studies based on literature that has tested the indicators previously and classify the technologies and systems applied in each case to be able to set two elaborated thresholds for each indicator. The thresholds are defined as "Minimum achievable thresholds" identified for case studies applying a minimum number of technologies and optimization of systems, and "Top-performing thresholds" identified for buildings that holistically integrate smart technologies and optimize building systems to achieve high rates of the indicators. These thresholds can define good-performing smart buildings/retrofit and high-performing smart buildings/retrofit.

To validate the KPIs, this work is applied to the HEART project; Holistic Energy and Architectural Retrofit Toolkit (funded by Horizon 2020). The HEART project focuses on improving energy efficiency in the building sector and aims to develop, test, and validate a holistic and multi-technological integrated and interconnected system for the deep renovation of residential buildings to become smart buildings. The HEART project is coordinated by Politecnico Di Milano, which makes possible access to the results, files, and datasets. Therefore, due to the availability of data, it has been selected as a case study to test the KPIs on a real existing building before and after the retrofit. The HEART toolkit works on retrofitting envelope solutions (thermal insulation and windows) and integrating and upgrading technical systems such as BEMS, PV systems, heat pumps, fan coils, power controllers, and storage systems. It consists of two case study buildings: the first one is located in Bagnolo in Piano, Italy and the second one is located in Lyon, France. The retrofitting of the Italian case study has been completed. However, due to COVID 19, the French case study is not yet finished, thus, the used case study in this thesis is the Italian case study. The role of this thesis in the HEART project is to test the selected KPIs on the case study to monitor the progress of the integrated technologies in the retrofitted buildings and validate the set thresholds for indicators.

The last objective focuses on identifying the framework for measuring the performance of smart retrofitted buildings. This requires developing a method that unifies the KPIs and allows them to be applied to a wider scale of buildings. Putting indicators on a common basis is done through the normalization process. Normalization converts the absolute value of the indicator into the one with no units and makes data comparable across indicators [63]. It positions indicators on a common baseline to avoid problems introduced by the different measurement units [64]. Thus, indexes are formed for each indicator to have a common unit among all and identify how far the indicator is from the threshold Indicator. The development of indexes allows assessing the success of the indicators in a smart retrofit project.

1.5 Expected Outcomes and Research Significance

The expected outcomes of this thesis are represented in the list defined below in Table 1:

***Table 1**. Identified Expected Outcomes of Ph.D. Thesis*

Category	Expected Outcomes
Energy Savings	• Reduce the load from systems and allow load shifting. • Define the flexibility of the grid.
Guideline's Improvements	• Improve the SRI for smart buildings and add quantification to its' methodology.
Building Systems Performance	• KPIs and defined thresholds for measuring smartness aspects of building systems including grid interaction, storage systems, and RES integration.
Building Occupant's Comfort	• Quantified benefits of smart buildings for occupants in terms of energy savings. • Allow building occupants to act as 'prosumers' that can consume and produce electricity and can self-consume their generated sustainable electricity.

In this context, this work presents a novel activity by which this research is expected to define the quantified benefit of SR for users and policymakers. The significance and novelty of the thesis are demonstrated in developing a framework for smart retrofitting by defining features, and technologies, moreover, setting a methodology to select representative KPIs for SR and identify the minimum thresholds to quantify measuring smart retrofitting in buildings. These findings are very fundamental in the ongoing advancements of technologies and the development of smart buildings and cities. This research aims also to improve the SRI to quantify measuring smart buildings' performance. Moreover, the KPIs are tested on a real European Smart Retrofit project (HEART project). Other than publishing the results of the research in the Ph.D. thesis, it is a part of monitoring the HEART project and dissemination of journal articles. This model for SR measurement can be scaled up to be applied to a larger number of buildings in the future. The framework developed in the thesis can allow building designers, users, and policymakers to monitor the energy performance of smart retrofit projects and measure their success.

1.6 Structure of the Thesis

To facilitate the reading and understanding of the thesis, this section gives a brief description of the main structure of the work. According to the research methodology described previously, this thesis is organized into six main chapters.

The introduction, Chapter 1, outlines the importance of the topic of Smart Buildings and the need for smart retrofitting in the European Union context and provides the background information in which the research sits. Also, it discusses the problems, research gaps, and research questions the study addresses.

Subsequently, Chapter 2 represents the state of the art for smartness in the built environment which reviews first the existing literature on smart buildings and classifies their functions, features, technologies, and the European legislation is done on smartness. Then a review is done on the Key Performance Indicators related to smart buildings' functions and features. The last part of the chapter introduces smart retrofitting of residential buildings and discusses its' opportunities and challenges in the European building context.

Consequently, Chapter 3 presents the methodology for evaluating smart retrofitting key performance indicators, setting thresholds, and details the selection process of representative key performance indicators.

Chapter 4 discusses the background of each selected indicator. Then, set thresholds for the selected indicators, show the case study, and presents the application of the key performance indicators on the HEART project.

Chapter 5 shows the benefits of the developed KPIs and their relation to the SRI. Afterward, it shows the normalization process of the indicators.

Eventually, Chapter 6 sets the framework of smart retrofitting in the built environment and concludes the thesis by highlighting some open challenges and future work.

Figure 3 summarizes the Ph.D. thesis outline and represents the schematic framework of the research and the main contents of each chapter.

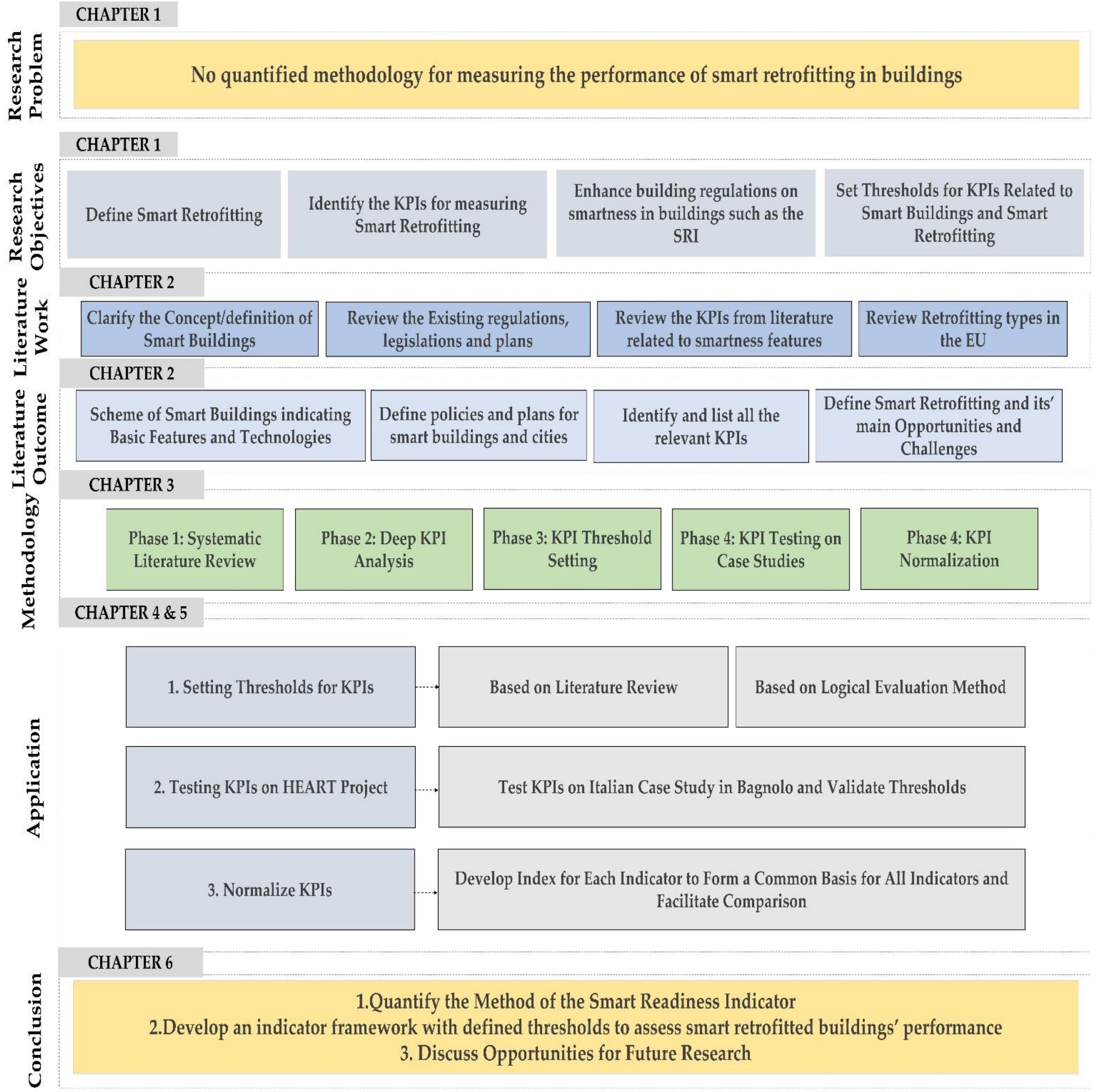

Figure 3. *PhD Thesis Structure*

CHAPTER

2

2. STATE-OF-THE-ART OF SMARTNESS IN THE BUILT ENVIRONMENT

The built environment in the EU and worldwide is in the process of moving from centralized, fossil fuel-based, highly energy-consuming buildings towards an environment that is more efficient, decentralized, consumer-focused, and powered by renewable energy. The process of moving toward smart cities and smart buildings was influenced by several international targets, regulations, and directives as explained previously in section 1.1. The concept of energy-efficient buildings developed from passive buildings that depend on passive design strategies such as orientation, building shape, window-to-wall ratio, thermal mass, strategic architectural features, allowing daylighting, double facades, natural ventilation, and others. Later, with the development of active strategies and increasing energy targets, the nZEBs have been developed to integrate not only passive design strategies but also renewable energy systems (solar, geothermal, wind) and energy-efficient technologies including efficient HVAC and lighting systems. Consequently, with the development of ICTs and the need to monitor and control energy efficiency and respond to the climate and grid, SBs have been developed. The concept of SBs will help in achieving the target of SCs. This chapter details these concepts and specifically highlights the research gap of SBs in literature.

The chapter aims to present a literature review analysis on smartness in the built environment. Figure 4 shows the structure of the state of the Art which is composed of a systematic literature review. It starts by clarifying the concepts and definitions of smartness in the building sector and shows the SBs' experience in European countries. Then, it defines the SBs features and technologies and reviews the existing legislation on smart buildings in Europe. Consequently, the relevant KPIs related to smartness in buildings based on the defined smart features and technologies are reviewed. The last part of this chapter investigates the existing retrofitting types, their technologies, and targets and then sets a definition for Smart Retrofitting based on the requirements of a smart building and the targets of previous retrofitting types. Moreover, a review is done on the opportunity of SR in the EU and the supporting EU projects initiated.

The methodology adopted in this chapter is based on a structured systematic literature review. The first step in the review is the keyword search. Four main academic databases were selected “ScienceDirect”, “Research Gate”, “Google Scholar” and “CORDIS

Database". The search strategy consisted first of identifying keywords related to smartness in the built environment, key performance indicators, and smart retrofitting. It involved several keywords which were refined later for more detailed research articles. These keywords were selected based on the research objectives and questions identified in Chapter 1. Specifically, when trying to identify SB basic features for the first part of the chapter, the Keywords included "Smart Buildings", "Smart Grids", "Smart Cities", "nZEB features", "Smart Technologies" "Building Technology", "Intelligent Buildings", "nZEB functions", "nZEB technology", "Energy Efficient Buildings", "Buildings Features/functions/technology" and many others. While for the keywords related to the KPIs, the selection was based on the indicators related to the defined features of smart buildings. For the last part of this chapter, the keywords were related to retrofitting. It included "nZEB Retrofit", "Deep Retrofit", "Major Retrofit", "Retrofit Technologies", "Building Retrofit" and others. These keywords resulted in a huge number of research articles that were refined several times to keep the most appropriate articles that address the objective of "finding SBs basic features" and then read and analyze these articles in detail. After filtering the insufficient and irrelevant articles by screening keywords, abstracts, and methodologies a total of 245 references were reviewed in this chapter.

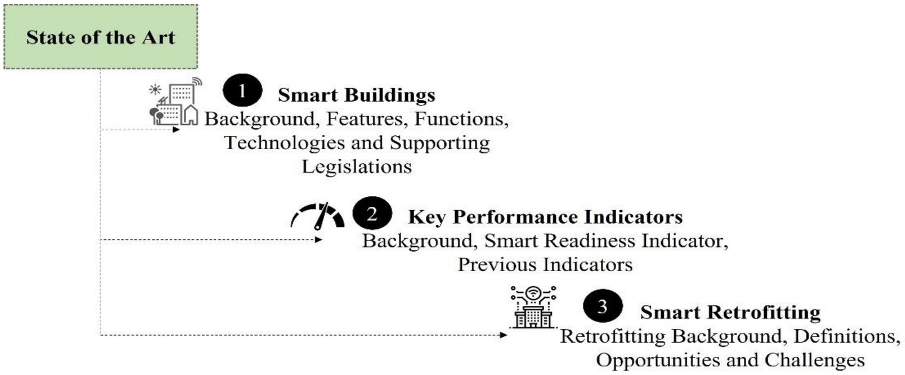

Figure 4. *State-of-the-Art Structure*

2.1 The Smart Capability of the Building Sector: Concepts, Definitions, and Characteristics

The terms "smartness", "digitalization" or "intelligence" of a building, home, and city have been provided in the literature previously. However, no internationally agreed definition of such concepts has been established, yet, the term "intelligence" has been often used in the past [65]. The term "smartness" is more recent and was adopted by the EPBD [10] as a key effort to improve the efficiency of the energy markets. In [66], the terms "intelligence" and "smartness" were explored in the context of SBs and Smart Cities (SCs) and concluded that the two terms are complimentary as long as they have a mutual aim to optimize the performance and impacts of buildings and cities. In [67], in

SCs context, the term “intelligent” refers to the diffusion of ICT in the infrastructure, technological development, innovation, and electronic and digital technologies, while “smartness” is not only limited to these but also to people and community needs.

SCs can be identified from several levels including urban, social, political, transportation, or building level; in this research, we focus on the relationship between buildings, district, and city infrastructure. According to [68], there are two perspectives on SCs; first, they enable real-time monitoring, efficient management, and enforcement of public safety and security using ICT infrastructure, second, they allow technical inspired innovation, creativity, and entrepreneurship by smart people. Several definitions of SCs were reviewed, for instance in [69], SC was described as a well-defined geographical area, by which ICT, logistics, and energy production work together to create benefits for citizens in terms of wellbeing, environmental quality, and intelligence development. While in [70] and [71], the definition of SCs focused on the utilization of networked infrastructure, the inclusion of urban residents in public services, high technologies, RES, and building automation systems integration which works together synergistically to improve conveniences, conserve energy and deploy resources effectively and efficiently.

In a smart environment, several components work together, such as Smart Homes, Smart Buildings, Smart Grids, and Smart Meters (SM): all these elements are very essential in forming a SC (Figure 5). In this thesis, we focus on the SB environment within a SC and its’ infrastructure. In [72], [73] SG was described as an advanced electric power grid infrastructure that uses digital technology to improve efficiency and enhance reliability and safety through automated control, sensing, and metering technologies with smooth integration of renewable and alternative energy sources. While according to [74] ; [75] SMs are claimed to be advanced energy metering systems that allow bidirectional communication of data and enable collecting information on the electricity fed to the power grid from customer premises and execute control commands remotely and locally.

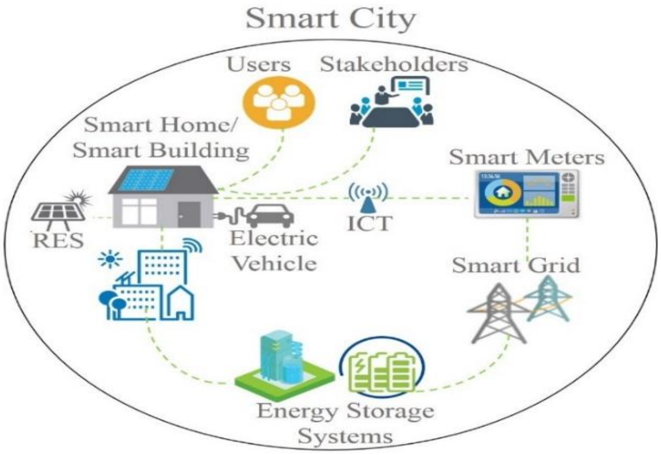

Figure 5. *Smart City Components*

The concept of SBs originated in the '80s [76], however, its' application and importance were emphasized in the revised EPBD and were identified as a key enabler for future energy systems where they allow a larger share of RES, energy flexibility, and distributed supply [77]. SBs have been defined in research, however, there is no commonly accepted definition yet. According to [77] and [71], it was claimed that a SB can manage and control RES, adapt to grid conditions, communicate with other buildings, and actively respond in an efficient manner to changing conditions concerning the operation of technical building systems or the external environment and demands from building occupants. In [78], SB was defined as a highly energy-efficient building that covers its very low energy demand by on-site or district system-driven RES and can (i) stabilize decarbonization of the energy system through energy storage and demand-side flexibility; (ii) empower its users with control over the energy flows; (iii) recognize and react to users' needs in terms of comfort, health, safety as well as operational requirements. Based on the several definitions reviewed on SC, SM, SB, and SG, there is a notable overlap between the reviewed definitions and thus, the most representative definitions have been summarized according to the scope of this thesis in Table 2.

Table 2. *Smartness Definitions in the Built Environment*

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

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

- Achieving the nZEB standard.
- Buildings' response to the external condition (grid and climate).
- Buildings' response to the user's needs.

- Utilization of Building Energy Management Systems (BEMS) to provide monitoring, control, and supervision of SBs' components.

2.1.1 Smart Buildings Experience in Europe

Smart building concepts have emerged widely during the last few years in Europe. Expertise from academic research, EC projects, and public ambits has been involved in the last decades to realize the aforementioned vision. As mentioned previously, the latest EPBD (Directive 2018/844/EU) [41] has encouraged the shift towards the smarter grid and smart metering in buildings and introduced the concept of Smart Buildings. The BPIE conducted a study on "Mapping Smart Readiness in Europe" [79] by measuring the full potential of ICT and innovative systems to adapt their operation to the needs of the occupant, improve their energy performance, and interact with the grid. The study included several criteria inclusive of nZEB requirements, smart meter deployment, dynamic pricing, Demand Response (DR), RES integration, heat pumps, and district heating for evaluation. Figure 6 addresses the question "Are the European countries ready for smart buildings?" however, the answer was No, since some countries have more insulated and healthier buildings, better smart infrastructure (smart meters and connectivity), and better-prepared regulatory frameworks (demand response and dynamic pricing). For instance, Sweden, Finland, Denmark, and the Netherlands are the leading countries due to progressive policies such as smart meter roll-out and investments in renewable energy. Moreover, these countries have a long history of effective building regulations. On the other hand, most of the slow starters score low on all the indicators except final energy consumption, which can be explained by climate conditions and financial restrains, rather than by highly developed energy efficiency measures.

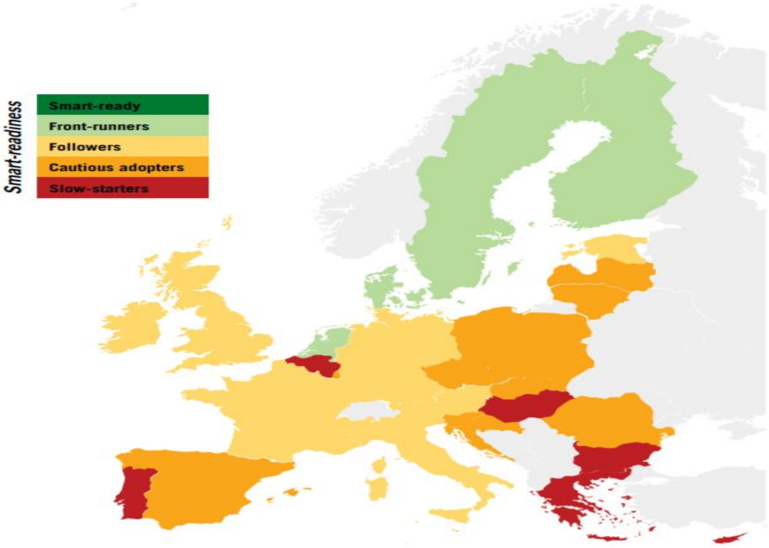

Figure 6. Smart Readiness Across Europe [79]

In parallel with policy developments, the EC has supported research, innovation over several years, and market uptake projects that help Europe use energy more sustainably. One of the main programs done to support SBs in the EU is the Horizon (H2020) program funded by the EC [80]. The program runs from 2014–2020 and provides an estimated €80 billion of funding and brings together research and innovation to ensure that scientific and technological breakthroughs lead to innovative products and services that tackle "the urgent challenges society faces" [81]. One of the main advantages of the research and innovation program for Europe is setting up a single database that contains all the projects across the different thematic areas. The CORDIS database (Community Research and Development Information Service) is the principal publicly accessible source of data on Horizon 2020 projects [82]. It contains data on signed grants and beneficiaries, abstracts, and certain publishable reports produced by projects. CORDIS enables searches to be carried out using keywords, or by searching [83] for project acronyms and reference numbers, or by topic, by type of action, or by several other criteria.

A study was done by Moseley [83] to investigate Horizon 2020 framework program supporting research, innovation, and smart buildings. The research was done using the CORDIS database to map and examine the areas that include building automation and control systems, DR, energy management, ICT, and user interfaces for energy efficiency related to SBs. A total of 16 features of energy-related smartness in buildings were identified. The research has found 42 relevant Horizon 2020 actions situated in 13 countries, in which 29 projects are exploring the user interface for control of a smart building, 25 projects study on-site storage, and 11 projects have investigated the links between smart buildings, electro-mobility, and smart charging. Nevertheless, within projects, the least areas investigated are electro-mobility and smart charging (12 projects), domestic appliances (11 projects), and self-learning/artificial intelligence (14 projects). This study has shown that the SBs projects across the EU do not deal with the holistic interaction of features and technologies, but rather they focus on one aspect and investigate it.

The EU is committed to developing a sustainable, competitive, secure, and decarbonized energy system by including measures in the civil sector, considering its high responsibility. Indeed, significant efforts from academic research, industrial ambit, and policies are devoted to the integration of buildings in smart energy systems, including the connection to district heating and cooling networks and the integration of RES-based distributed energy generation sources and flexibility solutions.

2.1.2 Smart Buildings Basic Features, Strategies, and Schemes

This section elaborates on one of the main objectives of the thesis; to set the minimum features of SBs to consequently define the requirements of a smart retrofit process. According to [84], SBs have the following five fundamental features:

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

In an attempt to measure the performance of SBs, the EPBD [85] has developed the SRI that measures the capacity of buildings to adapt to the building operation to the needs of the grid and occupants. The three key functionalities of smart readiness indicators in buildings are [42]:

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

Based on the reviewed studies, as a first attempt to identify and describe the SB's key features, the latter were categorized according to four main functions; they represent the macro-categories that describe the mandatory features that a SB must have, as follows. It is important to note that the four functions work synergistically (Figure 7).

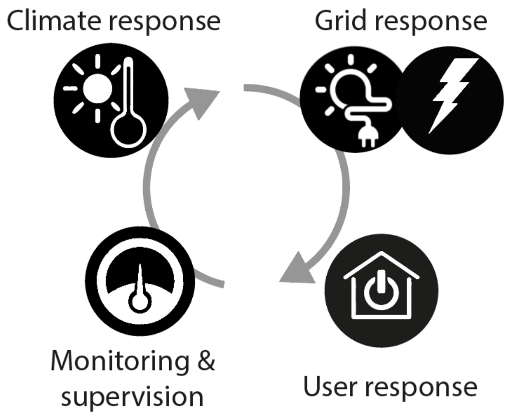

Figure 7. *Smart Buildings Basic Functions*

1. **Climate Response**: the buildings' capability to respond to external climate conditions (actual and expected), according to which the building must identify the best operating profile. Buildings must be able to minimize their energy demand and generate renewable energy to cover the energy consumption. The advancements of the Internet of Things (IoT) and control systems made it easier to get information from weather data. For instance, implementing sensors in all the components such as the building's HVAC, lighting, and solar shading system and connecting it to BEMS will facilitate connection with the external weather forecast conditions. Section 2.1.3.1 elaborates more on the application of BEMS for forecast predictions.
2. **Grid Response**: the buildings' action/reaction to signals/information coming from the grid, aiming to maximize the energy/economic efficiency at the district/city-scale (e.g., reduce grid overload, consume energy when there is maximum availability and the price is low, etc.). The key components of a SG are renewable generation, advanced metering infrastructure, and data exchange. The smart grid emphasizes maintaining interactions with users, including power consumption and dynamic pricing; that in turn is achieved through the deployment of various Demand Side Management (DSM) strategies [86]. The complete integration of DSM requires communication systems and sensors, automated metering, intelligent devices, and specialized processors (further details about DSM are discussed in sections 2.1.2.3 and 2.1.2.4).
3. **User Response**: the capability of the building to enable the real-time interaction of users with the technologies implemented. As claimed in [87], the user interacts with the BEMS to automatically create optimal load operation schedules, and different priorities and specify their comfort settings. BEMS [88], are suggested to enable end-users to interact with the automated energy systems and support the shift from energy consumer towards an active role as co-provider. Moreover, real-time interaction is also achieved through DR strategies in DSM [89], which links the price variations (or incentives) with the users' priorities.
4. **Monitoring and Supervision:** the capability to carry out a real-time monitoring of the building operation, or rather of its technical systems and of the users' behavior; it has the double aim to ease the above-mentioned features (1 to 3) and to allow an efficient operation (e.g., predictive maintenance, real-time identification of faults/unexpected behaviors, etc.) It was claimed in [90] and [91] that monitoring and data analysis are essential for appropriate commissioning and performance tracking due to the performance gap between predicted (e.g. design phase) and measured energy consumption.

Each of these functions is analyzed in detail in the next sections of the work, to set out the basic functions and technologies of SB. In detail, Table 3 reviews some representative studies with quantified benefits and categorizes them based on the basic features, elaborates the smartness features, and highlights the achievable results.

Table 3. *Smart Buildings features and Characteristics*

Basic Feature	Ref.	Smartness Features/ Technology	Important Characteristics/Functions	Quantified Benefits of Smartness Features
Climate Response	[92]	• Stochastic Model Predictive Control (SMPC) strategy.	• The controller uses weather predictions to select cost-effective energy sources to keep the room temperature at the required comfort levels.	• MPC resulted in a theoretical saving of 40% of the total energy consumption.
	[93]	• Online Model Predictive Control (MPC).	• Integrates building thermodynamics, occupancy data, weather forecast, and HVAC component for energy reduction and stabilizing temperature.	• 18.2% energy saving with different temperature regulation settings.
Grid Response	[94]	• Real-time electricity pricing and applying Economic Model Predictive Control (MPC).	• Economic MPC for controlling heat pumps using day-ahead electricity prices. • Load shifting to periods with low electricity prices.	• An optimized operating strategy saves 25-35% of the electricity cost compared to the baseline case.
	[95]	• Intelligent Sensor Nodes for HVAC. • Random Neural Network (RNN)-controller.	• Inputs for the RNN model are: 1) heating set point; 2) cooling set point; 3) heating error, 4) cooling error, and 5) CO_2 concentrations.	• The total energy saving with the RNN controller is 27.12%.
User Response	[96]	• User-BMS communications and fuzzy predictive model.	• HVAC system based on occupants' comfort profiles. • Sensing approach for user-BMS communications • Learn user's comfort profiles, using a fuzzy predictive model.	• User control modes showed a 39% reduction in daily average airflow rates of HVAC (compared to the conventional system).
	[97]	• Wireless Sensor Network (WSN). • BMS.	• Identify the optimal locations for different sensor types and gateways.	• BEMS increases the overall occupant comfort by 2.2% concerning the base case and saves energy by 19%.
Monitoring and Supervision	[98]	• Monitoring, measurement, and verification.	• Faults detection or inappropriate operations of the HVAC system, and reminders to the building operators to address these issues.	• Four pilot buildings showed an average energy saving of 15% with a payback of less than 12 months.

	[99]	• HVAC system fault detection and diagnostics. • Distribution system operators in the distribution network. • Building energy scheduling agents.	• SB coordination and aggregation method reduces building electricity costs and satisfies all distribution system operating constraints.	• Bi-level building load aggregation methodology resulted in an electricity cost reduction of 13% through a price-based MPC algorithm.

Based on the reviewed studies, it is noted that several technologies need to be implemented as fundamental requirements of SBs, such as BEMS and advanced control strategies, SMs, and RES. This table has presented the key studies about the characteristics of SBs with quantified benefits, however, many other studies have explored the implementation of the above-mentioned features without giving quantified results such as [100]; [101]; [102]. Thus, this shows the need for quantifying the benefits of the added smartness features and performance evaluation.

According to the review done, a schematic representation was developed in Figure 8 to highlight all the basic features, functions, technologies, and interfaces that define the smartness in a building based on the four functions previously suggested. Based on the proposed logic, SBs respond to the external conditions (climate and the grid) and internal conditions (user) and provide monitoring and supervision in the building. There are four basic features of the SBs: the nZEB target, flexibility, real-time interaction, and real-time monitoring. Technologies within the nZEB target are connected to flexibility (explained in detail in section 2.1.2.2) and to DSM. While flexibility is a feature that takes data from climate, user, and grid and gives an outcome of DSM with different strategies to respond and reduce the demand and load in buildings. The Energy Storage System (ESS) (explained in detail in section 2.1.3.3) is also a technology connected to the DSM to store the energy from RES and is managed by control systems in the building. The real-time interaction and real-time monitoring are connected to control systems through the internet connection and sensors and actuators, respectively, to ensure user interaction and operation and diagnosis of all the technologies and smart features within the building. Control systems (explained in detail in section 2.1.3.1) in SB are local and cloud-based which consist of classical and computational control systems, respectively. The details of the main components in this schematic illustration are presented in the following sections.

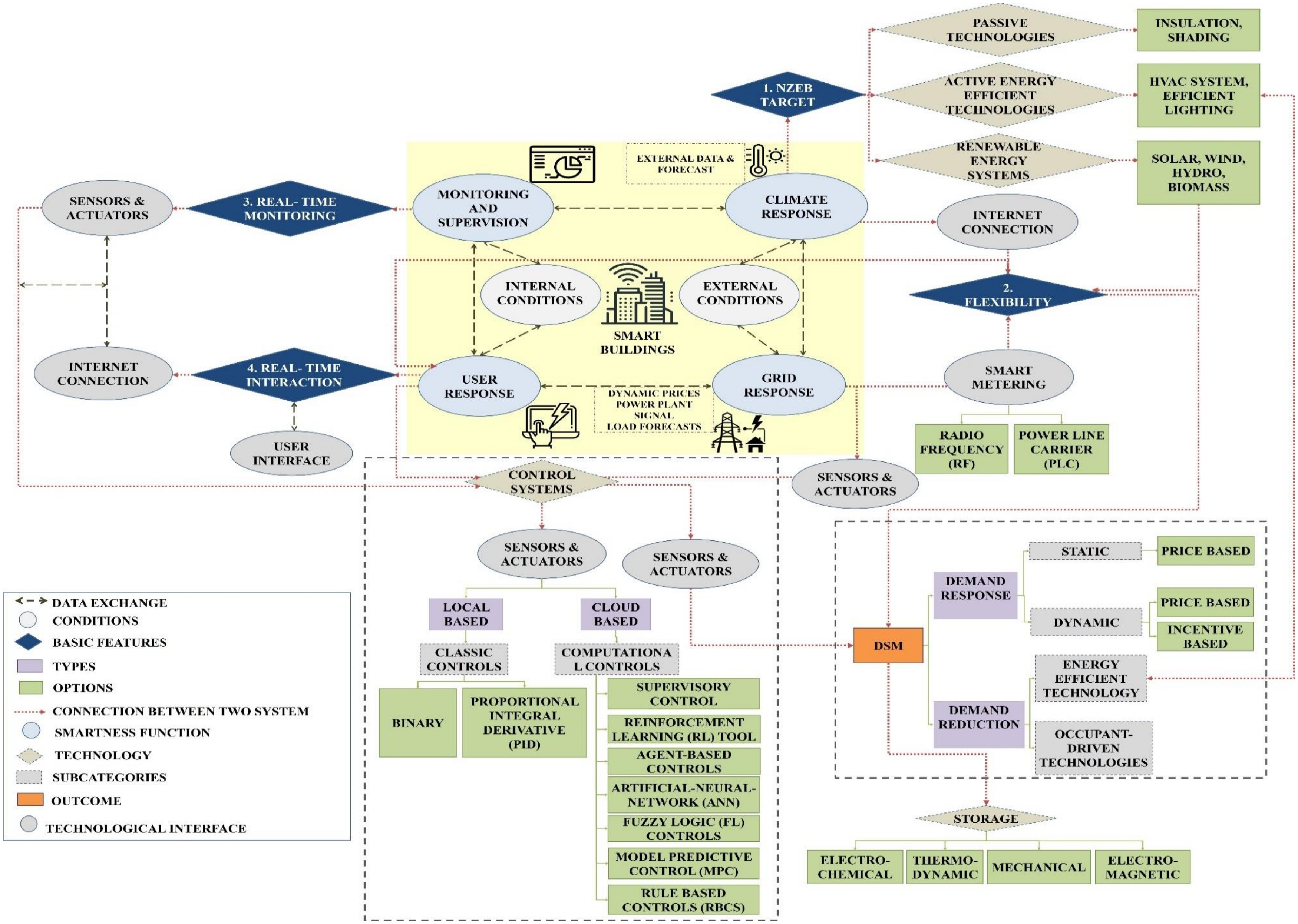

Figure 8. Smart Building Scheme

2.1.2.1 Nearly Zero Energy Buildings Target

The EPBD recast had set a target of achieving nZEBs for all new buildings in Europe by the beginning of 2021 [10]. The target has been stressed in many regulations and studies to reduce energy consumption in buildings and reduce CO_2 emissions.

Functions: it is agreed that to achieve nZEB, there are three main steps to be reached; application of passive strategies, energy-efficient technologies (efficient heating, cooling, and lighting), and then RES integration [103]; [104]. It was stated by [105] that the successful implementation of nZEB does not focus only on energy-efficient measures and the adoption of RES, but also considers the grid integration to achieve the appropriate balance between consumption and production. Thus, for proper interaction, the building must be integrated with smartness features to be able to manage and program the surplus amount of RES. The relation between nZEBs, smart features, and technologies is a process that requires an integrated design approach to achieve the target of SB and SC. In [106], it was highlighted that the interaction between the nZEB building and the SG is one of the main aspects of SCs. This target is a fundamental requirement for a SB since it will ensure that the building is energy efficient and prepare the building for integration with the SG, response to users, and application of control strategies.

Outcomes: achieving energy efficiency in buildings, cost-optimal solutions, reducing GHG and CO_2 emissions.

2.1.2.2 Flexibility

The increased share of RES integration in buildings goes in parallel with the electrification goal and the decentralized electricity production. However, it causes limited controllability of energy supply and increasing load variations over the day. Therefore, flexible energy systems have been developed as a solution to these issues. The International Energy Agency (IEA) [107], introduces the concept of 'Energy Flexible Buildings' with the project 'Annex 67'. Building Energy Flexibility is defined as [107], "the capacity of a building to manage its demand and generation according to local climate conditions, user needs, and grid requirements".

Functions: the buildings' ability to provide energy flexibility is influenced by several factors [108]: (1) its physical characteristics such as thermal mass, insulation, and architectural layout, (2) its technologies such as ventilation, heating, and storage equipment, (3) its control system that enables user interactions; the possibility to respond and react to external signals such as electricity price or CO_2 factors, and (4) the user's behavior and comfort requirements. Several authors have studied the application and features when applying energy flexibility in buildings. The majority of studies focus on the flexibility of heat pumps, hot water storage, and Thermal Energy Storage (TES) that contribute to shifting electrical loads [109], [110], [111]. Other studies have shown that structural thermal mass can be utilized to achieve flexibility in residential buildings [112], [113]. Moreover, control systems were used in the majority of studies when addressing the potential of load shifting and achieving flexibility in buildings [114], [115].

Outcomes: DSM is the outcome of flexibility and real-time interaction in SBs. DSM has two main functions, one to integrate with the user and one to integrate with the external environment. DSM is defined as the ability of planning and implements electric utility activities designed to influence customer uses of electricity in ways that will produce desired changes in the utility's load shape [116]. Based on [117] and [118], DSM is categorized into demand reduction and DR. Demand reduction [118] focuses on electricity saving through implementing energy-efficient equipment and user behavioral change (achieved through real-time interaction). While DR [86], is the change in electricity use by end-use customers from their regular consumption patterns in response to price changes. DR indicates all strategies implemented among the different DSM measures by consumers to adapt their load profiles to specific external requirements (i.e., grid), through shifting, reducing, or increasing the energy consumption [119]. Concerning flexibility, it has been claimed [120] that smart grids are based on the use of DSM, which includes the system operation, the minimization of the peak demand, and planning improvement. Therefore, DR can be achieved through flexibility and real-time interaction. The smart grid can achieve energy measures, peak load shaving, improve the efficiency of the grid, and reduce the need for power investments through DR. According to [121], DR facilitates the reduction of power consumption, saves energy, and maximizes capacity utilization of the distribution system's infrastructure by reducing or eliminating the need to build new lines and expand the system. DR strategies could be categorized into the following three aspects [122]; 1) Peak clipping (explained in section 2.1.2.4), 2) Valley filling and 3) Load shifting.

- Valley Filling describes the increase in the demand during off-peak periods while having the same load peak [123]. Its main function is to increase total energy consumption, while the peak demand is kept fixed and allows off-peak energy consumption through energy storage devices [124]. It can be achieved by reducing the number of operating hours of baseload plants.
- Load Shifting is to shift part of the demand at the peak period to the off-peak periods without reducing the users' total energy consumption within a day [124]. It is achieved through Time of Use (TOU) rates and/or the use of storage devices that shift the timing of conventional electric appliances' operation [123]. It shifts the load to a cheaper billing period if consumption cannot be reduced and allows remotely scheduling an appliance, by setting the timer on the appliance [125].

2.1.2.3 Real-Time Monitoring

The real-time monitoring feature is related to the monitoring and supervision function and is connected to the BEMS since it depends on the use of sensors, actuators, and control systems to collect, analyze, and monitor the data and energy consumption in the building. In [126] real-time monitoring has been defined as a tool that allows organized and statistically analyzed data sets on energy use in buildings and their energy efficiency and economic performance.

Functions: in real-time monitoring [126], data is collected, analyzed, and stored, and then it is ready for real-time interaction with users and the external building conditions. Thus, real-time monitoring collects information, to monitor the behavior of a building and allows predictive maintenance. The application of real-time monitoring can also be achieved through the Decision Support System (DSS) [127], which has a data-collection module, data-processing module, and data-analyzing module. DSS predicts the power demands from consumers, which can optimize the scheduling of the power supply. The data collected from distributed power grid units and the knowledge of domain experts work together to define measures for evaluating the success of particular activities in a power grid [127].

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

2.1.2.4 Real-Time Interaction

The real-time interaction feature is related to user interaction with external services (weather and grid conditions) and building technologies. In [128], real-time interaction had been claimed to allow the collection of users' feedback by a task-based interaction between user and building. Besides that, users can experience real-time interaction with the SB and have an overview of the functionalities of smart technologies [128].

Functions: the real-time interaction has an internet connection, sensor and actuators, and a direct connection to the users. In [129], the collection of real-time data of occupants and weather forecasts was used for prediction in building automation. In [130], the relationship between users and SBs was tested in a project done in Italy using a bi-directional interaction via a mobile application. The app is supported by sensors first to monitor and control comfort, indoor air quality, and HVAC parameters. The data is used to allow real-time charts displayed to the user for interaction and allow easy access to building status or to allow building automation systems (e.g., lighting systems control, heating ventilation, air conditioning system control, etc.).

Outcomes: it was suggested by [131] that real-time interaction results in shifting the role of a user from being a passive receiver to an active actor. As previously mentioned, DSM is also the outcome of real-time interaction by which it allows the planning and implementation of activities designed to impact the customer's use of electricity [132]. In DSM [133], [134] users are encouraged to consume less power during peak times or to shift energy use to off-peak hours to flatten the demand curve. Peak Clipping DR Resource (PCDR) strategy in DSM reduces peak energy consumption to stop the load from exceeding the supply capacity of distribution substations [122]. It supports loads with flexible procedures such as residential loads and loads with on-site generation units [135]. It can be achieved when users shift some of their activities to another time and reduce their electric consumption.

2.1.3 Smart Buildings Basic Technologies

In SBs, several technologies must be present to enable smart features. Based on the literature, the main key technologies related to the functions of SBs are classified in Figure 9.

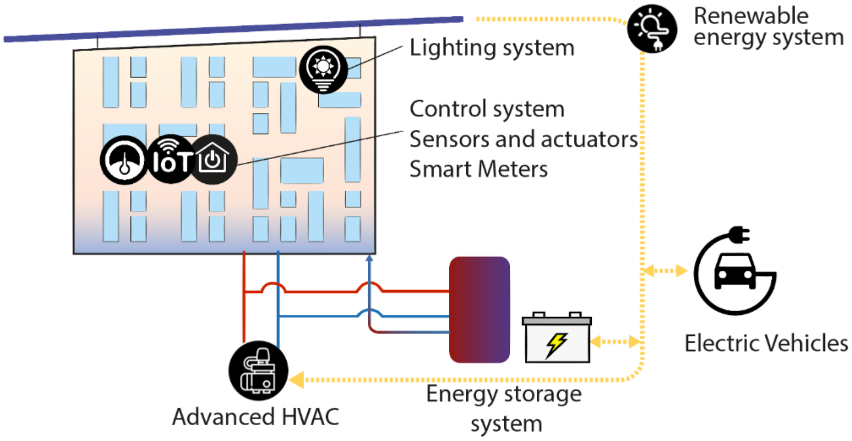

Figure 9. Key Technologies in Smart Buildings

2.1.3.1 Control Systems

Building automation is a complex, multidisciplinary topic that has been indicated with several terms in literature such as Building Automation System (BAS), Building Automation and Control System (BACS), Building Management System (BMS), Building Energy Management System (BEMS); Energy Management and Control System (EMCS), and Home Energy Management System (HEMS). However, it must be noted that, although there are several names and definitions, the common function is to report the building performance, decide on actions, and control the decided actions to save energy,

and cost, and reduce environmental impacts. We have selected BEMS in this thesis to discuss control systems in SBs.
The integration of advanced ICTs increases the efficiency of the SB by providing more automation, a reliable forecast of grid and weather, and a better operation of electrical appliances, resulting in higher energy quality and increased user satisfaction [136]. BEMS is the physical element that needs to reach real-time interaction and flexibility in buildings. It is composed of hardware and software:

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

The main communication channel for the operator in the BEMS is the hardware [137], which allows energy monitoring, integration with utilities and smart grid technologies through DSM, and ensures resilience and security. BEMS is responsible for monitoring and controlling the mechanical and electrical equipment of a building such as lighting, HVAC, Domestic Hot Water (DHW), shading systems control, fire systems, onsite power generation, security systems, and abnormal levels of energy use [138], [139].

According to [140], BEMS are integrated into several parts of the building by which they use dynamic information of users' activities (e.g. location), ambient conditions (e.g. weather, light), and energy supply conditions (e.g. cost, load). Generally, control systems are classified into [141]; conventional control systems [142], [143], and advanced or computational control systems [55]. However, for SBs, the use of advanced control systems is more relevant since they allow the interaction with external and internal conditions. [95] pointed out that two technical approaches to HVAC control are available: physical model-based techniques (such as model predictive control) and black-box techniques (such as RNNs, artificial neural networks (ANNs), and support vector machines). In literature [55], [144], [145], the most common way to respond to the external climatic condition is through the implementation of MPC. MPC provides optimal predictions of future disturbances such as ambient temperature, solar radiation, and occupancy, and presents the ideal control strategy to deal with conflicting optimization goals.

Furthermore, sensors and actuators are important parts of the BEMS where they represent technological interfaces in smart buildings. sensors and actuators are connected to features, functions, and technologies such as DSM, storage systems, and real-time monitoring, [146]. Sensors are defined as equipment that measures physical quantities and then converts them into digital signals. While actuators are used in control systems in two ways; first to manage information from sensors and actuate their control function directly, and second when the supervisory control layer (acquiring data from sensors) acts in an in-direct way. Sensors and actuators have been used for occupancy detection and behavioral modeling in buildings [147]; monitoring data in the SG [148], lighting control [149], BEMS [150], predictive control, and energy storage systems [151], etc. According to [152], the use of wireless sensors and actuators for building auditing and controlling presents a viable solution over traditional building monitoring and actuating systems. Sensors and actuators facilitate the application of ICTs in SB and the connection of all technologies and equipment in the building to the BEMS.

2.1.3.2 Renewable Energy Systems

The RES Directive recast focused on the 2030 EU target and had set a new binding renewable energy target of at least 32% with a clause for a possible upwards revision by 2023 [32]. The use of renewable energy systems for meeting building energy needs is becoming a means for environmental sustainability, increasing the reliability of on-site electrical production and the reduction of utility costs. The integration of RES in buildings has been extensively used to achieve the nZEB target to cover a substantial amount of energy, increase energy savings and reduce cost [153]. The RES contains programmable sources such as biomass which can be stored and used anytime and non-programmable energy sources such as wind and solar production. Therefore, the RES that can be installed on SBs are Photovoltaics (PV) [154], solar thermal collectors [155], pumped hydro energy [156], mini wind turbines [157], and biomass [158]. The intermittency and uncertainty of on-site RES can result in a mismatch between building energy demand and on-site generation. This can cause increasing challenges in the energy grid, such as exacerbating the imbalance between the supply and demand sides, increasing the curtailment rate of renewable energy generation, and causing unstable operation of the power grid [159]. To alleviate these problems, Demand Side Management strategies and flexibility must be linked to the RES since their profile must be predetermined with sufficient anticipation to ensure the reliability of energy dispatching.

2.1.3.3 Energy Storage Systems

Successful coordination between RESs and building loads plays a vital role in allowing ESSs to improve the reliability, security, and resiliency of micro-grid applications. Storage is identified as the technology that can capture energy and release it later for consumption [160]. According to [161], ESS provides remarkable opportunities to improve the efficiency and operation of smart buildings. In [162], it was described that a smart grid coupled with energy storage systems increases flexibility. The integration of ESS during peak load periods is also useful to shift electrical demands from on-peak to off-peak [163]. Moreover, the use of energy storage technologies allows a reduction in the demand side and saves the surplus energy in batteries. According to [164], energy flexible buildings that have electric heating, demand-side management, and efficient TES represent one of the most promising strategies for carbon reduction technologies. In [165], storage systems were managed according to energy prices; when the price is low, the battery is charged and when the price is high the battery is discharged. The authors in [166] pointed out that there is a wide range of storage technologies that have different capacities and speeds and times of response. Moreover, energy storage allows energy resilience by which it can balance energy demand and supply and also respond to abnormal changes in the energy supply.

On the other hand, based on the revised EPBD [77], there is an evident link between electric mobility through Electric Vehicles (EVs) and SBs. EVs act as generation/storage devices or an additional element of flexibility to provide energy and capacity to the building and enhance the power supply [167]. EVs stay connected to the grid once they are parked, thus delivering the energy from their batteries which can store and release energy in different conditions [168]. The RES can be used to charge the vehicles and when the energy production is higher than the total demands, the EV charges the batteries and when the building does not have enough energy, the EV releases the stored energy to supply the building [169].

2.1.3.4 Advanced HVAC and Lighting systems

HVAC systems are considered to be the most demanding systems in the building with a share of around 50% of the world's total building energy consumption [170]. Additionally, SBs typically integrate energy-efficient and responsive lighting system that uses ICTs. Energy-efficient HVAC and lighting technologies are fundamental parts of the active strategies to achieve the nZEB target as illustrated previously in Figure 8. Unlike conventional HVAC systems, in SBs, integrate with ESS technology [171], BEMS [172], ICTs [173], and DSM programs [174] to manage their consumption, and reduce peak load and achieve the nZEB target. SBs' HVAC system also allows building occupants and operators to have more control and can adjust and adapt intuitively according to the users' profile, preferences and needs using real-time weather forecast and grid data through MPC [175]. Smart Lighting is also claimed to be integrated with the BEMS system to allow information exchange and optimization, also to support built-in occupancy sensors and logic systems to automatically adjust its luminance with respect to time and occupancy [175]. Moreover, it is controlled through a wireless control unit to provide dimming, on/off control, and change the intensity of its glow [176]. The integration of smart lighting systems with advanced shading systems and BACS has been tested and showed higher energy-saving potential, more daylight penetration, and increased user satisfaction [177], [178].

2.1.3.5 Smart Meters

SM is another important technological interface that is connected to the BEMS and promotes communication between the smart grid and the buildings. In particular between the energy consumer, the meter operator, the supplier of energy or the utility, and the meter data management systems [179]. According to [180], a smart grid system has two types of information infrastructure; first, is the information flow from sensors and electrical appliances to smart meters, which is achieved through Powerline Carrier (PLC) or wireless communications (Radio Frequency), such as ZigBee, 6LowPAN, Z-wave. Second, is the flow between SM and the utility's data centers achieved via internet-based solution. Three main benefits are expected from SM system [181]: the availability of energy consumption information to users that enables them to optimize their consumption, the ability to assess and control meters remotely, and the ability to reduce energy waste since it can be automated to react to power shortages, failures, and excesses. Finally, SM is integrated into the BEMS and automatic functions are enabled when peak use approaches critical price thresholds or system constraints [182].

2.1.4 Buildings Legislation and Regulatory Framework on Smart Buildings and Smart Cities in the European Union

The need to develop policies and standards that enhance energy and technological innovation is a fundamental step toward the increase of smartness in the built environment. In section 1.1, an overview was given on the main EU building legislations done on energy efficiency. The timeline in Figure 1 has shown the extensive efforts done in the EU to support the move towards smart buildings and smart cities which were triggered by the extensive use of RES, the development of ICT, and the need to allow responsive cities and buildings to users, fluctuating climatic conditions and the electrical grid. Technological and scientific advancements such as energy production and management through RES, district heating, smart metering, intelligent street lighting, smart storage systems (heat pumps, vehicle-to-grid (V2G) storage, innovative batteries) as well as city information platforms (smart open data city platform, urban monitoring) and citizen engagement has all supported the move towards smarter cities. In light of such a fast-transitioning environment, the need to develop strategies that help impose smart city solutions was very crucial. In the EU, smart city policies are anchored in several directives and agreements. The COP21 Paris Agreement (2015) recognized the role of cities and urged them to reduce greenhouse gas emissions and adapt to climate change. The Sustainable Development Goals (SDGs) were introduced as the blueprint to achieve a better and more sustainable future, committed by many countries and by the EC to address urgent global challenges over the next 15 years [183]. The city plays an important role in ensuring this target; thus, it was highlighted in SDG 11 Sustainable Cities and

Communities and SDG 7 Affordable and Clean Energy, and SDG 13 Climate Action. Achieving these targets will realize more sustainable cities that will set the ground for smarter cities in the future. The SET-Plan developed in 2017 also encouraged accelerating the development of low-carbon technologies, Smart Cities, and improving the competitiveness of innovative energy technologies [184].

Standardization of smart urban metrics has gained wide attention from international standards organizations. The International Organization for Standardization (ISO) has concurred on standards for 'Smart Community Infrastructures' performance metrics. ISO/TC268 for "Sustainable cities and communities" [185], is responsible for the ISO 37100 series of standards that helps cities to define their sustainability objectives and put strategies in place to achieve them. ISO/TR 37150 [186] had introduced indicators such as Global City Indicators; Green City Index series; and Smart City realized by ICT. ISO Technical Report 37150:2014 (Smart community infrastructures - Review of existing activities relevant to metrics) [187] reviews existing activities relevant to metrics for smart community infrastructures including water, energy, waste transportation, and Information and Communications Technology (ICT). Consequently, ISO Technical Report 37151:2015 (Smart community infrastructures—Principles and requirements for performance metrics) [188] have detailed the principles and requirements for the definition, identification, and optimization of community infrastructure performance metrics, and gave recommendations for analysis, including smartness, interoperability, synergy, resilience, safety, and security of community infrastructures. While ISO/NP 37122 [189], "Sustainable Development in Communities- Indicators for Smart Cities", is being developed to enhance the existing indicators. Other standards on SCs were developed by the EC that address services and quality of life, accessibility, mobility, management, and other issues [190].

The need to monitor smart cities' progress in Europe has led to developing initiatives and platforms funded by the EC to evaluate smart city projects. The initiative creates standardized data collection processes to increase the adoption rate of smart city solutions. The two main initiatives developed are the Smart Cities Information System (SCIS) [191] and CITYkeys [192] which created a platform of interaction along with a list of Key Performance Indicators for the evaluation of systems and technologies demonstrated in smart city projects. The SCIS is a knowledge platform that allows data exchange, experience, and collaboration for the creation of smart cities [191]. It works on the development of indicators to measure technical and economic aspects of energy-related measures which apply to European-funded demonstration projects for smart cities and communities. The CITYkeys funded by the H2020 has developed and validated KPIs and data collection procedures for the monitoring and comparison of European Smart Cities [192]. The bases of the framework are the traditional sustainability categories of People, Profit, and Planet, but the performance measurement framework includes specific smart city KPIs that are more detailed and measure the integration level and openness of the technological solutions.

On the contrary, fewer regulations and policies were developed to support Smart Buildings. As the topic is emerging, regulations, policies, and incentive programs are still being developed. The EPBD recast [10], EC [77], and Building Performance Institute Europe (BPIE) [193] support the move towards smarter buildings in Europe. The EPBD recast in 2018 has introduced the SRI in buildings to measure the performance of SBs qualitatively. The SRI is introduced as an instrument for rating the smart readiness of buildings. It is predicted to be an optional EU scheme that will assess the readiness of buildings in terms of technical aspects and assess the ability to interact with their occupants, connect energy grids, and operate more efficiently. It is done by assessing the services, and functionality levels of the technologies in SBs. This indicator is very recent and still has not been applied to buildings. On the other hand, the IEA Annex 67 on energy flexibility and smartness of buildings [107] has developed a quantitative methodology to characterize and label energy flexibility that took into account not only the technical aspects or services at a building level but also includes its interaction with the energy system, occupants and other boundary conditions. Annex 67 also focused on the analysis of the potential energy flexibility in both residential and non-residential, single buildings and clusters of buildings, as well as how to control this flexibility without loss of comfort for the users in the buildings. It covered building technologies such as storage of heat in building constructions and in water tanks (e.g., DHW tanks), control of HVAC systems (e.g., heat pumps, air conditioning, and ventilation), and the interaction between the building load and on-side energy production based on renewable energy. Till now, Annex 67 was the only initiative developed to give quantitative measurements of smart building technologies focusing on flexibility. Moreover, EN 15232 standard was introduced to assess the impact of building automation, controls, and building management and classifies the control functions of the technical systems of buildings [194]. Moreover, it is used to evaluate the contribution of building management functions to the energy performance of buildings.

As highlighted previously, a significant number of legislations and policies have been done on the standardization of smart cities and infrastructure, however, there is a clear lack of policies, and regulations developed on smart buildings. This calls for a framework to identify the main metrics and indicators of SBs and SR. These indicators must be able to assess the performance of SBs in terms of the basic functions and features discussed previously.

2.2 Key Performance Indicators

Quantifying building energy performance through the development and use of KPIs is an essential step in achieving SB goals in both new and existing buildings. Thus, Specific metrics and KPIs are fundamental to support achieving energy efficiency in buildings. According to [195], KPIs are a way of measuring the performance of an organization and its success in achieving goals. [60] claimed that indicator systems can provide measurements of the current performance and give a clear view of achievement in terms of future performance targets and progress. KPIs are quantifiable and measurable metrics that are essential for addressing the success of a project. They measure the effectiveness of a project towards the achievement of specific key objectives [196]. Thus, the process of selecting KPIs is very essential in clarifying the project's goals. KPIs should express as precisely as possible to what extent an aim, a goal or a standard has been reached or even surpassed.

2.2.1 Smart Readiness Indicator

The SRI was introduced by the 2018 EPBD [41] as Smart Readiness Indicator for buildings to provide information on the technological readiness of buildings to interact with their occupants, and energy grids, and on their capabilities for more efficient operation and improved performance through using ICT technologies. It focuses on three key smart readiness functionalities:

1. The ability to maintain the operation and performance of the building through the adaptation of energy consumption.
2. The ability to respond to the needs of the occupant while allowing user-friendliness, maintaining healthy indoor climate conditions, and the ability to report on energy use.
3. The ability to provide the flexibility of a building's overall electricity demand and allow demand response with the grid and load shifting capacities.

SRI is designed to provide information on the smart services the building could deliver in both existing and new buildings in which the targeted audience is building occupants, owners, and investors. By providing a common language for all main stakeholders, the SRI can help boost the market uptake of smart-ready technologies through the establishment of a credible and integrated instrument.

The SRI methodology depends on the inspection of the "smart ready services" available in a building [85]. These services are set based on a combination of smart-ready technologies present in a building. Each of the services can be implemented with various degrees of smartness, referred to as "functionality levels". The services within a Smart Building operate in several identified domains including Heating, Cooling, Domestic hot water, Controlled ventilation, Lighting, Dynamic building envelope, Electricity, Electric vehicle charging, and Monitoring and control (Figure 10). These domains can affect various kinds of impacts including Energy Efficiency, Maintenance and fault prediction, Comfort, Convenience, Health and wellbeing, Information to occupants, Energy flexibility, and storage. In the proposed methodology, the impact scores of the individual services are summed up using the weighting factors and then compared with the maximum impact score that the specific building could obtain [42].

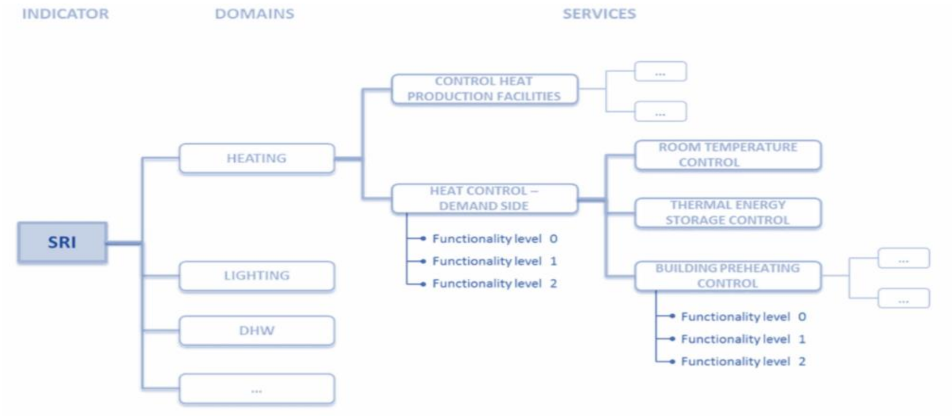

***Figure 10**. SRI Services and Domains* [85]

The final report on the technical support and development of SRI [197] sets evaluation methods of SRI which can be envisioned in two key steps.

- Method A: is a quick scan of the project with a focus on residential buildings and small non-residential buildings. The method is based on a checklist approach with a limited or simplified services list. For a single-family home, the evaluation could take less than an hour. The method permits both online self-assessment and a formal third-party expert assessment which can issue a formal certification.
- Method B: is a more detailed SRI assessment that focuses on non-residential buildings. The assessment could take half a day to one day, depending on the size and complexity of the building. It requires an on-site inspection to self-report functionality levels by a third-party qualified expert to issue a formal certification.

As a future evolution to the SRI methodology, Method C is a metered/measured method. It requires benchmarking to assess how much savings, flexibility, comfort improvements, etc. are delivered as a result of smart technologies. It is expected to quantify the actual performance of in-use buildings. The scope of this method could be broadened beyond the current scope of the SRI to become an assessment of actual performance, rather than solely focusing on smart services. Method C is currently considered to be a potential future evolution of a certification approach for a commissioned building. However, it was not detailed in the final technical study and was rather considered a potential future evolution of the SRI.

The SRI serves as a crucial step for evaluating smart buildings. However, the evaluation Methods "A" and "B" which are adopted in the current version of the SRI are qualitative and do not focus on evaluating the performance of the smart services from an energy point of view and rather serve as a checklist of the implemented technologies. "Method C" on the other hand is intriguing since it focuses on quantitative assessment of these services and technologies. Based on the review carried out previously, it can be deduced that there is a huge potential in "Method C" for quantifying the performance of smart buildings. Consequently, this thesis also covers the potential development of Method C of the SRI.

2.2.2 Smart Buildings Key Performance Indicators

The choice of KPIs impacts assessment results, thus, selecting the most appropriate KPIs is a big challenge. This section expands upon current methods used for assessing building KPIs. Several studies/reports have previously employed the KPI concept to define the smart, intelligent, or nZEB performance metrics. The indicators studied in the literature vary and can be categorized into different themes. The basic criterion set to collect the KPIs from the studies was to include only quantitative indicators that measure the energy performance in a building. The reviewed KPIs have been developed or studied in reports and projects, research articles, and building standards, however, some of them have not been tested, while others have been tested and reported in more than one study. KPIs for SBs present in literature can be distinguished according to the approach adopted to describe the building performances. Common terminology is important to communicate a SB basic feature. Thus, the KPIs have been summarized according to three generic categories that define the SB basic features discussed previously. The detailed framework of KPI selection and systems/components measured in KPIs are shown in Figure 11.

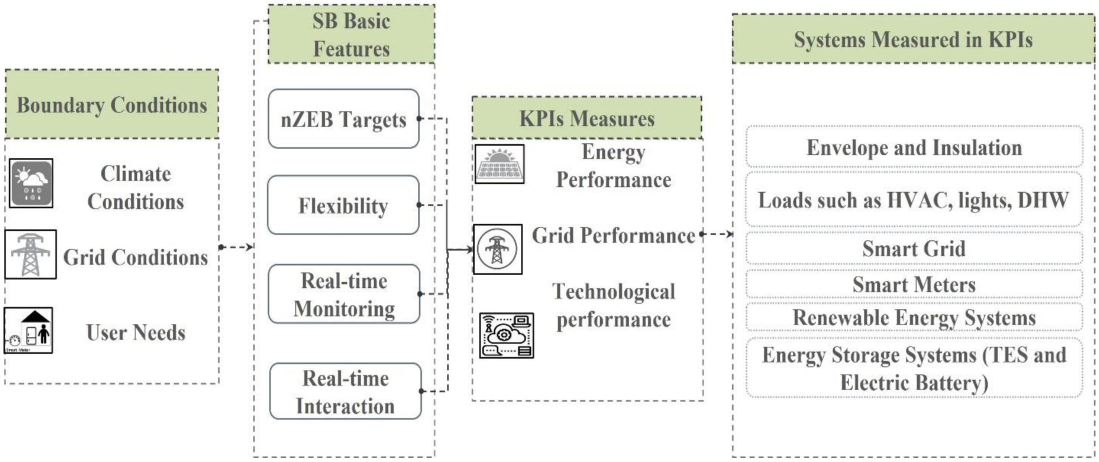

Figure 11. Smart Buildings Key Performance Indicators Framework

A list of 31 KPIs was prepared, in which the majority of indicators are quantitative and measure energy and power rate, and a few are non-energy indicators. Table 4 classifies these KPIs based on the SBs' basic functions and shows the definition of each with the references that developed/tested them in literature.

Table 4. Definitions and References of KPIs in Smart Buildings

SB Basic Features	Supporting KPIs (Units)	Indicator Definition	References
nZEB target **Climate Response, Grid Response**	1. **Non-renewable Primary Energy (**kWh/m^2)	Primary energy is the energy that has not been subjected to any conversion or transformation process. The indicator Sums up all delivered and exported energy (electricity, district heat/cooling, fuels) into a single indicator.	[198]; [199]; [200]; [201]; [202]; [203]
	2. **Energy Demand And Consumption (**kWh/(m^2/month or year))	Assess the building energy demand and consumption.	[204];[198]; [205]
	3. **Energy Savings** (%)	Percent reduction of energy consumption compared to the baseline case.	[206]; [198]; [207]; [208]
	4. **Global Energy Performance Indicator (kWh/m^2)**	The 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.	[209]**;** [210]**;** [211]
	5. **Degree of Energetic Self-Supply by RES** (%)	The ratio of locally produced energy from RES and consumption over a period of time (e.g., month, year).	[198]; [212]; [213]
	6. **Increased RES and Distributed Energy Resources hosting capacity** (%)	(Maximum permissible PV power injection into the feeders is referred to as the PV "hosting capacity"). The additional RES and energy resources can be installed in the network when new interventions are applied and compared to the BAU scenario.	[214]; [215]; [216]; [217]; [218]
Flexibility **Climate Response, Grid**	7. **Storage Capacity** (%)	The available storage capacity (the total amount of heat that can be absorbed during charging under nominal conditions) of storage technologies integrated into the smart grid.	[219]; [220]; [221]; [222]
	8. **Depth of Discharge (%)**	Describes the percentage of the battery that has been discharged relative to the overall capacity of the battery.	[220]; [223]; [224]

	9. **Storage Efficiency** (%)	The ratio between the discharged energy and the charged energy, typically over a full cycle.	[108]; [225]
	10. **Load Cover Factor** (%)	The percentage of electrical demand is covered by on-site electric generation.	[226]; [227]; [228]; [229]; [204]
	11. **Maximum Hourly Surplus (**-)	The maximum yearly ratio of how much the hourly local renewable supply overrides the demand during one single hour.	[230]; [231]; [206]
	12. **Maximum Hourly Deficit (**-)	The maximum yearly ratio of how much the hourly local demand overrides the local renewable supply during one single hour.	[230]; [231]; [206]
	13. **Demand Response (-**)	Load reduction potential of a device with respect to its rated power consumption during a Demand Response event.	[214]; [232]; [233]; [234]
	14. **Peak Load Reduction** (%)	Compare the baseline peak demand with the peak demand after technology implementation.	[198]; [235]; [236]; [237]
	15. **Flexibility Index (%)**	The indicator shows the reduction of heating demand not covered by RES.	[238], [239], [240], [241]; [233]; [229]
	16. **Flexibility Factor** (-)	Evaluate the ability to shift the energy use from high to low price periods.	[238]; [221]; [242]
	17. **Annual Mismatch Ratio** (-)	For this ratio, firstly, the Hourly Mismatch Ratio is determined considering the state of charge of the storage and the demand and supply situation at every hour of the year. Then, the AMR is derived as an arithmetic mean of all HMR values.	[230]; [243]; [244]; [244]
	18. **Load Matching Index** (%)	The average value over an evaluation period of how the on-site generation covers the energy load.	[245]; [204];[229]; [227]; [246]
	19. **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.	[230]; [243]; [247]
	20. **RES Self-consumption (Supply Cover Factor) (%)**	The degree of instantaneous on-site renewable energy consumption	[248]; [249]; [227]; [250]

	21. Flexible Shiftable Load S_{flex}	The percentage of shifted flexible loads over time (the deviation in energy consumption)	[251], [252], [239], [253], [254], [255]
Real-time monitoring **Monitoring and Supervision**	**22. Increased Power Quality and Quality of Supply** (%)	Average time needed for awareness, localization, and isolation of grid fault.	[198]; [256]; [217]
	23. Absolute Grid Support Coefficient (-) GSC_{abs}	Weights a time-resolved electricity consumption profile with a time-resolved grid signal. It is calculated on a period consisting of at least two-time steps assuming the electricity price is used as a reference quantity.	[238], [257]
	24. Relative Grid Support Coefficient (-) GSC_{rel}	Translates the amount of GSC_{abs} to a scale of -100 (worst case) to +100 (best case) which indicates the present potential for optimization. Assesses the optimization potential for heating or cooling system operation.	[238]; [257]
	25. 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.	[198]; [232]
	26. Reduced Energy Curtailment of RES and DER (%)	Reduction of energy curtailment due to technical and operational problems.	[198]; [232]
	27. Reduction of technical network losses (%)	Compares the energy losses of the baseline scenario against the ones from the smart building scenario.	[214]; [232]
Real-time interaction **User Response**	**28. No Grid Interaction Probability (-)**	The probability that the building is acting autonomously on the grid.	[228]; [227]; [204]; [229]; [258]
	29. Grid Interaction Index (%)	Describes the average grid stress, using the standard deviation of the grid interaction over a period of a year.	[204]; [245]; [227], [259]
	30. System Average Interruption Duration Index System (-)	Estimates the average interruption duration, which leads to the disturbance for network users and maintenance costs.	[214]; [260]; [261]; [262];
	31. 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.	[214]; [260]; [261]; [262]

These indicators vary from ones used for simple and fast benchmarking to more complicated indicators. Simple KPIs can be considered as basic indicators such as primary energy use in the building, energy demand and consumption, and energy savings indicators, that require basic data and knowledge of the building. While more complex indicators contain more detailed data such as flexibility indicators, grid interaction indicators, load cover factors, and others that consider internal building characteristics such as building loads, demands, and consumptions, as well as external building conditions e.g., weather, on-site renewable generation, interactions with the grid. The KPIs reviewed in the previous table are further classified into sub-categories for more clarification in Section 3.3. This categorization allows identifying the most appropriate KPIs for assessing the SB and SR performance.

2.3 Smart Retrofitting of Residential Buildings

Achieving smart cities requires the development of buildings towards energy efficiency. Since up to 90% of the existing European building, the stock will be standing and in use in 2050, renovation of existing buildings represents a great potential for reducing energy consumption. As discussed earlier, buildings have experienced a great development since the implementation of energy efficiency directives and regulations in the EU starting from energy-efficient buildings and moving to smart buildings. In parallel, building retrofitting has experienced an evolution based on the increasing efficiency targets. The development of ICT provides the opportunity to harness energy consumption reduction in existing buildings through analyzing and optimizing the energy performance of buildings.

2.3.1 Concept and Definition of Smart Retrofitting

The IEA estimates space heating and cooling to consume 53% of energy consumption globally in existing residential buildings [263]. This is specifically true for buildings with older HVAC systems. According to the Italian energy-environment service company "Officinae Verdi", HVAC accounts for about 40% of the energy costs of a typical commercial building, therefore, reducing that burden can make a substantial difference. Building retrofitting is considered one of the leading approaches to accurately reducing building energy consumption and GHG emissions. Building retrofitting for energy efficiency can result in significant cost savings by reducing energy demand. A significant amount of research has been done to develop and investigate different energy efficiency strategies to improve the energy performance of existing buildings [264], [265], [266], [267], [268].

Several regulations and reports were developed to support building retrofitting. For instance, the IEA launched a set of Annex projects to promote energy efficiency of existing buildings, such as Annex 46 – Holistic assessment toolkit on energy-efficient retrofit measures for government buildings [269]; Annex 50 – Prefabricated systems for low energy renovation of residential buildings [240]; Annex 55 – Reliability of energy-efficient building retrofitting [270]; and Annex 56 – Energy & greenhouse gas optimized building renovation [271]. These programs provided policy guidance, awareness, technical support, and financial assistance for the execution of energy-efficient retrofitting.

Retrofitting has been defined as the "upgrade" of components or elements of a building with the scope of improving the building's environmental performance [272]. The term "Retrofit" is similar to other terms in literature such as refurbishment, rehabilitation, renovation, improvements, and repairs on existing buildings [273]. The U.S. Green Building Council (USGBC) had defined green retrofit as "any kind of upgrade at an existing building that is wholly or partially occupied to improve energy and environmental performance, reduce water use, and improve the comfort and quality of the space in terms of natural light, air quality, and noise - all done in a way that it is financially beneficial to the owner" [274]. In [275], retrofitting has been defined as "the refurbishment of buildings to improve their sustainability, in particular, their energy efficiency and CO_2 emissions". These definitions aim to reduce CO_2 emissions and achieve energy efficiency in existing buildings through the renovation of existing technical systems and the utilization of RES as a source of electric energy. Certainly, selecting the appropriate strategies for retrofitting depends mainly on the climatic zone of the building, the age of the building, the existing building energy loads, and others. To understand the best practice strategies for retrofitting, a critical review was done in [276], the review included 108 buildings in different climatic zones and reviewed different strategies to reduce space heating and cooling demand and/or increase thermal comfort. Figure 12 presents these best practices according to different climatic zones with the wall/roof insulation, improved glazing, improved frame, and upgraded HVAC system strategies being the most dominant ones [276].

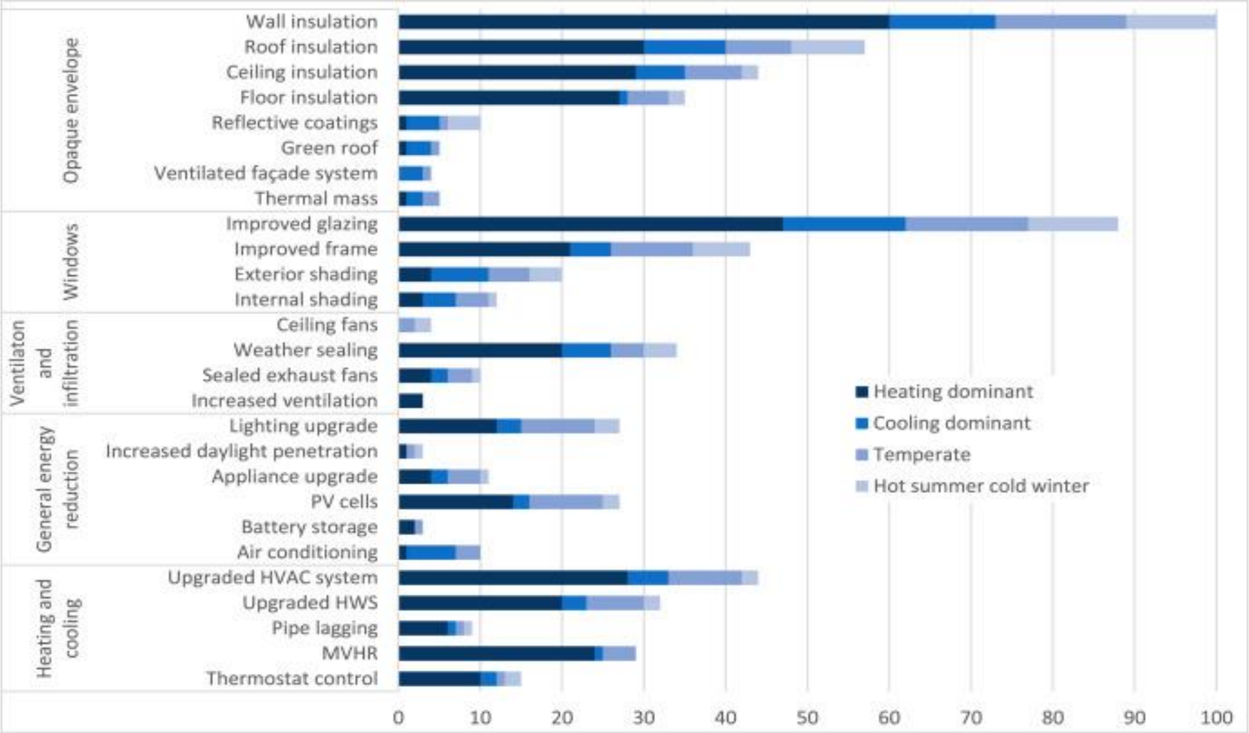

Figure 12. *Retrofit Measures According to Climatic Zones* [276]

Building renovation can involve the replacement or upgrade of single elements such as wall insulations, building façade refurbishment, or windows replacements or can be more holistic and perform whole building renovation which includes HVAC and lighting retrofit and focus on reducing the energy consumption and the integration of RES for on-site energy production. As a result, different degrees of energy retrofitting has been identified by several studies [277], [278]. It has been categorized into five basic categories: Minor, Moderate, Deep, Major, nZEB. Different levels of renovation can be distinguished based on the type of intervention and savings obtained. A summary of the definitions is presented in Table 5 which is concluded from the review done on defining these retrofitting strategies [277] and the BPIE [279]. Furthermore, the table provides some studies/reports that have defined or investigated these categories of retrofitting.

Table 5. *Classification of Retrofitting types and their Definitions*

Retrofitting Classification	Definition	Target	Citing Studies
Minor Retrofitting	Low-cost modifications are usually easy to implement and renovate limited space within an existing building. It results in final energy consumption reductions from 0 to 30% and is achieved through implementing from 1-3 improvement measures such as windows, a new boiler	30% final energy savings	[280], [277], [281]

	plant, or wall/roof insulation. The average total cost of the project can be 60 €/m^2 (The reference cost period is 2017).		
Moderate Retrofitting	Substantial renovation of existing building space which involves from 3-5 retrofit improvements resulting in energy reductions in the range 30%–60%, with an average total project cost of 140 €/m^2 (reference cost period is 2017).	30%–60% final energy savings	[281], [277], [282]
Deep Retrofitting	A very common type of retrofitting that has been implemented widely in the literature. Reduces the delivered and final energy consumption by 60%–90% compared with the pre-renovation level leading to very high energy performance. This type of renovation works on holistic deep thermal renovation. The average total project cost of 330 €/m^2 (the reference cost period is 2017).	60%-90% final energy savings	[277], [283], [281], [284], [285], [286], [287]
Major Retrofitting	Building renovation in which more than 25% of the surface of the building envelope and technical systems undergoes renovation and the total cost of renovation is higher than 25% of the value of the building, excluding the value of the land upon which the building is situated.	60%-90% final energy savings	[280], [288], [289]
nZEB Retrofitting	Building renovation by which the primary energy consumption of the building after renovation is reduced by 75% compared to the pre-renovation status. An additional primary energy minimum requirement of not more than 50-60kWh/m^2/y energy consumption for heating/cooling, domestic hot water, and the ventilation energy consumption of auxiliary building systems. The nearly zero or very low amount of energy required should be covered by RES produced on-site or nearby. An average total project cost of 580 €/m^2 is estimated (the reference cost period is 2017).	75% final energy savings	[277], [290], [291], [292], [293], [294], [295]

Retrofitting has developed through time to be more holistic and to cope with the changing policies and legislations and thus achieve higher energy savings. Advancement in ICTs provides the opportunity to harness the unrealized energy consumption reduction in existing buildings. Improvements in the technical and physical environment of information sensing, communication, and processing enable the monitoring of energy behavior of buildings in real-time, allowing building performance evaluation through energy modeling and simulation exploiting data from the field and real weather conditions [296]. Advancements in IoT-based sensors, meters, and control systems have become crucial for analyzing and optimizing the energy performance of buildings. The development of BEMS has made it easier to control the energy consumption and generation produced by RES onsite. The latest building Directive (EU) 2018/844 [32] has introduced SBs to allow buildings to manage their energy systems through BEMS, integrate users, and allow building flexibility with the grid. Thus, to cope with these regulations, it is crucial to introduce new terminology for building retrofitting that covers the aspects mentioned in nZEB retrofitting as well as the features employed in SBs. The various renovation concepts (minor, moderate, deep, major, nZEB etc.) should be replaced by a single concept that holistically cover all their aspects and include the features of SBs.

Broadening the scope of existing building retrofitting terminologies represents an intriguing aspect of the transformation toward smart cities. As discussed previously, the implementation of SCs requires a homogeneous action from buildings and grids. In this thesis, the concept of Smart Retrofitting is introduced as the future of building retrofitting concepts. During the last few years, the concept of transforming existing buildings into smarter buildings has been emerging. Yet, the concept of SR has not been accurately discussed in the literature and there is no agreed definition of it. SR has been defined previously by research done by the Amsterdam Institute for Advanced Metropolitan Solutions to identify the social and institutional conditions under which retrofitting of urban housing in Amsterdam and China may lead to energy efficiency [297]. They have defined Smart Retrofitting as "the restructuring of existing housing stock to increase buildings' resource efficiency and resource generation capacity involving a structural change in energy and informational flows, actor relations, governance arrangements, and consumer practices". This definition is brief and does not cover the aspects of "smartness" that were introduced in this thesis and in other research that defined smart features of a building. Moreover, it lacks defining the minimum requirements to achieve smart retrofitting. For instance, in Table 5, the different definitions of retrofitting types have focused on identifying the required minimum criterion to define a certain level of retrofitting. Thus, a more critical definition must be set taking into account the previous definitions of building retrofit and the objectives to be achieved in smart buildings.

Subsequently, based on the review done on Smart Buildings, we define smart retrofitting as "the process to transform an existing building into a SB, that is a nZEB with the capability to respond to the changing conditions of climate, and grid, communicate with the user and predict failures in the building operations through the utilization of ICT, RES, and BEMS". This definition requires the building to achieve the minimum requirement set by nZEBs and achieve the 'Smart Features' required in SBs. SR must allow monitoring and controlling of the renovated mechanical and electrical systems including the HVAC, lighting, domestic hot water, and other systems through the integration of sensors/actuators and BEMS. Furthermore, SR should allow managing the RES production and monitor its' interaction with the grid through the utilization of storage systems. To further clarify the definition of SR it is required to set minimum thresholds that define the success of SR process. Thus, the definition of SR is updated in this thesis after the application of the KPIs in the HEART project in Chapter 6.

2.3.2 Opportunities of Smart Retrofitting in the European Union Context

Smart retrofitting demonstrates a significant opportunity for the development of Smart Cities in the EU. SR is a new concept that is emerging in the EU, yet some projects have been funded by national funding programs such as Horizon 2020 or (7th Framework program) FP7 to renovate existing buildings using smart features and technologies that can interact with the grid [298]. To enforce the concept of SR in the European buildings, the EU Commission has proposed several projects to implement a new level of renovation which depends on deep renovation strategies to reach nZEBs using innovative smart technologies. However, these projects have not been categorized under the 'Smart Retrofitting' classification. In this section, a summary is provided of some representative EU renovation projects that have adopted smart technologies to accelerate the renovation process and reach the nZEB target (Table 6). The reviewed projects have been retrieved through the CORDIS database. In CORDIS database a huge number of projects can be found for projects that have undergone deep renovation or retrofitting to reach nZEB target using smart technologies, however, not all these projects focus on the four identified features of smart buildings i.e., achieving the nZEB target through active design strategies, providing monitoring and supervision, allowing flexibility, and allowing user interaction. Thus, to consider a retrofitting project under the category of Smart Retrofitting, the identified features must be all holistically present.

Table 6. *Smart Retrofitted Projects in the EU Retrieved Through CORDIS Database*

Smart Retrofit Project/ Project Status	Case Studies	Renovated Systems	Smartness features Integrated	Expected/ Achieved Result
Holistic Energy and Architectural Retrofit Toolkit (HEART project)/ Under progress [299]	- Italy demo-case: Large multifamily building with four floors. - France demo-case:	- Building Envelope (Walls and Windows) . - HVAC System (fan coils	- Adaptive Predictive Control System. - Cloud-based platform decision support system. - Replacement of Existing windows (glazing, insulation, frame). - BIPV system.	- Buildings will be in line with nZEB levels of energy consumption (<50 kWh/m2/y) – and should achieve energy savings of 90%.

	Large multifamily building with five floors.	and heat pump) - Domestic Hot Water System.	- Multifunctional thermal insulation system. - Thermal Energy Storage Tank. - Battery system. - Smart fan-coil. - Multi-input/ multi-output power controller. - Smart DHW system. - Hydronic modular DC Heat-pump.	- The results of this project can be applied to larger-scale buildings since it is estimated that there are around 1,005,000 similar buildings in Europe.
HEAT4COOL/ Under progress [300]	- Bulgaria demo case: - Two-floor multi-family 6 apartment dwelling. - Spain and Poland demo cases: - Commercial building with 4 floors. - Budapest demo-case: - District (Three commercial buildings).	- HVAC system. - Domestic Hot Water system.	- Solar Assisted Adsorption Heat Pump. - Advanced DC Heat Pump is driven by a PV system. - PV system. - Smart Control System (BEMS). - PCM storage. - Heat Recovery from Sewage water. - Demand response flexibility with the grid.	Provide, as a whole, at least 30% of energy consumption reduction in the retrofitting of residential buildings.
Energy Efficient Ventilated Façades for Optimal Adaptability and Heat Exchange (E2VENT)/ Completed [301]	- Spain demo-case: Educational building in Burgos. - Poland demo-case: Multi-story residential building.	- Building Envelope (Wall, Windows). - HVAC system.	- Smart Modular Heat Recovery Unit (SMHRU) for the air renewal. - Latent Heat Thermal Energy Storage (LHTES) is based on phase change materials. - Smart management that controls the system on a real-time basis. - Efficient anchoring system that limits thermal bridges.	- Primary energy savings of 17% for Spanish demo case and 36% for Poland demo case. - 40% of CO_2 emissions reductions. - Windows U-Value reduction.
RETROKIT (RetroKit - Toolboxes for	Three multi-family residential pilot	- Building envelope (façade,	- Integration of multifunctional façade and roof elements including:	- 50% reduction in thermal bridges.

systemic retrofitting)/ Completed [302]	buildings in Spain, Germany, and Sweden.	windows, and roof). - HVAC system.	• Ventilation air ducts. • Heating pipes. • Domestic hot and cold water. • Chilled water pipes. • Electrical and ICT cables. • Windows and wall insulation. - Ventilation heat recovery for HVAC. - Integration of PV panels and PV/T collectors into thermal insulation for façade and roofing solutions.	- Window solar thermal collector for hot water yields 300 kWh/m2 annually in Sweden. - Yearly thermal load reduction. - External wall insulation systems and paintings (ETICS) can reduce heating/cooling energy up to 50% depending on climatic conditions. - Façade/roof systems integrated with solar thermal, and PV gives 100 kWh/m^2y of renewable electricity.
Industrialized Energy Efficient Retrofitting of Resident Buildings in Cold Climates (E2REBUILD)/ Completed [303]	- Multi-story residential buildings in Germany, Sweden, Finland, Netherlands, France. - 112 identical, single-family terrace houses in Southeast London (United Kingdom).	- Building envelope (façade, windows, and roof). - HVAC system. - Domestic Hot Water system.	- Insulation of the whole building envelope. - Reduction of thermal bridges - Highly efficient centralized heating system. - Heat recovery in the ventilation system. - PV and PVT. - In some projects, the envelope has been retrofitted using a prefabricated envelope system based on TES Energy Facade. - In some projects, the existing balconies were converted into winter gardens.	- The Payback of the projects was around 28- 30 years. - CO_2 reduction ranged between 127 tCO_2/y- 265 tCO_2/y. - Energy consumption reduction ranged between 50-89%.
Affordable and Adaptable Public Buildings	- An office building within the educational	- Building envelope (façade,	- Internal super-insulated (VIP–Vacuum Insulated Panels) façade.	- Implementation of VIP comprises a reduction of 32% of the Heat Loss

through Energy Efficient Retrofitting A2PBEER/ Completed [304]	complex in Bilbao, Spain. - A cafeteria building in an educational complex in Ankara, Turkey. - A technological museum in Malmö, Sweden.	windows, and roof). - HVAC System. - Domestic Hot Water System. - Lighting system.	- Smart windows that can switch thermal properties in response to changing outdoor conditions. - Smart lighting components integrate low-consuming LED technology and natural lighting. - “Smart Dual Thermal Substation”, a new approach to district heating based on smart grid functionality.	Coefficient of the building envelope. - 45% energy consumption decrease. - The payback period is around 13 years depending on the solution implemented, climate, and previous conditions of the buildings.
HERB (Holistic energy-efficient retrofitting of residential buildings)/ Completed [305]	- Thirteen domestic buildings of different ages in seven different countries across Europe.	- Building envelope (façade, windows, and roof). - HVAC System. - Domestic Hot Water System. - Lighting system.	- Solid wall insulation with super insulations (including vacuum-insulated panels). - Transparent multi-functional façade technology. - Smart control systems. - Innovative heat pump systems with integrated thermal storage. - Novel photovoltaic-solar thermal (PVT) systems. - Integrated heat recovery panels with energy-efficient HVAC systems. - Energy-efficient light pipe technology.	- The annual energy consumption of buildings was around 50 kWh/m^2/year. - The payback period ranged between 12 and 27 years depending on the case study. - 80% reduction of the annual use of primary energy. - 60% reduction of the annual emission of CO_2.

The previous analysis has shown the tendency in the EU projects to adopt deep renovation strategies and implement smart technologies and ICTs. These projects are growing wider to accelerate the roll-out of smart building innovation, in line with the EPBD's new directive and the energy savings targets of 2030 and 2050. Hence, introducing the definition of Smart Retrofitting is very crucial in classifying these projects to be able to identify their objectives, targets, and main technologies.

2.3.3 Key Challenges of Smart Retrofitting

Despite the advantages of SBs, old buildings are challenging scenarios for implementing smart technologies. The previous review has shown the fundamental requirements, features, and technologies in a SB. The integration of smart technologies in new construction is always easier than in retrofit cases since new buildings provide a greenfield and can adapt to the integrated systems. On the other hand, in SR applications, it is important to address the key challenges that should be considered when integrating smart technologies. As previously shown, the process of SB requires achieving a nZEB first, then ensuring its' response to the changing conditions of climate, and grid, users' preferences, and predicting failures through the utilization of ICTs. Achieving nZEB is a target for new buildings as well as retrofit solutions, however, it should be noted that for retrofitting cases significant energy efficiency is not achieved only by envelope retrofitting (such as adding thermal insulation and windows replacement), but rather through the integration of these with active and renewable energy solutions (such as HVAC, efficient lighting, and control systems). The main challenges of SR implementation can be classified into three main categories:

- Technical integration challenges.
- Lack of policy challenges.
- Social challenges.

- **Technical integration challenges:**

In SR scenario, the existing mechanical systems in buildings should be optimized to integrate properly with the new energy-efficient interventions. Ensuring proper integration of energy-efficient HVAC is very critical since most building loads are caused by heating and cooling demand. The existing heat pump, fan coil, radiator, and compressor must be evaluated and optimized properly to integrate the new systems while keeping the important parts of the systems that can be modified only. For instance, the radiators can be replaced while using the existing hydronic distribution system. Similarly, retrofitting the DHW system can be replaced, yet still, use the existing hydronic distribution system if it was in a good condition. In smart retrofitting, upgrading the existing storage system or integrating a new storage system is very crucial. Thus, optimizing the existent TES is crucial to achieving high thermal energy density at lower temperature spans. One of the common elements to be retrofitted in buildings is the façade insulation. Therefore, the performance of existing should be enhanced, while preserving some original elements. Optimization of existing building components is crucial for achieving the best retrofitting strategies while preserving the existing structure. Moreover, in SR the integration of RES is very crucial and must be accompanied by reliable forecasting methods to estimate production and exchange profiles of non-programmable sources and facilitate the connection with the SG, SM, and storage system through BEMS. The integration of BEMS in SR is very difficult and has many challenges and barriers. It is important to install new technologies that must communicate with the existing buildings without installing new wires. Therefore, the most optimal solution would be installing advanced wireless control systems, such as the ANNs and RNNs that are efficient since they do not require removing existing structures to install wiring systems.

- **Lack of policies challenges:**

For retrofitting to be effective, supporting measures and policies are required to impose guidance, main requirements, and costs, and identify thresholds for achieving the best retrofitting outcome. Since smart retrofitting is a new concept, currently there is a lack of existing policies to guide and enforce its' applications. For instance, the EPBD [2018/844] [41], had imposed a long-term renovation strategy that indicated the cost-effective approaches for renovation relevant to the building type and climatic zone, supporting policies and actions to stimulate cost-effective deep renovation of buildings to achieve nZEBs. Annex 67 [107] was also developed to demonstrate how energy flexibility in buildings can provide generating capacity for energy grids, and to identify critical aspects and possible solutions to manage such flexibility. Moreover, to define the terminology and characterization of energy flexibility in buildings and the stakeholder's perspective on energy flexible buildings. Annex 67 has considered flexibility application on new buildings; thus, further annexes can be developed to demonstrate flexibility in retrofit solutions.

Similar policies should be adopted for SR to define targets/ milestones, quantify investment and funding sources, impose quality standards/certification systems for installers and products such as Smart meters minimum requirements, connection to Smart Grid policies, and BEMS integration with existing building technologies. Moreover, to guide the use of control systems in buildings with supporting Annex reports to specify the different control systems to be adopted with the technical installations specifications.

- **Social Challenges:**

The concept of SBs and SR supports the engagement of users through technological interfaces that takes into account user preferences, record their behavior and respond to their actions. This means that users should also be informed about using such technologies in their homes and adapt to them. Smart Retrofitting can be challenging when it comes to users' acceptance of this shift. Not all citizens are well informed about the availability of energy efficiency solutions and incentive programs that can be available in their territory. Building occupants are very important stakeholders in the smart retrofitting process. Therefore, awareness should be imposed on users to clarify the idea and benefit of smart retrofitting and to educate occupants on the usage of these technological interfaces that engages them with the building technologies. These incentives can be part of the policies that will support SR and clarify the qualitative and quantitative benefits for building owners and occupants.

2.4 State-Of-The-Art: Conclusion

In this state-of-the-art chapter, a theoretical framework of a Smart Building, its' basic features, functions, technologies, and KPIs for measuring its' performance has been outlined. The move towards smart buildings and smart cities in the EU was triggered by the extensive use of RES, the development of ICT, and the need to allow responsive cities and buildings to users, fluctuating climatic conditions, and the electrical grid. Due to the absence of a common definition of the Smart Buildings concept, a deep literature review has been done in this chapter to discuss the concept of smartness in the built environment. To understand SBs and their basic features and technologies it was important to review the definitions of smart cities, smart grids, and smart meters. In this thesis, we have defined Smart Buildings as "an nZEB that can manage the amount of RES in the building and the SG through advanced control systems, SM, energy storage, and demand-side flexibility. Also, it reacts to users' and occupants' needs and can diagnose faults in building operations". A schematic representation was provided to represent the basic features, functions, and technologies that should be present in a SB. The review done showed that the minimum features claiming smartness in buildings lie in the capability of response to external and internal conditions. External factors are mainly represented by variable weather and grid conditions, while internal ones include user interaction and the ability for monitoring/supervision of building systems.

Quantifying building energy performance through the development and use of KPIs is an essential step in achieving SB goals in both new and existing buildings. KPIs are quantifiable and measurable metrics that are essential for addressing the success of a project. Thus, a review was done on KPIs related to smartness features identified previously. Most of the selected indicators are quantitative and measure energy and power rate, and they focus on assessing the energy performance, grid performance, and technological systems performance in the building. In Chapter 3 a further analysis is done on the KPIs to make a refined list and choose the most representative ones.

The third part of the literature review scrutinized the evolution of building retrofit types including minor, moderate, deep, major, and nZEB retrofit. These different retrofit concepts can lead to establishing the concept of SR to cope with technological advancement and allow the building to be responsive to internal and external building conditions. According to the review done on SR types and SBs basic features and components, SR has been defined as "the process to transform an existing building into a SB, that is a nZEB with the capability to respond to the changing conditions of climate, and grid, communicate with the user and predict failures in the building operations through the utilization of ICT, RES, and BEMS”. This definition is updated in the thesis after the application of KPIs on the HEART project and setting the threshold for each KPI to define the quantified minimum requirement to achieve SR. The review had also given a recapitulation of the opportunity of SR in the EU context by investigating some existing SR projects done in the EU. Despite the advantages of SBs and SR, old buildings are challenging scenarios for implementing smart technologies. Thus, the technical, social, and regulatory challenges have been discussed while suggesting some recommendations to overcome them in the future.

CHAPTER

3

3. METHODS TO CHARACTERIZE AND QUANTIFY SMART RETROFITTING IN BUILDINGS

This chapter focuses on the methodologies to characterize and quantify smart retrofitting in buildings. The methodology is composed of five phases that were previously introduced in Chapter 1 and are detailed in this chapter, as described below.

Phase 1: Systematic Literature Review that was discussed in Chapter 2 and provides a review on smart buildings and retrofitting to clarify smart features, technologies, and definitions. In addition to reviewing the existing regulations, legislations, and plans made in this field, then reviews KPIs related to smartness features. Moreover, a review is done on the concept of smart retrofitted buildings in the European building context.

Phase 2: Deep KPI Analysis is presented in Chapter 3 in which deep KPI analysis is done by setting objectives, questions, and criteria to limit the number of KPIs to being quantitative and focus on the energy and power rate of the grid. An analysis of the KPIs is presented, where the KPIs with similar targets/functions are grouped and categorized into main themes. Then the most representative KPIs are selected as Smart Key Performance Indicators to measure smart retrofitting in buildings.

Phase 3: KPI Threshold Setting is interpreted in Chapter 4. A KPI has limited value if it is not compared to a reference or a baseline. Thus, it is important to set a threshold to define a range of acceptable values for each indicator since it sets the quantified objectives of each KPI. In this phase, a review is done on existing thresholds or acceptable range of values based on different legislations, codes, and research articles to identify previously defined thresholds then a Logical Evaluation of KPIs is performed.

Phase 4: KPI Testing is discussed also in Chapter 4 in which a Spreadsheet is developed in Excel to apply, test, and measure the performance of KPIs on a real case through testing them on the HEART project case study to investigate their performance in a smart retrofitted project.

Phase 5: KPI Normalization is shown in Chapter 5 where KPIs are normalized on a wider scale to allow comparison between indicators in different buildings.

The first part of the chapter explains each phase of the methodology. Then, an overview is presented on the European smart retrofitted projects to illustrate the technologies used in their projects and be able to select the indicators that can measure their performance. Consequently, the selection process of the KPIs is detailed. A critical classification of the indicators to select the most representative KPIs is carried out. The last part of this chapter deals with the main research challenges that emerged during the methodology application and how it was solved to adapt to the limitations.

3.1 General Methodology

As described in Section 1.4 previously, to address the research questions, a methodology has been developed that is based on a critical literature review and analysis to apply the results to the HEART project. The defined methodology foresees the implementation of a spreadsheet of selected KPIs on a group of buildings in a Smart Retrofit European project. The adopted methodology is further detailed in Figure 13 and shows the basic five phases and their steps which are reflected in the following sections.

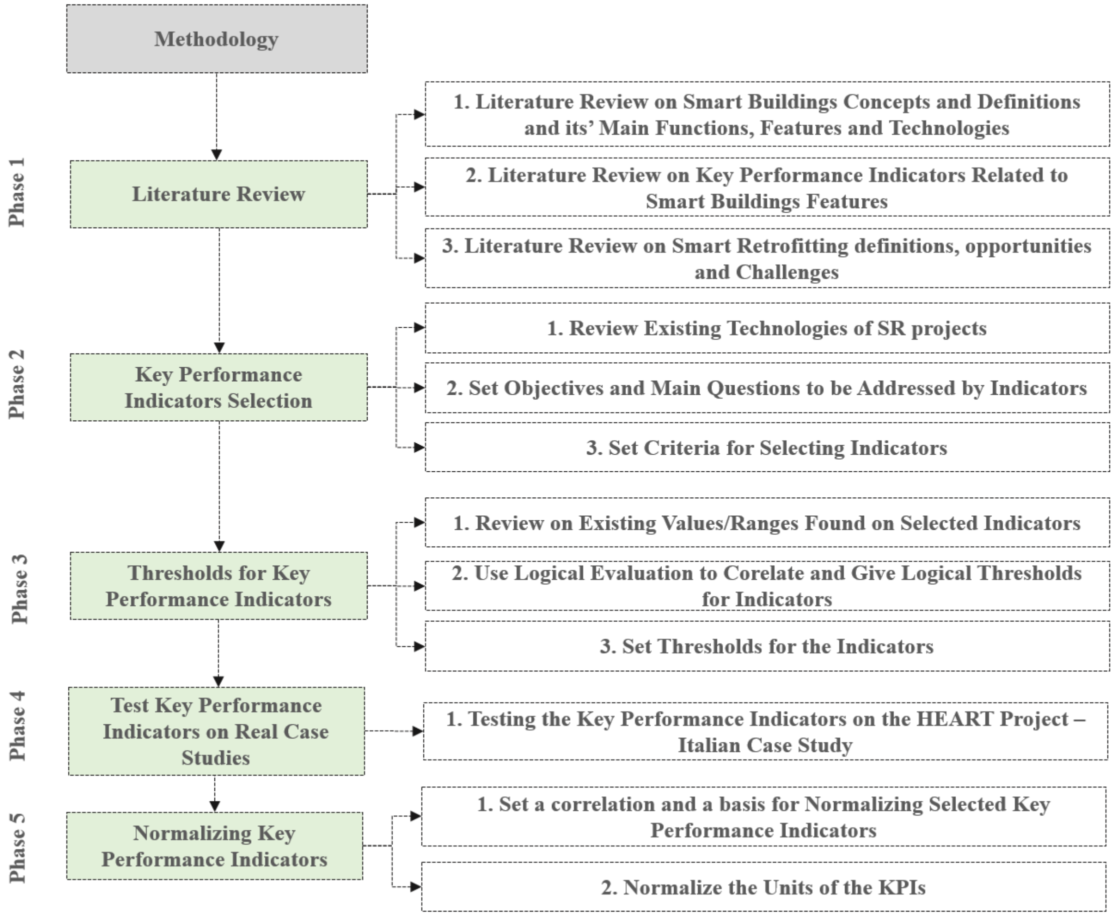

Figure 13. *Thesis Research Methodology*

3.1.1 Systematic Literature Review

As mentioned previously, the adopted methodology for the literature reviewed in this thesis is the systematic literature review. Phase 1 of the methodology in the thesis is the systematic literature review which was presented in Chapter 2. A systematic review aims to identify all evidence that fits the pre-specified criteria to answer research questions and hypotheses identifying knowledge gaps within the literature. A systematic literature review was done to investigate the concept of smartness in the built environment, provide a review of the main definitions found in the literature on smart buildings in a smart environment and summarize the main definitions to be adopted in this thesis. A schematic illustration of the basic functions, features, and technologies of SBs was presented. It is the main data collection method used in the thesis. For instance, Chapter 2 which details the SBs and SR was based on a comprehensive critical literature review using several databases.

This step was repeated several times in this thesis for addressing Smart Buildings definitions, Smart Retrofitting, and for finding Key Performance Indicators that address the features of SBs. Moreover, in Chapters 2 and 3 of this thesis, another level of a literature review is done to select the most appropriate KPI for measuring SR in buildings. This was done by searching several databases, EU Annexes, and Directives to identify previously studied KPIs and to identify the most suitable selection and categorization process of the KPIs. The review also gave a synopsis of the fundamental EU legislation, policies, and directives that led to the development of the smart buildings concept and its’ adoption in the EU. The last part of the literature review involved in this thesis is dedicated to setting suitable thresholds for the KPIs based on previous research, directives, and standards and is presented in Chapter 4.

3.1.2 KPI Selection Methodology

The main scope of this thesis is to identify the relevant KPIs for measuring the performance of smart retrofit buildings. Consequently, the first step was done in Chapter 2 reviewing existing indicators that are related to the smart building basic features; nZEB target, flexibility, real-time interaction, and real-time monitoring. The review yielded 37 indicators that were related to energy performance, grid performance, and technological performance. KPIs should express as precisely as possible to what extent an aim, a goal or a standard has been reached or even surpassed. The selection of representative KPIs is very crucial for measuring the performance of smart building/retrofitting. A clear way for selecting representative KPIs is a gap to address. For instance, Janjua et al. [306] 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 [307] have used categorization of indicators into groups related to the identified targets for the selection process. In other studies [223], [308], [309], literature reviews, interviews with experts and academic researchers, and questionnaire-based surveys were common methods used for KPI selection. In this thesis, a selection method is proposed that is based on five basic steps (Figure 14). After reviewing several indicators from the literature, these steps should be followed. First, the objectives of the KPIs are defined. The objectives of these KPIs are compared with the objectives that are defined by the research to be able to eliminate the ones that do not serve the basic purposes and aims of the research. Then, questions are raised to help reach the identified objectives and narrow down the KPIs. Next, KPIs with similar targets and objectives can be grouped to allow further sorting. Then the input parameters required to assess the defined objectives and targets are defined. For instance, through determining if PV production is an important parameter for the objective, energy consumption or building demand, etc. to determine which KPIs have these input parameters based on their mathematical equations. Finally, an impact criterion can be identified to help correlate these KPIs with other known indicators and allow further development and analysis for the KPIs in case of weighing and normalization process. With this methodology, KPIs can be logically and carefully selected. Thus, the basic features and technologies required to achieve these features are presented in Figure 15. Moreover, questions are raised to identify the objectives of the indicators to facilitate the selection of representative indicators.

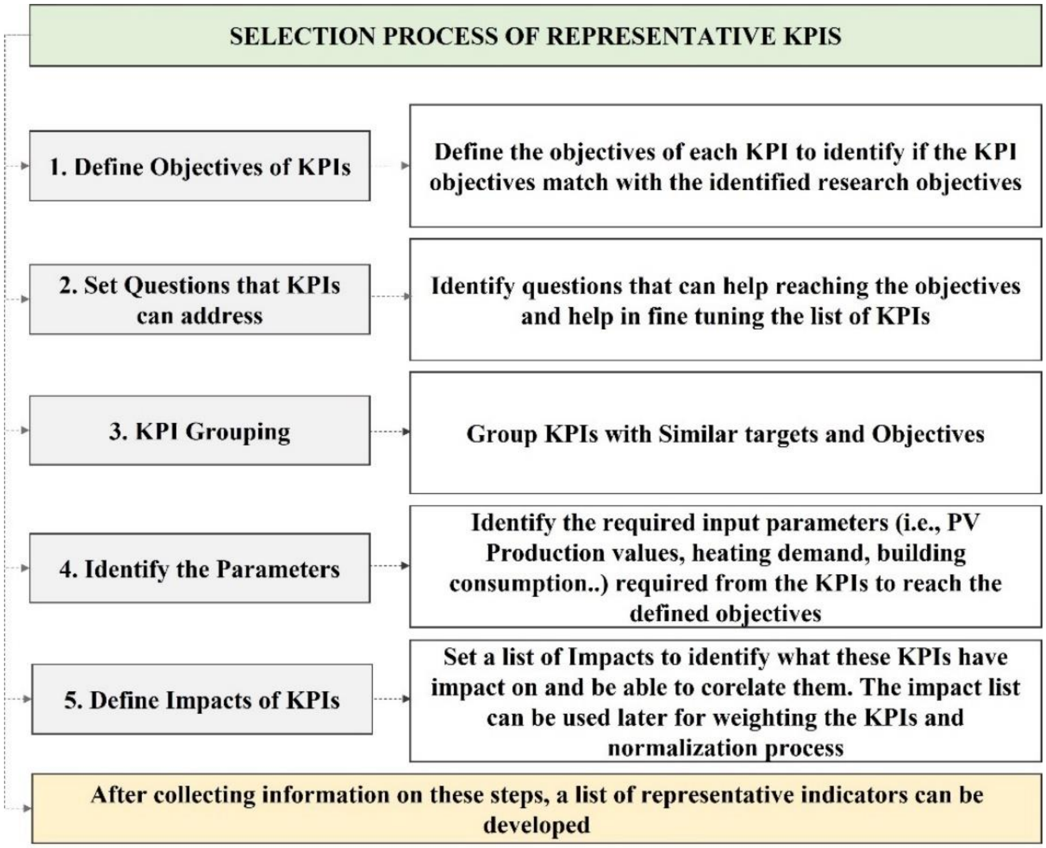

Figure 14. *KPI Selection Process*

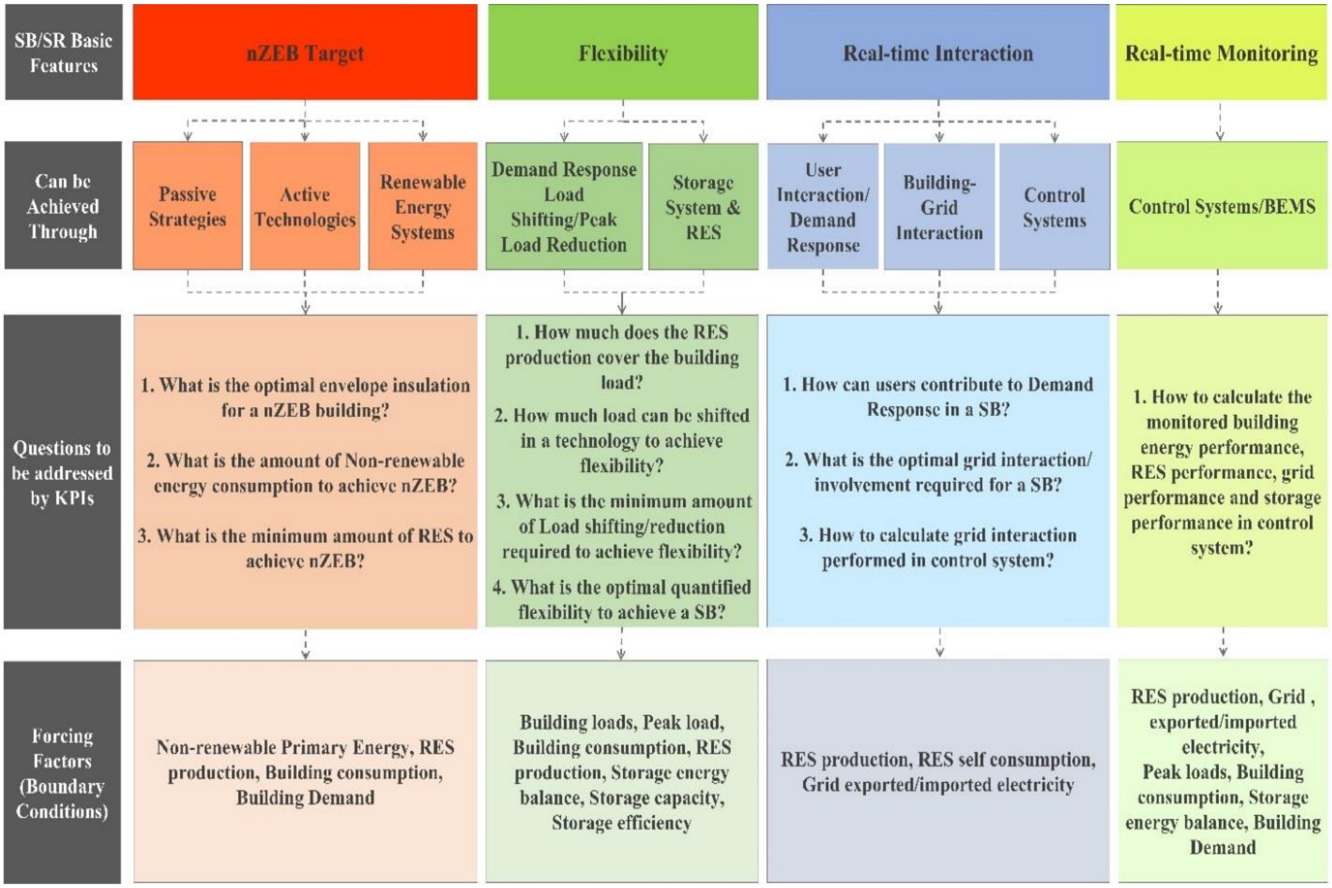

Figure 15. *Questions and Objectives of KPIs for SB/SR*

In the nZEB target group, some of the questions can be answered by basic indicators such as the U-value of the building envelope and the thermal transmittance, etc., however, these indicators do not indicate the smartness of a building, thus, are considered in the list of Smartness Indicators. Several KPIs have been developed in reports and projects, however, they have not been tested in research, while others have been tested and reported in more than one study. Some of the reviewed KPIs share similar targets/parameters by which they can be grouped and compared to each other. It should be noted that it is challenging to select a representative indicator from each group; however, the designer should decide and select the suitable indicator based on the available data, and boundary conditions, such as measurement scale, sampling, unit, and time of day, etc.

Thus, the indicators reviewed previously in section 2.2.2 were fine-tuned to include only the ones related to the following criteria:

1. Energy Performance: KPI is related to energy consumption or energy supply.
2. Grid Performance: KPI measures benefits for the grid.
3. Technological performance: KPI evaluates the technological system integrated into SBs including ICT integration, RES, EV, and/or storage system.

Thus, the indicators not related to these three criteria, energy performance, grid performance, and technological performance were omitted. Then, to group the indicators, a set of criteria was developed reflecting on the CIVITAS framework [310] using the following requirements (Figure 16):

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

The selection process of the indicators using the explained methodology is presented in Section 3.3.

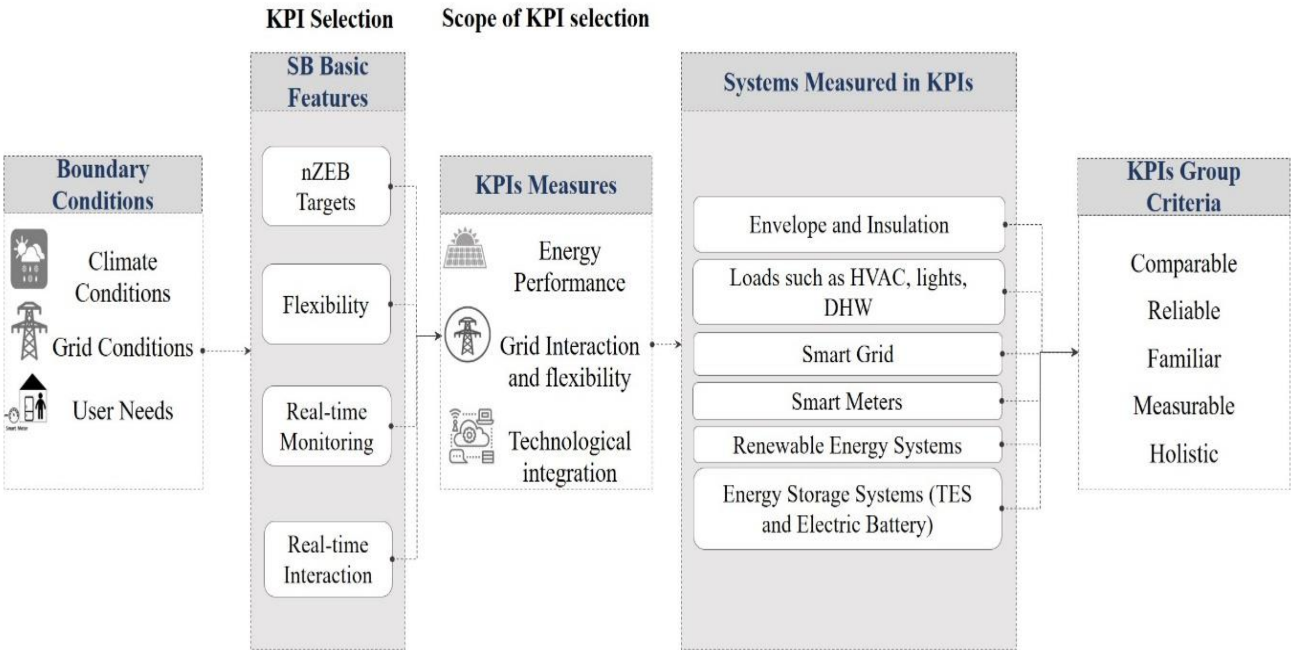

Figure 16. *Smart Retrofitting Key Performance Indicators Selection Framework*

3.1.3 Setting Thresholds for KPIs Methodology

Defining thresholds for KPIs is one of the basic targets of this thesis and formulates the significance of this research. A KPI has limited value if it is not compared to a reference or a baseline. It is important to set a threshold defining the range of acceptable values for each indicator since it sets the quantified objectives of the KPI. The evaluation of the presented technology/system should be done by comparing the KPI final value with a threshold that defines success/failure. Thresholds are frequently based on targets. Thresholds define acceptable high and low values for the data collected. KPI thresholds can be sometimes general, for instance, some indicators have national threshold levels in EU countries such as the CO_2 emissions reduction target and the nZEB energy reduction target. While other indicators depend on certain influencing parameters/factors that can change from one project or region to another such as climatic condition, building context, building use, area, and other factors.

Setting targets and thresholds is very crucial for understanding if smart and sustainability goals are met and to determine the level of success of new and retrofitted buildings. In the EPBD, numeric thresholds or ranges are not clearly defined to identify the nearly and net ZEBs characteristics, this had caused several interpretations both for the definition and limits across the EU Countries. The different limitations are affected by specific climate conditions, local targets, or building traditions, that allow different national targets. This makes it difficult to specify the thresholds and targets for smart buildings and smart retrofits. This gap should be addressed to allow a robust design for Smart buildings and Retrofitting.

Different methods have been discussed in the literature to set thresholds for indicators. In [219], three scenarios were used for identifying thresholds, first by setting a baseline which is a measurement recorded at the beginning of the project, then assuming that the threshold is the baseline, thus, the actual result after implementing the technology solution is compared to the baseline to see the percent of improvement. The second scenario was the Business as Usual (BaU) solution which is more complicated and requires monitoring the change in the value of the KPI throughout the project. Thus, it depends on the probability of the change in the KPI value. The third scenario gives more flexibility to the evaluator in setting the threshold by building on values recorded in the past, consequently through literature surveys, and then determining the most influencing aspects in the performance of the tested technology that affects the threshold. While in [311] two different approaches were introduced for identifying the threshold of control strategies that aim at reducing the energy costs for the end-users; the first approach analyzed the data prices for two entire years (2012 and 2013) and fixed thresholds based on this distribution. The second approach depends on prediction data rather than on past data in which it compared the current electricity price with the forecasted price for the next 12 hours. In another study [312], the used approach was based on recorded past data in which the thresholds were calculated using the previous price distribution of the two weeks before the calculation time.

Despite the importance of setting defined thresholds for KPIs, a clear methodology is still not adequately discussed in the literature. Hence, a method of identifying KPIs' thresholds is proposed in this thesis. More in detail, the thresholds will be set according to previous legislation and EU building standards, articles, and case studies that have tested the KPIs. This method is illustrated in Figure 17. First, a review is done of 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 (if available). This helped in identifying the range of possible values of the KPI. Second, a deeper investigation is done on the case studies in the literature that have tested these KPIs. In this phase, a Logical Evaluation Methodology (LEM) is followed to find the correlations between different indicators, and their influencing parameters and be able to set a specified threshold or range for each. The LEM links the objectives with the components and their respective inputs, and activities, with the achieved outputs [61]. Logical Evaluation is typically used to summarize what the project should do and shows the causal relationship of the target hierarchy. This method is also identified as the Logical Framework Approach (LFA) which is a systematic approach to design, execute and assess projects which encourages users to consider the relationships between available resources, planned activities, and desired changes or results [62]. This method has been applied by Attia [313] in his book on Net Zero Energy Buildings (NZEB) in which thresholds were discussed for the basic performance metrics in NZEBs including Carbon emissions, minimum energy efficiency, heating/cooling balance, indoor environmental, minimum RES integration, etc. The threshold of these metrics has been indicated using the evaluation method which pointed out the influencing parameters of each indicator to build on literature and identify the range/value of the indicator. In the present work, the Logical Evaluation Methodology has been used by analyzing case studies from literature according to the technological integration and features that influence the results of the KPIs implemented in a building. This was done by identifying several case studies based on literature that have tested the indicator, including both cases with minimum or basic technological endowment and cases with more advanced smart technologies.

Figure 17. *KPI Threshold Identification Methodology*

It is claimed in [4] that when fixing a threshold, it is preferred to leave some freedom for placing this threshold within some boundaries. For instance, for specifying the primary energy indicator, the EU Member States can define their national requirement for the energy demand in buildings within a boundary, considering the national and climatic conditions for each region. This can allow a specific trade-off between the most convenient and affordable technologies for reducing energy demand and increasing renewable energy share. In this research, two motivated thresholds for each KPI are thus set, based on different elaborations (Figure 18).

Smart Buildings must include a basic set of "smart technologies" which are technologies optimized for the building requirements in managing building systems [314]. It has been claimed that smart technologies should mainly include PVs, storage systems, IoT, sensors, smart meters, remote user interactive systems, control systems, and advanced HVAC systems [314], [315], [316]. Appropriate integration of smart technologies results in potential energy savings, reduced life cycle costs, ease of decision-making for maintenance management, improved air quality, and improved identification of problem areas within the system, thus improving maintenance decisions as well as overall building performance improvement [315]. Hence, for buildings integrating the basic set of "Smart technologies" without the best optimization of the systems in terms of sizing and performance, the achieved value represents the Minimum (Min) Acceptable Threshold. For any achieved value below the Min threshold, the building cannot be considered a smart building. While for buildings that integrate a full set of smart technological solutions including the "Smart technologies" in addition to smart HVAC and lighting systems, DHW system, building insulation technologies together with the optimal system optimization (e.g., optimization of PV and storage based on the building demand), the maximum reasonable achievable value with the best available technologies defines the Top Performing Threshold (Top). Thus, any value above the Top threshold means that a smart building reaches an outstanding performance. The values between the two proposed thresholds represent smart buildings/retrofits with satisfactory smart performance. Furthermore, the thresholds are defined over integer numbers with 10% steps. Compared to the value found in the literature, the threshold is defined by taking the mean value of the analyzed case studies representing (Min) and (Top) performing cases, and then the value is rounded down. In some cases, due to the lack of defined values in literature, the thresholds are proposed in this thesis and are subsequently validated in the HEART project case study.

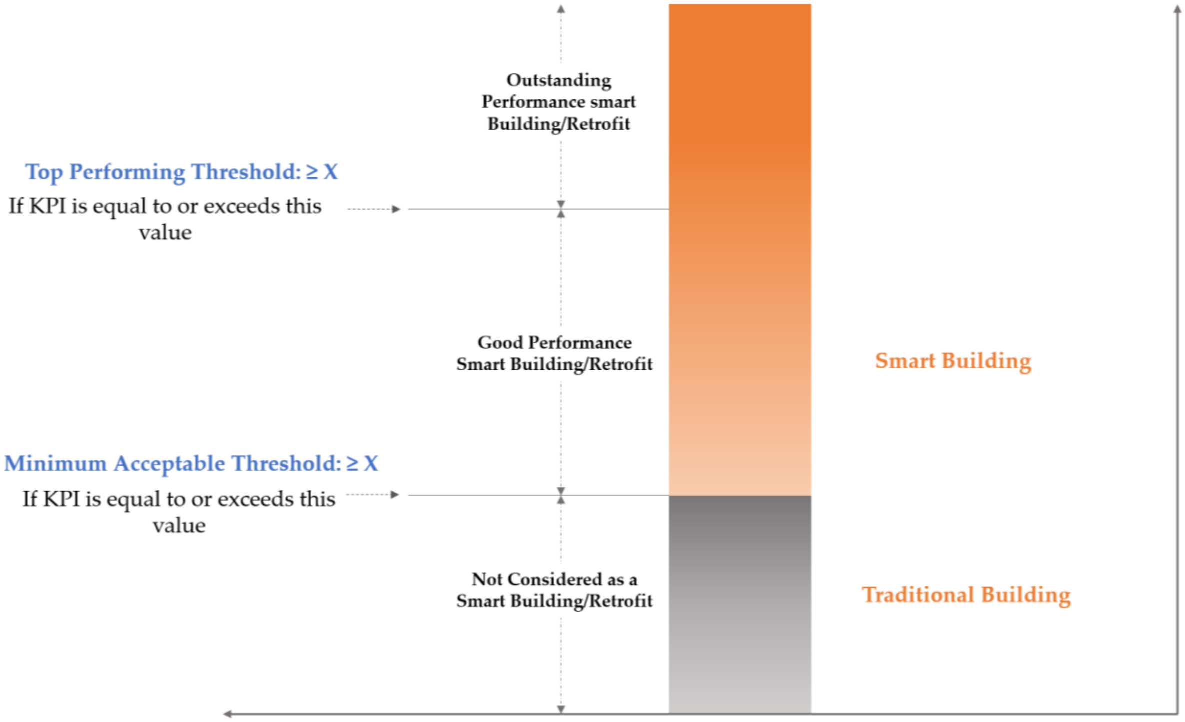

Figure 18. *KPIs Threshold Boundary Logic*

Furthermore, in this section, another systematic literature review was carried out in order to select the appropriate references for setting the thresholds of the indicators. Different articles, building legislations, and reports were retrieved from “Google Scholar”, “Science Direct”, “Eurostat” and “Research Gate”. The search done was specifically on case studies that have reported the performance of the selected KPIs and the building legislations that have identified thresholds for the indicators. Therefore, the first review has revealed a wide range of references that have discussed the indicators, however, the ones that did not report achieved results and did not test the indicators were eliminated.

3.1.4 KPI Normalization Method

Indicators are expressed using various units, ranges, or scales. To form a uniform system, they shall be put on a common basis which is served by a clear normalization process. The normalization method should put into consideration the data properties and the objectives of the indicator. A review is done on different normalization techniques in Chapter 5. The normalization method selected in this thesis is the “Min-Max” method [64]. Min-max normalization is one of the most common ways to normalize data. It performs a linear transformation on the original data and standardizes the indicators to achieve an identical range, for example between [0, 1], by subtracting the minimum value and dividing by the range of the extreme values [317]. Min-Max normalization conserves all relations of data as it uses the minimum and maximum of the original data. In this thesis, the normalization should put common grounds for all indicators to allow scaling up their application on a wider number of buildings. It is done by developing an Index for each selected Indicator to have a common unit for all indicators. This allows comparison of the identified indexes and assess the success of the retrofitted building. Hence, Figure 19 shows the KPI analysis steps in this thesis based on the description above.

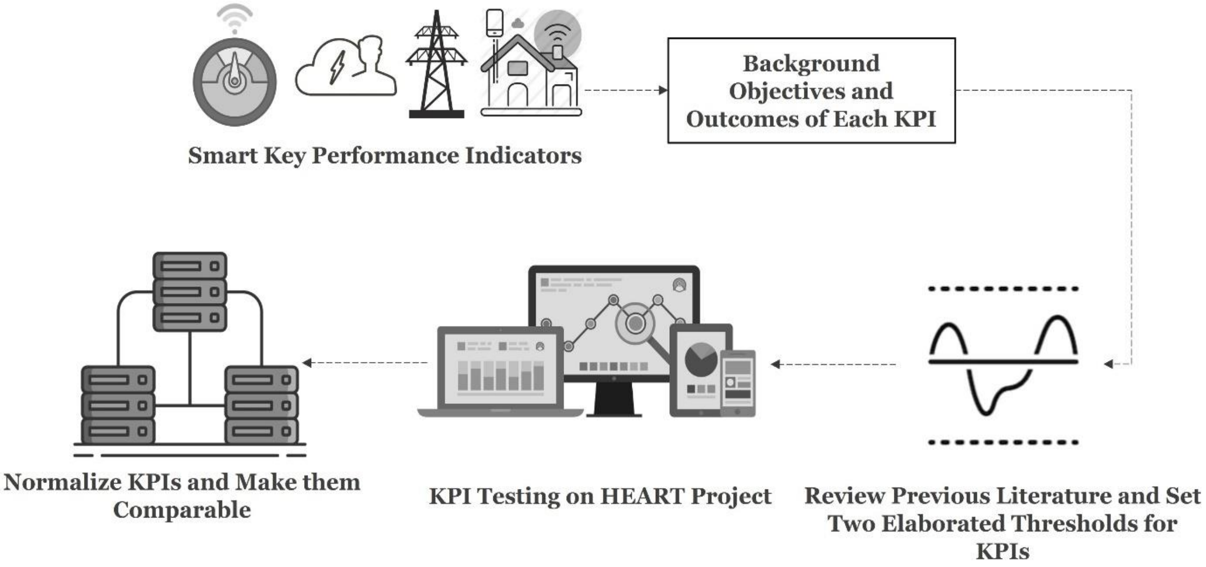

Figure 19. KPI Analysis in the Research

3.2 European Case Studies Demonstrating Smart Retrofitting

In the EU, several smart retrofitting projects have been developed in the last decade. Thus, it is important to explore them and investigate their technologies to be able to select KPIs that can be applied to different types of smart retrofit buildings. An analysis is done through the CORDIS database, to select EU projects done to retrofit buildings using smart technologies. The selected projects were part of the Horizon 2020 program which spans from 2014 to 2020 and the FP7 funding program which ran from 2007 to 2013. Many of these projects are completed, however, some of them are still running until now. The Horizon 2020 and FP7 programs were launched to accelerate building retrofitting to achieve nZEBs and, to support the movement towards smart buildings and smart cities [80], [298]. Several projects and case studies were developed to investigate smart retrofitting in buildings.

Twenty projects representing smart retrofitting case studies done in the European climatic context were collected through the CORDIS database (Table 7) [82].

Table 7. European Smart Retrofitted Buildings Case Studies

Code	Project Name	Project Scale	Climatic Context	Project Status
N1	HEART PROJECT (Holistic Energy and Architectural Retrofit Toolkit) [318]	Building level	European moderate climate	Ongoing
N2	GREENHP (Next-generation heat pump for retrofitting buildings) [319]	Building level	Several European zones with Average, cold, and warm climate	Completed
N3	A2PBEER (Affordable and Adaptable Public Buildings through Energy Efficient Retrofitting) [304]	Building /District level	Different European climatic zones including temperate, Mediterranean, and oceanic climates	Completed
N4	THE HEAT4COOL PROJECT [300]	Building /District level	Several European climates including warm and temperate, Subtropical Mediterranean, cold and temperate, and humid subtropical	Ongoing
N5	Industrialized energy-efficient retrofitting of residential buildings in cold climates (E2REBUILD) [303]	Building level	Several European Cold climate Zones	Completed
N6	Holistic energy-efficient retrofitting of residential buildings (HERB) [305]	Building level	Different European climates including continental, oceanic, and Mediterranean climates	Completed
N7	RetroKit - Toolboxes for systemic retrofitting [302]	Building level	Different European climates including temperate-oceanic, Mediterranean, and subarctic cold	Completed
N8	Envelope Approach to improve Sustainability and Energy Efficiency in Existing multi-story multi-owner residential buildings (EASEE) [320]	Building level	Different European climatic zones including continental, oceanic, and Mediterranean climates	Completed
N9	Energy Efficient Ventilated Façades for Optimal Adaptability and Heat Exchange enabling low energy architectural concepts for the refurbishment of existing buildings (E2VENT) [301]	Building level	Different European climatic zones including warm and temperate and Mediterranean climates	Completed
N10	Holistic Approach and Platform for the deep renovation of the med residential built Environment (HAPPEN) [321]	Building /District level	European Mediterranean climates	Ongoing

N11	Standardized approaches and products for the systemic retrofit of residential Buildings, focusing on Heating and cooling consumptions attenuation (BuildHEAT) [322]	Building level	European Mediterranean climate, cool semi-arid climate, and temperate Oceanic climate	Completed
N12	Residential Retrofit assessment platform and demonstrations for near-zero energy and CO_2 emissions with optimum cost, health, comfort, and environmental quality (ReCO2ST) [323]	Building level	Several European climates including temperate, Mediterranean, and Oceanic	Ongoing
N13	Development and advanced prefabrication of innovative, multifunctional building envelope elements for Modular Retrofitting and Connections (MORE-CONNECT) [324]	Building level	Several European climates including humid continental and warm and temperate	Completed
N14	Building and district thermal retrofit and management solutions (THERMOSS) [325]	Building /District level	Several European climates including oceanic and continental	Ongoing
N15	Demonstrating the effectiveness and commercial potential of CLIMAWIN intelligent windows for energy efficiency in the retrofit of buildings in Europe (CLIMAWINDA) [326]	Building level	Several European climates including temperate Atlantic climate, continental climate, and Mediterranean climate	Completed
N16	Development of Systemic Packages for Deep Energy Renovation of Residential and Tertiary Buildings including Envelope and Systems (INSPIRE) [327]	Building level	Several European climates including the Mediterranean climate and warm temperate.	Completed
N17	Accelerating Energy renovation solution for Zero Energy buildings and Neighborhoods (RenoZEB) [328]	Building level	Mediterranean Climate	Ongoing
N18	R & D in Sustainable Building Energy Systems and Retrofitting (R-D-SBES-R) [329]	Building level	Tropical Climate	Completed
N19	Refurbishment decision-making platform through advanced technologies for near Zero energy BUILDing renovation (REZBUILD) [330]	Building level	Several European climates including Mediterranean climate and continental.	Ongoing
N20	Demonstration of an integrated Renovation approach for Energy Efficiency at the Multi building scale (DREEAM) [331]	Building level	Several European climates including the Mediterranean, oceanic and continental.	Completed

The analysis done on these projects showed the different technologies used in smart retrofitting cases as shown in Figure 20. The use of RES and retrofitting of advanced control systems, envelope insulation, and heat pump are highly used in most projects.

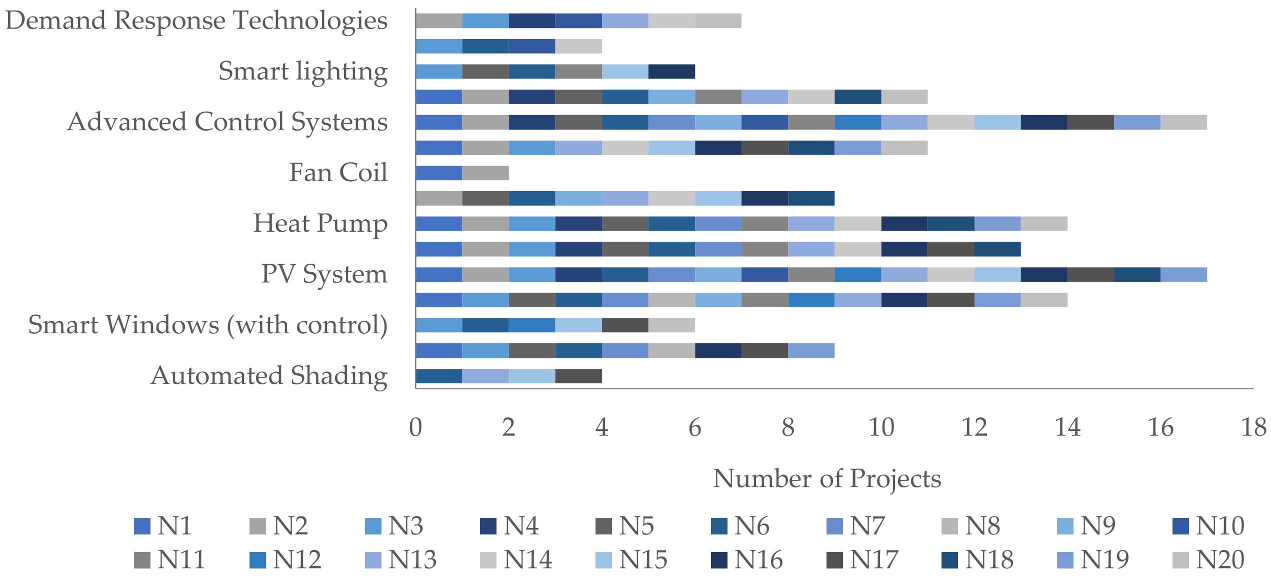

Figure 20. *Smart Retrofit Case Studies Technologies*

3.3 Selection of Smart Retrofitting Representative Key Performance Indicators

According to the KPI selection methodology discussed in Section 3.1.2, an analysis is done first to identify the required parameters for evaluating the technologies identified in smart retrofitted projects that were presented in the EU-reviewed projects. Furthermore, to relate these parameters and data to the SBs basic features described previously to identify the suitable KPI category required for evaluation (Table 8).

Table 8. *Required Data for Performance Measurement of Technologies and Systems Adopted in the SR projects*

Technology/ system developed in the project	Needed data for evaluation and performance measurement	SB Basic Feature (KPI category)
Decision Support System (DSS) and Building Energy Management Systems (BEMS)	Heating demand/ Cooling demand, electricity consumption, self-consumption, PV production, primary energy	nZEB target, Flexibility and Real-time monitoring
External thermal insulation	Heating demand/ Cooling demand, electricity consumption, heat losses	nZEB target

Partial window refurbishment	Heating demand/ Cooling demand, electricity consumption	nZEB target
Air-water heat pump	Heating demand/ Cooling demand, electricity consumption, electricity consumption	nZEB target
Thermal/electricity storage	Energy demand, energy consumption, PV production, grid interaction, energy exported to the grid, energy imported from the grid, storage capacity, storage energy losses, distribution energy losses, generation energy losses, storage charging, and discharging energy	nZEB target, Flexibility, Real-time monitoring
Smart fan coil units for heating/cooling	Heating demand/ Cooling demand, electricity consumption	nZEB target
Photovoltaic panels	Energy consumption, energy demand, PV production, self-consumption	nZEB target, Flexibility
Multi-Input/Multi-output controllers	Energy consumption, energy demand, PV production, grid interaction, energy exported from the grid, energy imported from the grid, storage performance	nZEB target, Flexibility, Real-time monitoring

Based on the required data for evaluation shown in Table 8, 26 KPIs out of the 31 presented in section 2.2.2 were selected for further analysis which 5 indicators were omitted since they are dealing with the power of the grid and require information that is difficult to get, i.e., increased power quality and quality of supply, reduction of energy price by ICT related technologies, reduction of technical network losses, system average interruption duration index system and system average interruption frequency index. Thus, further analysis of the 26 KPIs is presented in Table 9, where an interpretation of KPIs with similar targets/functions is done to group them aiming to answer the questions that have been raised in Figure 15 in Section 3.1.2 previously to select the most representative indicator.

Table 9. KPI Analysis and Interpretations

KPIs	Interpretation	The question addressed by KPI
1. Non-renewable Primary Energy (kWh/m2) **2. Global Energy Performance**	- KPIs can be grouped since they all share the objective of measuring the "overall building energy performance" (Group 1 - G1). This group does not assess the smartness of the building; however, it shows if the building is a nZEB which is the basic feature of a smart building as identified previously.	• What is the amount of Non-renewable energy consumption to achieve nZEB?

Indicator (EPgl) (kWh/m2) **3. Energy Demand and Consumption (kWh/(m2.month or year))** **4. Energy Savings (%)**	- These indicators are widely applied in literature; however, the “Non-renewable Primary Energy” indicator can be considered a more holistic indicator since it achieves the objective of this group and gives information about the building loads and energy savings in the building. Moreover, this indicator has been widely studied in the literature.	
5. Demand Response **6. Peak Load Reduction** **7. Flexibility Index (FI)** **8. Flexibility Factor (FF)** **9. Flexible Shiftable Load (Load Shifting) (S_{flex})**	- These indicators are responsible for “DSM assessment in SBs” (G2) and focus on measuring the flexibility of the shiftable loads in the building. - The “Demand response” and “Peak Load Reduction” share common targets by which they measure the load reduction potential in the building. - While the “Flexibility Factor” shows how the load is distributed compared to the peak load, respectively, but it does not give information on how much load can be shifted. - The Flexibility index shows the potential to shift the heating demand not covered by renewable energy, however, it has not been cited widely. - S_{flex} shows the amount of energy that can be shifted based on RES production, which has been claimed as the most dominant in flexibility applications. - Therefore, it can be concluded that the S_{flex} is capable of measuring “Demand Side Management” in the building by assessing the load shifting potential more holistically. Moreover, the use of load shifting as an indicator for flexibility has been widely applied in literature as it shows the amount of load shifted in response to price or RES availability which represents the main objective of flexibility evaluation.	- How much load can be shifted/Reduced in a building to achieve flexibility? - What is the minimum amount of Load shifting/reduction required to achieve flexibility? What is the optimal quantified flexibility to achieve a SB?
10. Degree of Energetic Self-Supply by RES **11. Increased RES and DER hosting capacity** **12. Load Cover Factor** **13. RES Self-consumption (Supply Cover Factor)**	- These KPIs can be grouped since they assess the production, consumption, and installation of “RES in SBs” (G3). - The KPIs share similar targets, however, according to the literature, the most studied KPIs are the “Load cover factor (Self-generation)” and the “Supply Cover Factor (RES Self-consumption)” which represents the percentage of the electrical demand covered by on-site electricity generation and the percentage of the on-site generation that is used by the building, respectively.	- How much does the RES production cover the building load? - What is the minimum amount of RES to achieve nZEB?

14. Maximum Hourly Surplus **15. Maximum Hourly Deficit** **16. Annual Mismatch Ratio** **17. Load Matching Index** **18. Mismatch Compensation Factor** **19. Reduced Energy Curtailment of RES and DER** (%)	- The Load matching index shares a similar definition to the load cover factor by which both show the percentage of electrical load covered by on-site generation, yet the mathematical equation of the cover factor gives a more detailed result. - Moreover, they are more holistic indicators since they evaluate the on-site generation and consumption with respect to the storage, losses, and building loads during the evaluation period. - Also, these indicators can contribute to addressing part of the questions related to the nZEB target and flexibility functions. - Measuring the “Mismatch compensation factor”, “Annual Mismatch Ratio” and “Reduced Energy Curtailment of RES and DER” has not been applied widely and is usually tested in particular cases only since it considers measuring mismatch at an aggregated level and not at each building level.	
20. Grid Interaction Index **21. No Grid Interaction Probability** **22. Absolute Grid Support Coefficient** **23. Relative Grid Support Coefficient**	- These indicators monitor the “Grid interaction in SBs” (G4). - The “Grid Interaction Index” and “No Grid Interaction Probability” are important indicators that have been tested in several studies and show the variable amount of purchased or delivered energy and when the building is acting autonomously on 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?
24. Storage Capacity **25. Storage Efficiency** **26. Depth of Discharge**	- These indicators measure the performance of the implemented energy storage system and can be combined as “Storage performance indicators” (G5). - The most used indicators in literature have been collected such as the storage capacity, efficiency, and depth of discharge, however, based on literature, these indicators still have unclear calculation methodologies, and their definitions are often oversimplified and must be further developed to consider the storage energy losses. - Therefore, based on selected indicators from G3 and G4, it would be better to calculate these indicators with and without storage to assess the obtainable benefit of the storage system in buildings.	- How to calculate the building energy performance, RES performance, grid performance, and storage performance monitored in the control system?

The analysis done has reduced the number of indicators from 26 to 5 indicators i.e., non-renewable primary energy indicator, Shiftable Flexible Load Indicator, RES-Self Consumption, Load Cover Factor, and Grid Interaction Index. The selected indicators can answer the questions raised previously in Figure 15 to identify the quantitative way of achieving the SB basic features of nZEB target, flexibility, real-time interaction, and real-time monitoring. Thus, to measure SBs/SR performance, a combination of five groups of KPIs can be applied which are presented in Table 10. Moreover, each of the collected KPIs has a certain impact on the building or district performance, as a result, an impact criterion has been developed. The impact criteria have been also developed previously in the SRI which shows the impacts on the users, and the energy grid [332]. In this thesis, the impact criterion developed considers also building energy performance and the effect of RES integration. These criteria helps in demonstrating the project's success and benefits and provides accountability to all stakeholders, including users, policymakers, and building designers. Hence, eight distinct impacts categories have been developed in this thesis as follows:

- Energy use: evaluate how efficient a building system is in delivering the service with a certain amount of energy consumption.
- Flexibility: the impact of the KPI on the grid, storage, and demand response.
- RES Generation: the share of renewable energy measured in the KPIs.
- Distributed Generation: onsite generation and energy storage systems including thermal and electrical.
- Building/Grid Energy Exchange: shows the interaction of energy between grid and building.
- Building Energy Evaluation: overall energy performance of the building.
- Maintenance and Fault Prediction: automated fault detection and diagnosis has the potential to significantly improve the maintenance and operation of technical building systems. This is addressed in indicators in which their results specify a fault or an error in the system by monitoring an unusual pattern in the outcomes.
- User Interaction: refers to the impacts of services on the provision of information on building operations to occupants.

After having set the impact criteria and selecting the KPIs that can answer the raised questions for measuring the performance of smart retrofitting, table 10 presents the five groups that can be applied to test the performance of SR and shows the 5 most cited KPIs in the literature as representative ones for each group.

Table 10. *SR Representative KPIs Assessment*

KPI Group	Most Cited KPI	Timestep	Equation	Definition	Impact Criteria
G1. Overall Building Energy Performance	1. **Non-Renewable Primary Energy** [198]; [200]; [201]; [202]; [203]	Annual	$E_{P,nren} = (\sum_{i} (E_{del,i} \cdot f_{del,nren,i}) - \sum_{i} (E_{exp,i} \cdot f_{exp,nren,i})$ $EP_P = \frac{E_{P,nren}}{A_{net}}$ (Eq.1) $E_{P,nren}$ non-renewable primary energy [kWh/y] EP_P Specific non-renewable primary energy [kWh/m²y] $E_{del,i}$ 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 (m²)	Primary energy is the energy that has not been subjected to any conversion or transformation process. The indicator Sums up all delivered and exported energy (electricity, district heat/cooling, fuels) into a single indicator.	• Energy use. • Building Evaluation. • RES Generation.
G2. DSM Assessment in SBs	2. **Shifted Flexible Load [%]** [251], [252], [239], [253], [254], [255]	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) S_{flex}, Shifted flexible load [%] $L_{ref,i}$ Reference load without flexibility [kW/m²] $L_{flex,i}$ Load with flexible operation [kW/m²]	The amount of load shifted for the considered flexibility technology at the time step *i*	• Energy use. • Grid/Building Energy Exchange. • RES Generation. • Flexibility.

G3. RES Assessment in SBs	**3. RES Self-consumption or (Supply cover factor) [-]** [248]; [249]; [227]; [250]	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) $M(t)$ 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 instantaneous on-site renewable energy consumption.	- Energy use. - Grid/Building Energy Exchange. - RES Generation. - Maintenance and Fault Prediction.
	4. Load Cover Factor [-] [226]; [227]; [228]; [229]; [204]; [258]; [250]	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) $S(t) = S_c - S_{dc}$ y_{load} load cover factor [-] $g(t)$ on-site generation [kWh] $S(t)$ storage energy balance [kWh] S_c charging storage energy [kWh] S_{dc} discharging storage energy [kWh] $\zeta(t)$ storage energy losses [kWh] $l(t)$ building load [kWh] t time $\tau1$ and $\tau2$ are the start and the end of the evaluation period	Load cover factor represents the percentage of the electrical demand covered by on-site electricity generation.	

G4. Grid Interaction	5. **Grid Interaction Index [-]** [204]; [245]; [227], [259]	Hourly/ Daily/ Monthly	$f_{grid,i} = STD\left[\frac{netgrid(i)}{max\lvert netgrid(i)\rvert}\right] x\ 100$ *(Eq.5)* $f_{grid,i}$ grid interaction index [-] *netgrid* net grid metering over a given period (e.g., monthly) compared to the maximum nominal contractual grid power given by contract with the energy company [kW]	Describes the average grid stress, using the standard deviation of the grid interaction over a period of a year.	• Energy use. • Grid/Building Exchange. • RES Generation. • Distributed Generation. • Maintenance and Fault Prediction.
G5. Storage Performance	**3. RES Self-consumption (***Supply cover factor)* [-] **4. Load Cover Factor [-]** **5. Grid Interaction Index [-]** **(These indicators are evaluated in this group since the presence of storage systems plays a crucial role in the final attained values)**	Daily/ Monthly Hourly/ Season/ Year	Indicator's equations are described above in G3, and G4	To evaluate the storage performance in buildings, the load matching and grid interaction indicators selected in G3, and G4 are calculated with and without storage to assess the obtainable benefit of the storage system and evaluate the storage performance in buildings.	• Energy use. • Grid/Building Energy Exchange. • RES Generation. • Distributed Generation. • Maintenance and Fault Prediction.

As seen from the previous selection, the majority of KPIs can be applied directly to new or retrofitted buildings (SBs or SR). Some are best used for retrofitted buildings since they compare the building at the baseline case (before retrofit) and after the smart technologies' integration (after retrofit). Indicators can have two different classifications; "General Indicators", which deal with whole building performance evaluation such as the Indicators in Group 1 which require more general parameters for evaluation, and "Specific Indicators" which require more specific parameters for evaluation and measure certain technology or system in the SR intervention such as the indicators from Group 2 to 5. In the next chapter, the selected KPIs are detailed, and thresholds are set for each KPI based on previous literature. Moreover, a spreadsheet is developed in Excel to prepare the layout used for calculating each indicator and specifying the required parameter and equation used for its' calculation. The results of this spreadsheet are discussed in Chapter 4.

CHAPTER
4

4. TESTING AND EVALUATING KEY PERFORMANCE INDICATORS

This chapter starts by describing background and the objectives of the five selected KPIs that measure the performance of smart retrofitted buildings are presented. Followed by a detailed analysis carried out to investigate the thresholds for each KPI based on a critical literature review and a Logical Evaluation Methodology as discussed in Chapter 3. Then the HEART project and the adopted case study in this thesis is described and the technologies developed in the case study are discussed. Next, the KPIs are tested and applied to the HEART Project, then the relation between the tested KPIs is analyzed. The process of the KPI definition for smart retrofitting is based on a small scale of buildings. It is developed and tested on a Spreadsheet tool that can be scaled up to be applied to a larger number of buildings.

4.1 Background and Objectives of Key Performance Indicators

KPIs, in general, measure the effectiveness of a project towards the achievement of specific key objectives [219]. KPIs should express as precisely as possible to what extent an aim, a goal or a standard has been reached or even surpassed. The following part describes the use of the selected indicators in the thesis. The indicators are described and defined first, then the use, objective, and outcome of each indicator are illustrated in an explanatory diagram. In this thesis, five different indicators have been selected to measure the performance of SB in terms of energy demand, consumption, availability of flexibility, and interaction with the grid. Indicators that measure the energy balance between on-site generation and building load are types of Load Matching and Grid Interaction indicators and serve as fundamental aspects in defining Nearly and Net-zero energy buildings. Load matching (LM) refers to the degree of correspondence or disagreement of the on-site generation with the building load profiles while Grid Interaction (GI) refers to the energy exchange profiles between the building and the grid, and its impact on the overall load of the grid. The studied indicators are:

1. Primary Energy Indicator.
2. Flexible Shiftable Load.
3. RES Self-Consumption.
4. Load Cover Factor.
5. Grid Interaction Index.

This section presents the background, definition, method of calculation, and basic parameters and illustrates the main objectives of the 5 selected indicators described in this section.

1. Primary Energy Indicator Background

Primary energy is a major metric for evaluating the nZEB target and energy performance of a building [333]. This performance indicator is essential for setting minimum requirements for new and renovated buildings. Primary Energy attempts to provide a single metric for all forms of energy that are supplied to, or transmitted through, a defined delivery boundary [334]. It was defined by Nakicenovic (1996) [335] as the embodied energy in resources as they exist in nature: the chemical energy embodied in fossil fuels or biomass, the potential energy of a water reservoir, the electromagnetic energy of solar radiation, and the energy released in nuclear reactions. Moreover, ISO 52000-1 [336] defined primary energy as “energy that has not been subjected to any conversion or transformation process”. The reduction in the use of primary energy for the end-uses covered by the EPBD is an important policy goal, both through minimum performance requirements and for the Energy Performance Certificates (EPCs) [334]. Primary energy is reported in energy content terms such as MWh or kWh or kWh/m^{2}y. The energy performance of a building is expressed by a numeric indicator of primary energy use in kWh/(m^2.y) for both energy performance certification and compliance with minimum energy performance requirements [10].

The EPBD recast Directive [10] had claimed that the building energy performance should be expressed by primary energy based on Primary Energy Factors (PEF) per energy carrier, which can be derived from national or regional annual average. The PEFs are numerical coefficients determined as the inverse of the ratio between one unit of energy delivered to the building and the number of units of primary energy to deliver it [337]. PEF of non-renewable – primary energy factor is used for accounting for non-renewable energy which represents a ratio between non-renewable primary energy consumption and final energy consumption. Annex IV of the Directive 2012/27/EU states an average European reference value of the electricity in MS a default PEF coefficient of 2.5 is applied [338]. The PEF calculation is usually carried out at the national or regional level, according to technical or political criteria. Several values are reported for the PEF in different Member States due to differences in local conditions, such as greater leakage from or compressor power for longer gas pipelines and different methodologies for calculating PEF. The PEF of the Electricity Generation Mix in the EU-28, 2010-2013 for non-renewable PEF decreased from 2.18 in 2010 to 2.06 in 2013. In Italy, the PEF was recorded as 1, 1, and 2.18 for oil-fired boiler, gas-fired boiler, and the electric air heat pump respectively. These values were also reported in several studies [339], [334], [340]. While in [341], the non-renewable primary energy factor for different energy carriers delivered as defined by EN ISO 52000-1 expressed as (fdel,nren) is 2.3. Moreover, the non-renewable primary energy for exported electricity (fexp,nren) is 2.3. Thus, this value was used for PEF in the thesis.

Non-renewable primary energy is calculated through equation 1:

$$E_{P,nren} = (\sum_i (E_{del,i} \cdot f_{del,nren,i}) - \sum_i (E_{exp,i} \cdot f_{exp,nren,i}) \quad (Eq.\ 1)$$

$E_{P,nren}$ non-renewable primary energy [kWh/a]
$E_{del,i}$ annual delivered energy on-site or nearby for energy carrier i, [kWh/a]
$E_{exp,i}$ annual exported energy on-site or nearby for energy carrier i, annual [kWh/a]
$f_{del,nren,i}$ 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 another way
A_{net} useful floor area (m^2)

Each indicator is set to achieve a certain objective in this thesis. The primary energy indicator is selected to indicate how much primary energy is supplied from non-renewable sources to the building. The following diagram (Figure 21) explains the objective of the KPI as well as the outcome of calculating it.

Figure 21. *Primary Energy Indicator Objective and Outcome*

2. Shiftable Flexible Load Indicator Background

In the framework of the IEA Annex 67 project, a quantification methodology to characterize energy flexibility available in buildings and districts is proposed. IEA EBC Annex 67 has defined energy flexibility as [239], "The ability to manage its demand and generation according to local climate conditions, user needs, and grid requirements". Energy flexibility of buildings will thus allow for demand-side management/load control and thereby demand response based on the requirements of the surrounding grids". In line with the definition provided, the energy flexibility of a building varies according to forcing factors or sometimes called penalty signals which induce building response and can be price signal, the CO_2 content in the grid, or the amount of RES in the grid [220]. These factors have the objective of minimizing the energy consumption, cost, or CO_2

footprint of the building. Thus, the energy flexibility of a building is quantified by assessing its response when a step-change in the penalty signal occurs. Energy flexible buildings should integrate penalty-aware controllers that provide them the capacity to adapt energy consumption in response to changes in the imposed penalty signal.

Therefore, Flexibility is quantified based on the ability of the building to shift building load to solar periods where the load is compensated by PV production or to off-peak periods where the electricity price is lower [253], [254], [255]. It is presented as the percentage of shifted flexible loads over time – the deviation in energy consumption. This is expressed as the following equation (Equation 2).

$$S_{flex} = \frac{\sum_{i=1}^{n} max\,(L_{ref,i} - L_{flex,i}\,, 0)}{\sum_{i=1}^{n} L_{ref,i}} \quad (Eq.2)$$

$S_{flex,}$ Shifted flexible load [%]
$L_{ref,i}$ Reference load without flexibility [kW/m^2]
$L_{flex,i}$ Load with flexible operation [kW/m^2]

To sum up, Figure 22 illustrates the main objectives of the Flexibility Index indicator and the outcomes of calculating it and evaluating the flexibility in the SR buildings.

Figure 22. *Shiftable Flexible Load Indicator Objective and Outcome*

3. RES Self-Consumption Indicator Background

Load matching indicators measure the degree of overlap between generation and load profiles (e.g., the percentage of load covered by on-site generation over a period of time) such as the Load match index, Load Cover Factor and Self-consumption indicator. The RES integration in buildings is one of the basic requirements for achieving nZEBs and SBs. Yet, when comparing building load with PV power profiles, a gap can be found in many time steps since they never occur simultaneously. This means that a very limited amount of renewable energy produced on-site can be immediately used. The ratio of energy produced locally to the energy consumed locally is known as self-consumption (SC), and higher SC is always the preferred scenario [342]. Self-consumption has been defined as “the amount of energy generated by a dwelling’s solar PV and consumed at that dwelling" [343]. It has been also defined as "the PV electricity consumed instantaneously or within a 15 min time frame" [248]. Self-consumption was also described as the "local use of PV electricity to reduce the buying of electricity from other producers" [344]. In some studies, it has been referred to as "Supply Cover Factor" [204], [250]. Introducing the self-consumption concept is transforming passive electricity consumers into active ones (prosumers) [345]. The "prosumer" refers to consumers producing electricity to support their consumption (and possibly for injection into the grid). The previous indicator, the flexibility index has investigated measuring the flexibility performance as the reduction of the energy demand not covered by renewables. Therefore, it is crucial to measure the amount of consumed energy produced by RES on-site.

Self-consumption was categorized as one of the load matching indicators as it shows the fraction of the load covered by on-site generation. Load matching can decrease the load on power grids and increase the benefits for users, building owners, and grid operators [249]. These include increasing PV self-consumption and decreasing peak loads. Two major technologies tend to increase PV self-consumption; energy storage (mainly using batteries) and active load shifting, which is an important part of the DSM concept [248]. The value of the SC ranges from 0 to 100%, where the higher the percentage the better. A high SC means that a large share of the PV production is self-consumed to supply the load.

Self-consumption can be defined more formally as the instantaneous building power consumption $L(t)$ and the instantaneous on-site PV power generation $P(t)$. It is denoted as $M(t)$ which is the instantaneously overlapping part of the generation and load profiles:

$$M(t) = min\{L(t), P(t)\}$$

In the case of energy storage (battery or heat storage) the SC is expressed as:

$$M(t) = min\{L(t), P(t) + S(t)\}$$

$S(t)$ is the power to and from the storage unit, i.e., $S(t) < 0$ when charging and $S(t) > 0$ when discharging. It considers the losses due to charging, storing, and discharging of the energy storage into account. Therefore, Self-consumption can be finalized as (Equation 3):

$$\varphi SC = \frac{\int_{t=t1}^{t2} M(t)d(t)}{\int_{t=t1}^{t2} P(t)d(t)} \; Eq.3$$

M(t) instantaneously overlapping of the generation and load profiles [kWh]
L(t) instantaneous building power consumption [kWh]
P(t) instantaneous on-site RES power generation [kWh]

φSC Self-consumption [-]

Figure 23 illustrates the main objectives and outcomes of the RES self-consumption KPI to be achieved in this thesis.

Figure 23. *RES Self-Consumption Indicator Objective and Outcome*

4. Load Cover Factor Indicator Background

Another important metric in the load matching indicators to show the percentage of load covered by on-site generation over a period of time is the load cover factor. The load cover factor is calculated as the ratio of useable electricity production to the total electricity demand, for some time i.e., 15 minutes intervals, for selected months [250]. Load cover factor was also defined in [346] as the percentage of the electrical demand covered by on-site electricity generation and is presented as (Equation 4):

$$y_{load} = \frac{\int_{\tau 1}^{\tau 2} min[g(t) - S(t) - \zeta(t), l(t)]dt}{\int_{\tau 1}^{\tau 2} l(t)dt} \quad Eq.4$$

$$\mathrm{S(t)} = S_c - S_{dc}$$

y_{load} load cover factor [-]
$g(t)$ on-site generation [kWh]
$S(t)$ storage energy balance [kWh]
S_c charging storage energy [kWh]
S_{dc} discharging storage energy [kWh]
$\zeta(t)$ storage energy losses [kWh]
$l(t)$ building load [kWh]
t time
$\tau 1$ *and* $\tau 2$ are the starts and the end of the evaluation period

This KPI is seen as a complementary indicator to the RES self-consumption or supply cover factor representing the percentage of the on-site generation that is used by the building, in which this indicator assesses the demand covered by the on-site generation. The two cover factors can have the same numerical value when the balance for the energy carrier is exactly zero in the observed period, while it would differ for nearly zero or plus balances. It is possible to illustrate both the daily and seasonal effects and the production patterns of different renewable energy technologies and strategies. The load cover factor is considerably higher when using the battery storage system [227].

The supply cover factor and load cover factor represent a good opportunity in assessing the influence of building storage systems on the energy demand and energy production profiles [204].

The load cover factor can be presented as a percentage, where the higher percentage the better, or as a factor between 0 and 1 where higher values mean the building does not need the assistance of electricity from the power grid. Thus, a load cover factor equal to one means that all the demand could be met by the local generation.

Figure 24 illustrates the main objectives and outcomes of the load cover factor KPI to be achieved in this thesis.

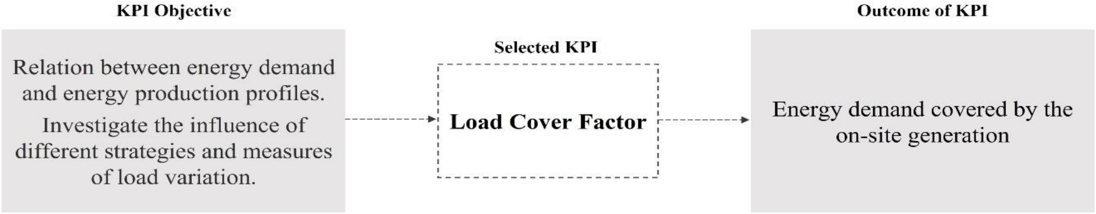

Figure 24. *Load Cover Factor Indicator Objective and Outcome*

5. Grid Interaction Index Background

A complementary indicator can support the No Grid Interaction Probability which is the Grid Interaction Index (GII) f_{grid}. The grid interaction index is intended to quantify the exchange with the grid. It is based on the standard deviation of the net grid metering over a given period (e.g., monthly) compared to the maximum within an annual cycle [229]. The Grid Interaction Index is expressed in percentage [%] and in relation to the time interval [hour, day, month] and can be useful to express the variation of the energy exchange between a building cluster and the grid and it is defined as "the ratio between net grid metering over a given period compared to the maximum/minimum value within an annual cycle" (Equation 5). A positive value describes a net exporting building. The index describes the fluctuation of the energy exchange of the building with the grid, not the amount of grid electricity needed. A nearly constant demand will yield a low grid interaction value and a more fluctuating demand a higher value [347]. Lower values of f_{grid} would indicate lower fluctuations in the hourly data. This can be because the index is normalized by the peak exchanged power and thus the higher peak value relative to the average fluctuations in the hourly data will yield a lower value.

$$f_{grid,i} = STD\left[\frac{netgrid(i)}{max|netgrid(i)|}\right] x\ 100\ (Eq.5)$$

$f_{grid,i}$ grid interaction index at time interval i (e.g., month, day, hour) [%].

$netgrid$ net grid metering over a given period (e.g., monthly) compared to the maximum nominal contractual grid power given by contract with the energy company [kW]

Grid interaction indicators take aspects of the unmatched parts of generation or load profiles into account (e.g., peak powers delivered to the electricity distribution grid). An almost constant import (or export) instead of high fluctuations is characterized by a low value of the annual f_{grid}. High values of grid interaction of exported electricity show a large amount of surplus electricity not used by the building and high grid interaction of imported electricity show that the building depends on the power grid [229].

Figure 25 illustrates the main objectives and outcomes of the grid interaction index KPI to be achieved in this thesis.

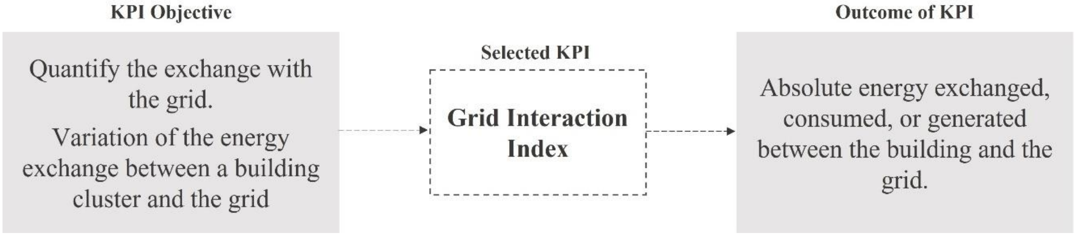

Figure 25. *Load Matching Index Indicator Objective and Outcome*

4.2 Key Performance Indicators Thresholds Elaboration

This section presents the thresholds of the selected indicators first based on a review done on reports, research articles, and regulations that have identified metrics and baselines or a range of acceptable values for these indicators. Then LEM is carried out on each indicator to set two elaborated threshold values based on previous case studies. The five indicators are analyzed in the next section.

4.2.1 Threshold Identification for Selected Indicators

- **Primary Energy Indicator**

Primary energy is one of the most studied indicators in literature. For setting the threshold of this KPI, a review is done on different studies, legislation and reports that have quantified the threshold of the Primary Energy indicator [201], [348], [339], [290], [349], [350], [351], [352], [353]. A review is done in Table 11 to present the existing values set by previous studies and standards that have quantified the outcome of Primary Energy (PE). The table gives information on the parameters considered in the calculation, climatic context, and finally the achieved value of the KPI in the study.

Table 11. Primary Energy Indicator Standards Requirement Review

Reference Study	Input Parameters	Country/ Climatic Context/ Building Type	Methodology	Achieved Primary Energy Result
Energy Efficiency of Buildings in Italy - Green Building Council Italia [201]	Non-renewable primary energy requirement for: - HVAC, DHW. - Ventilation, artificial lighting.	- Italy (Mediterranean Climate). - Residential Building.	Non-renewable PE equation	- 90 kWh / m² per year for single-family single buildings up to buildings with 4 residential units. - 70 kWh / m² per year for buildings with more than 4 residential units.
COHERENO- Collaboration for housing nearly zero-energy renovation nZEB criteria for typical single-family home renovations in various countries [290]	Heating, cooling, ventilation, domestic hot water, and auxiliary energy (monthly balancing period).	1. Brussels 2. Bulgaria 3. Cyprus 4. Denmark 5. France (Multiple climatic zones) - Single-family house.	- Review of data based on legislations and national nZEB approaches.	1. Brussels: PE consumption ≤ 45 kWh/ m²y 2. Bulgaria: a nZEB PE 50-60 kWh/ m²y). 3. Cyprus: PE <180 kWh/ m²y. 4. Denmark: PE is 20 kWh/ m²y. 5. France: New construction of residential buildings should have a threshold of 50 kWh/m²a primary energy, while renovated less than 80 kWh/ m²y.
Synthesis Report on the National Plans for Nearly Zero Energy Buildings (nZEBs) [350]	A numeric indicator of energy performance expressed as primary energy in kWh/m²y use defined in some EU Member States.	- 25 EU Member States (Several climatic zones) - Residential and non-residential buildings.	Study of interim targets for new and existing buildings based on policies and supporting measures.	- Several Countries have chosen 50 kWh/m²y primary energy in 2015, while others had primary energy ranging between 0 and 220 kWh/m²y in different climatic zones).
How to define nearly net zero energy buildings nZEB-REHVA proposal for uniformed national implementation of EPBD recast [351]	Definition for nearly net zero energy buildings non-renewable primary energy. Exported/delivered Energy. Primary Energy Factor.	- Paris (Oceanic climate).	Non-renewable PE equation	Calculated primary energy was 66 kWh/m²y.

Assessment of the progress towards the establishment of definitions of Nearly Zero Energy Buildings (nZEBs) in European Member States [352]	Heating, cooling, ventilation, DHW energy demand as well as building category, typology, physical boundary, type and period of balance, RES, metric, normalization, and conversion factors.	Eight MS (non-renewable primary energy) (Residential Buildings)	Overview on the Directive requirements related to nZEBs and the current MS situation	In kWh/(m^{2}y) Belgium: 30— Flemish region, 45—Brussels region, 60—Walloon region Cyprus: 180 Denmark: 20 Estonia: 50 France: 50 Ireland: 45 Latavia: 95 Slovakia: 32 (apartment buildings) 54 (family houses)
Towards Nearly Zero Energy Buildings in Europe: A Focus on Retrofit in Non-Residential Buildings [353]	Defining Energy requirements defined by EU Member States for nZEB levels.	25 EU Member States (Several climatic zones) (Residential buildings new and existing)	Overview on the energy requirements defined by MS for nZEB levels for both new and existing residential buildings (kWh/m^{2}y)	**New** **Deep Retrofit** kWh/m^{2}y Austria: 160 200 Belgium: 45-60 54 Bulgaria: 30-50 40-60 Cyprus: 100 100 Czech Republic: 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 Lithuania: Class A++ Class A++ Luxemburg: Class AAA NA 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

According to these studies, non-renewable primary energy is based on non-homogeneous calculation methods and general conditions among the Member States. It shows a wide variety of computational results for primary energy. The European Commission has claimed that the non-renewable primary energy consumption of nZEBs varies between 0 and 160 kWh/m²a for residential buildings [354]. 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 buildings is assessing the primary energy savings achieved. The EU commission has claimed that for very light renovations primary energy savings range between 3% and 30%, medium renovations savings range between 30% and 60%, and deep renovations savings are > 60%. In some countries, these requirements are combined with specific requirements on energy needs and minimum shares of renewable energy [277].

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

1. A targeted number expressed in kWh/(m^2y) varies among each country based on its climatic zone and based on energy requirements. For new buildings, the PE ranges between 0 and 220 kWh/(m^2y) and for retrofit buildings the PE ranges between 20 and 200 kWh/(m^2y) showing a wide range due to the different conditions and targets of each country.
2. An easier threshold of 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 represents the target of SBs and SR the PE savings are typically > 60%.

To validate the Primary Energy savings for buildings and set Min and Top performing thresholds, a review is done on case studies that have calculated the indicator, as reported below (Table 12).

Table 12. *Primary Energy Saving Indicator Case Studies Review*

Case Study Reference	Integrated Systems/Technologies	Methodology	Achieved Annual PE savings values
Future-Proof Buildings For All Europeans (Example of a typical building in Italy) [355]	Improved building fabric and gas boiler for heating Heat Pump supplied 100% by PV, compared to typical building fabric and no use of RES.	PE saving is calculated by equation.	PE savings of improved building systems compared to the reference scenario was 85%

nZEB Renovation Definition in a Heating Dominated Climate: Case Study of Poland (Research Article) [339]	- HVAC system. - DHW system. - Electric radiators. - PV system.	Calculation using equation for the energy needs for heating Q_H, and percentage of reduction of primary non-renewable energy demand	The percentage of reduction of the non-renewable PE demand was 75%.
Addressing the challenges of public housing retrofits [356]	- Milan: building envelope retrofit (thermal insulation double glazing windows and frame with thermal break, exterior solar shading on each window), high-performance centralized 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%
Empirical assessment of calculated and actual heating energy use in Hellenic residential buildings [357]	- Renovation of thermal envelope. - Double glazed windows. - DHW - 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%.
Building typologies as a tool for assessing the energy performance of residential buildings – A case study for the Hellenic building stock [358]	Several residential buildings retrofitted with single and multifamily housing typologies in five EU climatic zones through: - Thermal envelop retrofit (insulation and window refurbishment). - Heat pump and distribution pipes retrofit, - Installation of PV systems that covers 60% of DHW demand.	Software used to calculate the primary energy savings achieved after retrofit.	The PE savings ranges between 41% and 79% based on different climatic zones and typologies.

Energy retrofit for a single-family house: Life cycle net energy saving and environmental benefits [359]	Single-family renovation including thermal insulation of roof and façade, condensing boiler for replacing the existing boiler, and PV plant installation.	The primary energy reduction is calculated through TRNSYS simulations.	PE saving of 72% was achieved.

A range can be suggested for the threshold of the primary energy saving indicator. For a smart retrofit, the range should be between moderate to deep retrofitting requirements. Top-performing smart retrofit should include envelop retrofitting, integration of RES, control systems for building energy management, and allow flexibility. Thus, based on the previous case studies and literature review, minor renovations strategies achieved PE savings of around 30% estimated to the lower integer value while for the renovation that includes holistic retrofit strategies and integration of RES, DHW, and storage system, the PE saving can reach 80%. Therefore, the Min achievable threshold is ≥ 30%, while the Top performing threshold of PE should be ≥ 80%.

- **Shiftable Flexible Load Indicator**

Several studies have quantified Flexibility [360], [361], [362], [363], [364]. They describe to which extent a building can respond to the grid's need for flexibility. IEA EBC Annex 67 [365] has indicated that flexibility is defined as the deviation of a flexible load profile from a baseline profile without flexibility. The output is a percentage of shifted flexible loads over time – which is the deviation in energy consumption presented as "$Sflex$". In this thesis, the Flexibility can be calculated using Equation.2 representing the load shifting as the Shiftable Flexible Load. Higher flexibility represents more load shifting potential. These studies claim that flexibility can be achieved by recognizing penalty signals or influencing factors such as temperature set points, humidity, electric vehicles, electricity price, RES production values, etc., by which the flexibility will respond. The studies also show that the insulation level of the envelope, the storage system, control system, and RES installed play a major role in energy shifting. However, no defined threshold defines the right flexibility level. Moreover, there is a lack of current legislation and standards on Flexibility. Until now, no recommended value has been established by countries for load shifting. Thus, in order to set thresholds for the load shifting, a review is done in Table 13 to investigate the smart building/retrofit case studies that have quantified load shifting. The analysis shows the main technologies investigated, methodology and the achieved result to categorize the thresholds to Min acceptable threshold and Top performing threshold.

Table 13. *Shifted Flexible Load Indicator Case Studies Review*

Reference Study	Integrated Systems/Technologies	Methodology	Achieved Annual Shifted Flexible Load Value
Numerical Analysis of the Impact of Thermal Inertia from the Furniture Indoor Content and Phase Change Materials on the Building Energy Flexibility/ (Research Article) [360]	- Envelope thermal mass. - Heating systems (radiators and water-based under-floor heating). - Additional indoor thermal mass parameters. - Storage system. - Thermal storage system with control strategy based on electricity price. - Furniture with PCM. - PCM wallboards.	- FI calculation using the building cases equipped with convective radiators and no TES strategy are taken as references. - MATLAB-Simulink to model building. - Two different classes of insulation modelled.	- PCM integrated into wallboards can achieve load shifting of 42%.
Energy flexibility quantification of grid-responsive buildings: Energy flexibility index and assessment of their effectiveness for applications [363]	- Electrical vehicles. - PV panel. - Optimized envelop thermal insulation. - HVAC system. - Control strategy for charging/discharging the storage system.	- Building energy performance simulation is conducted in TRNSYS comparing the building in the baseline scenario (without activating any energy flexibility sources) with post-retrofit interventions. - Load shifting flexibility is achieved through EVs, stationary batteries, and passive building thermal mass.	- Optimized charging/discharging results in load shifting flexibility capacity 2507 kWh showing 34%.
Quantifying demand flexibility of power-to-heat and thermal energy storage in the control of building heating systems [366]	- Heat pump. - PCM tank. - Water tank. - Thermal energy storage. - Combined Heat and Power (CHP) system. - Model predictive control (Price-based control strategy).	- Flexibility through Shifting of the electrical consumption. - Models of the building heating system are implemented in a simulation framework using MATLAB. - Flexibility is calculated based on low and high price periods.	- By adding TES tanks and cost-optimal control, the load shifting is 67% (PCM tank), and 86% (water tank).

Implementation and Simulation of Real Load Shifting Scenarios Based on a Flexibility Price Market Strategy—The Italian Residential Sector as a Case Study [367]	- Flexible loads such as washing machine, dishwasher, tumble dryer, vacuum cleaner - PV system. - DHW. - HVAC systems. - Multi sensors. - Heat pumps. - Electricity meters.	- Price-Market-based Strategy. - Testing was conducted on different scenarios of housing with varying number of occupants and schedules. - The simulations were implemented using the Excel environment, with Macros written in Visual Basic for Applications (VBA).	- The Results showed that the achieved load shifting varied between 53% to 66% based on different the scenarios.
Comparison of Flexibility Factors and Introduction of A Flexibility Classification Using Advanced Heat Pump Control [251]	- High thermal insulation. - High thermal mass. - Ground-source heat pump. - DHW. - PV system. - Control system.	- 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.	- Results revealed that load shifting was between 40% and 85% for the different penalty signals.
Influence of envelope, structural thermal mass and furnishings on space heating energy flexibility [368]	- PCM wallboards - Heating system (convective radiators and under-floor heating system. - High thermal mass. - Control system. - Thermal storage system. - PV system.	- Different scenarios were generated with two categories of the building envelope (houses from 1980 and passive houses), three thermal mass classes with three sub-variations in each, two types of heating systems, and four additional indoor thermal mass configurations. - Thermodynamic multi-zone models of the building were created with the MATLAB-Simulink software. - The Control system responds to price and RES availability.	- Houses built in 1980 heated by the radiator can have load shifted between 30% and 40%, while under-floor heating can have load shifting of 40% to 50%. - Passive houses using radiators, the load shifted between 60% and 90%, and using floor heating load shifting is between 70% and 95%.

How the Italian Residential Sector Could Contribute to Load Flexibility in Demand Response Activities: A Methodology for Residential Clustering and Developing a Flexibility Strategy [369]	- Smart meter system. - Control system. - HVAC system. - PV system. - DHW. - LED lights. - Electric heat pumps.	- Database consisting of 751 typical Italian dwellings (14 dwelling archetypes defined). - Calculated power demand profile and the hourly Italian electricity price trend over 2018 and 2019. - Hourly pricing mechanism following the day-ahead market outcomes for load shifting.	- Annual flexibility found to be 34% for load shifting.
Evaluation of energy flexibility of low-energy residential buildings connected to district heating [370]	- HVAC. - DHW. - 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 are defined as percentiles of the monthly marginal cost. - Shift load to low price periods.	- For the different control scenarios, the load shifting ranged between 52% and 79%.

Based on the reviewed studies, it is noted that building flexibility depends highly on the presence of PV systems, storage systems, control systems, and building insulation. Thus, based on the reviewed studies it shows that with some smart technologies integration, a minimum of 30% (mean of case studies with minimum integrated smart technologies rounded to the lowest integer value) of load shifting can be achieved, thus such a value was identified as the Min achieved threshold, while for high thermal mass scenarios, optimized systems, and integrated RES and storage systems the maximum reasonable achievable load shifting with the current technologies is 70% (mean of case studies integrating a full set of smart technologies and system optimization rounded to the lowest integer value) representing Top-performing threshold.

- **RES Self-Consumption Indicator**

RES Self-Consumption (SC) is an important indicator that has been discussed and tested in several policies, reports, and research articles. It is the electricity that is produced from RES, not transferred to the distribution/transmission grid, and consumed by the owner instantaneously [371]. Maximizing SC leads to minimizing the export of the electricity grid 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 producer. Table 14 presents some quantified requirements of RES SC based on official reports in the EU.

Table 14. *RES Self-consumption Indicator Standards Requirement Review*

Reference Study	Tested Parameters/ Boundary Factors	Country/ Climatic Context/ Building Type	Methodology	Achieved RES Self-Consumption Result
Best practices on Renewable Energy Self-consumption [372]	- PV system. - Storage system. - Demand-side response strategies.	- Central European household	- EU Commission report on the best practices on RES SC applying Demand-side response strategies	- Up to 65-75% RES SC can be achieved.
Review And Analysis Of PV Self-Consumption Policies/ Report [344]	- 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.	- 10 different EU countries.	- Some countries reported a minimum allowed SC target. - These countries have been selected from the IEA PVPS participating countries, as well as some additional countries presenting SC features. - Some countries reported specific targets while others did not identify minimum targets for SC.	- **Germany**: minimum requirement of 10% SC for residential housing. - **Spain**: all systems used for SC above 10 kW are charged with a fee per kWh consumed. - **Sweden**: SC must be at least as large as the number of kWh the PV owner feed into the grid and get a tax credit. - **Belgium**: SC is applied only for system above 10 kW. - **Finland**: simple SC system without incentives. - **France:** In SC, PV systems can receive a feed-in tariff that compensates for the excess electricity fed into the grid. - **Italy**: for systems above the 500-kW limit, a pure SC scheme is used.

		- **Switzerland**: SC for multi-family housing is allowed. - **Netherlands**: Above the net-metering limit, self-consumption is allowed but not incentivized. - **UK**: SC for small systems (<30 kW) is encouraged through a generation tariff and an export tariff, applicable to the electricity fed into the grid.

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 previous case studies. A summary is reported in Table 15 based on different case studies that have tested, quantified the RES SC, and categorized them according to the main influencing technologies, methodology, and achieved results.

Table 15. *RES Self-Consumption Indicator Case Studies Review*

Reference Study	Integrated Systems/Technologies	Methodology	Achieved Annual RES Self-Consumption Value
Analysis Of Load Match And Grid Interaction Indicators In Net Zero Energy Buildings With High-Resolution Data - IEA Joint Project SHC Task 40 / ECBCS Annex 52 [204]	- PV panels. - Optimized storage system. - Heat pump. - Electric chillers (in some buildings). - Smart control (in some buildings).	- Monitored data are available for six buildings, which represent different building typologies, technologies, and PV sizing. - Calculation of Monthly generation of the net exported electricity in kW. - 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.
An optimization and sizing of photovoltaic system with supercapacitor for	- PV panels. - Control system.	- Photovoltaic system working with a supercapacitor device demonstrates its large	- Annual SC with a storage system and controller is 56.7%.

improving self-consumption [342]	- Battery storage system.	potential for self-consumption improvement and grid stabilization.	- Annual SC without energy storage and controllers is only 26%.
Optimal charge control strategies for stationary photovoltaic battery systems [373]	- Battery storage. - PV system. - Control system.	- Predictive charge control strategies for stationary PV battery systems based on dynamic programming. - Optimal charge control strategies. - Optimized battery storage sizing.	- SC without storage is 34%. - SC with optimized storage sizing is 64%.
Sizing of Residential PV Battery Systems [374]	- Battery storage. - PV system. - Control system.	- Meteorological and load demand data sets were used as input for the simulation. - Sensitivity analysis was conducted for different scenarios.	- SC is approx. 35% without storage. - SC is approx. 65% with storage.
Simulation and analysis of a solar-assisted heat pump system with two different storage types for high levels of PV electricity self-consumption [375]	- DHW. - Heat pump. - PV system. - Battery storage system.	- Increase RES self-consumption by combining PV system with battery storage, controller and an inverter, and hot water storage tank for residential building.	- SC without storage is approximately 55%. - SC with storage is 88%.
Demand-side management through heat pumps, thermal storage and battery storage to increase local self-consumption and grid compatibility of PV systems [376]	- Heat pump. - PV system. - Battery storage system. - DHW.	- Testing the effect of different battery capacities and heat pump 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 35% and 50%. - SC when considering a heat pump, storage,

			and domestic hot water ranges between 45% and 70%.
Dimensioning of Decentralized Photovoltaic Storages with Limited Feed-in Power and their Impact on the Distribution Grid [377]	- PV system. - Storage system. - Control system.	- Investigated the optimal dimensioning for a battery with a control system to improve self-consumption in residential buildings.	- SC with PV only is 38%, while with storage and control system is 57%.
Control algorithm for a residential photovoltaic system with storage [378]	- Control system. - PV system. - Storage system.	- Optimization for a residential photovoltaic system with storage and control strategy based on linear optimization to maximize self-consumption. - Two control algorithms were applied: based on cost minimization without forecast, and cost minimization based on PV production and the load forecast using a linear forecast.	- For different storage capacities, and different control algorithms the SC ranged between 30% and 60%.
Increase the rate of utilization of Residential photovoltaic generation by EV charge-discharge control [379]	- Electric vehicle. - PV system. - Control system.	- EV charge-discharge control proposed, and their effects analyzed. - Combining an electric vehicle, electricity meter, and control system with a PV system in a smart house can result in increasing SC.	- SC using PV only was 41%, while with combining EV and control SC was 79%.

Based on the review done, it is noted 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 PV system and with minimum technological integration and without the integration of a storage system the mean value is 30% (rounded to the lower integer value) representing the Minimum achieved threshold. While by integrating storage systems, heat pumps, control systems, and optimizing the size of PV and storage, the SC maximum reasonable achievable value with the current technologies is 70% (mean value rounded to the lower integer) representing the Top performing threshold.

- **Load Cover Factor Indicator**

The Load Cover Factor (LCF or γ_{load}) measures the percentage of the electrical demand covered by on-site electricity generation over a period of time. It also gives quite a good picture of the correlation between on-site demand and the supply of energy. The factor ranges between 0 and 1 and can be represented as a percentage between 0 and 100%, in which the higher the indicator the better where it shows the amount of load covered by RES production. To date, there is no agreed minimum value of LCF for smart buildings or nZEBs. Yet, it has been tested by different studies, thus, a logical evaluation is done on the indicator according to several previous case studies. Table 16 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.

Table 16. *Load Cover Factor Indicator Case Studies Review*

Reference Study	Integrated Systems/Technologies	Methodology	Achieved Annual Load Cover Factor Values (γ_{load})
Analysis of load match and grid interaction indicators in net-zero energy buildings with simulated and monitored data [204]	- PV system. - DHW. - Heat pump. - Electric-driven chillers.	- Five case studies were selected in different climatic zones. - High-resolution data was used from both monitored and simulated buildings. - Load matching indicators are calculated at different time resolutions.	Annual LCF ranged between 21% and 56% according to different case studies based on the variation of onsite production, electricity load profiles as well as heat load profiles.
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 [229]	- PV system. - Storage system. - HVAC system. - Control system.	- A net plus-energy house modeled in EnergyPlus based on a high-level battery controller simulated with different PV-battery sizes. - Four scenarios of PV system configuration were tested to improve Load Matching and Grid Interaction (LMGI) indicators.	Annual LCF ranged between 25% and 60% based on different PV sizing.
Grid impact of a net-zero energy building with	- BIPV system. - HVAC system.	- Net-zero energy building with BIPV, a heat pump with cooling functionality	Annual LCF achieved is 97%.

BIPV using different energy management strategies [380]	- Smart control system. - Storage system. - Heat pump.	simulated in Dynamic thermohydraulic simulations in (Dymola). - Load shifting strategy of heat pump implemented.	
Grid interaction and environmental impact of a net zero energy building [228]	- 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 nominal storage capacity and.	- LCF was 30% when only PV system was used. - When the storage system and the fuel cell systems were utilized and the sizing of the three systems were optimized, the LCF reached 70%.
Grid Impact Indicators for Active Building Simulation [258]	- Heat pump. - Thermal energy storage (TES) (to shift Heat Pump demand). - Control systems. - PV system.	- Building modeling with Modelica software. - Three different control conditions were implemented for the storage tank to shift HP electricity consumption to time with higher PV system output.	- LCF without daytime control is around 20% and with daytime, control is around 30%.
Energy matching analysis for net-zero energy buildings [381]	- DHW. - PV system. - HVAC system. - Biomass-based co-generation heat and power technologies. - Thermal tracking strategy.	- The single-family house is served by four conventional heating systems and seven biomass-based co-generation heat and power technologies simulated. - No storage system was used. - Comparison between different Biomass-based micro- and small-scale Combined Heat and Power (CHP).	- Among CHPs, the CHP- polymer electrolyte membrane fuel cell has the highest LCF of 42%.

Thus, based on the reviewed studies it is shown that the LCF depends mostly on the PV on-site production rate, the presence of a control system, and optimization of PV and storage sizing. The minimum achievable LCF when 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 PV sizing is optimized and several technologies are integrated such as storage systems, control systems, heat pumps, etc., the annual LCF can achieve high values and reach maximum reasonable achievable value with the smart technologies of 70% representing top-performing threshold in smart building/retrofit.

- **Grid interaction index Indicator**

The grid interaction index (GII or f_{Grid}) describes the variability of energy exchanged between the building and the grid within a year, normalized on the highest absolute value. It depends on measured or simulated data of delivered and exported quantities. It is a measure of the fluctuation of energy exchange between the building and the grid. Thus, the most optimal GII value lies in reducing the stress on the grid while maintaining the energy power balance, meaning the lower the index the less interaction with the grid. No quantified threshold has been set for this indicator, yet different studies have evaluated the GII and quantified its' achievable value, thus, thresholds can be defined. It should be noted that the GII is calculated according to different time resolutions such as hourly, daily, and monthly. Yet, the grid interaction must be evaluated with a time resolution of an hour or preferably even lower since the index is normalized by the peak exchanged power and thus the higher peak value relative to the average fluctuations in the hourly data will yield a lower value. Moreover, 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 17 reviews different case studies according to their influencing technologies, methods, and achievable values. The GII is calculated at different time resolutions including hourly (h), daily (d), and monthly (m). Thus, the threshold for this indicator is set at three different time intervals.

Table 17. *Grid Interaction Index Case Studies Review*

Reference Study/Type of Study	Integrated Systems/Technologies	Methodology	Achieved Grid Interaction Index Values
Load Matching and Grid Interaction of Net Zero Energy Buildings [382]	- HVAC. - DHW. - PV system. - Storage system.	- Three buildings presenting nZEB and two net plus energy buildings. - PV production exceeds the annual needs. - Load matching and grid interaction were tested at three different time intervals: hourly, daily, and monthly.	- For building 1, Portugal: $f_{Grid,m}$ is 37%, $f_{Grid,d}$ is 25% and $f_{Grid,h}$ is 31%. - For building 2, USA: $f_{Grid,m}$ is 55%, $f_{Grid,d}$ is 29% and $f_{Grid,h}$ is 29%. - For building 3, Germany: $f_{Grid,m}$ is 43%, $f_{Grid,d}$ is 35% and $f_{Grid,h}$ is 25%.

Analysis of load match and grid interaction indicators in net zero energy buildings with high-resolution data [204]	- PV panels. - Optimized storage system. - Heat pump. - Electric chillers (in some buildings). - Smart control (in some buildings). - Battery storage system.	- Monitored data are available for six buildings, which represent different building typologies, technologies, and PV sizing. - Calculation of Monthly generation of the net exported electricity in kW. - 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. - The values are not affected by different energy technologies or systems with or without batteries.
Net Zero Energy Solar Buildings at High Latitudes: The Mismatch Issue [383]	- PV system. - Storage system.	- nZEB building - Monthly and hourly time resolution. - Stochastically generated electricity demand and PV generation modeled from empirical irradiance data. - Model can generate detailed and realistic data down to a 1-min resolution and has been validated. - Storage system shifts excess generation to times with a net demand.	- GII is higher with the monthly resolution. - $f_{Grid,m}$ is 72% and $f_{Grid,h}$ is 27%.
Understanding Net Zero Energy Buildings: Evaluation of Load Matching and Grid Interaction Indicators [227]	- PV system. - Storage system. - Smart meter.	- Test the load matching and grid interaction (LMGI) indicators. - Hourly data set from simulations for an experimental house have been used to test the LMGI indicators. - Simulations have been performed in cooperation with Fraunhofer ISE with the DYMOLA simulation environment. - One set of data corresponds to a system without storage. The other data set corresponds to a system with a battery.	- $f_{grid,h}$ with battery is 0.26 and without battery is 0.29.

Evaluation and optimization of a Swedish net ZEB using load matching and grid interaction indicators [384]	- PV system. - Battery Energy storage. - Hot water storage tank. - Solar thermal collectors.	- Net ZEB residential building load matching and grid interaction using simulated data sets with hourly resolution. - Test different options including changing the slope of solar thermal collectors, battery capacity, and PV installed capacity. - Hourly, monthly, and daily grid interaction calculated.	- 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 %. - Introducing small energy storage systems such as hot water tanks or batteries, results in small effects on load match and grid interaction.
Optimal design of renewable energy solution sets for net zero energy buildings [385]	- Evacuated tube solar collector. - Absorption chiller. - Ground source heat pump (composed of a water-to-water heat pump and a vertical U-type borehole heat exchanger. - Air source heat pump. - PV system. - DHW.	- Investigated buildings in different cities representing low-energy buildings whose passive parameters are optimized and validated. - Building energy simulation using TRNSYS. - Multi-criteria decision-making optimal models' analysis and overall performance evaluation results using LMGI indicators. - Grid interaction index indicator evaluation using equation.	- $f_{Grid,m}$ variates between 38% and 77% depending on the different cities. - Most optimal $f_{Grid,m}$ is achieved at 38% when an air source heat pump for cooling and a flat plate solar collector delivers hot water for heating and domestic usage. - $f_{Grid,m}$ of 46% is achieved when using a biodiesel generator. - $f_{Grid,m}$ of 40% which was achieved when adopting a ground source heat pump and a vertical U-type borehole heat exchanger for heating/cooling, and DHW production.
A case study of solar technologies adoption: criteria for BIPV integration in sensitive built	- BIPV. - DHW. - Control system.	- Analysis of two buildings in different cities to compare electric load data and PV power generation and associate load matching index and grid interaction index.	- The most efficient typology of BIPV yielded $f_{Grid,d}$ 29%, and $f_{Grid,h}$ 34%.

environment [386]		- Decision-making process for different configurations of BIPV. - Grid interaction Index calculated at daily, hourly time steps.	
A Study of Load Matching on the Net-Zero Energy House [387]	- PV systems. - DHW. - Thermal and electrical storage systems.	- The GII was monitored for seven residential buildings equipped with different technologies and different sizing of PV systems.	- The $f_{Grid,h}$ for the case studies varied between 15% and 21%.

The GII depends highly on the PV production, PV system capacity, and control system. Moreover, it is usually calculated with three different time steps: hourly, daily, and monthly. Based on the review done in Table 17, a range of thresholds can be suggested for each time step considering that the lower the indicator, the better, since it shows less dependence on the grid. 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 minimum achievable 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 Top-performing value of $f_{Grid,m}$ is 30%. Similarly, for the daily GII, the minimum achievable value of $f_{Grid,d}$ is 40%, while the top-performing threshold of $f_{Grid,d}$ is 20%. For the hourly GII, the minimum achievable value of $f_{Grid,h}$ is 30%, and the top-performing threshold of $f_{Grid,h}$ is 10%.

4.2.2 Summary of Threshold Evaluation

A summary can be drawn based on the literature review previously reported, to set the final thresholds for the selected KPIs. A graphical representation is shown in Figure 26 to illustrate the range of thresholds for residential buildings. Moreover, Figure 26 shows the most influencing parameters of the KPIs, and their required values defined by previous building legislations.

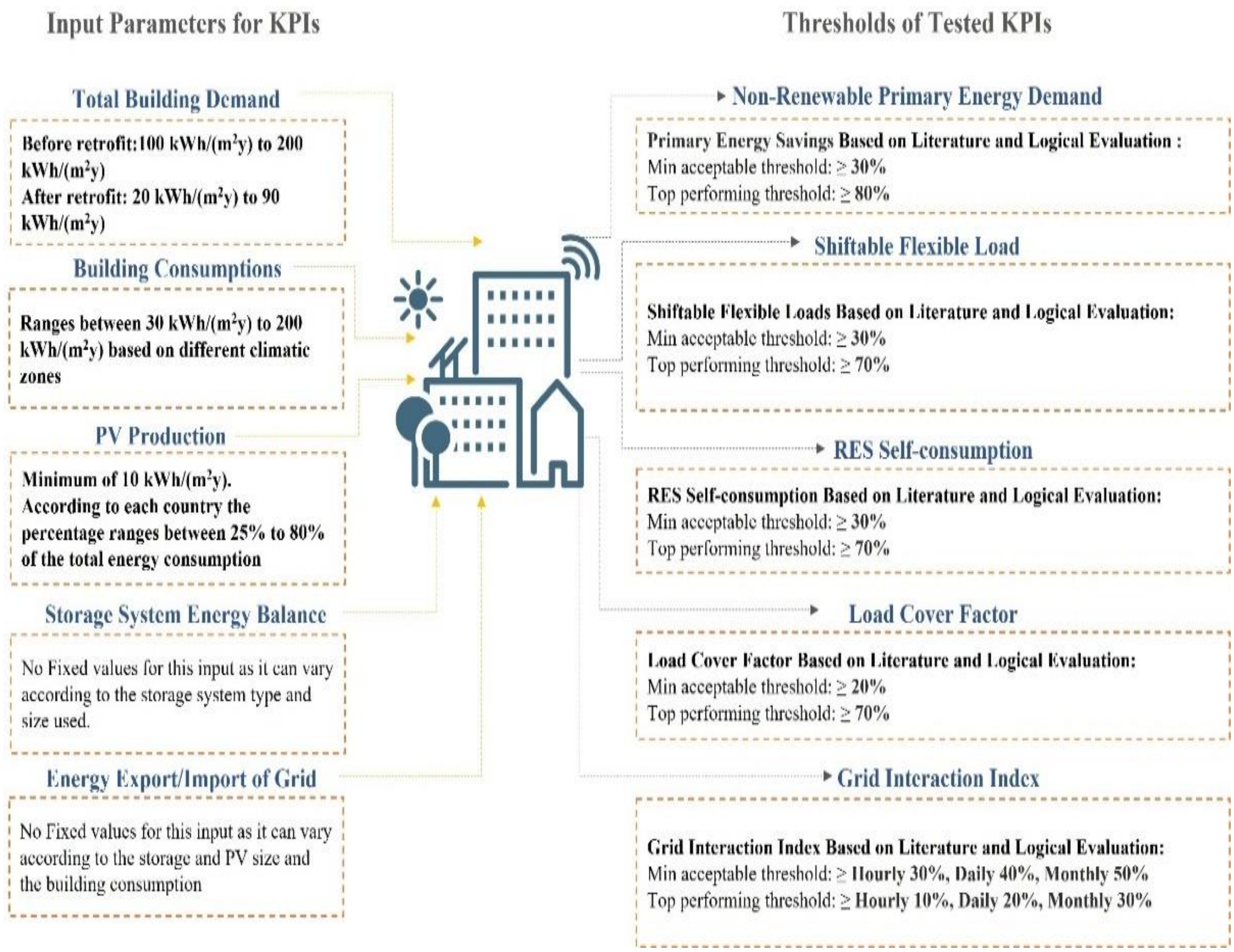

Figure 26. Summary of Key Performance Indicators Thresholds Evaluation

4.3 Case Study Description: The HEART project

This thesis was developed within the Holistic Energy and Architectural Retrofit Toolkit (HEART) project. It has 16 partners from 10 countries and has a geographical focus in Central and Southern Europe.

The HEART toolkit incorporates different components and technologies, which cooperate to transform an existing building into a smart building [299]. The project advances and improves energy efficiency and the use of renewable energies in buildings across Europe, particularly in Central and Southern Europe, where climate change is leading to increased electricity consumption both during the summer and winter seasons. HEART project aims at building a holistic retrofit toolkit to transform existing buildings into nZEBs. HEART partners cooperate to create a multifunctional toolkit within which different subcomponents – ICT, BEMS, HVAC, BIPV, and Envelope Technologies –

cooperate synergistically to achieve extremely high levels of energy efficiency in the residential building stock. The system's central core consists of a cloud-based computing platform that focuses on managing and operational logic to support decision-making in planning and construction, as well as energy performance and monitoring during operation. The toolkit provides energy saving, energy flux optimization, data exchange, stakeholders' active engagement, and Smart Grid interactivity.

The application of envelope technologies (thermal insulation and windows) ensures a reduction in thermal load, while the application of installation technologies (PV, heat pump, fan coils, storage units) grants energy efficiency and usage of renewable energy sources. The optimization of the energy management and the network integration is performed by the web platform, exploiting external (weather forecast, energy fee variations) or internal (input and feedback from the tenants) information. With this respect, the platform exploits the previously elaborated virtual model, applying a predictive/adaptive logic guiding the efficiency of the whole building system.

A spreadsheet is developed in Excel where the KPIs are applied and tested on the findings of the project to evaluate the performance of the project. Furthermore, to validate the estimation of the KPIs threshold based on a smart retrofitted real case study.

The input of real-time data on energy consumption in HEART's computational logic allows the Building Automation and Control System to:

- Learn about the building's behavior and its end-user habits and preferences.
- Identify optimal operating profiles.
- Manage and supply the consumed and/or self-produced energy.
- Allow real-time monitoring.
- Identify misuses, failures, and maintenance requirements.
- Allow active involvement of end-users.
- Enable dynamic interfacing with the grid.

4.3.1 Italian Case Study Description

The case study is a building located in the city of Bagnolo in Piano (Reggio Emilia, Italy) (Figure 27). It is a four-story building, having a total of 12 apartments (4 apartments per floor); cellars and parking areas are located on the ground floor. The total conditioned area of the building is 678 [m^2] [388]. The plan of the typical floor is shown in Figure 28 [389].

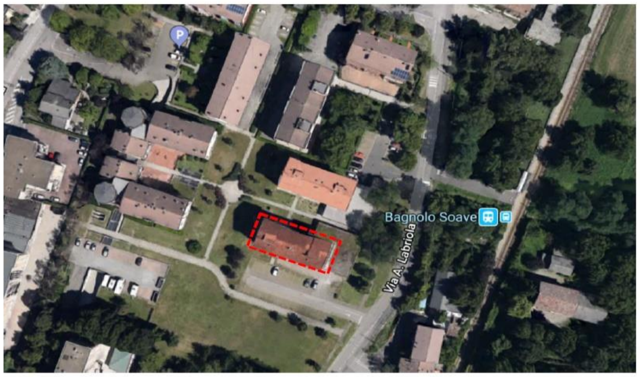

Figure 27. Site Plan of the Italian Case Study Building [389]

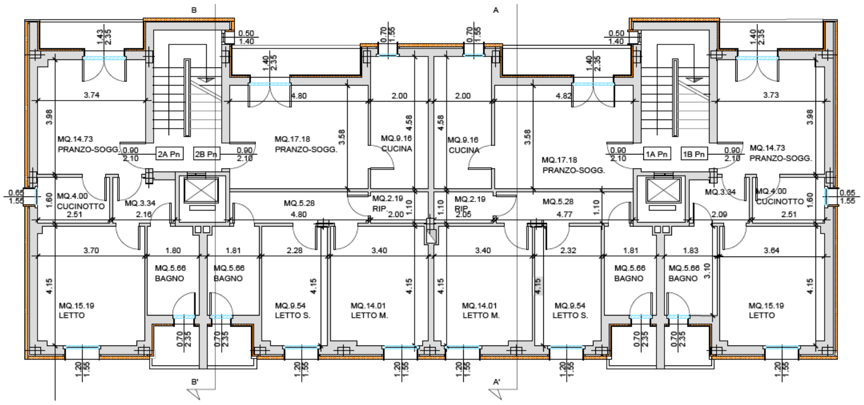

Figure 28. Typical Floor Plan of the Italian Case Study Building [389]

The temperature and relative humidity for Bagnolo in Piano site recorded from July 2018 until March 2020 was distributed from –7.7 to 38.2 °C, with an average of 14 °C, while the relative humidity has an average value of 69.8%. The cumulative HDD in the heating season 2018/2019 is 2450 degree days. The cumulative CDD for summer 2019 is 164 degree days. The heating system before retrofit is powered by a centralized boiler placed in the technical room which was installed in 1993. Such a system integrates a blown-air burner fed with natural gas; the boiler has a maximum thermal power of 90.4 kW and a net thermal power of 81.4 kW. The old heating emission system consisted of 4 radiators for one type of apartment and 5 radiators for the other type of apartment. There is no centralized cooling system before retrofit; multi-split units are installed only in 5 apartments. Therefore, the cooling system was not considered in the simulations. Moreover, DHW is produced by decentralized gas and electric boilers, and its production was not considered in the simulations. All existing windows have double glazing panes. Two types of window frames are considered, both without a thermal break: the first has a wood structure (U_f = 2.2 W/m^{2}K), and the U value is 3.3 [W/m^{2}K] whereas the second has an aluminum frame (U_f = 7.0 W/m^{2}K) and a U value is 4.1 [W/m^{2}K]. Furthermore, the external walls of the building are composed of two different types. The first type is composed of internal plaster, hollow brick, and external plaster and has a U-value of 1.195 [W/m²K], whereas the second type consists of internal plaster, hollow brick, polyethylene sheets, lime renders, hollow brick and external plaster, and has a U-value of 0.49 [W/m²K].

4.3.2 Implemented Smart Retrofit Technologies Description

It is important to understand the used smart technologies in the selected case study to be able to define the important metrics required for the KPIs and assign which technologies can the KPI measure. To reach the nZEB target and achieve energy efficiency, the following retrofit technologies are implemented in the retrofit case study:

1. To decrease the thermal energy demand of the building envelope for heating and cooling:
   - **Modular façade thermal insulation** is composed of panels that are pre-shaped and pre-drilled at the industrial level.
   - **Specific techniques/components for windows retrofit**, to increase the performance of existing windows, while preserving some original elements.
2. To generate thermal energy for heating, cooling, and domestic hot water production using high-efficiency equipment and by exploiting renewable energy sources:
   - **Hydronic air-to-water DC heat pumps** can use renewable DC power to generate heating and cooling energy.
   - **Smart DC fan-coils for heating, cooling, and DHW production**. The units are designed to substitute radiators, using the existing hydronic distribution system. A special unit is designed for the installation in bathroom/kitchens, to also provide DHW exchanging heat always with the existing hydronic distribution system. During the summer, this configuration allows the complete recovery of waste heat generated by the fan coils working in cooling mode.
   - **Universal PV tiles** are integrated into pitched roofs.
3. Dispatch and store energy within the building, utilizing:
   - **High-efficiency water storage tank,** which allows cost-effective thermal storage of PV electricity, is characterized by a modular and compact structure, thanks to the use of PCM and a high-insulation casing.
   - **Multi-Input/Multi-Output power controller (MIMO),** with the main function to dispatch and regulate at the building level the DC energy generated by PV tiles, to power the other DC subcomponents, to allow the interface with electric storage (Battery) and the interconnection with the AC grid.
4. Allow effective decision-making in the design phase and energy management in the operating phase, using:

- **Cloud-platform integrating a DSS and a BEMS**, based on a simplified building virtual model and optimized logic to ease the decision-support, the design, and the energy management phases, by using a unique tool.
- **Sensors, actuators, and communication devices (IoT devices)** to be based on the Narrowband IoT communication standard to allow a low-cost and effective interaction among the cloud platform and the toolkit subcomponents.

4.4 Testing and Implementation of Key Performance Indicators

This section details the application of the selected KPIs in the Italian Case study of the HEART project. The HEART project is a holistic smart retrofit project that should have a performance close to the top-performing threshold since it had addressed all the influencing parameters/technologies of the KPIs that were discussed in the previous section. These technologies include the RES integration, storage system, control system, DHW system, heat pumps, smart fan coil, and BEMS in addition to the system optimization to meet building demands. Thus, the KPIs and their thresholds are validated on a real smart retrofit building. To test the KPIs an Excel Spreadsheet has been developed by specifying the inputs required for calculation with their corresponding equations for each KPI. Hourly data that was retrieved from TRNSYS simulations have been used as the basis for calculations. The building was numerically modeled using TRNSYS software together with TRNBuild to implement the building characteristics using Type 65 in the model and validated with real acquired data [390] (details of the model are provided in the HEART Deliverable document which is confidential and not public). A specific yearly weather file is generated from DEXT3R weather dataset of ROLO (Reggio Emilia province) [389]. The dataset includes hourly data for dry bulb temperature, relative humidity, and solar radiation of each specific year. No cooling was considered in the building before retrofit, only heating demand was considered. After the retrofit, rule-based control logic was developed. The control signals are retrieved for each control rule and are modeled by Type 2D in TRNSYS which is the differential controller. The Control heating setpoint was 20°C and the cooling setpoint was 26°C. Phase Change Materials (PCM) thermal energy Storage temperature ranges between 26°C to 28°C and has a capacity of 40 kWh [391], [388]. TES and air-to-water heat pump Types in TRNSYS are generated by HEART experts' custom types. 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 1.39 [W/m^2. K]. Furthermore, the BEMS implements logic operation to control and deliver the electric energy flux, information, and thermal energy, as well as the coordination of the main devices – Multi-Input Multi-Output (MIMO), heat pump, TES tanks, PV, and Fan coils in the building [392].

The KPIs require hourly, monthly, or yearly data. These calculations measure the implemented technologies in the retrofitted building and specify if they are within the "Minimum Acceptable Limit" or the "Top Performing Limit" boundary.

4.4.1 Testing Key Performance Indicators on the HEART Project

1. Implementation of Primary Energy Indicator on the Italian Case Study

As identified by [351], the primary energy indicator sums up all delivered and exported energy (electricity, district heat/cooling, fuels) into a single indicator. Primary energy is calculated from delivered and exported energy with national non-renewable primary energy based on Equation 1.

The building retrofit is being finished and thus hourly data was retrieved from TRNSYS model that was validated on monitoring results of a partial retrofit phase have been used as the basis for calculations [391], [388]. These calculations measure the implemented technologies in the retrofitted buildings and specify if they are within the limit boundaries of thresholds set in the previous sections. Cooling was not considered in the building before retrofit, only heating demand was considered. The following table (Table 18) represents the data of the building before retrofit was used for non-renewable primary energy calculation.

Table 18. *Data for Non-renewable Primary Energy Calculations - Before Retrofit*

Non-Renewable Primary Energy Variables Before Retrofit Based on Equation 1	
***Edel,i* [kWh/y] (Delivered energy)**	69624
***Eexp,i* [kWh/y] (Exported energy)**	0.00
fdel,nren,i (Delivered energy non-renewable primary energy factor)	2.30
fexp,nren,i (Exported energy non-renewable primary energy factor)	2.30

After the retrofit, heating, cooling, and DWH energy demand were calculated. The PV production covers 50% of the building energy consumption. Table 19 represents the annual energy demand, consumption, and PV production after the retrofit.

Table 19. *Data for Non-renewable Primary Energy Calculations - After Retrofit*

Non-renewable Primary Energy Variables After Retrofit Based on Equation 1	
Annual PV Production [kWh/y]	12392
Annual Building Consumption [kWh/y]	21908
***Edel,i* [kWh/y]**	13982
***Eexp,i* [kWh/y]**	4465
fdel,nren,i	2.3
fexp,nren,i	2.3

The primary energy is calculated for the case study building before and after retrofit is detailed below and illustrated in Figure 29:

Before retrofit: the building before retrofit does not include RES thus the building delivered energy is the consumed energy, while there is no exported energy. Thus, based on Eq.1 the non-renewable primary energy was found to be 160137 kWh/y which equals 217 [kWh/m^2.y].

After retrofit: based on Eq.1 the calculated non-renewable primary energy was found to be 21887 kWh/y, which equals 30 [kWh/m^2.y]. Therefore, it meets the threshold assigned by national levels to reach a nZEB target.

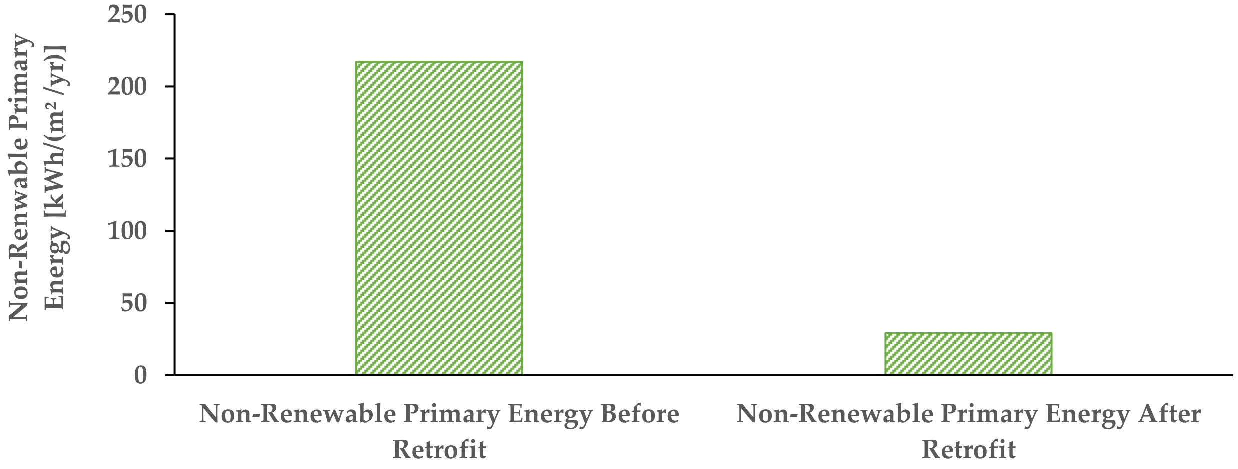

Figure 29. *Annual Non-Renewable Primary Energy Before and After Retrofit in kWh/m^2*

Overall, primary energy savings is 86% when the heat is supplied from electric heat pumps and smart fan coils compared to when it is from gas boiler heating.

2. Implementation of Shiftable Flexible Load Indicator in the Italian Case Study

To calculate the Shiftable flexible load indicator, two-building scenarios are considered, reference and smart which are the building before retrofit and after the retrofit, respectively. The flexibility is quantified through load shifting which is achieved with the control system that responds to the charging/discharging of TES. The heating system consists of a central system that includes a direct-current (DC) air/water HP and TES unit. The final distribution elements of the heating system are fan-coil units that contain a small DC-HP in each unit. Therefore, the TES unit should satisfy the boundary conditions of the considered heating system, where the maximal water supply temperature to the fan coils is 25°C and the return temperature to the centralized heating system is 15–20°C. The central DC-HP supplies heat to the heating system and supply it to the centralized TES for load-shifting. Load-shifting provides the operation of DC-HP at the most favorable outside conditions and allows its continuous operation during the period of charging the

TES unit which is charged with a constant water temperature. With load-shifting, the thermal load is shifted to the time when demand for heating takes place. Therefore, the higher the amount of stored heat, the higher the ratio of meeting the heating needs with load-shifting. The logic of the control system of the HEART allows the TES to shift load and has been further described in [391].

The load shifting was resembled in Equation 2 discussed previously. It allows monitoring of the amount of annual load shifted due to the presence of TES. The S_{flex} is calculated using hourly time resolution. The annual load was shifted from 51116 kWh to 21778 kWh translating to a shiftable flexible load of 57%. Hence, using TES together with PV production, can alleviate the peak load demand and improve the energy efficiency of the system.

3. Implementation of RES Self-Consumption Indicator in the Italian Case Study

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 PV plant is 10 kW installed to meet the building requirements. The monthly values of the production from the PV plant are reported in Figure 30. Based on the PV output the energy imported and exported to the grid was calculated. The data used for calculating this indicator are the PV production, building consumption, energy import to building, and energy export to the grid. Self-consumption was defined formally as the instantaneous building power consumption and was defined in Equation 3.

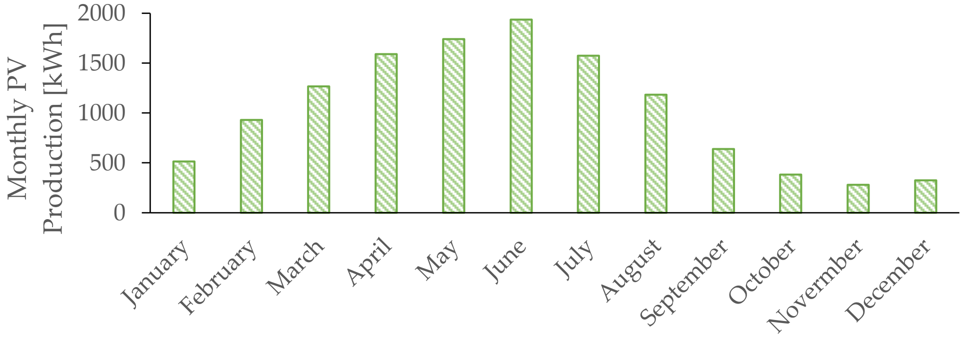

Figure 30. *Monthly Renewable Energy Production of the Installed PV Plant*

The imported energy from the grid is calculated based on the following assumption and presented in Table 20.

If the building consumption is > than the PV production, then the imported energy is the building consumption – PV production, otherwise, it is 0.

While for the PV exported to the grid, the following calculation was done:

If the PV production is > building consumption, then the exported energy is the PV production – building consumption, otherwise, it is 0.

The hourly simulations of PV production, and energy imported and exported to the grid is calculated (Table 20). The PV SC is calculated considering the charging and discharging of the storage system. The annual SC with storage is assessed using Equation 3 and was found to be 64%. To monitor the effect of TES in the building for the performance of this indicator, the SC is evaluated without the integration of the storage system and was found to be 1.37%. This result shows that the integration of the storage system is very crucial in calculating the RES SC indicator.

Table 20. *RES Self-Consumption Indicator Calculation Variables*

RES Self-Consumption Indicator Calculation Based on Equation 3	
Annual PV Production [kWh]	12392.04
Annual Building Consumption [kWh]	21908.44
Annual Energy fed into the grid [kWh]	4465.82
Annual Energy is taken from the grid [kWh]	13982.22
Annual Building own consumption (Energy used directly in a building) [kWh]	7926.22

For a more detailed assessment, a representative day is selected in summer and winter to calculate the SC. Figure 31 shows the PV production, self-consumption, and building consumption during a representative day in May. On this selected day SC is around 49%. As can be seen, there is an amount of surplus PV production from 13:00 to 17:00, thus, SC can be increased by shifting the building load to these hours to allow PV production to be self-consumed immediately.

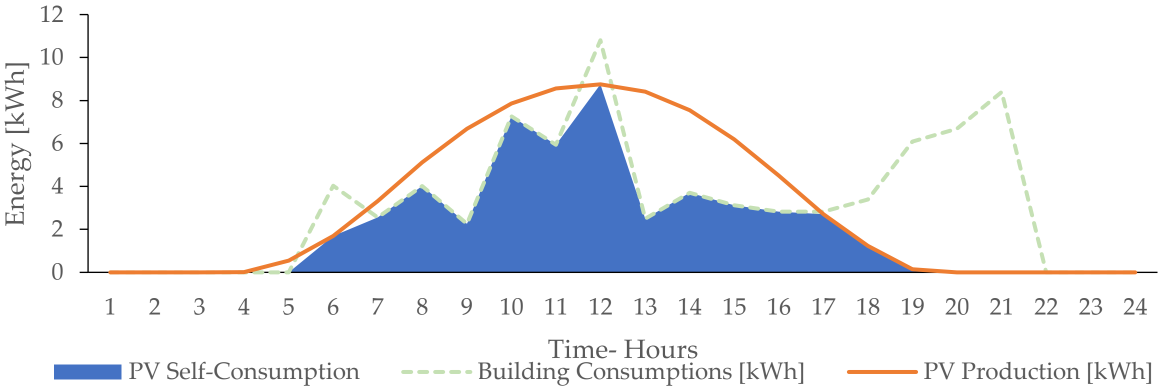

Figure 31. *Building Consumption, PV production and Self-Consumption in a Representative Day in May*

Another representative day is selected during the winter season in February (Figure 32). On this selected day SC is around 13%. This is since the peak loads occur during the hours of no on-site electricity production which are distributed from 6:00 to 9:00 and then from 18:00 to 22:00. Thus, there is a surplus of PV production during this day which needs to be used by shifting the loads during the day from 12:00 to 17:00.

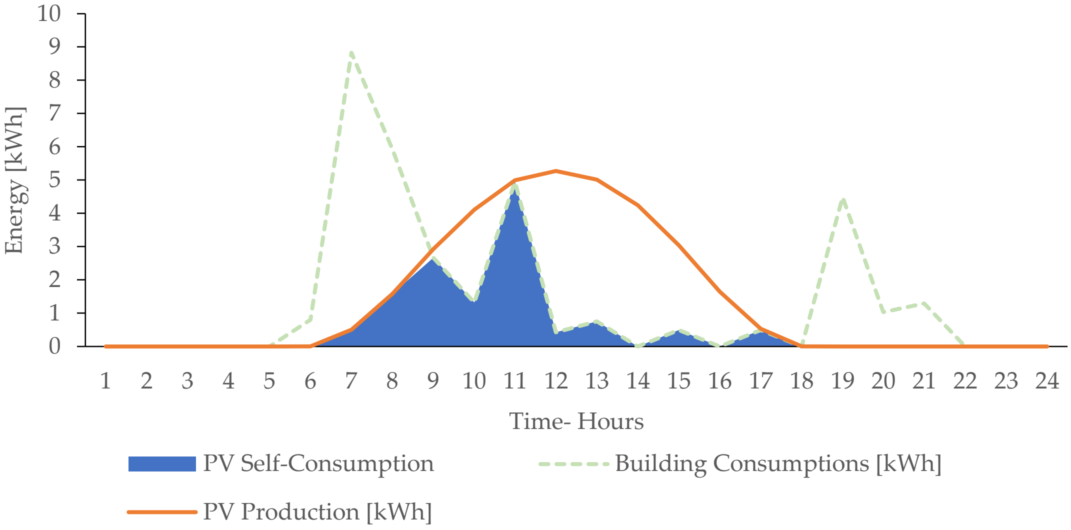

***Figure 32**. Building Consumption, PV production and Self-Consumption in a Representative Day in February*

4. Implementation of Load Cover Factor Indicator in the Italian Case Study

The load cover factor calculation is required to complete the evaluation of the PV in the building by which the self-consumption shows the consumed amount of RES onsite and the load cover factor shows the amount of demand covered by RES. Thus, similar parameters are required to calculate this indicator. Equation 4 has described the calculation of the load cover factor. In the following calculations, the considered parameters are the on-site generation, storage charging and discharging energy, and building consumption.

Load Cover factor was calculated at four different time resolutions, hourly, daily, monthly, and yearly. This factor can illustrate both the daily and seasonal effects by showing the production pattern of renewable energy and applied operation/control strategies. The values of the load cover factor were calculated using Equation 4 to show the variations throughout the year and are presented in Figure 33. The annual load cover factor shows that the PV electricity production covers 62% of the electricity demand of the building including heating, cooling, and DHW. While at the same timestep, the LCF without a storage system was found to be 48%. The storage system has an important role in this indicator since it can store the PV production and make use of it during the night times. As shown in Figure 33, as the time resolution increases the LCF decreases. To understand the seasonal effects of the LCF and how it is reflected in the annual indexes, the monthly variations with storage system integration are shown in Figure 34. Starting from October-January the LCF is low due to the low PV production in these months. February, on the other hand, has a high LCF due to the higher PV production values and lower electric consumption. Similarly, March, April, August, and September have lower consumption values and higher PV production, thus, most of the consumption is covered by the production achieving around 100% LCF. While May, June, and July have higher consumption values and lower PV production values. The hourly values give quite a good representation of the correlation between on-site demand and the energy supply.

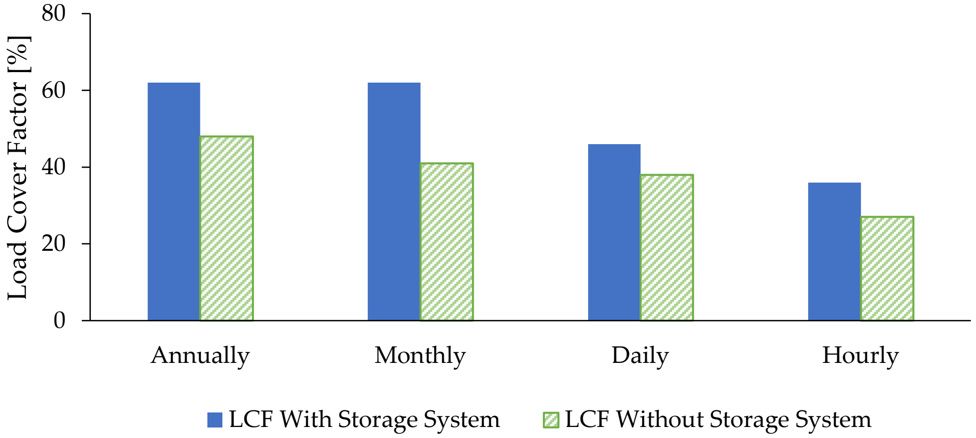

Figure 33. *Load Cover Factor Indicator with and without Storage System at Different Time Resolutions*

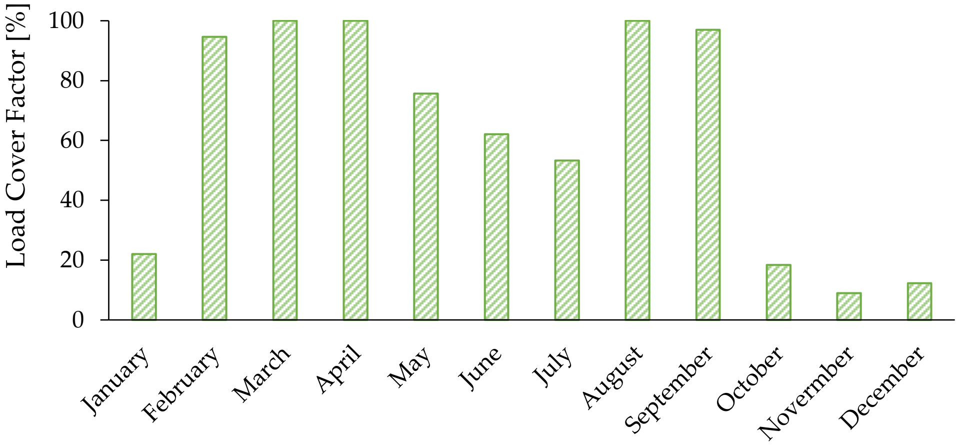

Figure 34. *Monthly Load Cover Factor Indicator Variations*

5. Implementation of Grid Interaction Index Indicator in the Italian Case Study

The index describes the fluctuation of the energy exchange of the building with the grid, not the amount of grid electricity needed. The Grid Interaction Index (f_{grid}) is calculated at three different time resolutions including hourly, daily, and monthly. Equation 5 presented previously consists of the net grid normalized to the grid connection capacity.

Similar to the previous indicators the GII is calculated with and without storage. First, the indicator was calculated without storage integration. According to Equation 5, the index based on the three different time resolutions with and without TES is presented in Figure 35 showing the variation in the energy exchanged between the building and the grid. It is shown that the highest index is in the monthly resolution, while the least is the hourly time resolution showing a higher peak value relative to the average fluctuations in the hourly data that leads to a lower value. On the other hand, the GII without storage is higher than with storage which is evident since the absence of a storage system causes higher interaction with the grid.

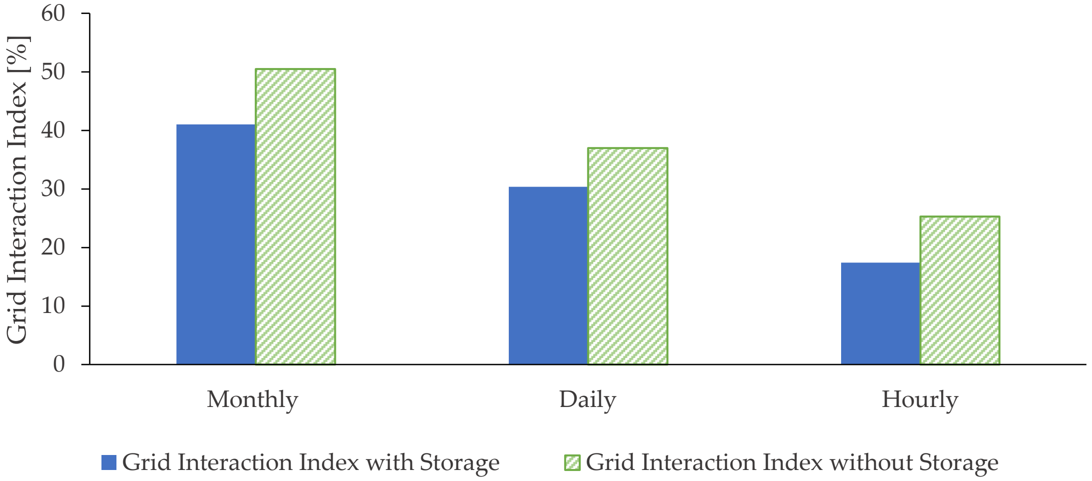

Figure 35. *Grid Interaction Index Comparison with and without Storage at Different Time Resolutions*

4.4.2 Summary of Testing KPIs on the HEART Project Case Study

The previous part has shown the calculation of the indicators in the HEART Italian case study. Some indicators were tested by considering the storage system and by eliminating it since this parameter can affect the result significantly and thus to measure the percentage of improvement the system adds when evaluating these indicators. To summarize the results, Table 21 presents the achieved results from the tested indicators with storage systems and compares them to the range of acceptable values that can identify the thresholds for the indicators.

Table 21. Summary of Results of KPIs' Tested on the HEART – Italian Case Study

Indicator	Achieved Result	Identified Values Based on Literature	Interpretation
1. Primary Energy Indicator	29.70 kWh/m^2/y 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 efficient HVAC system was implemented and supported by RES.
2. Shiftable Flexible Load	Annual Load Shifting of 56%	Minimum Acceptable Limit: 30% Top Performing Limit: 70%	The storage size is limited considering the area of the technical room. Thus, the achieved load shifting is based on the available building conditions.
3. RES Self-Consumption	φ_{SC} with storage 64%	Minimum Acceptable Limit:30% Top Performing Limit:70%	Reasonable value considering that it's a residential building with the peak load not in phase with solar energy availability.
4. Load Cover Factor Indicator	$\gamma_{\text{load},y}$ 62%	Minimum Acceptable Limit:20% Top Performing Limit:70%	The LCF is closer to the top-performing threshold due to the limit of the PV size considering the geometric design of the building and the maximum power of the converter.
5. Grid Interaction Index	$f_{grid,h}$ 17% $f_{grid,d}$ 30% $f_{grid,m}$ 41%	Minimum Acceptable Limit: Hourly 30%, Daily 40%, Monthly 50% Top Performing Limit: Hourly 10%, Daily 20%, Monthly 30%	The GII values lie in between the minimum and top limits due to the reasons explained above for the solar availability of the building and the conditions for the PV and storage sizing to match the building design conditions.

CHAPTER

5

5. GENERALIZING AND NORMALIZING KEY PERFORMANCE INDICATORS

The previous chapter has investigated the application of the KPIs to a specific case. In this chapter, a more generalized description is provided for the indicators. First, the benefits of the indicators are discussed in relation to the sustainability pillars including social, economic, and environmental aspects. Then, to address the relation between the developed indicators and the SRI, a comparison is carried out to support its' quantification. Finally, a normalization process is done to develop a common numerical scale that abstracts the diverse indicators scales. This step is done to make comparisons possible among a wider number of buildings and be able to test the KPIs on several buildings and compare their performance. The chapter sets a preliminary method for normalizing KPIs by setting an index for each KPI to measure the success of each indicator and paves the way for further research for developing a weighting and aggregation method to make a common index for the KPIs.

5.1 Benefits of Key Performance Indicators for Buildings Smart Retrofitting

After setting quantified measuring KPIs for the performance of smart buildings/retrofit, it is important to assess the benefits of those KPIs in relation to sustainability aspects. Moreover, since one of the main objectives of the thesis is to improve the methodology of the SRI, the relation between the developed KPIs and the SRI should be explored. This section investigates these two aspects and sets the KPIs concerning the broader building environment.

5.1.1 Sustainability Aspects of Key Performance Indicators for SR Projects

Given the applicability of KPIs for the performance assessment of retrofitted buildings, the use of the indicator approach is rapidly becoming one of the most valuable tools for the quantification of the benefits of retrofit implementation [59], [393], [394], [395]. To conclude the previous KPI selection analysis, thresholds set, and case study results, a guideline is developed to show the KPIs required data, advantages, disadvantages, and impacts. This guideline can be used as an initial step to support building designers and owners to facilitate easier calculation steps and interpretations for SB/SR projects (Table 22). Moreover, to relate the KPIs to the sustainability pillars, an assessment has been made showing how each KPI can affect the environmental, social, and economic impacts presented in Table 22 Achieving the identified thresholds of these indicators also results in several impacts that can be categorized in the following fields:

- Economic: Increased annual energy savings, Life cycle cost-saving, Project profitability.
- Environmental: Energy and Carbon Emissions, reduced emissions given by embodied energy decrease, reduced emissions given by RES energy production increase.
- Social: User Satisfaction, Enhanced quality of life, user awareness.

Table 22. *KPIs Sustainability Impacts on SR/SB*

KPI	Required Data	Impact			Comments
		Environ-mental	Social	Economical	
Non-renewable Primary Energy Indicator	• Annual delivered energy on-site or nearby for energy carrier [kWh/ m²/a] • Annual exported energy on-site or nearby for energy carrier [kWh/ m²/a] • Floor area (m²)	√		√	• This indicator can imply if the building falls within the nZEB targets or not. • Determine the cost of renovation. • It can show the reduced emissions given by embodied energy decrease.
Shiftable Flexible Load	• Heating demand before retrofit [kWh/ m²/a]. • Heating demand after retrofit [kWh/ m²/a]. • Renewable energy production [kWh/ m²/a]. • Electricity price [kWh/ m²/a]. • Heating energy is used during high and medium price periods (with and without storage strategy) [kWh/ m²/a].	√	√	√	• Flexibility allows load reductions and shifting in response to price/grid signals as well as response to user needs and demands. Therefore, if the threshold values are achieved it can have environmental, economic, and social impacts.

RES Self-Consumption	• The energy to and from the storage unit when charging and discharging [kWh/ m²/a]. • Instantaneous building energy consumption [kWh/ m²/a]. • Instantaneous on-site RES energy generation [kWh/ m²/a].	√	√	√	• If the threshold is achieved, it leads to less amount of electricity bought from the grid leading to a reduction in the demand for fossil fuels and, in turn, lower the levels of CO_2 emissions. • Benefits to economic stakeholders to assess the profitability of self-consumption. • Social impacts by making 'prosumers' able to self-consume their generated sustainable electricity. • Higher rates of self-consumption can show electricity demand response management where peak energy use is shifted to off-peak periods. • Facilitate the integration of variable renewables onto the grid and lower the overall costs of the energy system through load shifting.
Load Cover Factor	• On-site generation [kWh/ m²/a]. • The power to and from the storage unit when charging	√	√	√	• Successfully achieving this indicator can ensure load matching between the produced energy and

	and discharging [kWh/ m²/a]. • ζ(t) storage energy losses [kWh/ m²/a]. • Building consumption [kWh/ m²/a].				consumed energy. This can lead to buying less energy from the grid and in return reducing the environmental impacts. • Furthermore, a high LCF can show the influence of different strategies and measures of load modulation, such as demand-side management which is affected by the "Prosumers" who can reduce building loads. • Eventually, reducing building loads, and allowing higher load cover factors will lead to cost savings.
Grid Interaction Index	• Building Consumption [kWh/ m²/a]. • Annual delivered energy on-site or nearby for energy carrier [kWh/ m²/a] • Annual exported energy on-site or nearby for energy carrier [kWh/ m²/a] • On-site generation [kWh/ m²/a]. • Net grid metering over a given period [kWh/ m²/a]. • Maximum grid connection capacity [kWh/ m²/a].	√	√	√	• Lower grid interaction will lead to economical savings and reduced environmental impacts. • Low grid interaction is achieved by low delivered and exported energy to the grid. Therefore, when the building is autonomous of the grid, the "Prosumer" can use the locally produced energy on-site.

Table 22 has summarized the five essential indicators for evaluating the smartness of retrofitted buildings. Most of the indicators cover the three sustainability impacts including environmental, social, and economic.

5.1.2 Relation Between SRI and Smartness Key Performance Indicators

This section addresses one of the main objectives of this thesis which lies in improving the SRI and helping to quantify it through the developed KPIs and their defined thresholds. To make a valid comparison between the SRI and the Smartness KPIs developed in this thesis, the SRI is first calculated. The SRI calculation procedure is developed by the European Commission and is based on a multi-criteria assessment to evaluate multiple domains and impact criteria [396]. The overall SRI score indicates the building's performance by assessing how close to, or far from the maximum level of smartness. As previously mentioned in Section 2.2.1, the method of calculating the SRI involves three different approaches: Method A, Method B, and Method C.

Therefore, in this thesis, Method A has been selected as a method of evaluating the HEART project smart readiness since it is a simplified method that can be carried out without an expert and is suitable for residential buildings. For the testing of the SRI, an Excel-based calculation tool has been provided in the technical support study developed by the SRI developers [197]. Figure 36 summarizes the steps required to calculate the SRI which is realized based on the latest version of the SRI methodology [197]. It should be noted that Method A is a simplified method that allows self-assessment for the building evaluation, however, it can cause less accurate results related to the smart readiness of the buildings and result in less reliability. Therefore, for more detailed valuation and reliability, it is advised to use Method B which will require a Third-party expert to make on-site inspection to evaluate the adopted technologies and services and thus allow more accurate assessment.

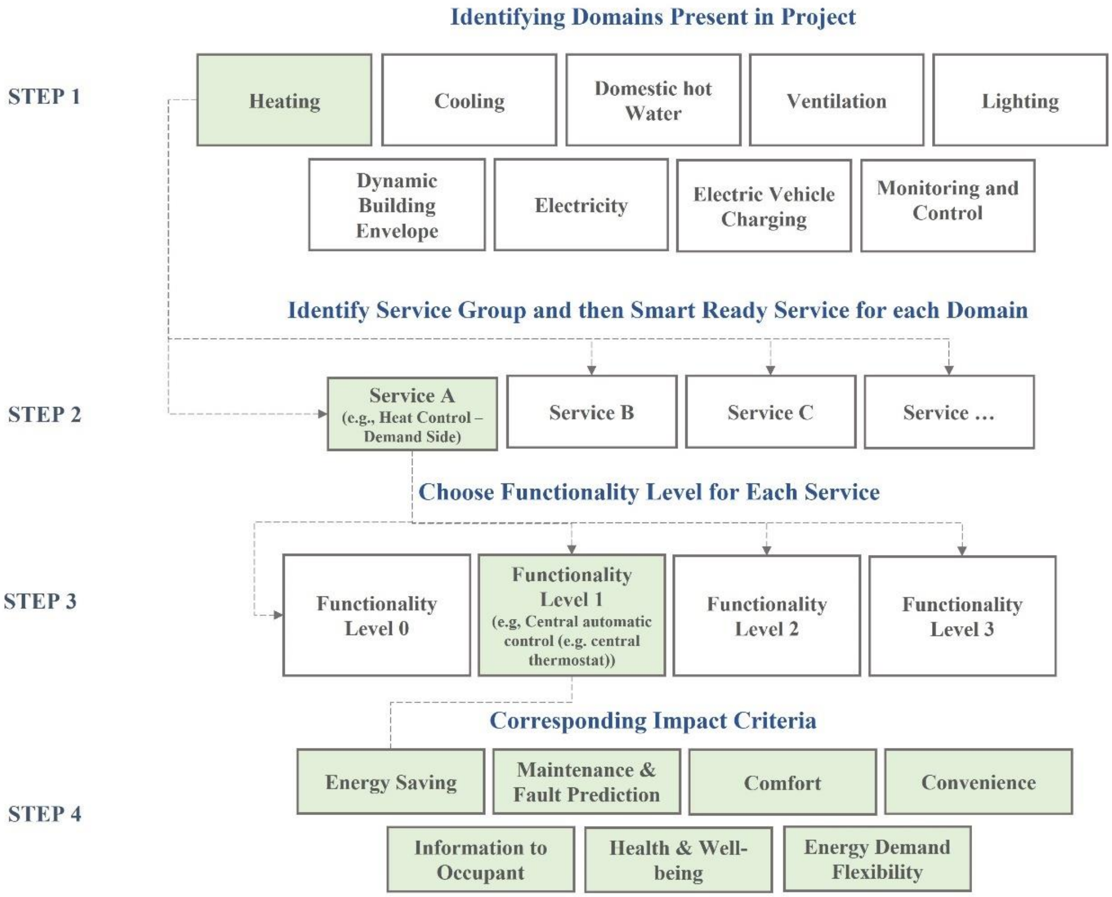

Figure 36. *SRI Calculation Logic*

In the first step of SRI assessment, general building data were identified as presented in Table 23. The table shows the possible available options for each input with the corresponding selected options for each one in bold. The selected domains covered in the HEART Italian case study are presented showing that all domains are present excluding the Electric Vehicle.

Table 23. *SRI Calculation Input Data of HEART Project*

Input Information	Available Options
Building Type	**Residential**; non-residential
Building Usage	Single-family house; small multi-family house; **large multi-family house**; office; educational; healthcare; other
Climate Zone	Northern Europe; **Southern Europe**; Western Europe; North-Eastern Europe; South-Eastern Europe
Net Floor Area of the Building	<200 m²; 200-500 m²; **500-1000 m²**; 1000-10,000 m²; 10,000-25,000 m²; >25,000 m²
Year of Construction	<1960; **1960-1990**; 1990-2010; >2010; not yet constructed
Building State	Original; **renovated**

Domains	**Heating, Domestic hot water, Cooling, Ventilation, Lighting, Dynamic building envelope, Electricity, Monitoring, and control,** Electric vehicle charging

In the second section of the Excel-based tool, a triage process is carried out to identify which services should be considered for the final score. For each domain, specific smart ready services are defined according to the system characteristics of the service considered. Table 24 reports the relevant smart services in the building were selected in a triage process through a review of the buildings' technical documents. From this, the functionality level of each service was recorded based on the identified levels in the catalog for each case building. Different levels of functionality are assigned to each service, with each having its own scale of smartness, on an increasing scale from 0 (i.e., "non-intelligent" service) to a maximum value (which can vary from 1 to 4 depending on the service) for advanced features.

Table 24. *SRI Triage Process Results on the HEART Project*

Domain	Service Group	Smart Ready Service	Functionality Level	Description of Functionality Selected
Heating	**Heat control - demand side**	Heat emission control	Functionality Level 3	Individual room control with communication between controllers and BACS
	Control heat production facilities	Storage and shifting of thermal energy	Functionality Level 2	HW storage vessels are controlled based on external signals (from BACS or grid)
	Control heat production facilities	Heat generator control (all except heat pumps)	Functionality Level 2	Variable temperature control depending on the load (e.g., depending on supply water temperature set point)
	Control heat production facilities	Heat generator control (for heat pumps)	Functionality Level 2	Variable control of heat generator capacity depending on the load or demand (e.g., hot gas bypass, inverter frequency control)
Domestic Hot Water	**Information to occupants and facility managers**	Report information regarding heating system performance	Functionality Level 4	Central or remote reporting of performance evaluation including forecasting and/or benchmarking; also including predictive management and fault detection
	Control DHW production facilities	Control of DHW storage charging (with direct electric heating or	Functionality Level 2	Automatic control on / off and scheduled charging enable

		integrated electric heat pump)		multi-sensor storage management
	Flexibility DHW production facilities	Control of DHW storage charging	Functionality Level 2	Automatic charging control based on local availability of renewables or information from the electricity grid (DR, DSM)
	Information to occupants and facility managers	Report information regarding domestic hot water performance	Functionality Level 1	Indication of actual values (e.g., temperatures, submetering energy usage)
Cooling	**Cooling control - demand side**	Cooling emission control	Functionality Level 1	Central automatic control
	Control cooling production facilities	Generator control for cooling	Functionality Level 3	Variable control of cooling production capacity depending on the load AND external signals from the grid
	Information to occupants and facility managers	Report information regarding cooling system performance	Functionality Level 4	Central or remote reporting of performance evaluation including forecasting and/or benchmarking; also including predictive management and fault detection
	Flexibility and grid interaction	Flexibility and grid interaction	Functionality Level 3	Cooling system capable of flexible control through grid signals (e.g., DSM)
Ventilation	**Air flow control**	Supply airflow control at the room level	Functionality Level 3	Central Demand Control based on air quality sensors (CO_2, VOC, humidity, ...)
	Feedback - Reporting information	Reporting information regarding IAQ	Functionality Level 1	Air quality sensors (e.g., CO_2) and real time autonomous monitoring
Lighting	**Artificial lighting control**	Occupancy control for indoor lighting	Functionality Level 1	Manual on/off switch + additional sweeping extinction signal
Dynamic Building Envelop	**Window control**	Window solar shading control	Functionality Level 2	Motorized operation with automatic control based on sensor data
	Feedback - Reporting information	Reporting information regarding the performance	Functionality Level 2	Position of each product, fault detection & predictive maintenance

		of dynamic building envelope systems		
Electricity	**Feedback - Reporting information**	Reporting information regarding local electricity generation	Functionality Level 2	Actual values and historical data
	DER - Storage	Storage of (locally generated) electricity	Functionality Level 4	On-site storage of energy (e.g., electric battery or thermal storage) with controller optimizing the use of locally generated electricity and possibility to feed back into the grid
	Feedback - Reporting information	Reporting information regarding energy storage	Functionality Level 3	Performance evaluation including forecasting and/or benchmarking
	Feedback - Reporting information	Reporting information regarding electricity consumption	Functionality Level 2	real-time feedback or benchmarking on building level
Monitoring and Control	**Feedback - Reporting information**	Central reporting of TBS performance and energy use	Functionality Level 2	Central or remote reporting of real-time energy use per energy carrier, combining TBS of at least 2 domains in one interface
	Smart Grid Integration	Smart Grid Integration	Functionality Level 2	Coordinated demand-side management of multiple TBS
	Single platform that allows automated control & coordination between TBS + optimization of energy flow based on occupancy, weather, and grid signals	Single platform that allows automated control & coordination between TBS + optimization of energy flow based on occupancy, weather, and grid signals	Functionality Level 3	Single platform that allows automated control & coordination between TBS + optimization of energy flow based on occupancy, weather, and grid signals
Total SRI Achieve	**80%**			

Later, the scores assigned to the individual services are summed up for each domain and then divided by the maximum individual scores to obtain a “domain impact score”. For each impact measure, the total score is calculated as a weighted sum of the “domain impact scores”. The SRI is then obtained as a weighted sum of the total impact scores. According to the Excel sheet, the Total SRI achieved for the HEART Italian case study is 80%. Moreover, Figure 37 and Figure 38 report the weight in percentage according to the seven SRI impacts scores, and the contribution of the percentage of the contribution of the nine domains, respectively. It shows that energy efficiency is the most attained impact. Moreover, all 7 impacts are achieved in a balanced percentage. While based on the domain scores attained based on the recorded functionality levels, it is shown that the DHW was fully achieved, in addition to the monitoring and control and cooling which were also successfully implemented.

From an economic perspective, a recent study done by Apostolopoulos et al., [397] has recently proposed a cost estimate of smart retrofitting in relation to the SRI achieved score. Results specify that buildings, constructed after the implementation of the EPBD, can increase smartness at a relatively low cost than older buildings. it showed that buildings that achieve more than 60% SRI score require on average 134 €/m^2. This is because these retrofit scenarios focus on a more holistic renovation that covers a high level of impact scores and domain scores. Therefore, for the HEART Italian case study, since 80% SRI score was achieved, this implies that more than 134 €/m^2 is the cost of renovation (costs estimation reference period during late 2021).

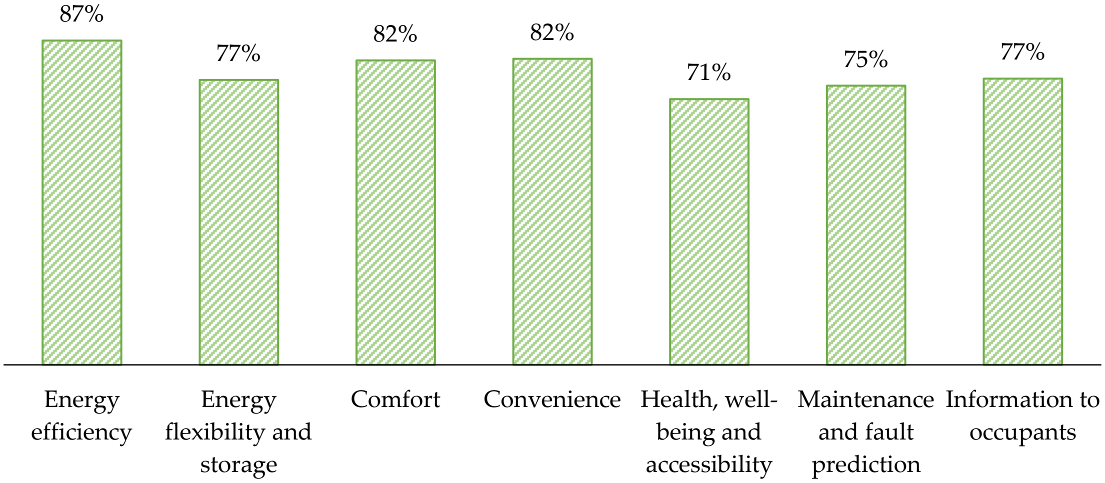

Figure 37. *SRI Impact Scores of HEART Project*

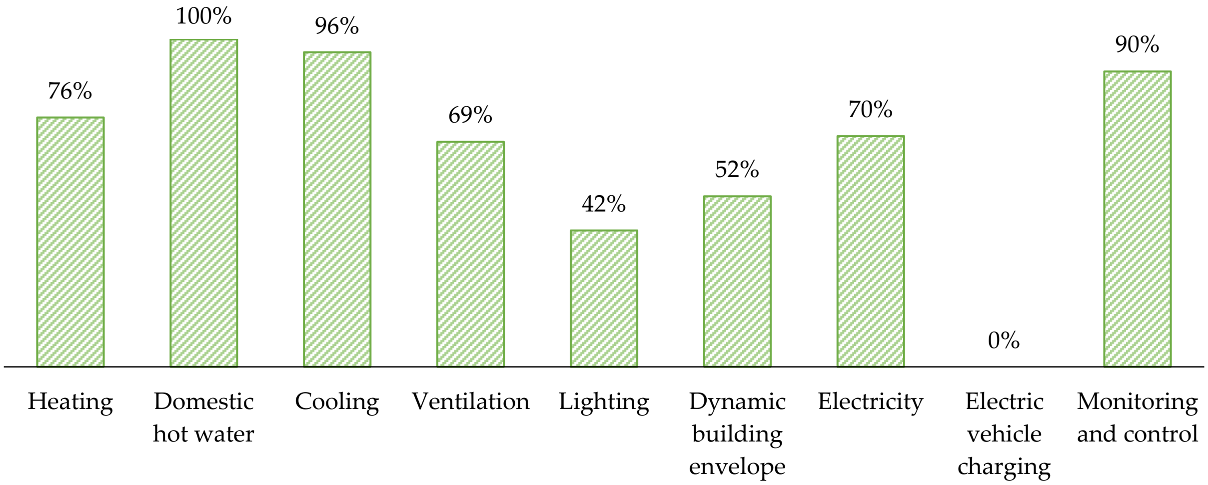

Figure 38. *SRI Domain Scores of HEART Project*

After calculating the SRI, it is possible to understand the relation between the SRI and the identified smartness key performance indicators. Figure 39 illustrates the functionalities of the SRI with their corresponding impacts and the smart KPIs functionalities with their corresponding indicators. In which the SRI allows optimizing energy efficiency, adapts to the needs of occupants, and adapts to signals from the grid, while the Smart KPIs include achieving nZEB targets, responding to signals from the grid, therefore, allowing flexibility, allowing real-time monitoring and real-time interaction. Thus, the developed KPIs can be used as a further detailed assessment of how the smart technologies perform. It is shown that the developed KPIs also share the domains of the SRI developed by the EPBD. This demonstrates that the KPIs do not replace the SRI, however, it can provide a further detailed assessment for the checklist assessment done by the SRI to evaluate the energy performance and the quantified benefit of the integrated smart technologies.

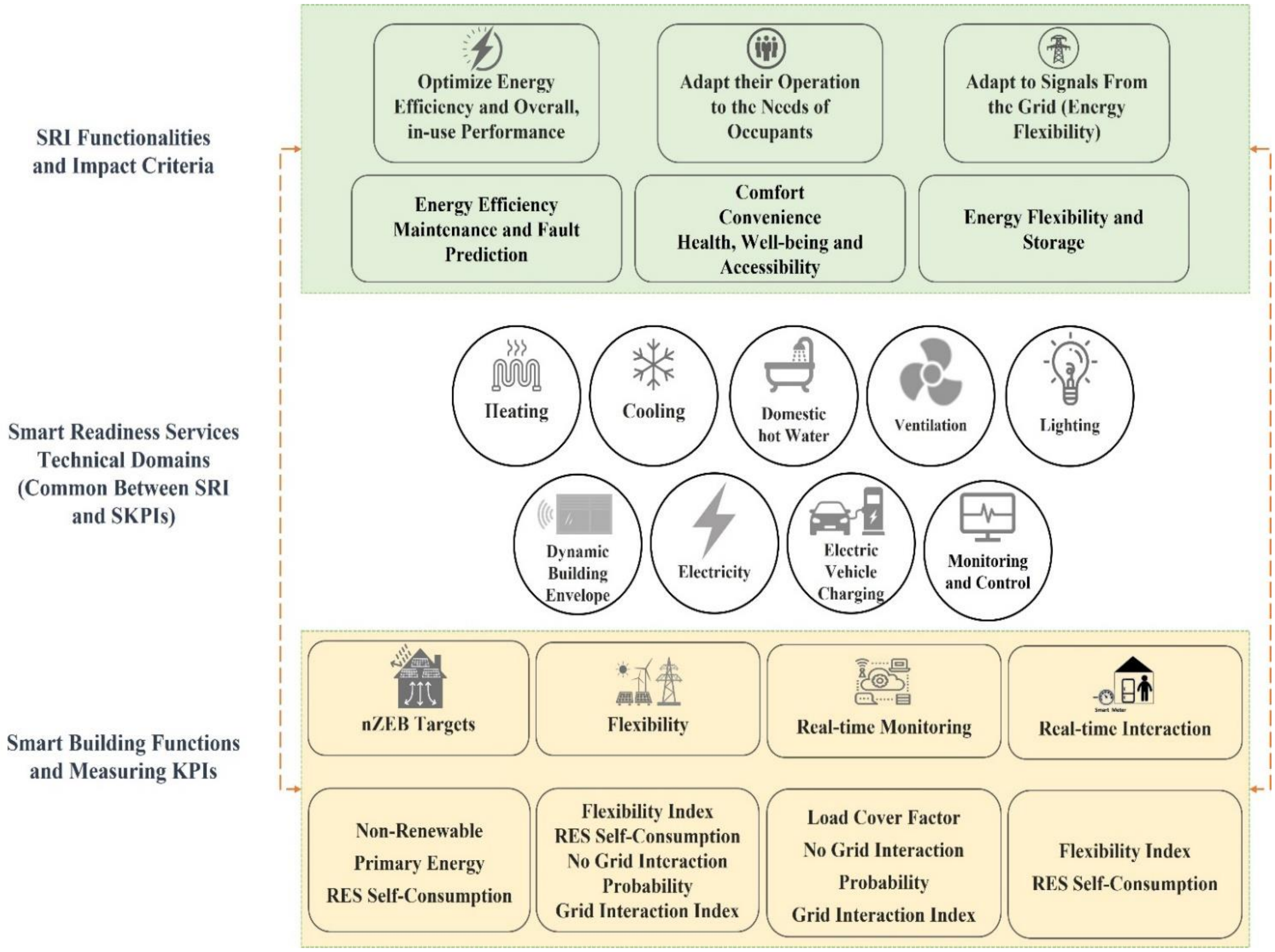

Figure 39. Relation Between SRI and Smartness Key Performance Indicators

5.2 Normalization Process

After setting quantified thresholds for the KPIs, to complete the evaluation of energy performance, not only should energy be quantified, but the corresponding figures should be normalized to make comparisons possible. Normalization makes data comparable across indicators so that the information can be combined in a meaningful way. Commonly, indicators are assessed in different measurement units and various ranges and value scales, thus, they need to be positioned on a common baseline. Normalization positions indicators on a common baseline to avoid problems introduced by the different measurement units [64]. Normalization was carried out in different research to form a common base for the indicators. For instance, the Sustainable Development Goals Index (SDGI) developed by Schmidt-Traub et al. [398], and the Human Development Index (HDI) published by the United Nations Development Program [399] have set indexes using a rescaling approach to set the values from 0 to 100, with 0 denoting worst performance and 100 describing the optimum. Toosi et. al [400] have carried out a normalization method for Life Cycle Assessment sustainability indicators, which was based on dividing the indicator actual value by the baseline defined as the Business-as-Usual model's performance (BAU) for new building design or the pre-retrofit performance for retrofitting design. Abu-Rayash and Dincer [401] have developed a normalization method for smart city indicators forming indexes for each domain of a smart city. The method of normalization deployed is feature scaling which involved min-max values to ensure that all results are within the range of [0,1]. In the SRI developed by the EPBD [197], a normalization process was done for the summed impacts. It was done by dividing the sum of the nominal impact scores by the sum of the maximum possible nominal impact scores that could be reasonably attained for the given building and multiplying by 100. The final aggregate score thus represents an overall percentage of the maximum score. This ratio, expressed as a percentage, is the SRI score of a building or building unit.

Furthermore, in [64] several normalization procedures have been described including:
1. Classification method which normalizes the indicators using the rank or classification of the value. This simple normalization technique is unaffected by discrepant data points and allows the performance to be tracked over time in terms of relative positions (rankings).

2. Z-scores method which converts indicators into a common scale with zero mean and one standard deviation.

3. Min-Max method is a very common method and standardizes the indicators to achieve an identical range, for example between [0, 1], by subtracting the minimum value and dividing by the range of the extreme values.

4. Relative to the maximum value method that assigns a value of 1 to the highest value of a specific indicator, while the other values are classified as a fraction of the maximum. Therefore, the closer the value is to the maximum, the closer it is to 1.

5. Relative to the mean/median value method that assigns a value of 1 to the chosen reference value of a specific indicator, for example, the median, and therefore values above the reference receive a value higher than 1 and the smallest ones receive values below 1.

Therefore, different methodologies exist for the normalization of indicators, however, the nature of each indicator should be understood to choose a proper normalization method. Moreover, it is important to understand the purpose of normalization for the research. For Instance, in [402], the indicators are normalized to provide a framework for benchmarking practitioners and policymakers that suggests applicable combinations of denominators for a balanced normalization process. While in [403], the normalization was done as a preparation for the weighting step, by bringing the characterized impact results to a scale that is relevant for further weighting and comparisons across impact categories. In this thesis, the normalization aims at forming indexes of the KPIs to make them comparable with different projects (Figure 40). The normalized indexes identify how far the is indicator from the top-performing threshold. This allows forming a framework for stakeholders such as policymakers and users to understand the smartness of a building and how it is performing.

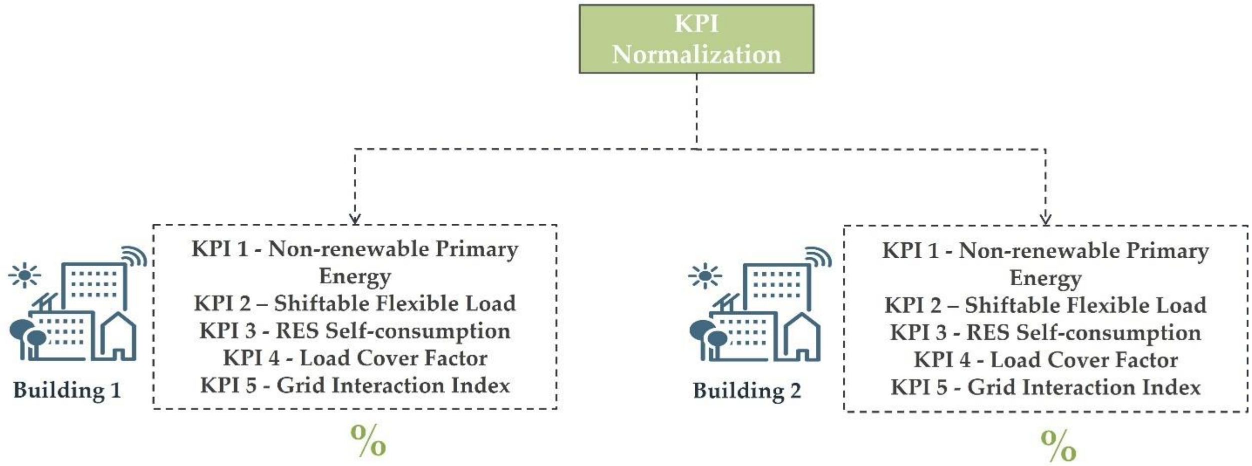

Figure 40. *Normalization of the KPIs*

Looking at the nature of the KPIs for calculating the normalization it is noticed that most of them do not have a baseline before retrofitting, i.e., for instance, the RES SC, grid interaction index, load cover factor, and flexibility indicator depend on the integration of RES in the building, which is usually done after retrofit, therefore there is no baseline for the indicator. This excludes the normalization methods that use the building baseline as a reference. While in this thesis, the thresholds developed previously, had allowed the formation of minimum, and maximum values for each indicator. Therefore, based on the previous methods, the most suitable one is the Min-Max method or also called the rescaling for defining an index for each indicator. The index (or indexes) is simply a high-order indicator of the KPIs [64]. Therefore, in this thesis, the index is defined as a quantified numerical value that evaluates the percentage of the achieved threshold of the indicator. Figure 41 illustrates a pyramid relating the basic functions and features of a smart building that were defined at the beginning of the thesis, and its' development path reaching to input parameters that identified the KPIs, then moving to quantify the thresholds of the KPIs by specifying "Minimum Acceptable Threshold" and "Top Performing Threshold", and finally, setting an index for each KPI that can make them comparable and can allow them to be scaled up to other projects.

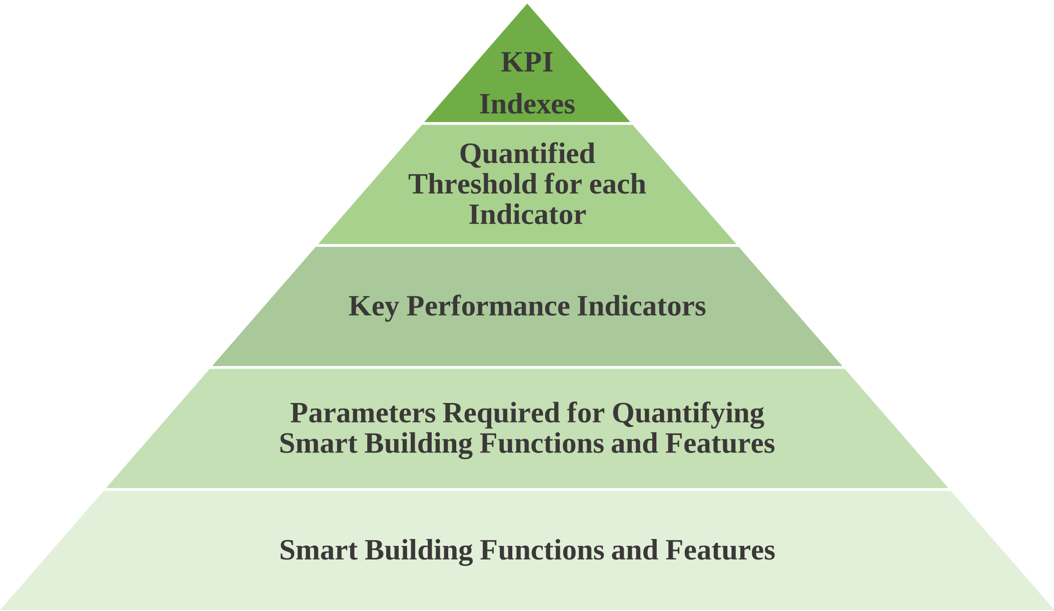

Figure 41. *Relationship between Primary data, KPIs, and the Final Indexes*

5.3 Normalization Application

Building on the thresholds identified previously for the KPIs, the normalization of indicators can be developed. The Min-Max method or (rescaling) is classified as an internal normalization where variables are normalized with references linked to the alternative assessed in the study [403]. It is a simple method and consists in rescaling the range of indicators to scale the range in [0, 1]. The general formula for the min-max method is calculated using the following equation (Equation 6):

$$x' = \frac{x - min\ (x)}{max(x) - min\ (x)}\ Eq.6$$

x *is the original value of the indicator*
x'*is the normalized value*

This index shows to which extent the design scenario has higher or lower performance compared to the threshold. A higher index means better performance in the design process. Thus, for calculating the indexes, the logic for the five indicators is described in Equation 7, where x is the calculated KPI and xI is the index of the indicator.

$$xI = \frac{x - Minimum\ Acceptable\ Limit\ (x)}{Top\ Performing\ Limit\ (x) - Minimum\ Acceptable\ Limit\ (x)}\ Eq.7$$

Hence, the normalization can be done on the HEART Italian project is carried out and represented in Table 25. It should be noted that if the KPI value exceeds the maximum threshold, then the index is greater than 1. However, in the min-max normalization, the range should be between 0 and 1 to represent how far is the achieved value from the maximum. Therefore, achieving an index value greater than 1 is automatically represented as 1 showing that the maximum threshold has been successfully achieved.

Table 25. *Normalization of HEART Italian Case Study – KPI Indexes*

KPI	Achieved Indicator value	Index
Non-renewable Primary Energy	$\boldsymbol{PE_{nren}}$ **86%**	$PE_{nren}\ Index = \frac{PE_{nren} - \text{Minimum Acceptable Limit}(PE_{nren})}{\text{Top Performing Limit}(PE_{nren}) - \text{Minimum Acceptable Limit}(P}$ $PE\ Index = \frac{86-30}{80-30}=1.12 \approx \mathbf{1}$
Flexibility Indicator	*LS* **57%**	$Shiftable\ Flexible\ Load\ Indicator = \frac{FI - Minimum\ Acceptable\ Limit\ (FI)}{Top\ Performing\ Limit\ (FI) - Minimum\ Acceptable\ Limit\ (FI)} =$ $Flexibility\ Index = \frac{57-30}{70-30} = \mathbf{0.67}$
RES Self-Consumption	φ_{SC} **64%**	$RES\ SC\ Index = \frac{\varphi_{SC} - \text{Minimum Acceptable Limit}\ (\varphi_{SC})}{\text{Top Performing Limit}\ (\varphi_{SC}) - \text{Minimum Acceptable Limit}\ (\varphi_{SC})}$ $RES\ SC\ Index = \frac{64-30}{70-30} = \mathbf{0.85}$
Load Cover Factor Indicator	$\gamma_{load,y}$ **62%**	$LCF\ Index = \frac{\boldsymbol{\gamma}\mathbf{load} - \text{Minimum Acceptable Limit}\ (\boldsymbol{\gamma}\mathbf{load})}{\text{Top Performing Limit}\ (\boldsymbol{\gamma}\mathbf{load}) - \text{Minimum Acceptable Limit}\ (\boldsymbol{\gamma}\mathbf{load})} =$ $LCF\ Index = \frac{62-20}{70-20} = \mathbf{0.84}$
Grid Interaction Index	$f_{grid,h}$ **17%**	$GII\ Index = \frac{\boldsymbol{fgrid} - \text{Minimum Acceptable Limit}\ (\boldsymbol{fgrid})}{\text{Top Performing Limit}\ (\boldsymbol{fgrid}) - \text{Minimum Acceptable Limit}\ (\boldsymbol{fgrid})} =$ $GII\ Index = \frac{17-30}{10-30} = \mathbf{0.65}$

With this, a conclusion can be made by showing how far the index is from the maximum threshold. This can be generalized to other buildings (e.g., smart buildings/retrofit of a similar type). Moreover, these indexes can be further developed to form a single Index for smart retrofitting.

CHAPTER
6

6. CONCLUSIONS AND FUTURE WORK

This chapter sets the final framework for smart retrofitting, summarizes the main outcomes of this research, and discusses open challenges and future work.

6.1 Framework on Smart Retrofitting in the European Buildings Context

Achieving energy efficiency in buildings is an ambitious target for energy and carbon emissions reduction in nZEBs, Smart buildings, and retrofitting using commonly agreed and well-specified indicators. indicators should be linked to targets and thresholds to be able to achieve the specified energy efficiency in buildings. Moreover, this allows having a common language within the EU to get along with the growth of smart and energy-flexible buildings. Thus, clear definitions of the objectives and targets of the smart building should be set to estimate the explicit requirements and minimum levels to be achieved by smart buildings/retrofits.

Different frameworks have been set in the EU to provide guidelines, minimum thresholds, calculation methodologies, and steps for achieving certain targets in the building energy efficiency sector. The EN15603:2008 [404] gave an evaluation of the energy efficiency of new buildings and retrofits including calculation of energy needs, and primary energy, and assess the measured energy rating based on the delivered and exported energy through establishing a methodological framework for calculating cost-optimal levels of minimum energy performance requirements. Similarly, the Directive 2009/28/EC on renewable energy [22], has established a common framework for the production of energy from RES. It mandated that the EU community targets not less than 20% share from RES in gross energy final consumption in buildings and 10% in the transport sector. Moreover, as a part of the EU Green Deal [405], the commission required the worst-performing 15% of the building stock of each Member State to be upgraded from the Energy Performance Certificate's Grade G to at least Grade F by 2027 for non-residential buildings and 2030 for residential buildings. The target of this initiative is to maximize the potential for decarbonization and decrease energy poverty. Moreover, the Energy Renovation Framework was developed by the World Green Building Council [406]. A Framework has been developed for the following countries: Croatia, Hungary, Ireland, Italy, Poland, Spain, Turkey, and the United Kingdom which represents a tool that allows cities to monitor and quantify the real impact of energy renovation. It breaks down the holistic benefits of renovation initiatives into environmental, social, and economic indicators.

Accordingly, in this thesis, a framework is developed for measuring the performance of smart retrofitting and thus, quantifying its' benefits. The general framework presents the basic functions, features, and technologies of smart buildings (Figure 42). Then, it details the methodology of selecting representative KPIs to measure the energy performance of smart retrofit buildings. It also shows the impacts of the KPIs on the buildings' aspects and in relation to the SRI. The minimum energy requirements of the indicators for smart retrofitted residential buildings were set based on a methodology involving a literature review and a Logical Evaluation Method that correlated the indicators with their parameters. Finally, a standardized basis for the indicators is developed by normalizing the indicators into an index for each indicator. The index facilitates monitoring the success of each indicator by assessing how far the achieved result is from the maximum threshold.

Moreover, as indicated in Section 2.3.1, the definition of Smart Retrofitting is more detailed now considering the minimum thresholds for achieving it. Hence, it is defined as:

"The process of transforming an existing building into a SB, that is an nZEB with Primary Energy savings between 30% and 80% and have the capability of responding to the changing conditions of climate, and grid, communicate with the user, and predict failures in the building operations through the utilization of ICT, RES, and Building Energy Management Systems (BEMS). It shall allow Load Shifting in response to RES production/changing electricity prices of 30% to 70% annually and minimize grid interaction to around 10% - 30% of hourly interaction throughout a year. Moreover, it should allow RES Self-Consumption of 30% to 70% and Load covered by RES of 20% to 70% annually".

Consequently, a combination of indicator thresholds and indexes can form a clearly defined framework for measuring the smartness of a retrofitted building and comparing it to other similar residential buildings. This framework can allow building designers, users, and policymakers to evaluate the energy performance of smart retrofit projects and measure their success.

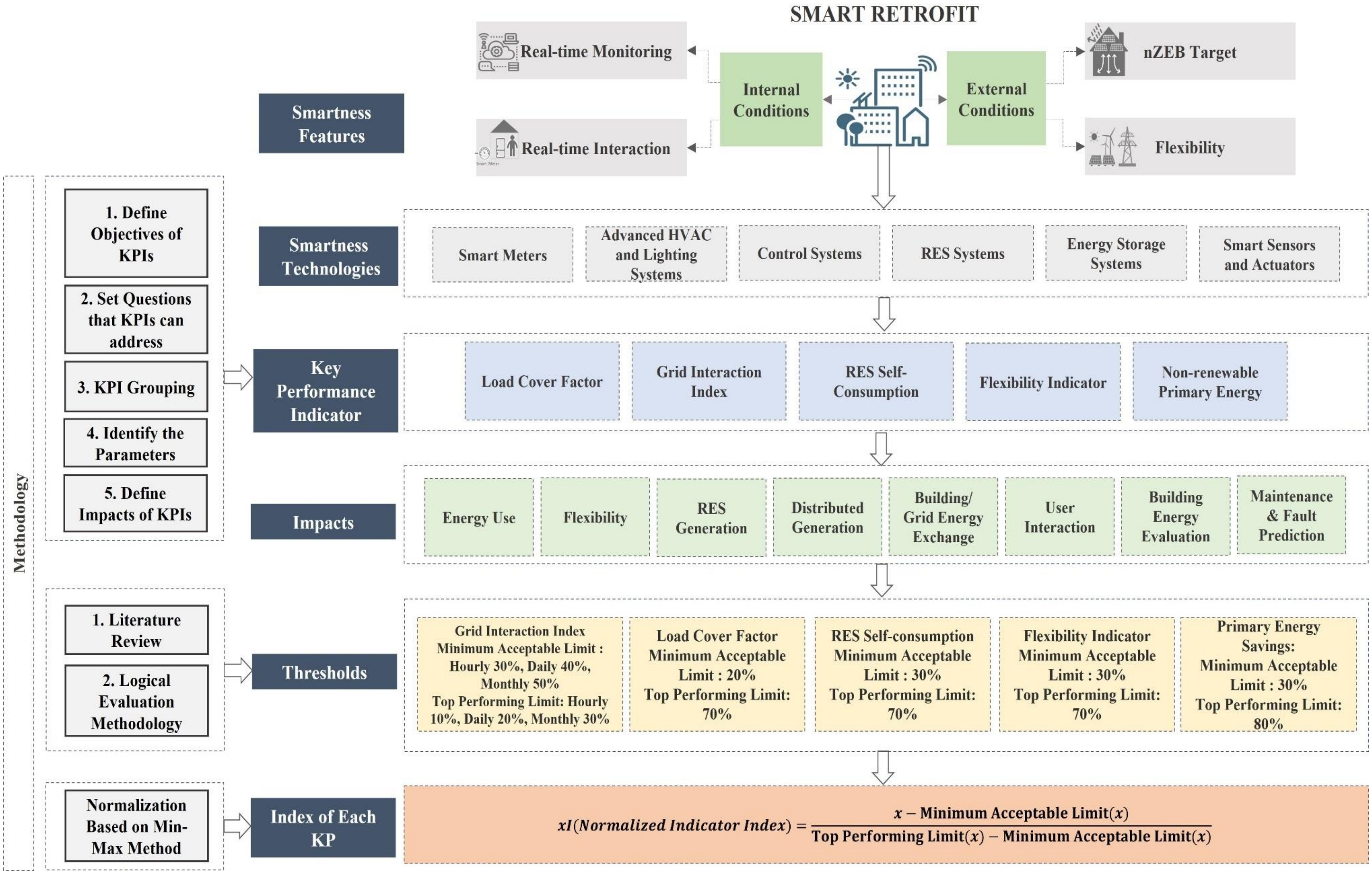

Figure 42. *Defined Methodology for Smart Retrofitting Framework*

6.2 Main conclusions

EU environmental and energy policy in the building sector has evolved representing concepts such as sustainability and energy efficiency. The EC has established the long-term objective of decreasing the CO_2 emission levels for the building sector by 80- 95% in 2050, compared to 1990 levels. Several legislations and energy efficiency policies on buildings have been developed. The policies adopted started more than five decades ago and have achieved considerable strides in terms of scope, scale, and ambition. The diversification of instruments and tools deployed in energy efficiency policy has varied through the years. Starting from setting requirements for the building insulation and boilers and gradually becoming more holistic to encompass energy performance for the entire building. Building requirements and policies have been in continuous update and improvement to cope with the advancements of technology and the move toward supporting ICT systems offering flexibility to designers, architects, and engineers for cost-optimized solutions. Moreover, the targets of CO_2 and GHG emissions reductions have been increased through the years through enforcing more stringent regulations which were also supported by different regulations and resolutions.

Today, around 75% of the EU building stock is energy inefficient. Such energy loss can be curtailed by improving existing buildings and striving for smart solutions and energy-efficient materials. Renovating existing buildings is expected to cut the EU's total energy consumption by 5-6% and reduce CO_2 emissions by about 5%. Despite this, currently, on average, less than 1% of the national building stock is renovated each year. While to meet the target climate and energy objectives, the current rates of renovations should be 3%. The EU recently introduced new ambitious policies to help steer member states towards building renovation. The EPBD has introduced the concept of nZEB and encouraged facilitating a highly energy-efficient and decarbonized building stock through the renovation of existing buildings into nZEBs. Moreover, Clean Energy for All European Package was introduced to better reflect the EU's aim of driving the clean energy transition. As a part of this, the Renovation Wave aims at doubling the annual energy renovation rates in the next 10 years. As well as improving the quality of life for people living in and using the buildings. In parallel, the concept of Smart Buildings has been introduced in the EPBD to cope with the transition towards smarter buildings and integrate technological systems. However, there was no clear definition of it, instead, the integration of smart grid, smart vehicles, and smart technologies was emphasized as a part of the smart building. Furthermore, the Commission developed common European schemes for rating the smart readiness of buildings. This was done by introducing the Smart Readiness Indicator to be used to measure the capacity of buildings to use Information and ICTs and electronic systems to adapt the operation of buildings to the needs of the occupants and the grid and to improve the energy efficiency and overall performance of buildings. However, the methodology of the SRI is qualitative and only evaluates the presence of the services and technologies rather than evaluating their' performance. With the new paradigms in building regulations and moving towards smarter buildings, in parallel, there has been an increasing necessity to have buildings with interactive features, to dynamically respond to users' needs and/or changing boundary conditions either external, such as climate, and grid prices or internal, such as occupants' requirements. Thus, the need for Smart Retrofitting is crucial to upgrade the definition of energy-efficient or nZEB retrofitting to reflect the new possibilities of transforming existing buildings into more responsive and efficient buildings and cities. Moreover, quantifying the energy performance of the smart buildings/retrofitting is very crucial for understanding the minimum performance of achieving smartness in buildings. Taken together, the basic research question of this thesis was:

"What are the most representative Key Performance Indicators for measuring Smart Retrofitting, and what are the minimum performance thresholds?"

For dealing with these issues, this Ph.D. research sets a clear framework for Smart Retrofitting, defines the basic KPIs for measuring the energy performance of smart retrofit, and sets the minimum thresholds for quantifying smartness in buildings.

The thesis started from deep literature work that defined the smartness in the built environment and smart buildings (Chapter 2). Then, it identified the relevant KPIs that measure the performance of smart buildings and defined smart retrofitting in the context of upgrading the current definitions of deep and nZEB retrofit to smart retrofitting that considers the technological integration, the energy flexibility in the building, the interaction with the climate and the grid and the response to the users' needs. In Chapter 3 a clear methodology for the selection of representative KPIs was laid which can be applied in other research to select and narrow down a list of indicators to more representative ones based on the objective and purpose of the study. The selection method yielded five representative KPIs to measure the energy performance of smart retrofit case studies. Consequently, a methodology has been defined for quantifying the minimum required performance to attain the smartness score of a building. KPIs have limited value if they were not compared to a reference or a baseline. It is important to set a threshold defining the range of acceptable values for each indicator since it sets the quantified objectives of the KPI. Thus, in Chapter 4 the thresholds in this thesis were defined based on previous case studies in the literature that have tested the indicators and defined the achieved values. Then a Logical Evaluation Methodology was developed to identify the thresholds based on correlations of the input parameters and their defined values in legislation and regulations and how they affect the main indicator. Thus, two motivated values for the KPI thresholds were set based on elaboration; the "Minimum acceptable Limit" and "Top-performing Limit" defining a minimum threshold for the

KPI showing that a certain target shall be achieved to calculate the KPI and define the minimum smartness in a building and defining the highest elaborated value of the KPI for a smart building showing a high-performance smart building, respectively. The values between these two thresholds show that it is a smart performing building. Finally, in Chapter 5 an index for each indicator was developed based on the Min-Max normalization methodology. The normalized indexes identify how far the indicator is from the top-performing threshold. This allows forming a framework for stakeholders such as policymakers and users to understand the smartness of a building and how it is performing.

To conclude, the main achieved outcomes of this thesis are:

1. Develop a Scheme to define Smart Buildings, their' basic features, functions, and underlying technologies.
2. Develop a Methodology for selecting Key Performance Indicators.
3. Set Representative Indicators for measuring the energy performance of Smart Buildings/Grid which are the Non-renewable Primary Energy Indicator, Flexibility Indicator, RES Self-consumption Indicator, Load Cover Factor, and Grid Interaction Index.
4. Develop a Methodology for setting thresholds for Key Performance Indicators.
5. Apply two boundaries of thresholds for the indicators; "Minimum Achievable Limit" for defining the minimum value for reaching a smart building, and "Top Performing Limit" in which a higher level than this limit would define a top-performing smart building, while the values in between the limits define a normal performing smart building/retrofit.
6. Quantify the SRI developed by the EPBD and allow testing of the performance of the integrated smart technologies rather than only assessing their presence.
7. Normalize the scale of the indicators to be able to compare the results with a larger scale of buildings.
8. Define smart retrofitting as "The process of transforming an existing building into a SB, that is a nZEB with Primary Energy savings between 30% and 80% and have the capability of responding to the changing conditions of climate, and grid, communicate with the user and predict failures in the building operations through the utilization of ICT, RES, and Building Energy Management Systems (BEMS). It shall allow Load Shifting in response to RES production/changing electricity prices of 30% to 70% annually and minimize grid interaction to around 10% - 30% of hourly interaction throughout a year. Moreover, it should allow RES Self-Consumption of 30% to 70% and Load covered by RES of 20% to 70% annually".

This procedure foresees the implementation of KPIs as a smartness score identification for smart retrofit residential buildings. The five indicators can be compared in different case studies using the identified indexes and assess the success of the retrofitted building. This can also help in building post-retrofit evaluation to assess the energy performance in buildings. It can serve as a detailed quantitative assessment besides the Smart Readiness Indicator which starts by assessing the existing technologies and options adopted in a smart building. Then the identified KPIs can assess the performance of these technologies since they can address all the domains and impacts identified in the SRI.

6.3 Research Limitations

Nonetheless, during this thesis, some limitations were identified. For instance, as presented previously in Section 3.5, after the selection of representative KPIs, an analysis was carried out on the research projects that have carried out smart retrofitting in different European countries. The aim was to collect data on the retrofitted buildings and test the KPIs on these buildings to monitor their performance. However, the activity resulted in few responses, having incomparable data due to unequal time steps, lack of data of the building before retrofit, or lacking many fundamental parameters for the KPI evaluation. Therefore, the KPIs were tested only on the Italian case study of the HEART project. Furthermore, the KPIs were successfully tested on the monitored data of the Italian case study, since, due to COVID-19 pandemic, there were delays in the implementation of the French case study that resulted in delays in the motoring and simulation data. Therefore, unfortunately, it was not possible to test the indicators also on the French case study within the timeframe of the thesis.

Furthermore, the research focus was on measuring the energy and grid performance of smart retrofit buildings. While it did not focus on social and cultural aspects since they are out of scope. However, the indicators analyzed in the thesis focus on the technologies in the smart buildings that can facilitate the user’s comfort and satisfaction. For instance, the real-time interaction feature in smart buildings involves the implementation of monitoring screens and applications that users can monitor and control their usage and respond to their actions, thus, it improves the quality of life and allow user satisfaction. Moreover, as was specified in section 5.1.1, the RES Self-consumption, Flexibility, Load Cover Factor, and Grid Interaction Indicators all can impact the social sustainability aspects by making ‘prosumers’ able to self-consume their generated sustainable electricity and can reduce peak loads and allow load shifting by scheduling peak demands during hours of RES production and lower electricity prices. Therefore, the thesis did not focus on the social aspects directly, however, it touched on the impacts of the work on the social and cultural aspects.

6.4 Future Research

The broad topics discussed in this thesis have drawn attention to many gaps in the literature that can be further emphasized and detailed for future work. The following paragraphs summarize several paths for further investigations:

- According to the limitations of this thesis, the first future activity consists in testing the indicators on a wider number of buildings, to enable a generalization of the results and perform further validation. This is going to be developed as work after the Ph.D. as a part of a visiting period at ENTPE (École Nationale des travaux publics de l'État) in Lyon, France in the building energy lab (LTDS). The KPIs will be tested on the French case study which will be completed soon, and if possible, on another residential building in the EU.

- The applied methodology in the thesis also foresees an advancement in the normalization by introducing weighting factors for impact criteria and aggregation of the developed indexes. The proposed indexes in this thesis had set the ground for decision making which will facilitate the comparison of indicators and allow the stakeholder to choose which indicator is more favorable to choose over others if selecting the best performance building was the target. Hence, a further opportunity lies in developing a methodology for weighting and aggregation of the KPIs. A robust weighting method should be selected by assigning fixed weights, equal weights, or energy balance weights to set a score on each impact criteria defining the relative weight of the impact criteria. After identifying the method and eliminating any uncertainties, the indices will formulate the final aggregated index measuring smart retrofitting that can balance the need for energy savings, the needs of occupants, and the needs of the energy grid.

- Furthermore, based on the gaps identified in previous literature, an opportunity lies in improving the flexibility indicator. This is since all the other defined indicators; the non-renewable primary energy, RES Self-consumption, Load Cover Factor, and Grid Interaction Index have all been clearly defined, established, and tested in real case studies. Yet, the flexibility indicator has many definitions and different calculation methodologies. This is since the building energy flexibility is influenced by several factors such as energy storage systems, control systems, users' behavior, climate conditions, and others. Yet, as agreed in different research, three main properties should be addressed in Flexibility indicators, time, energy, and costs. Moreover, most of the developed indicators on flexibility have limited availability of real monitored data used to calculate it. Therefore, there is an open opportunity to further investigate this indicator and develop an optimal and holistic way of calculating it and testing it on real case studies.

- Another important aspect of the currently ongoing research is the availability of data on Smart Retrofitted Buildings. With the emergence of smart buildings and smart retrofitting, the number of research that is investigating the quantitative performance of related topics such as flexibility, demand-side management, advanced control systems, grid interaction, RES self-consumption, and other aspects, testing on real case studies is very crucial. Although the number of EU projects that cover smart buildings aspects and smart retrofitting is growing, there remains a lack in the availability of data on the monitored and actual performance of these projects. Therefore, to support the ongoing research, a database should be created to facilitate finding hourly data of recorded building energy demands, consumptions before and after retrofit, and data on the RES integration, storage performance, grid interaction, etc. This database can foster research and allow better monitoring and validation of the current developed research.
- Further validation for the SRI methodology application is to be carried out through comparison with the expert-assessment "method B". Method A was used in this thesis for assessing the SRI in the HEART project, whereas for a more detailed assessment for the SRI, method B can be done through on-site inspection and involving a third-party qualified expert to evaluate the existing services and technologies.
- Furthermore, despite the vast number of policies, building regulations, and initiatives being developed in the EU, a gap is still found in policies and requirements of energy flexibility including load shifting and reduction, grid interaction, energy exchange with the grid, and smart metering systems in the EU building context. Thus, future work is recommended to extend this research to clarify the definitions of these elements, their minimum performance, requirements, and methods of applications in regulatory and policy instruments and annexes.

References

[1] EIA, "Energy Information Administration (EIA)- Commercial Buildings Energy Consumption Survey (CBECS)," 2020. [Online]. Available: https://www.eia.gov/consumption/commercial/. [Accessed: 25-Mar-2020].

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

[3] G. Martinopoulos, K. T. Papakostas, and A. M. Papadopoulos, "A comparative review of heating systems in EU countries, based on efficiency and fuel cost," *Renew. Sustain. Energy Rev.*, vol. 90, pp. 687–699, Jul. 2018, doi: 10.1016/J.RSER.2018.03.060.

[4] T. Boermans *et al.*, *Principles for nearly Zero-Energy Buildings*. Buildings Performance Institute Europe (BPIE), 2011.

[5] V. Masson-Delmotte, P. Zhai, H. Pörtner, and D. Roberts, "Global warming of 1.5° C: Summary for policy makers," 2018.

[6] Sustainable Energy for All, "Sustainable Energy for All ," 2020. [Online]. Available: https://www.seforall.org/. [Accessed: 27-Jul-2020].

[7] IRENA, "Renewable capacity highlights," Mar. 2019.

[8] N. Scarlat, J. F. Dallemand, F. Monforti-Ferrario, M. Banja, and V. Motola, "Renewable energy policy framework and bioenergy contribution in the European Union - An overview from National Renewable Energy Action Plans and Progress Reports," *Renewable and Sustainable Energy Reviews*, vol. 51. Elsevier Ltd, pp. 969–985, 27-Jul-2015, doi: 10.1016/j.rser.2015.06.062.

[9] European-Commission, "DIRECTIVE 2002/91/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 December 2002 on the energy performance of buildings," Apr. 2003.

[10] 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*, vol. 18, no. 06, p. 2010, 2010.

[11] C. Camarasa, C. Nägeli, Y. Ostermeyer, M. Klippel, and S. Botzler, "Diffusion of energy efficiency technologies in European residential buildings: A bibliometric analysis," *Energy Build.*, vol. 202, p. 109339, Nov. 2019, doi: 10.1016/J.ENBUILD.2019.109339.

[12] European Union Publications Office, "Council Directive 78/170/EEC of 13 February 1978 on the performance of heat generators for space heating and the production of hot water in new or existing non- industrial buildings and on the insulation of heat and domestic hot-water distribution in new non-industrial buildings, CELEX1," Feb. 1978.

[13] European Union Publications Office, "Council Directive 92/42/EEC of 21 May 1992 on efficiency requirements for new hot-water boilers fired with liquid or gaseous fuels, CELEX1," Sep. 2013.

[14] European Union Publications Office, "Directive 96/57/EC of the European Parliament and of the Council of 3 September 1996 on energy efficiency requirements for household electric refrigerators, freezers and combinations thereof," Jul. 2010.

[15] M. Kestner, "First energy efficiency directives under SAVE programme," *Energy in Europe*, 1991. [Online]. Available:

https://scholar.google.com/scholar?hl=it&as_sdt=0%2C5&q=First+energy+efficiency+directives+under+SAVE+programme&btnG=. [Accessed: 28-Nov-2020].

[16] M. T. Van Wees, M. A. Uyterlinde, and M. Maly, "Energy efficiency and renewable energy policy in the Czech Republic within the framework of accession to the European Union," *Energy*, vol. 27, no. 11, pp. 1057–1067, Nov. 2002, doi: 10.1016/S0360-5442(02)00068-3.

[17] J. L. Míguez *et al.*, "Review of the energy rating of dwellings in the European Union as a mechanism for sustainable energy," *Renewable and Sustainable Energy Reviews*, vol. 10, no. 1. Pergamon, pp. 24–45, 01-Jan-2006, doi: 10.1016/j.rser.2004.08.003.

[18] Union European Publications Office, "Action Plan for energy efficiency (2000-2006)," Mar. 2007.

[19] European Commission, "COMMUNICATION FROM THE COMMISSION Action Plan for Energy Efficiency: Realising the Potential ," Brussels, Oct. 2006.

[20] T. Fawcett, J. Rosenow, and P. Bertoldi, "Energy efficiency obligation schemes: their future in the EU," *Energy Effic.*, vol. 12, no. 1, pp. 57–71, Jan. 2019, doi: 10.1007/s12053-018-9657-1.

[21] European Commission, "2020 climate & energy package," 2020. [Online]. Available: https://ec.europa.eu/clima/policies/strategies/2020_en. [Accessed: 30-Nov-2020].

[22] European Commission, "DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL," Jun. 2009.

[23] European Commission, "Energy roadmap 2050 Energy," Luxembourg, 2012.

[24] M. da Graça Carvalho, "EU energy and climate change strategy," *Energy*, vol. 40, no. 1, pp. 19–22, Apr. 2012, doi: 10.1016/j.energy.2012.01.012.

[25] European Commission, "Energy Efficiency Plan 2011," Brussels, Mar. 2011.

[26] E. E. Directive, "Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32," *Off. Journal, L*, vol. 315, pp. 1–56, 2012.

[27] European-Commission, "Energy efficiency directive," *The 2012 energy efficiency directive*, 21-Aug-2019. [Online]. Available: https://ec.europa.eu/energy/topics/energy-efficiency/targets-directive-and-rules/energy-efficiency-directive_en. [Accessed: 23-Nov-2020].

[28] European Commission, "A policy framework for climate and energy in the period from 2020 to 2030," Brussels, Jan. 2014.

[29] European Commission, "2030 climate & energy framework | Climate Action," 2019. [Online]. Available: https://ec.europa.eu/clima/policies/strategies/2030_en. [Accessed: 30-Nov-2020].

[30] European Commission, "Clean energy for all Europeans ," Luxemburg, Mar. 2019.

[31] European Commission, "Strategic Energy Technology Plan," Jul-2014. [Online]. Available: https://ec.europa.eu/energy/topics/technology-and-innovation/strategic-energy-technology-plan_en. [Accessed: 19-Jan-2021].

[32] European Union Council, "DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the promotion of the use of energy from renewable sources," 2018.

[33] European Commission, "European Green Deal," 2019. [Online]. Available: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en.

[Accessed: 01-Nov-2021].

[34] European Commission, “Renovation wave ,” 2020. [Online]. Available: https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/renovation-wave_en. [Accessed: 02-Nov-2021].

[35] European Commission, “New European Bauhaus,” 2021. [Online]. Available: https://europa.eu/new-european-bauhaus/about/about-initiative_en. [Accessed: 14-Mar-2022].

[36] European-Commission, “Energy performance of buildings directive,” 2017. [Online]. Available: https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en. [Accessed: 24-Nov-2020].

[37] United Nations Framework Convention on Climate Change, “What is the Kyoto Protocol,” *What is the Kyoto Protocol?*, 2020. [Online]. Available: https://unfccc.int/kyoto_protocol. [Accessed: 24-Nov-2020].

[38] M. Economidou, V. Todeschi, P. Bertoldi, D. D’Agostino, P. Zangheri, and L. Castellazzi, “Review of 50 years of EU energy efficiency policies for buildings,” *Energy and Buildings*, vol. 225. Elsevier Ltd, p. 110322, 15-Oct-2020, doi: 10.1016/j.enbuild.2020.110322.

[39] BPIE, “Energy Performance Certificates across Europe From design to implementation,” Brussels, 2010.

[40] S. Geissler and N. Altmann, “How to make the best use of EPCs,” Brussels, Sep. 2015.

[41] European Commission, “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,” Brussels, Jun. 2018.

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

[43] ECTP, “Energy Efficient Buildings,” *2020*. [Online]. Available: http://e2b.ectp.org/. [Accessed: 03-Dec-2020].

[44] H. Erhorn and H. Erhorn-Kluttig, “Terms and definitions for high performance buildings,” Jan. 2011.

[45] A. J. Marszal *et al.*, “Zero Energy Building - A review of definitions and calculation methodologies,” *Energy Build.*, vol. 43, no. 4, pp. 971–979, Apr. 2011, doi: 10.1016/j.enbuild.2010.12.022.

[46] World Green Building Council, “The Net Zero Carbon Buildings Commitment,” 2016. [Online]. Available: https://www.worldgbc.org/thecommitment. [Accessed: 03-Dec-2020].

[47] Whole Building Design Guide, “Net Zero Energy Buildings,” 08-Feb-2016. [Online]. Available: https://www.wbdg.org/resources/net-zero-energy-buildings. [Accessed: 03-Dec-2020].

[48] F. Liu, A. S. Meyer, and J. F. Hogan, *Mainstreaming Building Energy Efficiency Codes in Developing Countries*. The World Bank, 2010.

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

[50] J. Laski and V. Burrows, “From Thousands to Billions Coordinated Action towards 100%

Net Zero Carbon Buildings By 2050," *World Green Build. Counc.*, 2017.

[51] Rutger Broer, F. Mariangiola, F. Á. Xerome, K. Judit, and J. Ivan, "DEEP RENOVATION: SHIFTING FROM EXCEPTION TO STANDARD PRACTICE IN EU POLICY," Brussels, 2021.

[52] J. C. Smith *et al.*, "Impact of variable renewable energy on US electricity markets," in *IEEE PES General Meeting*, 2010, pp. 1–12, doi: 10.1109/PES.2010.5589715.

[53] A. Chel and G. Kaushik, "Renewable energy technologies for sustainable development of energy efficient building," *Alexandria Eng. J.*, vol. 57, no. 2, pp. 655–669, Jun. 2018, doi: 10.1016/J.AEJ.2017.02.027.

[54] S. Wang, "Making buildings smarter, grid-friendly, and responsive to smart grids," *Sci. Technol. Built Environ.*, vol. 22, no. 6, pp. 629–632, Aug. 2016, doi: 10.1080/23744731.2016.1200888.

[55] F. Oldewurtel *et al.*, "Use of model predictive control and weather forecasts for energy efficient building climate control," *Energy Build.*, vol. 45, pp. 15–27, Feb. 2012, doi: 10.1016/J.ENBUILD.2011.09.022.

[56] G. T. Costanzo, G. Zhu, M. F. Anjos, and G. Savard, "A system architecture for autonomous demand side load management in smart buildings," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 2157–2165, 2012.

[57] Eurostats, "Energy consumption in households," Jun-2020. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_consumption_in_households. [Accessed: 18-Jan-2021].

[58] J. Davis, K. Mengersen, S. Bennett, and L. Mazerolle, "Viewing systematic reviews and meta-analysis in social research through different lenses," *Springerplus*, vol. 3, no. 1, 2014, doi: 10.1186/2193-1801-3-511.

[59] 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," *Renewable and Sustainable Energy Reviews*, vol. 56. Elsevier Ltd, pp. 906–915, 01-Apr-2016, doi: 10.1016/j.rser.2015.11.096.

[60] I. Jefferson, D. V. L. Hunt, C. A. Birchall, and C. D. F. Rogers, "Sustainability indicators for environmental geotechnics," *Proc. Inst. Civ. Eng. Eng. Sustain.*, vol. 160, no. 2, pp. 57–78, 2007, doi: 10.1680/ensu.2007.160.2.57.

[61] E. Forestier, "Performance Monitoring Indicators A handbook for task managers," *Oper. POLICY Dep. WORLD BANK*, 1996.

[62] F. Honsell, M. Lenisa, and L. Liquori, "A Framework for Defining Logical Frameworks," *Electron. Notes Theor. Comput. Sci.*, vol. 172, pp. 399–436, Apr. 2007, doi: 10.1016/J.ENTCS.2007.02.014.

[63] B. Vučićević, M. Stojiljković, N. Afgan, V. Turanjanin, M. Jovanović, and V. Bakić, "Sustainability assessment of residential buildings by non-linear normalization procedure," *Energy Build.*, vol. 58, pp. 348–354, Mar. 2013, doi: 10.1016/J.ENBUILD.2012.10.012.

[64] E. Kogachi, A. Ferreira, C. Cavalcante, and M. Embiruçu, "Development of performance evaluation indicators for table grape packaging units. 2. global indexes," *Sustain.*, vol. 13, no. 11, Jun. 2021, doi: 10.3390/SU13116367.

[65] J. K. W. Wong and H. Li, "Development of intelligence analytic models for integrated building management systems (IBMS) in intelligent buildings," *Intell. Build. Int.*, vol. 1, no. 1, pp. 5–22, Jan. 2009, doi: 10.3763/inbi.2009.0011.

[66] A. Ghaffarianhoseini *et al.*, "Intelligent or smart cities and buildings: a critical exposition and a way forward," *Intell. Build. Int.*, vol. 10, no. 2, pp. 122–129, Apr. 2018, doi: 10.1080/17508975.2017.1394810.

[67] V. Albino, U. Berardi, and R. M. Dangelico, "Smart cities: Definitions, dimensions, performance, and initiatives," *J. Urban Technol.*, vol. 22, no. 1, pp. 3–21, 2015.

[68] A. M. Townsend, *Smart cities : big data, civic hackers, and the quest for a new utopia*. 2013.

[69] R. P. Dameri, "Searching for Smart City definition: a comprehensive proposal," *Int. J. Comput. Technol.*, vol. 11, no. 5, 2013.

[70] A. Caragliu, C. Del Bo, and P. Nijkamp, "Smart Cities in Europe," *J. Urban Technol.*, vol. 18, no. 2, pp. 65–82, Apr. 2011, doi: 10.1080/10630732.2011.601117.

[71] B. Morvaj, L. Lugaric, and S. Krajcar, "Demonstrating smart buildings and smart grid features in a smart energy city," in *Energetics (IYCE), Proceedings of the 2011 3rd International Youth Conference on*, 2011, pp. 1–8.

[72] D. Kolokotsa, "The role of smart grids in the building sector," *Energy and Buildings*, vol. 116. Elsevier Ltd, pp. 703–708, 15-Mar-2016, doi: 10.1016/j.enbuild.2015.12.033.

[73] U. . D. Energy, "Smart Grid | Department of Energy," 2018. [Online]. Available: https://www.energy.gov/science-innovation/electric-power/smart-grid. [Accessed: 17-Mar-2019].

[74] S. S. S. R. Depuru, L. Wang, V. Devabhaktuni, and N. Gudi, "Smart Meters for Power Grid – Challenges, Issues, Advantages and Status," in *2011 IEEE/PES Power Systems Conference and Exposition*, 2011, pp. 1–7, doi: 10.1109/PSCE.2011.5772451.

[75] Jixuan Zheng, D. W. Gao, and Li Lin, "Smart Meters in Smart Grid: An Overview," in *2013 IEEE Green Technologies Conference (GreenTech)*, 2013, pp. 57–64, doi: 10.1109/GreenTech.2013.17.

[76] J. Sinopoli and J. Sinopoli, "What Is a Smart Building?," *Smart Build. Syst. Archit. Owners Build.*, pp. 1–5, Jan. 2010, doi: 10.1016/B978-1-85617-653-8.00001-6.

[77] European-Commission, "Smart Buildings," 2019. [Online]. Available: https://epbd-ca.eu/topics-teams/topics/ct-6-smart-buildings. [Accessed: 15-Jul-2019].

[78] M. De Groote, J. Volt, and F. Bean, "Smart Buildings Decoded," *Build. Perform. Inst. Eur.*, 2017.

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

[80] European-Commission, "Horizon 2020 | The EU Framework Programme for Research and Innovation." [Online]. Available: https://ec.europa.eu/programmes/horizon2020/en. [Accessed: 22-Mar-2020].

[81] European Commission, "Horizon 2020," 2020. [Online]. Available: https://ec.europa.eu/inea/en/horizon-2020. [Accessed: 06-Jan-2021].

[82] European Commission, "CORDIS | European Commission," 2020. [Online]. Available: https://cordis.europa.eu/en. [Accessed: 06-Jan-2021].

[83] P. Moseley, "EU support for innovation and market uptake in smart buildings under the

Horizon 2020 framework programme," *Buildings*, vol. 7, no. 4, Nov. 2017, doi: 10.3390/buildings7040105.

[84] Q. Lê, H. B. Nguyen, and T. Barnett, "Smart homes for older people: Positive aging in a digital world," *Futur. internet*, vol. 4, no. 2, pp. 607–617, 2012.

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

[86] M. Hussain and Y. Gao, "A review of demand response in an efficient smart grid environment," *Electr. J.*, vol. 31, no. 5, pp. 55–63, Jun. 2018, doi: 10.1016/J.TEJ.2018.06.003.

[87] K. Ponds, A. Arefi, A. Sayigh, and G. Ledwich, "Aggregator of demand response for renewable integration and customer engagement: Strengths, weaknesses, opportunities, and threats," *Energies*, vol. 11, no. 9, p. 2391, 2018.

[88] D. Geelen, A. Reinders, and D. Keyson, "Empowering the end-user in smart grids: Recommendations for the design of products and services," *Energy Policy*, vol. 61, pp. 151–161, 2013.

[89] J. Alejandro Gomez Herrera, "User-Oriented Demand Response for Smart Buildings," 2017.

[90] J. Granderson, "Energy information handbook: Applications for energy-efficient building operations," 2011.

[91] A. Erkoreka, C. Gorse, M. Fletcher, and K. Martin, "EBC Annex 58 Reliable Building Energy Performance Characterisation based on full scale dynamic measurements," 2016.

[92] F. Oldewurtel *et al.*, "Energy efficient building climate control using stochastic model predictive control and weather predictions," in *Proceedings of the 2010 American control conference*, 2010, pp. 5100–5105.

[93] T. Zhang, M. P. Wan, B. F. Ng, and S. Yang, "Model Predictive Control for Building Energy Reduction and Temperature Regulation," in *2018 IEEE Green Technologies Conference (GreenTech)*, 2018, pp. 100–106, doi: 10.1109/GreenTech.2018.00027.

[94] R. Halvgaard, P. Niels Kjølstad, H. Madsen, and J. B. Jørgensen, "Economic model predictive control for building climate control in a smart grid," in *2012 IEEE PES Innovative Smart Grid Technologies (ISGT)*, 2012, doi: 10.1109/ISGT.2012.6175631.

[95] A. Javed, H. Larijani, A. Ahmadinia, R. Emmanuel, M. Mannion, and D. Gibson, "Design and implementation of a cloud enabled random neural network-based decentralized smart controller with intelligent sensor nodes for HVAC," *IEEE Internet Things J.*, vol. 4, no. 2, pp. 393–403, 2017.

[96] F. Jazizadeh, A. Ghahramani, B. Becerik-Gerber, T. Kichkaylo, and M. Orosz, "User-led decentralized thermal comfort driven HVAC operations for improved efficiency in office buildings," *Energy Build.*, vol. 70, pp. 398–410, Feb. 2014, doi: 10.1016/J.ENBUILD.2013.11.066.

[97] D. Sembroiz, D. Careglio, S. Ricciardi, and U. Fiore, "Planning and operational energy optimization solutions for smart buildings," *Inf. Sci. (Ny).*, vol. 476, pp. 439–452, Feb. 2019, doi: 10.1016/J.INS.2018.06.003.

[98] W. Shen, H. H. Xue, G. Newsham, and E. Dikel, "Smart building monitoring and ongoing commissioning: A case study with four canadian federal government office buildings," *2017 IEEE Int. Conf. Syst. Man, Cybern.*, 2017, doi: 10.1109/SMC.2017.8122598.

[99] Y. Liu *et al.*, "Coordinating the operations of smart buildings in smart grids," *Appl. Energy*,

vol. 228, pp. 2510–2525, Oct. 2018, doi: 10.1016/J.APENERGY.2018.07.089.
[100] F. A. Qureshi and C. N. Jones, "Hierarchical control of building HVAC system for ancillary services provision," *Energy Build.*, vol. 169, pp. 216–227, Jun. 2018, doi: 10.1016/J.ENBUILD.2018.03.004.
[101] Z. Xu, X. Guan, Q.-S. Jia, J. Wu, D. Wang, and S. Chen, "Performance analysis and comparison on energy storage devices for smart building energy management," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 2136–2147, 2012.
[102] S. Hadri, Y. Naitmalek, M. Najib, M. Bakhouya, Y. Fakhri, and M. Elaroussi, "A Comparative Study of Predictive Approaches for Load Forecasting in Smart Buildings," *Procedia Comput. Sci.*, vol. 160, pp. 173–180, 2019, doi: 10.1016/j.procs.2019.09.458.
[103] K. J, S. A, K. T, V. M, N. J, and T. T, "Cost optimal and nearly zero (nZEB) energy performance calculations for residential buildings with REHVA definition for nZEB national implementation," *Energy Build.*, vol. 43, no. 11, pp. 3279–3288, 2011.
[104] J. Kurnitski *et al.*, "How to define nearly net zero energy buildings nZEB," 2011.
[105] T. Karlessi *et al.*, "The concept of smart and NZEB buildings and the integrated design approach," *Procedia Eng.*, pp. 1316 – 1325, 2017.
[106] A. Claudi, "Tools and techniques supporting new nZEB design methodologies in Mediterranean climate," *Firenze Univ. Press*, 2018, doi: 10.13128/Techne-22724.
[107] S. Jensen and M. Henrik, "Annex 67: Energy Flexible Buildings-Energy Flexibility as a key asset in a smart building future-Contribution of Annex 67 to the European Smart Buildings," 2017.
[108] G. Reynders, "Quantifying the impact of building design on the potential of structural storage for active demand response in residential buildings," 2015.
[109] N. J. Hewitt, "Heat pumps and energy storage – The challenges of implementation," *Appl. Energy*, vol. 89, no. 1, pp. 37–44, Jan. 2012, doi: 10.1016/J.APENERGY.2010.12.028.
[110] A. Arteconi, N. J. Hewitt, and F. Polonara, "State of the art of thermal storage for demand-side management," *Appl. Energy*, vol. 93, pp. 371–389, 2012.
[111] G. Masy, E. Georges, C. Verhelst, V. Lemort, and P. André, "Smart grid energy flexible buildings through the use of heat pumps and building thermal mass as energy storage in the Belgian context," *Sci. Technol. Built Environ.*, vol. 21, no. 6, pp. 800–811, 2015.
[112] J. Le Dréau and P. Heiselberg, "Energy flexibility of residential buildings using short term heat storage in the thermal mass," *Energy*, vol. 111, pp. 991–1002, 2016.
[113] G. Reynders, T. Nuytten, and D. Saelens, "Potential of structural thermal mass for demand-side management in dwellings," *Build. Environ.*, vol. 64, pp. 187–199, 2013.
[114] J. Široký, F. Oldewurtel, J. Cigler, and S. Prívara, "Experimental analysis of model predictive control for an energy efficient building heating system," *Appl. Energy*, vol. 88, no. 9, pp. 3079–3087, 2011.
[115] F. Tahersima, J. Stoustrup, S. A. Meybodi, and H. Rasmussen, "Contribution of domestic heating systems to smart grid control," in *2011 50th IEEE Conference on Decision and Control and European Control Conference*, 2011, doi: 10.1109/CDC.2011.6160913.
[116] C. W. Gellings, "The Concept of Demand-Side Management for Electric Utilities," *Proc. IEEE*, vol. 73, no. 10, pp. 1468–1470, 1985, doi: 10.1109/PROC.1985.13318.
[117] B. Parrish, R. Gross, and P. Heptonstall, "On demand: Can demand response live up to

expectations in managing electricity systems?," *Energy Res. Soc. Sci.*, vol. 51, pp. 107–118, May 2019, doi: 10.1016/J.ERSS.2018.11.018.

[118] A. U. Mahin, M. A. Sakib, M. A. Zaman, M. S. Chowdhury, and S. A. Shanto, "Developing demand side management program for residential electricity consumers of Dhaka city," in *2017 International Conference on Electrical, Computer and Communication Engineering (ECCE)*, 2017.

[119] M. Saffari, A. de Gracia, C. Fernández, M. Belusko, D. Boer, and L. F. Cabeza, "Optimized demand side management (DSM) of peak electricity demand by coupling low temperature thermal energy storage (TES) and solar PV," *Appl. Energy*, vol. 211, pp. 604–616, Feb. 2018, doi: 10.1016/j.apenergy.2017.11.063.

[120] A. Gabaldon *et al.*, "Assessment and simulation of demand-side management potential in urban power distribution networks," in *2003 IEEE Bologna Power Tech Conference Proceedings,* 2003, vol. 4, pp. 5-pp.

[121] A. Hirsch, Y. Parag, and J. Guerrero, "Microgrids: A review of technologies, key drivers, and outstanding issues," *Renew. Sustain. Energy Rev.*, vol. 90, pp. 402–411, 2018.

[122] K. Sun and T. Hong, "A framework for quantifying the impact of occupant behavior on energy savings of energy conservation measures," *Energy Build.*, vol. 146, no. April, pp. 383–396, 2017, doi: 10.1016/j.enbuild.2017.04.065.

[123] H. A. Attia, "Mathematical Formulation of the Demand Side Management (DSM) Problem and its Optimal Solution," in *Proceedings of the 14th International Middle East Power Systems Conference (MEPCON'10)*, 2010.

[124] R. Deng, Z. Yang, M.-Y. Chow, and J. Chen, "A survey on demand response in smart grids: Mathematical models and approaches," *IEEE Trans. Ind. Informatics*, vol. 11, no. 3, pp. 570–582, 2015.

[125] Y. W. Law, T. Alpcan, V. C. S. Lee, A. Lo, S. Marusic, and M. Palaniswami, "Demand Response Architectures and Load Management Algorithms for Energy-Efficient Power Grids: A Survey," in *2012 Seventh International Conference on Knowledge, Information and Creativity Support Systems*, 2012, pp. 134–141, doi: 10.1109/KICSS.2012.45.

[126] V. Marinakis, C. Karakosta, H. Doukas, S. Androulaki, and J. Psarras, "A building automation and control tool for remote and real time monitoring of energy consumption," *Sustain. Cities Soc.*, vol. 6, pp. 11–15, Feb. 2013, doi: 10.1016/J.SCS.2012.06.003.

[127] H. Yang, P. Li, Z. He, X. Guo, S. Fong, and H. Chen, "Enterprise Information Systems A decision support system using combined-classifier for high-speed data stream in smart grid A decision support system using combined-classifier for high-speed data stream in smart grid," 2015, doi: 10.1080/17517575.2015.1086495.

[128] S. Balandin, S. Andreev, and Y. Koucheryavy, "Internet of things, smart spaces, and next generation networking," in *A Notification Model for Smart-M3 Applications*, 2014, pp. 121–132.

[129] M. Stunder, P. Sebastian, B. Chube, and M. Koontz, "Integration of real-time data into building automation systems," 2003.

[130] S. Rinaldi, F. Bittenbinder, C. Liu, P. Bellagente, L. C. Tagliabue, and A. L. C. Ciribini, "Bi-Directional Interactions between Users and Cognitive Buildings by means of Smartphone App," in *2016 IEEE International Smart Cities Conference (ISC2)*, 2016.

[131] J. Lertlakkhanakul, J. W. Choi, and M. Y. Kim, "Building data model and simulation platform for spatial interaction management in smart home," *Autom. Constr.*, vol. 17, no. 8, pp. 948–957, 2008.

[132] L. Gelazanskas and K. A. A. Gamage, "Demand side management in smart grid: A review and proposals for future direction," *Sustain. Cities Soc.*, vol. 11, pp. 22–30, Feb. 2014, doi: 10.1016/J.SCS.2013.11.001.

[133] A. Mahmood *et al.*, "A New Scheme for Demand Side Management in Future Smart Grid Networks," *Procedia Comput. Sci.*, vol. 32, pp. 477–484, 2014, doi: 10.1016/j.procs.2014.05.450.

[134] Z. Yahia and A. Pradhan, "Optimal load scheduling of household appliances considering consumer preferences: An experimental analysis," *Energy*, vol. 163, pp. 15–26, 2018.

[135] M. Behrangrad, H. Sugihara, and T. Funaki, "Analyzing the system effects of optimal demand response utilization for reserve procurement and peak clipping," in *IEEE PES General Meeting*, 2010, pp. 1–7, doi: 10.1109/PES.2010.5589597.

[136] G. Lobaccaro, S. Carlucci, and E. Löfström, "A review of systems and technologies for smart homes and smart grids," *Energies*, vol. 9, no. 5, p. 348, 2016.

[137] G. J. Levermore, *Building energy management systems : applications to low energy HVAC and natural ventilation control*. E & FN Spon, 2000.

[138] K. Sayed and H. A. Gabbar, "Building Energy Management Systems (BEMS)," in *Energy Conservation in Residential, Commercial, and Industrial Facilities*, Hoboken, NJ, USA: John Wiley & Sons, Inc., 2018, pp. 15–81.

[139] J. Ock, R. R. A. Issa, and I. Flood, "Smart Building Energy Management Systems (BEMS) simulation conceptual framework," in *2016 Winter Simulation Conference (WSC)*, 2016, pp. 3237–3245, doi: 10.1109/WSC.2016.7822355.

[140] H. Chen, P. Chou, S. Duri, H. Lei, and J. Reason, "The design and implementation of a smart building control system," in *2009 IEEE International Conference on e-Business Engineering*, 2009, pp. 255–262.

[141] P. H. Shaikh, N. B. M. Nor, P. Nallagownden, I. Elamvazuthi, and T. Ibrahim, "A review on optimized control systems for building energy and comfort management of smart sustainable buildings," *Renew. Sustain. Energy Rev.*, vol. 34, pp. 409–429, Jun. 2014, doi: 10.1016/J.RSER.2014.03.027.

[142] M. Kasahara, T. Matsuba, Y. Kuzuu, and T. Yamazaki, "Design and tuning of robust PID controller for HVAC systems," *ASHRAE Trans.*, vol. 105, no. 154, 1999.

[143] E. H. Mathews, D. C. Arndt, C. B. Piani, and E. Van Heerden, "Developing cost efficient control strategies to ensure optimal energy use and sufficient indoor comfort," *Appl. Energy*, vol. 66, no. 2, pp. 135–159, 2000.

[144] M. Killian and M. Kozek, "Ten questions concerning model predictive control for energy efficient buildings," *Build. Environ.*, vol. 105, pp. 403–412, Aug. 2016, doi: 10.1016/J.BUILDENV.2016.05.034.

[145] Y. Ma, F. Borrelli, B. Hencey, B. Coffey, S. Bengea, and P. Haves, "Model predictive control for the operation of building cooling systems," *IEEE Trans. Control Syst. Technol.*, vol. 20, no. 3, pp. 796–803, 2012.

[146] N. Aste, M. Manfren, and G. Marenzi, "Building Automation and Control Systems and

performance optimization: A framework for analysis," *Renew. Sustain. Energy Rev.*, vol. 75, pp. 313–330, Aug. 2017, doi: 10.1016/J.RSER.2016.10.072.

[147] M. Jia and R. S. Srinivasan, "Occupant behavior modeling for smart buildings: A critical review of data acquisition technologies and modeling methodologies," in *2015 Winter Simulation Conference (WSC)*, 2015, pp. 3345–3355, doi: 10.1109/WSC.2015.7408496.

[148] N. Kayastha, D. Niyato, E. Hossain, and Z. Han, "Smart grid sensor data collection, communication, and networking: a tutorial," *Wirel. Commun. Mob. Comput.*, vol. 14, no. 11, pp. 1055–1087, Aug. 2014, doi: 10.1002/wcm.2258.

[149] T. Labeodan, C. De Bakker, A. Rosemann, and W. Zeiler, "On the application of wireless sensors and actuators network in existing buildings for occupancy detection and occupancy-driven lighting control," *Energy Build.*, vol. 127, pp. 75–83, Sep. 2016, doi: 10.1016/j.enbuild.2016.05.077.

[150] H. Doukas, K. D. Patlitzianas, K. Iatropoulos, and J. Psarras, "Intelligent building energy management system using rule sets," *Build. Environ.*, vol. 42, no. 10, pp. 3562–3569, Oct. 2007, doi: 10.1016/J.BUILDENV.2006.10.024.

[151] E. Biyik and A. Kahraman, "A predictive control strategy for optimal management of peak load, thermal comfort, energy storage and renewables in multi-zone buildings," *J. Build. Eng.*, vol. 25, p. 100826, Sep. 2019, doi: 10.1016/J.JOBE.2019.100826.

[152] J. A. Stankovic, "When Sensor and Actuator Networks Cover the World," *ETRI J.*, vol. 30, no. 5, pp. 627–633, Oct. 2008, doi: 10.4218/etrij.08.1308.0099.

[153] S. Attia *et al.*, "Overview and future challenges of nearly zero energy buildings (nZEB) design in Southern Europe," *Energy Build.*, vol. 155, pp. 439–458, 2017.

[154] L. Ma *et al.*, "Multi-party energy management for smart building cluster with PV systems using automatic demand response," *Energy Build.*, vol. 121, pp. 11–21, 2016.

[155] M. S. Buker and S. B. Riffat, "Building integrated solar thermal collectors–A review," *Renew. Sustain. Energy Rev.*, vol. 51, pp. 327–346, 2015.

[156] G. de Oliveira e Silva and P. Hendrick, "Pumped hydro energy storage in buildings," *Appl. Energy*, vol. 179, pp. 1242–1250, Oct. 2016, doi: 10.1016/j.apenergy.2016.07.046.

[157] G. van Bussel and S. Mertens, "Small wind turbines for the built environment," 2005.

[158] A. Michopoulos, V. Skoulou, V. Voulgari, A. Tsikaloudaki, and N. A. Kyriakis, "The exploitation of biomass for building space heating in Greece: Energy, environmental and economic considerations," *Energy Convers. Manag.*, vol. 78, pp. 276–285, 2014, doi: 10.1016/j.enconman.2013.10.055.

[159] A. R. Jordehi, "Optimisation of demand response in electric power systems, a review," *Renew. Sustain. Energy Rev.*, vol. 103, pp. 308–319, Apr. 2019, doi: 10.1016/J.RSER.2018.12.054.

[160] R. Gupta, A. Bruce-Konuah, and A. Howard, "Achieving energy resilience through smart storage of solar electricity at dwelling and community level," *Energy Build.*, vol. 195, pp. 1–15, Jul. 2019, doi: 10.1016/J.ENBUILD.2019.04.012.

[161] K. K. Zame, C. A. Brehm, A. T. Nitica, C. L. Richard, and G. D. Schweitzer III, "Smart grid and energy storage: Policy recommendations," *Renew. Sustain. Energy Rev.*, vol. 82, pp. 1646–1654, Feb. 2018, doi: 10.1016/J.RSER.2017.07.011.

[162] B. P. Roberts and C. Sandberg, "The role of energy storage in development of smart grids,"

Proc. IEEE, vol. 99, pp. 1139–1144, 2011, doi: 10.1109/JPROC.2011.2116752.

[163] I. Worighi, A. Maach, and A. Hafid, “Modeling a smart grid using objects interaction,” in *2015 3rd International Renewable and Sustainable Energy Conference (IRSEC)*, 2015.

[164] J. Lizana, D. Friedrich, R. Renaldi, and R. Chacartegui, “Energy flexible building through smart demand-side management and latent heat storage,” *Appl. Energy*, vol. 230, pp. 471–485, Nov. 2018, doi: 10.1016/J.APENERGY.2018.08.065.

[165] Y. Guo, M. Pan, Y. Fang, and P. P. Khargonekar, “Decentralized coordination of energy utilization for residential households in the smart grid,” *IEEE Trans. Smart Grid*, vol. 4, no. 3, pp. 1341–1350, 2013, doi: 10.1109/TSG.2013.2268581.

[166] B. Römer, P. Reichhart, J. Kranz, and A. Picot, “The role of smart metering and decentralized electricity storage for smart grids: The importance of positive externalities,” *Energy Policy*, vol. 50, pp. 486–495, 2012.

[167] C. Guille and G. Gross, “A conceptual framework for the vehicle-to-grid (V2G) implementation,” *Energy Policy*, vol. 37, no. 11, pp. 4379–4390, 2009.

[168] University of Delaware, “Car Prototype Generates Electricity, And Cash -- ScienceDaily,” 2007. [Online]. Available: https://www.sciencedaily.com/releases/2007/12/071203133532.htm. [Accessed: 14-Oct-2019].

[169] Z. Wang, L. Wang, A. I. Dounis, and R. Yang, “Integration of plug-in hybrid electric vehicles into energy and comfort management for smart building,” *Energy Build.*, vol. 47, pp. 260–266, 2012.

[170] I. Korolija, “Heating, ventilating and air-conditioning system energy demand coupling with building loads for office buildings.,” 2011.

[171] M. Fiorentini, P. Cooper, and Z. Ma, “Development and optimization of an innovative HVAC system with integrated PVT and PCM thermal storage for a net-zero energy retrofitted house,” *Energy Build.*, vol. 94, no. 1, pp. 21–32, 2015.

[172] H. Mirinejad, S. Sadati, M. Ghasemian, and H. Torab, “Control techniques in heating, ventilating and air conditioning (hvac) systems 1,” 2008.

[173] J. Serra, D. Pubill, A. Antonopoulos, and C. Verikoukis, “Smart HVAC control in IoT: Energy consumption minimization with user comfort constraints,” *Sci. World J.*, vol. 2014, 2014.

[174] M. Cai, S. Ramdaspalli, M. Pipattanasomporn, S. Rahman, A. Malekpour, and S. R. Kothandaraman, “Impact of HVAC Set Point Adjustment on Energy Savings and Peak Load Reductions in Buildings,” in *2018 IEEE International Smart Cities Conference (ISC2)*, 2018, pp. 1–6, doi: 10.1109/ISC2.2018.8656738.

[175] F. M. Bhutta, “Application of smart energy technologies in building sector — future prospects,” in *2017 International Conference on Energy Conservation and Efficiency (ICECE)*, 2017, pp. 7–10, doi: 10.1109/ECE.2017.8248820.

[176] D. T. Delaney, G. M. P. O’Hare, and A. G. Ruzzelli, “Evaluation of energy-efficiency in lighting systems using sensor networks,” *BuildSys First ACM Work. Embed. Sens. Syst. Energy-Efficiency Build.*, pp. 61–66, 2009, doi: 10.1145/1810279.1810293.

[177] S. E. Selkowitz, E. S. Lee, and O. Aschehoug, “Perspectives on advanced facades with dynamic glazings and integrated lighting controls,” in *International Conferences on Solar*

Energy in Buildings, 2003.

[178] L. Martirano, M. Manganelli, L. Parise, and D. A. Sbordone, “Design of a fuzzy-based control system for energy saving and users comfort,” in *2014 14th International Conference on Environment and Electrical Engineering*, 2014.

[179] N. Zivic, O. Ur-Rehman, and C. Ruland, “Smart Metering for Intelligent Buildings,” *Trans. Networks Commun.*, vol. 4, no. 5, Oct. 2016, doi: 10.14738/tnc.45.2234.

[180] V. C. Gungor *et al.*, “Smart grid technologies: Communication technologies and standards,” *IEEE Trans. Ind. informatics*, vol. 7, no. 4, pp. 529–539, 2011.

[181] D. B. Avancini, J. J. P. C. Rodrigues, S. G. B. Martins, R. A. L. Rabêlo, J. Al-Muhtadi, and P. Solic, “Energy meters evolution in smart grids: A review,” *J. Clean. Prod.*, 2019.

[182] K. Förderer, M. Lösch, R. Növer, M. Ronczka, and H. Schmeck, “Smart Meter Gateways: Options for a BSI-Compliant Integration of Energy Management Systems,” *Appl. Sci.*, vol. 9, 2019.

[183] United-Nations, “Sustainable Development Goals,” 2019. [Online]. Available: https://sustainabledevelopment.un.org/sdgs. [Accessed: 26-Feb-2020].

[184] Europa, “Strategic Energy Technology (SET) Plan | Energy - Research and Innovation - European Commission,” 2019. [Online]. Available: https://ec.europa.eu/research/energy/index.cfm?pg=policy&policyname=set. [Accessed: 31-Jan-2019].

[185] ISO/IEC, “Information technology ISO/IEC JTC 1 Smart cities,” Geneva, 2015.

[186] ISO, “ISO/TR 37150:2014 - Smart community infrastructures -- Review of existing activities relevant to metrics,” 2014. [Online]. Available: https://www.iso.org/standard/62564.html. [Accessed: 08-Jul-2019].

[187] ISO, “ISO - ISO/TR 37150:2014 - Smart community infrastructures — Review of existing activities relevant to metrics,” Feb-2014. [Online]. Available: https://www.iso.org/standard/62564.html. [Accessed: 20-Jan-2021].

[188] ISO, “ISO - ISO/TS 37151:2015 - Smart community infrastructures — Principles and requirements for performance metrics,” May-2015. [Online]. Available: https://www.iso.org/standard/61057.html. [Accessed: 20-Jan-2021].

[189] ISO, “ISO/DIS 37122(en), Sustainable development in communities — Indicators for Smart Cities,” 2019. [Online]. Available: https://www.iso.org/obp/ui/#iso:std:iso:37122:dis:ed-1:v1:en:en (Accessed: 22 January 2019). [Accessed: 17-Mar-2019].

[190] European Commission, “Smart Cities,” *2021*. [Online]. Available: https://ec.europa.eu/eip/ageing/standards/city/smart-cities/une-1783012015_en. [Accessed: 20-Jan-2021].

[191] European Commission, “Smart cities Information System (SCIS),” 2020. [Online]. Available: https://smartcities-infosystem.eu/content/about-smart-cities-information-system-scis. [Accessed: 23-Jan-2021].

[192] European Commission, “CITYKeys ,” 2020. [Online]. Available: http://www.citykeys-project.eu/. [Accessed: 23-Jan-2021].

[193] BPIE, “BPIE - Buildings Performance Institute Europe,” 2020. [Online]. Available: http://bpie.eu/. [Accessed: 15-Mar-2020].

[194] British Standards Institution, “EN 15232 - Energy Performance of Buildings,” 2017.

[Online]. Available: https://standards.iteh.ai/catalog/standards/cen/d9e4b452-93a7-4b7e-b8f8-90e37adddbc2/en-15232-1-2017. [Accessed: 09-Jul-2022].

[195] M. Nelke and C. Håkansson, *Competitive intelligence for information professionals*. Chandos Publishing, 2015.

[196] H. H. Shah, Y. Ma, and S. R. Gulliver, "Selecting key performance indicators for sustainable intelligent buildings," in *IWCSC 2010 - Interdisciplinary Workshop on Communication for Sustainable Communities*, 2010, vol. 1, no. 1, doi: 10.1145/1951493.1951496.

[197] S. Verbeke, D. Aerts, G. Reynders, Y. Ma, and P. Waide, "Final report on the technical support to the development of a smart readiness indicator for buildings - Publications Office of the EU," Brussels, Jun. 2020.

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

[199] European-Commission, "IN-DEPTH ANALYSIS IN SUPPORT OF THE COMMISSION COMMUNICATION COM(2018) 773," 2018.

[200] S. Pezzutto, F. Haas, D. Exner, and S. Zambotti, "Europe's building stock and its energy demand: A comparison between Austria and Italy," in *Green Energy and Technology*, no. 9783319757735, Springer Verlag, 2018, pp. 35–47.

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

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

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

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

[205] N. N. Abu Bakar *et al.*, "Energy efficiency index as an indicator for measuring building energy performance: A review," *Renewable and Sustainable Energy Reviews*, vol. 44. Elsevier Ltd, pp. 1–11, 2015, doi: 10.1016/j.rser.2014.12.018.

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

[207] J. Liu, L. W, L. J, and W. B, "Efficiency of energy recovery ventilator with various weathers and its energy saving performance in a residential apartment," *Elsevier*, vol. 42, no. 1, pp. 43–49, 2010, doi: 10.1016/j.enbuild.2009.07.009.

[208] D. Zhang, N. Shah, and L. G. Papageorgiou, "Efficient energy consumption and operation management in a smart building with microgrid," *Energy Convers. Manag.*, vol. 74, pp. 209–222, 2013, doi: 10.1016/j.enconman.2013.04.038.

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

[210] S. Attia, *Net Zero Energy Buildings (NZEB): Concepts, frameworks and roadmap for project analysis and implementation*. Elsevier, 2018.

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

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

[213] V. Sougkakis, K. Lymperopoulos, N. Nikolopoulos, N. Margaritis, P. Giourka, and K.

Angelakoglou, "An Investigation on the Feasibility of Near-Zero and Positive Energy Communities in the Greek Context," *Smart Cities*, vol. 3, no. 2, pp. 362–384, May 2020, doi: 10.3390/smartcities3020019.

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

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

[216] 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*, 2017, doi: 10.1109/ISGT.2017.8086006.

[217] 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.

[218] G. Bissell *et al.*, "DEFINITION AND PRACTICAL APPLICATION OF KEY PERFORMANCE INDICATORS TO SUPPORT EUROPEAN GRID OPERATORS TO ENABLE THE ENERGY POLICY GOALS," 2014.

[219] K. Angelakoglou *et al.*, "A Methodological Framework for the Selection of Key Performance Indicators to Assess Smart City Solutions," *Smart Cities*, vol. 2, no. 2, pp. 269–306, Jun. 2019, doi: 10.3390/smartcities2020018.

[220] C. Del Pero, N. Aste, H. Paksoy, F. Haghighat, S. Grillo, and F. Leonforte, "Energy storage key performance indicators for building application," *Sustain. Cities Soc.*, vol. 40, pp. 54–65, Jul. 2018, doi: 10.1016/J.SCS.2018.01.052.

[221] C. Finck, R. Li, R. Kramer, and W. Zeiler, "Quantifying demand flexibility of power-to-heat and thermal energy storage in the control of building heating systems," *Appl. Energy*, vol. 209, pp. 409–425, Jan. 2018, doi: 10.1016/j.apenergy.2017.11.036.

[222] G. Reynders, J. Diriken, and D. Saelens, "Generic characterization method for energy flexibility: Applied to structural thermal storage in residential buildings," *Appl. Energy*, vol. 198, pp. 192–202, Jul. 2017, doi: 10.1016/j.apenergy.2017.04.061.

[223] L. F. Cabeza, E. Galindo, C. Prieto, C. Barreneche, and A. Inés Fernández, "Key performance indicators in thermal energy storage: Survey and assessment," *Renew. Energy*, vol. 83, pp. 820–827, Nov. 2015, doi: 10.1016/j.renene.2015.05.019.

[224] F. Haghigat, P. Tuohy, G. Fraisse, and C. Del Pero, "IEA ECES Annex 31 Final Report - Energy Storage with Energy Efficient Buildings and Districts: Optimization and Automation," International Energy Agency, Feb. 2019.

[225] 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.

[226] 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.

[227] J. Salom, J. Widén, J. Candanedo, I. Sartori, K. Voss, and A. Marszal, "Understanding net zero energy buildings: evaluation of load matching and grid interaction indicators," in *proceedings of building simulation*, 2011, vol. 6, pp. 2514–2521.

[228] G. Tumminia *et al.*, “Grid interaction and environmental impact of a net zero energy building,” *Energy Convers. Manag.*, vol. 203, p. 112228, Jan. 2020, doi: 10.1016/j.enconman.2019.112228.

[229] G. A. Dávi, M. Castillo-Cagigal, E. Caamaño-Martín, and 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,” in *32nd European Photovoltaic Solar Energy Conference and Exhibition EVALUATION*, 2016.

[230] M. Ala-Juusela, M. Sepponen, and T. Crosbie, “Defining the concept of an Energy Positive Neighbourhood and related KPIs,” in *Proceedings of Sustainable Places Conference*, 2014.

[231] 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.

[232] IRIS, “Deliverable 1.1 Report on the list of selected KPIs for each Transition Track,” 2018.

[233] A. Arteconi and F. Polonara, “Assessing the Demand Side Management Potential and the Energy Flexibility of Heat Pumps in Buildings,” *Energies*, vol. 11, no. 7, p. 1846, 2018.

[234] R. Yin *et al.*, “Quantifying flexibility of commercial and residential loads for demand response using setpoint changes,” *Appl. Energy*, vol. 177, pp. 149–164, Sep. 2016, doi: 10.1016/j.apenergy.2016.05.090.

[235] K. H. Chua, Y. S. Lim, and S. Morris, “Peak reduction for commercial buildings using energy storage,” in *IOP Conference Series: Earth and Environmental Science*, 2017, vol. 93, no. 1, doi: 10.1088/1755-1315/93/1/012008.

[236] N.-K. Kim, M.-H. Shim, and D. Won, “Building Energy Management Strategy Using an HVAC System and Energy Storage System,” *Energies*, vol. 11, no. 10, p. 2690, Oct. 2018, doi: 10.3390/en11102690.

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

[238] R. Li and S. You, “Exploring potential of energy flexibility in buildings for energy system services,” *CSEE J. Power Energy Syst.*, vol. 4, no. 4, pp. 434–443, 2018.

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

[240] M. Zimmermann, “Prefabricated Systems for Low Energy Renovation of Residential Buildings Energy Conservation in Buildings ,” Birmingham, 2012.

[241] I. Vigna, I. De Jaeger, D. Saelens, M. Lovati, R. Lollini, and R. Pernetti, “Evaluating Energy and Flexibility Performance of Building Clusters,” in *Proceedings of Building Simulation 2019: 16th Conference of IBPSA*, 2020, vol. 16, pp. 3326–3333, doi: 10.26868/25222708.2019.210448.

[242] A. Santos *et al.*, “Control strategies and algorithms for obtaining Energy Flexibility in buildings Energy in Buildings and Communities Programme Annex 67 Energy Flexible Buildings,” Denmark, 2019.

[243] H. Lund, A. Marszal, and P. Heiselberg, “Zero energy buildings and mismatch compensation factors,” *Energy Build.*, vol. 43, no. 7, pp. 1646–1654, Jul. 2011, doi: 10.1016/j.enbuild.2011.03.006.

[244] D. Uspenskaia, K. Specht, H. Kondziella, and T. Bruckner, "Challenges and barriers for net-zero/positive energy buildings and districts—empirical evidence from the smart city project sparcs," *Buildings*, vol. 11, no. 2, pp. 1–25, Feb. 2021, doi: 10.3390/buildings11020078.

[245] K. Voss *et al.*, "Load Matching and Grid Interaction of Net Zero Energy Buildings," 2016, pp. 1–8, doi: 10.18086/eurosun.2010.06.24.

[246] M. Z. Degefa, M. Lehtonen, M. McCulloch, and K. Nixon, "Real-time matching of local generation and demand: The use of high resolution load modeling," in *IEEE PES Innovative Smart Grid Technologies Conference Europe*, 2016, doi: 10.1109/ISGTEurope.2016.7856186.

[247] A. Athienitis and W. O'Brien, "Modelling, Design, and Optimization of Net-Zero Energy Buildings.," Wiley, 2015, pp. 216–222.

[248] R. Luthander, J. Widén, D. Nilsson, and J. Palm, "Photovoltaic self-consumption in buildings: A review," *Applied Energy*, vol. 142. Elsevier Ltd, pp. 80–94, 05-Mar-2015, doi: 10.1016/j.apenergy.2014.12.028.

[249] R. Fachrizal and J. Munkhammar, "Improved photovoltaic self-consumption in residential buildings with distributed and centralized smart charging of electric vehicles," *Energies*, vol. 13, no. 5, Mar. 2020, doi: 10.3390/en13051153.

[250] A. Prasanna, V. Dorer, and N. Vetterli, "Optimisation of a district energy system with a low temperature network," *Energy*, vol. 137, pp. 632–648, Oct. 2017, doi: 10.1016/j.energy.2017.03.137.

[251] M. Hall and A. Geissler, "Comparison of Flexibility Factors and Introduction of A Flexibility Classification Using Advanced Heat Pump Control," *Energies 2021, Vol. 14, Page 8391*, vol. 14, no. 24, p. 8391, Dec. 2021, doi: 10.3390/EN14248391.

[252] Z. Luo *et al.*, "Demand Flexibility of Residential Buildings: Definitions, Flexible Loads, and Quantification Methods," *Engineering*, Mar. 2022, doi: 10.1016/J.ENG.2022.01.010.

[253] Y. Ding, Y. Lyu, S. Lu, and R. Wang, "Load shifting potential assessment of building thermal storage performance for building design," *Energy*, vol. 243, p. 123036, Mar. 2022, doi: 10.1016/J.ENERGY.2021.123036.

[254] R. Brännlund and M. Vesterberg, "Peak and off-peak demand for electricity: Is there a potential for load shifting?," *Energy Econ.*, vol. 102, p. 105466, Oct. 2021, doi: 10.1016/J.ENECO.2021.105466.

[255] A. Arteconi, N. J. Hewitt, and F. Polonara, "State of the art of thermal storage for demand-side management," *Appl. Energy*, vol. 93, pp. 371–389, May 2012, doi: 10.1016/J.APENERGY.2011.12.045.

[256] 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*, 2015, pp. 1104–1108, doi: 10.1109/EEEIC.2015.7165321.

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

[258] B. Verbruggen and J. Driesen, "Grid impact indicators for active building simulations," *IEEE Trans. Sustain. Energy*, vol. 6, no. 1, pp. 43–50, Jan. 2015, doi:

10.1109/TSTE.2014.2357475.

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

[260] W. J. Harder and R. A. M. G. Joosten, "KEY PERFORMANCE INDICATORS FOR SMART GRIDS Master Thesis on Performance Measurement for Smart Grids," 2017.

[261] 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.

[262] D. Pramangioulis, K. Atsonios, N. Nikolopoulos, D. Rakopoulos, P. Grammelis, and E. Kakaras, "A Methodology for Determination and Definition of Key Performance Indicators for Smart Grids Development in Island Energy Systems," *Energies*, vol. 12, no. 2, p. 242, Jan. 2019, doi: 10.3390/en12020242.

[263] IEA, "Energy Efficiency Indicators – Analysis - IEA," 2021. [Online]. Available: https://www.iea.org/reports/energy-efficiency-indicators. [Accessed: 13-Feb-2021].

[264] E. Asadi, M. G. Da Silva, C. H. Antunes, and L. Dias, "Multi-objective optimization for building retrofit strategies: A model and an application," *Energy Build.*, vol. 44, no. 1, pp. 81–87, Jan. 2012, doi: 10.1016/j.enbuild.2011.10.016.

[265] F. Ardente, M. Beccali, M. Cellura, and M. Mistretta, "Energy and environmental benefits in public buildings as a result of retrofit actions," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 1. Elsevier Ltd, pp. 460–470, 01-Jan-2011, doi: 10.1016/j.rser.2010.09.022.

[266] S. E. Chidiac, E. J. C. Catania, E. Morofsky, and S. Foo, "Effectiveness of single and multiple energy retrofit measures on the energy consumption of office buildings," *Energy*, vol. 36, no. 8, pp. 5037–5052, Aug. 2011, doi: 10.1016/j.energy.2011.05.050.

[267] K. Golić, V. Kosorić, and A. K. Furundžić, "General model of solar water heating system integration in residential building refurbishment - Potential energy savings and environmental impact," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 3. Elsevier Ltd, pp. 1533–1544, 01-Apr-2011, doi: 10.1016/j.rser.2010.11.052.

[268] Y. Xing, N. Hewitt, and P. Griffiths, "Zero carbon buildings refurbishment - A Hierarchical pathway," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 6. Elsevier Ltd, pp. 3229–3236, 01-Aug-2011, doi: 10.1016/j.rser.2011.04.020.

[269] F. Stößel, H. Erhorn, H. Erhorn-Kluttig, and A. Zhivov, "IEA ECBCS Annex 46 Holistic Assessment Toolkit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo)," Berlin, 2009.

[270] M. Fink, A. Holm, and F. Antretter, "Annex 55 Reliability of Energy Efficient Building Retrofitting-Probability Assessment of Performance and Cost (RAP-RETRO) Practice and guidelines," Gothenburg, 2015.

[271] R. Bolliger *et al.*, "Methodology for Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation (Annex 56) Energy in Buildings and Communities Programme Contribution to cooling in the Mediterranian Area, Politecnico di Milano," 2017.

[272] Y. Tan, G. Liu, Y. Zhang, C. Shuai, and G. Q. Shen, "Green retrofit of aged residential buildings in Hong Kong: A preliminary study," *Build. Environ.*, vol. 143, pp. 89–98, Oct.

2018, doi: 10.1016/j.buildenv.2018.06.058.

[273] X. Liang, Y. Peng, and G. Q. Shen, "A game theory based analysis of decision making for green retrofit under different occupancy types," *J. Clean. Prod.*, vol. 137, pp. 1300–1312, Nov. 2016, doi: 10.1016/j.jclepro.2016.07.200.

[274] U.S. Green Building Council, "Green Retrofits | U.S. Green Building Council," 2021. [Online]. Available: https://www.usgbc.org/education/sessions/green-retrofits-4724579. [Accessed: 14-Feb-2021].

[275] C. Gleeson, J. Yang, and T. Lloyd-Jones, "European Retrofit Network: Retrofitting Evaluation Methodology Report," 2011.

[276] A. Carratt, G. Kokogiannakis, and D. Daly, "A critical review of methods for the performance evaluation of passive thermal retrofits in residential buildings," *Journal of Cleaner Production*, vol. 263. Elsevier Ltd, p. 121408, 01-Aug-2020, doi: 10.1016/j.jclepro.2020.121408.

[277] D. D'Agostino, P. Zangheri, and L. Castellazzi, "Towards Nearly Zero Energy Buildings in Europe: A Focus on Retrofit in Non-Residential Buildings," *Energies*, vol. 10, no. 1, p. 117, Jan. 2017, doi: 10.3390/en10010117.

[278] A. Joyce, C. Higgins, D. Staniaszek, and L. Wiggington, "WHAT IS A DEEP RENOVATION DEFINITION?," Feb. 2013.

[279] BPIE, "Europe's buildings under the microscope BPIE - Buildings Performance Institute Europe," Oct. 2011.

[280] Commonwealth of Australia, "Major, Minor Building Refurbishment - Fact Sheet 9," Department of the Environment and Water Resources Australian Greenhouse Office, 2007.

[281] BPIE, "EUROPE'S BUILDINGS UNDER THE MICROSCOPE A country-by-country review of the energy performance of buildings," Oct. 2011.

[282] I. ARTOLA, K. RADEMAEKERS, R. WILLIAMS, and J. YEARWOOD, "Boosting Building Renovation: What potential and value for Europe?," Brussels, Oct. 2016.

[283] M. Fabbri, M. De Groote, and O. Rapf, "Building Renovation Passports - Customised Roadmaps towards deep renovation and better homes," Brussels, Nov. 2016.

[284] K. N. Streicher, S. Mennel, J. Chambers, D. Parra, and M. K. Patel, "Cost-effectiveness of large-scale deep energy retrofit packages for residential buildings under different economic assessment approaches," *Energy Build.*, vol. 215, p. 109870, May 2020, doi: 10.1016/j.enbuild.2020.109870.

[285] G. Luddeni, M. Krarti, G. Pernigotto, and A. Gasparella, "An analysis methodology for large-scale deep energy retrofits of existing building stocks: Case study of the Italian office building," *Sustain. Cities Soc.*, vol. 41, pp. 296–311, Aug. 2018, doi: 10.1016/j.scs.2018.05.038.

[286] S. Henderson, "Residential Deep Energy Retrofits in Cold Climates," in *Sustainability, Energy and Architecture: Case Studies in Realizing Green Buildings*, Elsevier Inc., 2013, pp. 113–130.

[287] J. M. Cui, A. Ianakiev, and M. García-Fuentes, "To Examine Appropriate Deep-retrofit Practice using Simulation Results in an EU-funded Urban Regeneration Project," in *Energy Procedia*, 2017, vol. 105, pp. 2549–2556, doi: 10.1016/j.egypro.2017.03.733.

[288] European Commission, "Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings," Brussels, May 2010.

[289] F. Pardo-Bosch, C. Cervera, and T. Ysa, “Key aspects of building retrofitting: Strategizing sustainable cities,” *J. Environ. Manage.*, vol. 248, p. 109247, Oct. 2019, doi: 10.1016/j.jenvman.2019.07.018.

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

[291] K. Sørnes, I. Sartori, E. Fredriksen, and F. Rodriguez, “Final report on common definition for nZEB renovation,” Nov. 2014.

[292] D. D’Agostino, B. Cuniberti, and I. Maschio, “Criteria and structure of a harmonised data collection for NZEBs retrofit buildings in Europe,” in *Energy Procedia*, 2017, vol. 140, pp. 170–181, doi: 10.1016/j.egypro.2017.11.133.

[293] P. Moran, J. O’Connell, and J. Goggins, “Sustainable energy efficiency retrofits as residenial buildings move towards nearly zero energy building (NZEB) standards,” *Energy Build.*, vol. 211, Mar. 2020, doi: 10.1016/j.enbuild.2020.109816.

[294] D. D’Agostino and L. Mazzarella, “Data on energy consumption and Nearly zero energy buildings (NZEBs) in Europe,” *Data Br.*, vol. 21, pp. 2470–2474, Dec. 2018, doi: 10.1016/j.dib.2018.11.094.

[295] T. D. Mora, F. Cappelletti, F. Peron, P. R.-E. Procedia, and undefined 2015, “Retrofit of an historical building toward NZEB,” *Elsevier*.

[296] L. Bottaccioli *et al.*, “Building Energy Modelling and Monitoring by Integration of IoT Devices and Building Information Models,” in *Proceedings - International Computer Software and Applications Conference*, 2017, vol. 1, pp. 914–922, doi: 10.1109/COMPSAC.2017.75.

[297] B. van Vliet and F. de Feijter, “Smart Retrofitting of Urban Housing,” Amsterdam, 2019.

[298] European Commission, “FP7 Seventh Framework Program,” 2020. [Online]. Available: https://wayback.archive-it.org/12090/20191127213419/https:/ec.europa.eu/research/fp7/index_en.cfm. [Accessed: 22-Feb-2021].

[299] HEART, “HEART Project,” *European Union Horizon 2020 Research and Innovation Program*, 2020. [Online]. Available: https://heartproject.eu/. [Accessed: 22-Feb-2021].

[300] CORDIS, “Smart building retrofitting complemented by solar assisted heat pumps integrated within a self-correcting intelligent building energy management system. | Heat4Cool Project | H2020 | CORDIS | European Commission,” 2016. [Online]. Available: https://cordis.europa.eu/project/id/723925. [Accessed: 27-Mar-2020].

[301] CORDIS, “E2VENT - Design and integration of an adaptable module for residential building renovation,” *Journal of Facade Design and Engineering*, 2017. .

[302] CORDIS, “RetroKit - Toolboxes for systemic retrofitting,” 2012. [Online]. Available: https://cordis.europa.eu/project/id/314229. [Accessed: 27-Mar-2020].

[303] CORDIS, “Industrialised energy efficient retrofitting of resident buildings in cold climates | E2REBUILD Project | FP7 | CORDIS | European Commission,” 2011. [Online]. Available: https://cordis.europa.eu/project/id/260058. [Accessed: 27-Mar-2020].

[304] CORDIS, “Affordable and Adaptable Public Buildings through Energy Efficient Retrofitting | A2PBEER Project | FP7 | CORDIS | European Commission,” 2013. [Online]. Available: https://cordis.europa.eu/project/id/609060. [Accessed: 27-Mar-2020].

[305] CORDIS, “Holistic energy-efficient retrofitting of residential buildings | HERB Project |

FP7 | CORDIS | European Commission," 2012. [Online]. Available: https://cordis.europa.eu/project/id/314283. [Accessed: 27-Mar-2020].

[306] S. Y. Janjua, P. K. Sarker, and W. K. Biswas, "Development of triple bottom line indicators for life cycle sustainability assessment of residential bulidings," *J. Environ. Manage.*, vol. 264, p. 110476, Jun. 2020, doi: 10.1016/J.JENVMAN.2020.110476.

[307] M. Khorram, P. Faria, O. Abrishambaf, and Z. Vale, "Key performance indicators regarding user comfort for building energy consumption management," *Energy Reports*, vol. 6, pp. 87–92, Dec. 2020, doi: 10.1016/J.EGYR.2020.12.018.

[308] Y. Li, J. O'Donnell, R. García-Castro, and S. Vega-Sánchez, "Identifying stakeholders and key performance indicators for district and building energy performance analysis," *Energy Build.*, vol. 155, pp. 1–15, Nov. 2017, doi: 10.1016/J.ENBUILD.2017.09.003.

[309] M. C. Dejaco, F. Re Cecconi, and S. Maltese, "Key Performance Indicators for Building Condition Assessment," *J. Build. Eng.*, vol. 9, pp. 17–28, Jan. 2017, doi: 10.1016/J.JOBE.2016.11.004.

[310] T. Van Rooijen and N. Nesterova, "Applied framework for evaluation in CIVITAS PLUS II," 2013.

[311] L. Schibuola, M. Scarpa, and C. Tambani, "Demand response management by means of heat pumps controlled via real time pricing," *Energy Build.*, vol. 90, pp. 15–28, Mar. 2015, doi: 10.1016/j.enbuild.2014.12.047.

[312] M. J. Ruá and 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.*, vol. 8, no. 2, pp. 183–203, Apr. 2015, doi: 10.1007/s12053-014-9286-2.

[313] S. Attia, *Net Zero Energy Buildings (NZEB): Concepts, frameworks and roadmap for project analysis and implementation*. Elsevier, 2018.

[314] C. Lamnatou, D. Chemisana, and C. Cristofari, "Smart grids and smart technologies in relation to photovoltaics, storage systems, buildings and the environment," *Renew. Energy*, vol. 185, pp. 1376–1391, Feb. 2022, doi: 10.1016/J.RENENE.2021.11.019.

[315] A. O. Windapo and A. Moghayedi, "Adoption of smart technologies and circular economy performance of buildings," *Built Environ. Proj. Asset Manag.*, vol. 10, no. 4, pp. 585–601, 2020, doi: 10.1108/BEPAM-04-2019-0041.

[316] T. Karlessi *et al.*, "The Concept of Smart and NZEB Buildings and the Integrated Design Approach," *Procedia Eng.*, vol. 180, pp. 1316–1325, Jan. 2017, doi: 10.1016/J.PROENG.2017.04.294.

[317] S. Jain, S. Shukla, and R. Wadhvani, "Dynamic selection of normalization techniques using data complexity measures," *Expert Syst. Appl.*, vol. 106, pp. 252–262, Sep. 2018, doi: 10.1016/J.ESWA.2018.04.008.

[318] CORDIS, "Holistic Energy and Architectural Retrofit Toolkit | HEART Project | H2020 | CORDIS | European Commission," 2017. [Online]. Available: https://cordis.europa.eu/project/id/768921. [Accessed: 27-Mar-2020].

[319] CORDIS, "Next generation heat pump for retrofitting buildings | GREENHP Project | FP7 | CORDIS | European Commission," 2012. [Online]. Available: https://cordis.europa.eu/project/id/308816. [Accessed: 27-Mar-2020].

[320] CORDIS, "EASEE (Envelope Approach to improve Sustainability and Energy efficiency in

Existing multi-storey multi-owner residential buildings),” 2012. [Online]. Available: https://cordis.europa.eu/project/id/285540/reporting. [Accessed: 27-Mar-2020].

[321] CORDIS, “Holistic Approach and Platform for the deep renovation of the med residential built Environment,” 2018. [Online]. Available: https://cordis.europa.eu/project/id/785072. [Accessed: 27-Mar-2020].

[322] CORDIS, “Standardized approaches and products for the systemic retrofit of residential Buildings, focusing on Heating and cooling consumption attenuation,” 2015. [Online]. Available: https://cordis.europa.eu/project/id/680658. [Accessed: 27-Mar-2020].

[323] CORDIS, “Residential Retrofit assessment platform and demonstrations for near zero energy and CO2 emissions with optimum cost, health, comfort and environmental quality,” 2018. [Online]. Available: https://cordis.europa.eu/project/id/768576. [Accessed: 27-Mar-2020].

[324] CORDIS, “Development and advanced prefabrication of innovative, multifunctional building envelope elements for MOdular REtrofitting and CONNECTions,” 2014. [Online]. Available: https://cordis.europa.eu/project/id/633477. [Accessed: 27-Mar-2020].

[325] CORDIS, “Building and district thermal retrofit and management solutions,” 2016. [Online]. Available: https://cordis.europa.eu/project/id/723562. [Accessed: 27-Mar-2020].

[326] CORDIS, “Demonstrating the effectiveness and commercial potential of CLIMAWIN intelligent windows for energy efficiency in retrofit of buildings in Europe,” 2013. [Online]. Available: https://cordis.europa.eu/project/id/315324/it. [Accessed: 27-Mar-2020].

[327] CORDIS, “INSPIRE (Development of Systemic Packages for Deep Energy Renovation of Residential and Tertiary Buildings including Envelope and Systems),” 2012. [Online]. Available: https://cordis.europa.eu/project/id/314461/reporting. [Accessed: 27-Mar-2020].

[328] CORDIS, “Accelerating Energy renovation solution for Zero Energy buildings and Neighbourhoods,” 2017. [Online]. Available: https://cordis.europa.eu/project/id/768718. [Accessed: 27-Mar-2020].

[329] CORDIS, “R & D in Sustainable Building Energy Systems and Retrofitting,” 2011. [Online]. Available: https://cordis.europa.eu/project/id/269205. [Accessed: 27-Mar-2020].

[330] CORDIS, “Refurbishment decision making platform through advanced technologies for near Zero energy BUILDing renovation,” 2017. [Online]. Available: https://cordis.europa.eu/project/id/768623. [Accessed: 27-Mar-2020].

[331] CORDIS, “Demonstration of an integrated Renovation approach for Energy Efficiency At the Multi building scale,” 2015. [Online]. Available: https://cordis.europa.eu/project/id/680511. [Accessed: 27-Mar-2020].

[332] VITO, “Smart Readiness Indicator for Buildings | Smart Readiness Indicator for Buildings,” 2019. [Online]. Available: https://smartreadinessindicator.eu/. [Accessed: 03-Feb-2019].

[333] “Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings.”

[334] R. Hitchin and K. E. Thomsen, “Primary Energy Factors and Members States Energy Regulations Primary factors and the EPBD,” 2010.

[335] N. Nakicenovic *et al.*, “ENERGY PRIMER,” 1997.

[336] ISO, “ISO 52000-1:2017, Energy performance of buildings — Overarching EPB

assessment," 2017. [Online]. Available: https://www.iso.org/obp/ui/#iso:std:65601:en. [Accessed: 24-Jan-2021].

[337] L. Leoncini, "The Primary Energy Factors play a central role in European 2020 targets achievement ," 2020.

[338] European Parliament and Council, "Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency | Build Up," 2012. [Online]. Available: http://www.buildup.eu/en/practices/publications/directive-201227eu-european-parliament-and-council-25-october-2012-energy. [Accessed: 31-Jan-2019].

[339] S. Firląg and M. Piasecki, "NZEB Renovation Definition in a Heating Dominated Climate: Case Study of Poland," *Appl. Sci.*, vol. 8, no. 9, p. 1605, Sep. 2018, doi: 10.3390/app8091605.

[340] U. R. Fritsche and G. Hans-Werner, "Development of the Primary Energy Factor of Electricity Generation in the EU-28 from 2010-2013," Darmstadt, Mar. 2015.

[341] International Organization for Standardization, "ISO - ISO 52000-1:2017 - Energy performance of buildings — Overarching EPB assessment — Part 1: General framework and procedures," 2017. [Online]. Available: https://www.iso.org/standard/65601.html. [Accessed: 24-Jan-2021].

[342] M. Jaszczur and Q. Hassan, "An optimisation and sizing of photovoltaic system with supercapacitor for improving self-consumption," *Appl. Energy*, vol. 279, p. 115776, Dec. 2020, doi: 10.1016/j.apenergy.2020.115776.

[343] E. McKenna, E. Webborn, P. Leicester, and S. Elam, "Analysis of international residential solar PV self-consumption," in *ECEEE 2019 Sumer Study*, 2019.

[344] G. Masson, Jose Ignacio Briano, and Maria Jesus Baez, "A METHODOLOGY FOR THE ANALYSIS OF PV SELF-CONSUMPTION POLICIES," 2016.

[345] C. Mateo *et al.*, "Impact of solar PV self-consumption policies on distribution networks and regulatory implications," *Sol. Energy*, vol. 176, pp. 62–72, Dec. 2018, doi: 10.1016/j.solener.2018.10.015.

[346] I. Sartori, A. Napolitano, K. V.-E. and buildings, and undefined 2012, "Net zero energy buildings: A consistent definition framework," *Elsevier*.

[347] K. Voss, I. Sartori, A. Napolitano, S. G.-… and Buildings, and undefined 2010, "Load matching and grid interaction of net zero energy buildings," *repositorio.lneg.pt*.

[348] A. Dodoo, "Primary energy and economic implications of ventilation heat recovery for a multi-family building in a Nordic climate," *J. Build. Eng.*, vol. 31, p. 101391, Sep. 2020, doi: 10.1016/j.jobe.2020.101391.

[349] J. F. Garcia and L. Kranzl, "Ambition Levels of Nearly Zero Energy Buildings (nZEB) Definitions: An Approach for Cross-Country Comparison," *Build. 2018, Vol. 8, Page 143*, vol. 8, no. 10, p. 143, Oct. 2018, doi: 10.3390/BUILDINGS8100143.

[350] 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.

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

[352] 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.*, vol. 1,

pp. 20–32, Mar. 2015, doi: 10.1016/j.jobe.2015.01.002.

[353] D. D'Agostino, P. Zangheri, and L. Castellazzi, "Towards nearly zero energy buildings in Europe: A focus on retrofit in non-residential buildings," *Energies*, vol. 10, no. 1, 2017, doi: 10.3390/en10010117.

[354] EC-Europa, "Nearly zero-energy buildings and their energy performance | Energy," 2020. [Online]. Available: https://ec.europa.eu/energy/eu-buildings-factsheets-topics-tree/nearly-zero-energy-buildings-and-their-energy-performance_en. [Accessed: 03-Sep-2021].

[355] 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)," *Build. Perform. Inst. Eur.*, May 2019.

[356] C. S. Monteiro, F. Causone, S. Cunha, A. Pina, and S. Erba, "Addressing the challenges of public housing retrofits," *Energy Procedia*, vol. 134, pp. 442–451, 2017, doi: 10.1016/J.EGYPRO.2017.09.600.

[357] C. A. Balaras, E. G. Dascalaki, K. G. Droutsa, and S. Kontoyiannidis, "Empirical assessment of calculated and actual heating energy use in Hellenic residential buildings," *Appl. Energy*, vol. 164, pp. 115–132, Feb. 2016, doi: 10.1016/J.APENERGY.2015.11.027.

[358] E. G. Dascalaki, K. G. Droutsa, C. A. Balaras, and 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.*, vol. 43, no. 12, pp. 3400–3409, Dec. 2011, doi: 10.1016/J.ENBUILD.2011.09.002.

[359] M. Beccali, M. Cellura, M. Fontana, S. Longo, and M. Mistretta, "Energy retrofit of a single-family house: Life cycle net energy saving and environmental benefits," *Renew. Sustain. Energy Rev.*, vol. 27, pp. 283–293, Nov. 2013, doi: 10.1016/J.RSER.2013.05.040.

[360] H. Johra, P. K. Heiselberg, and 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*, 2017, pp. 35–42, doi: 10.26868/25222708.2017.012.

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

[362] R. G. Junker *et al.*, "Characterizing the energy flexibility of buildings and districts," *Appl. Energy*, vol. 225, pp. 175–182, 2018.

[363] H. Tang and S. Wang, "Energy flexibility quantification of grid-responsive buildings: Energy flexibility index and assessment of their effectiveness for applications," *Energy*, vol. 221, p. 119756, Apr. 2021, doi: 10.1016/j.energy.2021.119756.

[364] A. K. Athienitis, E. Dumont, N. Morovat, K. Lavigne, and 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*, 2020, pp. 12–31.

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

[366] C. Finck, R. Li, R. Kramer, W. Z.-A. Energy, and undefined 2018, "Quantifying demand

flexibility of power-to-heat and thermal energy storage in the control of building heating systems," *Elsevier*.

[367] F. Mancini, J. Cimaglia, G. Lo Basso, and 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 2021, Vol. 14, Page 3080*, vol. 14, no. 11, p. 3080, May 2021, doi: 10.3390/EN14113080.

[368] H. Johra, P. Heiselberg, and J. Le Dréau, "Influence of envelope, structural thermal mass and indoor content on the building heating energy flexibility," *Energy Build.*, vol. 183, pp. 325–339, Jan. 2019, doi: 10.1016/J.ENBUILD.2018.11.012.

[369] F. Mancini, S. Romano, G. Lo Basso, J. Cimaglia, and 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 2020, Vol. 13, Page 3359*, vol. 13, no. 13, p. 3359, Jul. 2020, doi: 10.3390/EN13133359.

[370] K. Foteinaki, R. Li, T. Péan, C. Rode, and J. Salom, "Evaluation of energy flexibility of low-energy residential buildings connected to district heating," *Energy Build.*, vol. 213, p. 109804, Apr. 2020, doi: 10.1016/J.ENBUILD.2020.109804.

[371] J. Dehler *et al.*, "Self-Consumption of Electricity from Renewable Sources," *Eur. Energy Transit. Insights Policy Mak.*, pp. 225–236, Jan. 2017, doi: 10.1016/B978-0-12-809806-6.00027-4.

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

[373] J. Li and M. A. Danzer, "Optimal charge control strategies for stationary photovoltaic battery systems," *J. Power Sources*, vol. 258, pp. 365–373, Jul. 2014, doi: 10.1016/j.jpowsour.2014.02.066.

[374] J. Weniger, T. Tjaden, and V. Quaschning, "Sizing of residential PV battery systems," in *Energy Procedia*, 2014, vol. 46, pp. 78–87, doi: 10.1016/j.egypro.2014.01.160.

[375] R. Thygesen and 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*, vol. 103, pp. 19–27, May 2014, doi: 10.1016/J.SOLENER.2014.02.013.

[376] C. Williams, J. Binder, and 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," *2012 3rd IEEE PES Innov. Smart Grid Technol. Eur. (ISGT Eur. IEEE*, pp. 1–6, 2012.

[377] E. Waffenschmidt, "Dimensioning of Decentralized Photovoltaic Storages with Limited Feed-in Power and their Impact on the Distribution Grid," *Energy Procedia*, vol. 46, pp. 88–97, Jan. 2014, doi: 10.1016/J.EGYPRO.2014.01.161.

[378] Y. Riesen, C. Ballif, and N. Wyrsch, "Control algorithm for a residential photovoltaic system with storage," *Appl. Energy*, vol. 202, pp. 78–87, Sep. 2017, doi: 10.1016/J.APENERGY.2017.05.016.

[379] M. Osawa *et al.*, "Increase the rate of utilization of Residential photovoltaic generation by EV charge-discharge control," *2012 IEEE Innov. Smart Grid Technol. - Asia, ISGT Asia 2012*, 2012, doi: 10.1109/ISGT-ASIA.2012.6303134.

[380] 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*, 2015, pp. 579–584.

[381] A. Mohamed and A. Hasan, “Energy matching analysis for net-zero energy buildings,” *Sci. Technol. Built Environ.*, vol. 22, no. 7, pp. 885–901, Oct. 2016, doi: 10.1080/23744731.2016.1176850.

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

[383] J. Widén and E. Wäckelgård, “Net Zero Energy Solar Buildings at High Latitudes: The Mismatch Issue,” in *Conference: EASST 2010 Conference: Practicing Science and Technology, Performing the Social*, 2010.

[384] B. Berggren, J. Widen, B. Karlsson, and M. Wall, “EVALUATION AND OPTIMIZATION OF A SWEDISH NET ZEB-USING LOAD MATCHING AND GRID INTERACTION INDICATORS,” *IBPSA-England, 2012*, 2012.

[385] F. Harkouss, F. Fardoun, and P. H. Biwole, “Optimal design of renewable energy solution sets for net zero energy buildings,” *Energy*, vol. 179, pp. 1155–1175, Jul. 2019, doi: 10.1016/J.ENERGY.2019.05.013.

[386] F. Frontinia, M. Manfren, and L. C. Tagliabue, “A case study of solar technologies adoption: criteria for BIPV integration in sensitive built environment ,” *Energy Procedia*, vol. 30, pp. 1006–1015, 2012.

[387] B.-J. Kim, H.-W. Lim, D.-S. Kim, and U.-C. Shin, “A Study of Load Matching on the Net-Zero Energy House,” *J. Korean Sol. Energy Soc.*, vol. 38, no. 4, pp. 55–66, Aug. 2018, doi: 10.7836/KSES.2018.38.4.055.

[388] M. Manfren *et al.*, “Parametric energy performance analysis and monitoring of buildings—HEART project platform case study,” *Sustain. Cities Soc.*, vol. 61, p. 102296, Oct. 2020, doi: 10.1016/J.SCS.2020.102296.

[389] European Commission, “Holistic Energy and Architectural Retrofit Toolkit (HEART) Deliverables,” 2020.

[390] 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.

[391] R. Koželj, U. Mlakar, E. Zavrl, U. Stritih, and 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.*, vol. 248, p. 111196, Oct. 2021, doi: 10.1016/J.ENBUILD.2021.111196.

[392] D. Ibaseta *et al.*, “Monitoring and control of energy consumption in buildings using WoT: A novel approach for smart retrofit,” *Sustain. Cities Soc.*, vol. 65, p. 102637, Feb. 2021, doi: 10.1016/J.SCS.2020.102637.

[393] H. A. Khudhair and Z. Isik, “◎Key Performance Indicators in Retrofitting Projects: A Review,” in *10th Int’l Conference on Studies in Architecture, Civil, Design & Environmental Engineering*, 2018, pp. 70–75, doi: 10.17758/EARES1.EAP0518205.

[394] O. McGinley, P. Moran, and J. Goggins, “An Assessment of the Key Performance Indicators (KPIs) of Energy Efficient Retrofits to Existing Residential Buildings,” *Energies 15(1), 334*, vol. 15, no. 1, p. 334, Jan. 2022, doi: 10.3390/en15010334.

[395] T. Vilutiene and Č. Ignatavičius, “Towards Sustainable Renovation: Key Performance Indicators for Quality Monitoring,” *Sustainability*, vol. 10, no. 6, p. 1840, Jun. 2018, doi: 10.3390/SU10061840.

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

[397] V. Apostolopoulos, P. Giourka, G. Martinopoulos, K. Angelakoglou, K. Kourtzanidis, and N. Nikolopoulos, “Smart readiness indicator evaluation and cost estimation of smart retrofitting scenarios - A comparative case-study in European residential buildings,” *Sustain. Cities Soc.*, vol. 82, p. 103921, Jul. 2022, doi: 10.1016/J.SCS.2022.103921.

[398] G. Schmidt-Traub, C. Kroll, K. Teksoz, D. Durand-Delacre, and J. D. Sachs, “National baselines for the Sustainable Development Goals assessed in the SDG Index and Dashboards,” *Nat. Geosci. 2017 108*, vol. 10, no. 8, pp. 547–555, Jul. 2017, doi: 10.1038/ngeo2985.

[399] United Nations, “Human Development Index (HDI) | Human Development Reports,” *2021*. [Online]. Available: https://hdr.undp.org/en/content/human-development-index-hdi. [Accessed: 08-Mar-2022].

[400] H. Amini Toosi, M. Lavagna, F. Leonforte, C. Del Pero, and N. Aste, “A novel LCSA-Machine learning based optimization model for sustainable building design-A case study of energy storage systems,” *Build. Environ.*, vol. 209, p. 108656, Feb. 2022, doi: 10.1016/J.BUILDENV.2021.108656.

[401] A. Abu-Rayash and I. Dincer, “Development of integrated sustainability performance indicators for better management of smart cities,” *Sustain. Cities Soc.*, vol. 67, p. 102704, Apr. 2021, doi: 10.1016/J.SCS.2020.102704.

[402] M. Trompet and D. J. Graham, “A Balanced Approach to Normalizing Bus Operational Data for Performance Benchmarking Purposes,” in *Transportation Research Board 91st Annual Meeting*, 2012.

[403] M. Pizzol, A. Laurent, S. Sala, B. Weidema, F. Verones, and C. Koffler, “Normalisation and weighting in life cycle assessment: quo vadis?,” *Int. J. Life Cycle Assess.*, vol. 22, no. 6, pp. 853–866, Jun. 2017, doi: 10.1007/S11367-016-1199-1.

[404] European Committee for Standardization, “CEN - EN 15603 - Energy performance of buildings - Overall energy use and definition of energy ratings,” 01-Jan-2008. [Online]. Available: https://standards.globalspec.com/std/1146572/EN 15603. [Accessed: 12-Mar-2022].

[405] European Commission, “European Green Deal: Commission proposes to boost renovation and decarbonisation of buildings,” *Renovation and decarbonisation of buildings*, 15-Dec-2021. [Online]. Available: https://ec.europa.eu/commission/presscorner/detail/en/IP_21_6683. [Accessed: 12-Mar-2022].

[406] World Green Building Council, “Renovation Strategy Framework,” *Capturing the benefits of building renovation*, Sep-2021. [Online]. Available: https://www.worldgbc.org/our-renovation-strategy-framework. [Accessed: 12-Mar-2022].