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Smart readiness indicator evaluation and cost estimation of smart retrofitting scenarios - A comparative case-study in European residential buildings

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ABSTRACT

The current research applies the SRI methodology in two typologies of typical residential buildings, Single-Family Houses and Multi-Family Houses, in five EU Countries, to evaluate the retrofitting cost towards buildings smartification and assess the SRI score when different retrofitting scenarios are applied. To that end, a three-step assessment process is adopted. First, the SRI is calculated for the baseline scenario representing the national minimum requirements according to the EPBD. Next, the SRI is calculated after applying a retrofitting scenario that includes market available technologies towards Nearly Zero Energy Buildings. Last, a more comprehensive retrofitting scenario of integrated technologies towards Positive Energy Buildings is assessed. Results indicate that buildings, constructed after the implementation of the EPBD, can increase smartness with a relatively low cost than older buildings, although their initial overall SRI score generally leads to an SRI Class G (0–20%), with buildings performing better in "Health, well-being and accessibility" and "Comfort" impact categories. Smart-orientated retrofitting scenarios focusing on building automation and control measures can increase such buildings class up to "C" (65–80%), performing better in optimizing energy efficiency when applying retrofits towards NZEB. Applying retrofitting scenarios that could potentially lead to energy positiveness mainly supports building interaction with the grid.

1. Introduction

The concept of "green" and "smart" buildings is gaining momentum globally, due to its promising impact on i) resource efficiency, ii) renewable energy generation and iii) climate change mitigation (Rameshwar, Solanki, Nayyar, & Mahapatra, 2022). Buildings account for 36% of worldwide final energy consumption and around 37% of energy-related carbon dioxide (CO_2) emissions (United Nations Environment Programme, 2021). In the European Union (EU), the building stock is responsible for 40% of the total EU energy consumption and 36% of total greenhouse gases (GHG) emissions (European Commission, 2020), whilst around 75% of the existing buildings are energy inefficient (Joint Research Centre 2019), owed to the presence of several old non-renovated residential buildings built before 1980. Based on relevant estimations, around 250 M homes, at a rate of approximately 23 K homes per day until 2050, should be renovated in order to achieve the EU's energy efficiency and climate targets (University of Cambridge Institute for Sustainability Leadership CISL, 2018). The European Climate Law (Regulation, 2021), adopted in 2021, sets the ambitious targets of reducing GHG emissions by 55% until 2030 and of reaching climate neutrality by 2050 in line with the European Green Deal vision (European Commission, 2019). Deep renovation of the building stock is a key enabler for decarbonizing the energy system as well as reducing energy consumption and increasing grid flexibility, thus facilitating the further uptake of renewable energy sources (RES) (BPIE (Buildings Performance Institute Europe) 2021). To that end, as part of the European Green Deal, European Commission (EC) introduced in 2020 the "Renovation Wave" initiative (European Commission, 2020), which involves an action plan towards increasing significantly the rate and depth of building renovation by 2030, while stimulating the creation of green and smart buildings, causing improved quality of life (European Commission, 2020).

The recent advances in smart technologies unlocked new ways for buildings to interact with the energy infrastructure, speeding up energy

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transition and contributing substantially to the creation of a healthier and more comfortable built environment with reduced energy requirements and carbon impact (Attoue, Shahrour, & Younes, 2018, To, Lai, Lam, & Chung, 2018). The "smart building" concept brought new opportunities for the digitalization and decarbonization of the building stock (Al Dakheel, Del Pero, Aste, & Leonforte, 2020). Smart buildings are based on the utilization of advanced technologies (Akkaya, Guvenc, Aygun, Pala, & Kadri, 2015), such as the Internet of Things (IoT), that facilitate the realization and delivery of control services (Kumar et al., 2021) ensuring optimal performance and seamless operation of building systems in an energy-efficient manner that results in energy savings as well as considerable improvement of users' comfort and wellbeing (Jia, Komeily, Wang, & Srinivasan, 2019). From an energy perspective, smart buildings need to be energy efficient buildings covering their energy requirements at a large extent by on-site RES, in order to be nearly zero energy buildings (NZEBs), in line the Energy Performance of Buildings Directive (EPBD) from 2021 onwards (D'Agostino, Tzeiranaki, Zangheri, & Bertoldi, 2021). The integration of cutting-edge smart technologies will enhance the energy performance of smart buildings, in order to generate surplus of energy, paving the way for the essential next step of building-grid interconnection and the operation of the building as prosumer (Vigna, Pernetti, Pasut, & Lollini, 2018), towards positive energy buildings (PEBs) (Ala-Juusela, Rehman, Hukkalainen, & Reda, 2021). The installation and interconnection of the different smart systems, creates a central and multidimensional building management environment, covering a wide range of smart actions that can offer also real-time monitoring of all building parameters (Li et al., 2019) and useful reporting information during the building lifecycle (Omar, 2018). Considering that people spend around 80–90% of their time indoors (Park & Nagy, 2018), quality of life is also a crucial aspect in which smart systems and services can assist by optimizing the building behaviour in terms of improving health, comfort, security, and productivity (Sharif & Pokharel, 2022, Šujanová, Rychtáriková, Sotto Mayor, & Hyder, 2019).

The enhancement of the smartness level in the building stock is of great importance for the sustainability of buildings and the environment (Ghaffarianhoseini et al., 2018), as it is a fundamental element of self-resiliency and on a wider context, that of a smart city (Apanaviciene, Vanagas, & Fokaides, 2020). However, when it comes to improving the smartness of the building stock, accurate and reliable analysis of operation patterns and an overarching set of fit-for-purpose smart retrofitting measures, are required. Smartification measures should be able to respond to the local context of climate conditions, policies and regulations as well as to adapt properly to the different types of building typologies and specific needs of urban areas. Aiming to highlight the strengths and benefits of smart technologies and foster their integration in buildings, the recast of the EPBD launched the Smart Readiness Indicator (SRI) (Directive 2018) a common EU scheme for rating the smart readiness of buildings. SRI can play an essential role in evaluating the impacts of building smartification on the energy flexibility of the building (Vivian, Chiodarelli, Emmi, & Zarrella, 2020), while supporting decision-making and action planning towards the smart and sustainable transformation and modernization of the EU building stock. In this context, SRI acts as a key policy instrument for all the stakeholders engaging in buildings retrofitting, i.e., building occupants and owners, property managers, building designers and engineers, product manufacturers, technology providers, and policy-makers. SRI aims to enhance the role of the building into the energy infrastructure by enabling its interaction with users and power networks (Märzinger & Österreicher, 2020), while also creating favourable conditions for the introduction of novel smart systems and innovative building materials with the best standards in the market and the best practices for application in the building sector (Janhunen, Leskinen, & Junnila, 2020). SRI implementation is supposed to help in the integration of energy efficient buildings, NZEBs and PEBs, into a smart city promoting grid flexibility and energy communities. For example, the national regulation in Denmark allows the establishment of customer-owned enterprises led by communities in order to participate in local grid and district heating networks (Caramizaru & Uihlein, 2020). In Greece, regulation on energy communities aims to achieve the improvement of end-use energy efficiency at local and regional level via smart energy management and storage, as well as to foster alternative production, supply and self-consumption of clean energy especially to islands and vulnerable households towards alleviating energy poverty (The Greek Office of the Heinrich Böll Foundation, 2022). In Austria, the national legislation focuses mainly on community-based electricity generation and trading from renewable sources (Fina & Fechner, 2021). Lower-income EU Member States such as Czech Republic and Bulgaria need to reform their national regulatory framework regarding the role of energy communities in the promotion of energy efficiency measures and modernisation of the energy system via smart and renewable technologies (Pappa & Vansintjan, 2020).

Since SRI is a new research topic, a limited number of studies in the field currently exist, applying the SRI methodology to specific case buildings, districts, and climate zones (Becchio, Corgnati, Crespi, Pinto, & Viazzo, 2021, Janhunen, Leskinen, & Junnila, 2020, Märzinger & Österreicher, 2020), Märzinger & Österreicher, 2019). Most studies have reported inconsistencies and methodological gaps in the SRI calculation amongst different refurbishment options assessed, as well as subjectivity and problematic interpretation in the selection of the relevant building services in the SRI implementation. Researchers (Janhunen, Pulkka, Säynäjoki, & Junnila, 2019) outlined that the SRI framework needs critical improvements to be applicable for cold climate countries, since it does not address properly that of Finland, where for example, there are high heating needs and there are mainly district heating networks (DHNs) used to cover heat demand, while others (Vigna, Pernetti, Pernigotto, & Gasparella, 2020) implemented the SRI detailed method to a nearly zero-energy office building in Italy, and their analysis outlined the impact of the subjective decisions in the selection of applicable services and associated functionality levels on the SRI calculation and assessment. Another study (Fokaides, Panteli, & Panayidou, 2020) attempted to identify gaps in the SRI methodology by using the current technical framework approach in a mixed-use building in Cyprus. The authors claim that the SRI is not well-developed and tailor-made for small residential buildings, due to the absence of Building Management Systems (BMS) to offer central monitoring and control. They concluded that the SRI framework implies a high level of subjectivity in some cases in the selection and evaluation of services and functionalities, highlighting also the need for the development of a commonly accepted database for smart building systems and revision of the methodology in the short run. The need for reconsiderations in the SRI methodology in order to contain specific properties of non-residential Mediterranean climate buildings was also showcased in another relevant publication (Ramezani, Silva Manuel, & Simões, 2021). Varsami & Burman, 2022 stressed out that the SRI methodology cannot consider properly all the EU objectives for 2050 while also the fact that the SRI assessment is based on qualitative criteria and not on the actual performance. A set of key recommendations that will help upgrade the current SRI methodology in the residential sector was also proposed (Canale et al., 2021).

Aim of this paper is to investigate the impact of potential retrofitting scenarios on the smartification of residential buildings for two specific typologies, i.e., a) single-family houses (SFH) and b) multi-family houses (MFH) in various EU countries covering all five SRI defined climate zones. As buildings that have been built after 2010 (EPBD) can be considered energy efficient, the paper focuses on buildings of this era, proposing retrofitting scenarios that are limited into active systems consideration, without renovation of the building envelope. The initial state and the smart readiness level achieved after the retrofitting actions on the specific buildings, are assessed in terms of the SRI scheme. An analysis on various retrofit scenarios examined, offers insight on the SRI improvement achieved in relation to the cost of the interventions

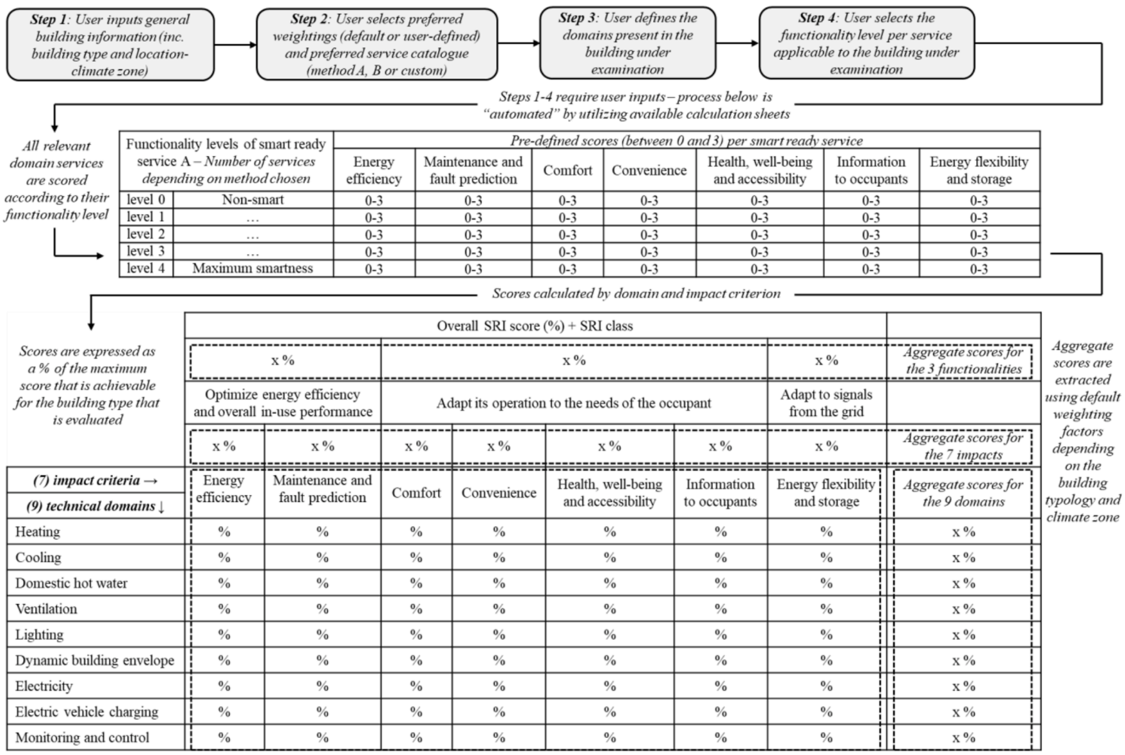


Fig. 1. Overall SRI assessment process.

Table 1
Methods that can be applied to assess the SRI (adapted from Directorate-General for Energy (European Commission) 2020).

	Method A	Method B	Method C
Smart-ready service catalogue	Lists a limited, simplified catalogue of 27 services	Lists full catalogue of 54 services	Self-reporting based on Building Automation and Control Systems
Applicability	Residential and small non-residential (<500m^2)	Non-residential buildings (residential if desired)	Residential and non-residential (restricted to occupied buildings)
Other information	Checklist approach, online self-assessment by end-user (no certification) or on-site third-party assessment (formal certification)	Checklist approach, online self-assessment by end-user (no certification) or on-site third-party assessment (formal certification)	Requires data over a long period, detailed specifications not available yet

described in each scenario. In this context, the main goal of the study is to contribute on the collection of practical experience and to generate relevant knowledge on the application of the SRI in a real-life context, while evaluating the cost of integrating smart technologies in buildings. The remainder of the article is structured as follows: Section 2 outlines key methodological aspects and background for the use and calculation of the SRI in buildings. Section 3 presents the study approach adopted for establishing the retrofit scenarios and conducting the SRI assessment in the selected typical buildings of the five SRI defined climate zones and respective countries, while Section 4 provides the SRI results and analysis of the renovation scenarios in relation with SRI improvement and intervention cost. The paper ends with a summary of key conclusions (Section 5).

2. The smart readiness indicator – a quick overview of the evaluation process

The concept of SRI was introduced in the 2018 revision of the EPBD (Directive 2018), with a goal to provide a common EU scheme for rating the smart readiness of buildings. Subsequent regulations (Commission Delegated Regulation 2020), (Commission Implementing Regulation, 2020) and technical studies (Directorate-General for Energy (European Commission) 2020), (Directorate-General for Energy (European Commission) 2020) launched the currently ongoing SRI testing phase, according to which EU countries can implement, in an optional way for the moment, this rating scheme. The introduction of the SRI came as a response to the need to accelerate building renovation investments and leverage smart energy-efficient technologies in the building sector across Europe. The SRI assesses the ability of a building to operate in a way so as to optimize its energy efficiency and overall performance, its ability to adapt to signals from the grid (energy flexibility), and respond to the needs of the building occupants (European Commission, 2022). As such, it deals mostly with the electromechanical infrastructure of buildings and not on the building envelope.

The methodology for calculating the SRI is described in detail in Directorate-General for Energy (European Commission) 2020 and summarized in Fig. 1. The final SRI rating depends on the examined buildings ability to facilitate "smart-ready" services, which are included in a "smart-ready service catalogue", addressing nine (9) technical domains, namely 1) Heating, 2) Domestic hot water (DHW), 3) Cooling, 4) Ventilation, 5) Lighting, 6) Dynamic building envelope, 7) Electricity, 8) Electric vehicle charging and 9) Monitoring and control. Examples of smart ready services include (one indicative example per domain respectively): heat emission control, control of DHW storage charging, cooling emission control, supply air flow control at the room level, occupancy control for indoor lighting, window solar shading control, reporting information regarding local electricity generation, EV charging capacity, smart grid integration. The full catalogue of SRI smart ready services contains a list of 54 services. The whole list of the services is provided in Annex 1.

Table 2
Functionality levels and assigned scores for the smart-energy service “Heat emission control”.

Functionality levels for smart-energy service “Heat emission control”		Score per impact category Energy efficiency	Energy flexibility and storage	Comfort	Convenience	Health, well-being and accessibility	Maintenance and fault prediction	Information to occupants
Level 0	No automatic control	0	0	0	0	0	0	0
Level 1	Central automatic control (e.g., central thermostat)	1	0	1	1	1	0	0
Level 2	Individual room control (e.g., thermostatic valves or electronic controller)	2	0	2	2	2	0	0
Level 3	Individual room control with communication between controllers and to BACS	2	0	2	3	2	1	0
Level 4	Individual room control with communication and occupancy detection	3	0	2	3	2	1	0

With a view to provide flexibility on the evaluation process depending on the building typology and resources available, the following three methods to assess the SRI are suggested: A) Simplified method, B) Expert SRI assessment and C) In-use smart building performance. Details regarding the differences and recommended applicability between these methods are provided in Table 1. The user of the methodology also needs to select which domains are present in the building or are absent but mandatory (e.g., due to national regulation) or are absent and not mandatory. Based on these choices, a tailored smart-ready service catalogue is created.

Each smart-ready service is assessed against seven (7) desired impacts, i.e., 1) Energy efficiency, 2) Energy flexibility and storage, 3) Comfort, 4) Convenience, 5) Health, well-being, and accessibility, 6) Maintenance and fault prediction and 7) Information to occupants. These impacts are further clustered under three (3) overall categories, which reflect the main goals of SRI: a) optimize energy efficiency and overall in-use performance, b) adapt operation to the needs of the occupant, c) adapt to signals from the grid. The assessment is performed by selecting from a checklist, the “functionality level” which is relevant for every service. In total five (5) functionality levels are available (Level 0–4), however there are services for which the functionality levels are less (Level 0–2 or Level 0–3). A higher functionality level denotes that a specific service is smartly implemented offering more beneficial impacts to building occupants or to the grid, compared to services that score a lower functionality level. A score from “0″ to “3″ points according to the functionality level defined for each service is automatically assigned per impact category by the methodology. Not all services are relevant to every impact category. An example of functionality levels and assigned scores, according to the defined methodology (Directorate-General for Energy (European Commission) 2020), is provided in Table 2, for the case of ‘Heat emission control’ service. Functionality levels per smart service can be found in Smart Readiness Indicator for Buildings (2022).

Different aggregated scores (e.g., per domain, per impact, per one of the three overall categories and a total SRI) can be extracted building upon the results of the smart-ready services assessment and default or user-defined weighting factors, dependant on the building typology and the climate zone, where the building is located. The methodology defines two types of weighting factors, i.e. weighting factors for the nine domains towards a vertical aggregation and weighting factors for the seven impact criteria towards a horizontal aggregation (see Fig. 1). The scores of the individual services need to be first aggregated on a domain score. The aggregation of service scores on the domain level, follows an equal weighting approach, considering each service within a domain as equally important. The aggregation of the domain scores towards a single impact score relies on the relative domain importance in each impact criterion. The default weighting of the domains per each impact category is based on a hybrid approach applying an energy balance method for impact criteria related to energy performance as well as equal, fixed or even zero weighting factors in the remaining domains per impact, according to their relevance, with the aim of weighting (Directorate-General for Energy (European Commission) 2020). The energy balance method takes into account the importance of a relevant domain to the building’s energy use to assign weights depending on the climatic zone and building type. The weighting factors of the domains in relation with each impact category are presented in Annex 2.

For each impact criterion, a total impact score is calculated as a weighted impact sum of all domain impact scores, based on an equal weighting approach for the aggregation of impact categories for the three key functionalities.[1] The total SRI score is then obtained as a weighted aggregated sum of the seven impact categories’ scores or the three key functionalities’ scores. Depending on the local and site-specific context, some domains and services may be not relevant, not applicable, or not desirable. A triage method is applied to identify the relevant services for a specific building. In case some services are evaluated as non-relevant, not applicable, or non-desirable then the total SRI score is calculated as the ratio of the building score over the maximum attainable score of the specific building and not the theoretical maximum.

In the present study, the SRI estimations have been conducted by utilizing the SRI assessment package provided by the European Commission, and more specifically, the calculation sheet for SRI assessment method A/B Version 4.4.[2] The calculation is based on the outcomes of the second technical study report (Directorate-General for Energy (European Commission) 2020). The utilization of this tool is expected to increase the quality of results and comparability with future studies. The research design, as well other key assumptions applied in this study are provided in more detail in the following section.

3. Research design

This study was designed to evaluate the retrofitting cost towards smartification for typical residential buildings, by utilizing the SRI methodology for benchmarking the change in smartness, when different retrofitting scenarios are applied. Initially the SRI was calculated for a baseline scenario i.e., the current status of typical residential buildings and then, for two consecutive cycles of retrofitting towards smartification scenarios (*Scenario A* and *Scenario B*) with the goal to increasing the

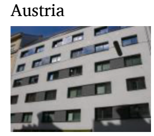
[1] 33% for the “energy efficiency and overall in-use performance” split by 16.7% for each of “energy efficiency” and “maintenance & fault prediction”; 33% for the “needs of the occupants” split by 8.3% for “comfort”, “convenience”, “health and well-being” and “information to occupants”; and 33% assigned to the “signals from the grid (energy flexibility and storage)”.

[2] The SRI assessment package is available upon request in the following link: https://ec.europa.eu/eusurvey/runner/SRI-assessment-package

Table 3
Key Characteristics of the Case of "*Single-Family Houses*" for the baseline scenario.

Country	Denmark	Czech Republic	Greece	Bulgaria	Austria
					
Climate Zone	North Europe	North-East Europe	South Europe	South-East Europe	West Europe
Construction Year	2011	2010	2011	2009	2010
Floor Area	151 m^2	105 m^2	128 m^2	111 m^2	153 m^2
National Minimum Requirements					
Denmark	Heating	District Heating			
	Ventilation	Natural ventilation			
	DHW	District Heating			
Czech Republic	Heating	Gas central heating system, high efficiency: condensing boiler, good insulation of pipes			
	Ventilation	Natural ventilation			
	DHW	Central hot water system, medium efficiency: heat generation combined with heating system (condensing boiler), no circulation loop			
Greece	Heating	New noncondensing fuel oil boiler with outdoor temp compensation / central distribution, pipeline mainly inside heated spaces, well insulated			
	Ventilation	Natural ventilation			
	DHW	New fuel oil boiler with storage tank and stand-by immersion resistance. Solar collectors for 60% of DHW			
Bulgaria	Heating	Biomass heating (wood pellets heating)			
	Ventilation	Natural ventilation			
	DHW	Individual electrical DHW heater			
Austria	Heating	Oil central heating, high efficiency: condensing boiler, minimized distribution heat losses			
	Ventilation	Natural ventilation			
	DHW	Central hot water system, high efficiency: heat generation combined with heating system (condensing boiler)			

Table 4
Key Characteristics of the Case of "*Multi-Family Houses*" for the baseline scenario.

Country	Denmark	Czech Republic	Greece	Bulgaria	Austria
					
Climate Zone	North Europe	North-East Europe	South Europe	South-East Europe	West Europe
Construction Year	2010	2010	2011	2009	2010
Floor Area	656 m^2	1876 m^2	638 m^2	387 m^2	906 m^2
National Minimum Requirements					
Denmark	Heating	District heating			
	Ventilation	Exhaust air ventilation system			
	DHW	District heating			
Czech Republic	Heating	District heating			
	Ventilation	Natural ventilation			
	DHW	District heating			
Greece	Heating	New noncondensing fuel oil boiler with outdoor temp compensation / central distribution, pipeline mainly inside heated spaces, well insulated			
	Ventilation	Natural ventilation			
	DHW	New fuel oil boiler with storage tank and stand-by immersion resistance. Solar collectors for 60% of DHW			
Bulgaria	Heating	District heating			
	Ventilation	Natural ventilation			
	DHW	Individual electrical water heater			
Austria	Heating	Gas central heating, high efficiency: condensing boiler, minimized distribution heat losses			
	Ventilation	Natural ventilation			
	DHW	Central hot water system, high efficiency: heat generation combined with heating system (condensing boiler)			

buildings' energy performance but mainly its smartness considering plug-and-play, cost efficient interventions. The baseline scenario represents buildings with the national minimum requirements in terms of energy performance (according to the relevant country legislation after the enforcement of EPBD), and are typical in terms of visual appearance, commonly found construction elements and corresponding U-values. The selected buildings for the baseline scenario are equipped with exemplary heat supply systems with commonly found system types (Martinopoulos, Papakostas, & Papadopoulos, 2018). As buildings that have been built after 2010 (EPBD) they can be considered energy efficient and thus the proposed retrofitting scenarios are limited to active systems without considering renovation of the building envelope. To that end in *Scenario A* currently market available technologies are considered which could also be utilized to help the buildings move towards Nearly Zero Energy Building (NZEB), while *Scenario B* integrates more technologies that move past NZEB and that can contribute in classifying the buildings as PEBs.

The SRI proposed calculation method was applied in two typical for benchmark building typologies that cover most of the existing EU building stock. The two building typologies were examined for five European countries, representing the five climate zones as defined in Directorate-General for Energy (European Commission) 2020 i.e. North Europe (Denmark), Western Europe (Austria), Southern Europe (Greece), North-Eastern Europe (Czech Republic), and South-Eastern Europe (Bulgaria). All buildings selected are built after the EPBD was implemented as a legal instrument in the European Union with the Directive 2002/91/EC, revised by Directive 2010/31/EU i.e., within the construction period between 2009 and 2018. The selection of 'new'

Table 5
Key Characteristics of the Case of "*Single-Family Houses*" for *Scenario A*.

Ambitious Standard (Scenario A) Requirements		
Denmark	Heating	District Heating with heat exchanger
	Ventilation	Ventilation system with heat recovery
	DHW	District heating with heat exchanger Installation of a hot water storage tank for sanitary uses
	Generation/ Storage	PV system (BAPV/BIPV)
	Building Automation	Building management system (BMS) to control the HVAC system, lighting, and load for the produced renewable electricity Air quality sensors (e.g., CO_2, PM etc.) and lighting sensors
Czech Republic	Heating	Gas central heating system, high efficiency: condensing boiler, good insulation of pipes
	Ventilation	Ventilation system with heat recovery
	DHW	Central hot water system, high efficiency: heat generation combined with heating system (condensing boiler) Installation of a hot water storage tank for sanitary uses
	Generation/ Storage	PV system (BAPV/BIPV)
	Building Automation	Building management system (BMS) to control the HVAC system, lighting, and load for the produced renewable electricity Air quality sensors (e.g., CO_2, PM etc.) and lighting sensors
Greece	Heating	Condensing boiler with outdoor temperature compensation and room controls – fuel oil / central distribution, pipeline mainly inside heated spaces, well insulated
	Ventilation	Natural ventilation
	DHW	Installation of a hot water storage tank for sanitary uses and utilization of solar thermal collectors
	Generation/ Storage	PV system (BAPV/BIPV)
	Building Automation	Building management system (BMS) to control the HVAC system, lighting, and load for the produced renewable electricity Air quality sensors (e.g., CO_2, PM etc.) and lighting sensors
Bulgaria	Heating	Biomass heating (wood pellets heating)
	Ventilation	Natural ventilation
	DHW	Electrical water heater and installation of a hot water storage tank for sanitary uses and utilization of other RE production
	Generation/ Storage	PV system (BAPV/BIPV)
	Building Automation	Building management system (BMS) to control the HVAC system, lighting, and load for the produced renewable electricity Air quality sensors (e.g., CO_2, PM etc.) and lighting sensors
Austria	Heating	Oil central heating, high efficiency: condensing boiler, minimized distribution heat losses
	Ventilation	Natural ventilation
	DHW	Central hot water system, high efficiency: heat generation combined with heating system, Installation of a hot water storage tank for sanitary uses
	Generation/ Storage	PV system (BAPV/BIPV)
	Building Automation	Building management system (BMS) to control the HVAC system, lighting, and load for the produced renewable electricity Air quality sensors (e.g. CO_2, PM etc.) and lighting sensors

buildings for this study is based on the fact that newer buildings (constructed after the implementation of the EPBD) have a higher potential for smartification with a relatively lower cost than buildings constructed before the implementation of the EPBD.

Both *Method A* and *Method B* of the SRI methodology were applied

Table 6
Key Characteristics of the Case of "*Multi-Family Houses*" for *Scenario A*.

Ambitious Standard (Scenario A) Requirements		
Denmark	Heating	District heating with heat exchanger
	Ventilation	New ventilation system with heat recovery
	DHW	District heating with re-circulation, Installation of a hot water storage tank for sanitary uses
	Generation/ Storage	PV system (BAPV/BIPV)
	Building Automation	Building management system (BMS) to control the HVAC system, lighting, and load for the produced renewable electricity Air quality sensors (e.g., CO_2, PM etc.) and lighting sensors
Czech Republic	Heating	District heating with heat exchanger
	Ventilation	Ventilation system with heat recovery
	DHW	District heating with re-circulation, Installation of a hot water storage tank for sanitary uses
	Generation/ Storage	PV system (BAPV/BIPV)
	Building Automation	Building management system (BMS) to control the HVAC system, lighting, and load for the produced renewable electricity Air quality sensors (e.g., CO_2, PM etc.) and lighting sensors
Greece	Heating	Condensing boiler with outdoor temperature compensation and room controls – fuel oil / central distribution, pipeline mainly inside heated spaces, well insulated
	Ventilation	Natural ventilation
	DHW	Installation of a hot water storage tank for sanitary uses and utilization of solar thermal collectors
	Generation/ Storage	PV system (BAPV/BIPV)
	Building Automation	Building management system (BMS) to control the HVAC system, lighting, and load for the produced renewable electricity Air quality sensors (e.g., CO_2, PM etc.) and lighting sensors
Bulgaria	Heating	District heating
	Ventilation	Natural ventilation
	DHW	District heating with re-circulation Installation of a hot water storage tank for sanitary uses
	Generation/ Storage	PV system (BAPV/BIPV)
	Building Automation	Building management system (BMS) to control the HVAC system, lighting, and load for the produced renewable electricity Air quality sensors (e.g., CO_2, PM etc.) and lighting sensors
Austria	Heating	District heating
	Ventilation	Natural ventilation
	DHW	Central hot water system, high efficiency: heat generation combined with heating system (district heat) Installation of a hot water storage tank for sanitary uses
	Generation/ Storage	PV system (BAPV/BIPV)
	Building Automation	Building management system (BMS) to control the HVAC system, lighting, and load for the produced renewable electricity Air quality sensors (e.g., CO_2, PM etc.) and lighting sensors

(see Table 1). Although *Method B* is mainly orientated towards more complex buildings (*non-residential*), this was applied because of the higher level of information it provides in terms of the smart-ready services it examines. This study used the default weighting factors for multicriteria evaluation (Directorate-General for Energy (European Commission) 2020). Data regarding the building topologies, as well as heating, ventilation and DHW systems for typical buildings, i.e. similar buildings with regard to appearance and structure that can commonly be found in the countries explored and represent the two selected

Table 7
Key Characteristics of the Case of "*Single-Family Houses*" and *"Multi-Family-Houses"* for *Scenario B*.

Countries	SFH/MFH
Denmark, Czech Republic, Greece, Bulgaria, Austria	- Replacement of heating systems with heat pumps or district heating where available - Ventilation with heat recovery (where not present) - Use of flexible thermal and/or electrical storage (EV storage) - V2G system (bi-directional EV charging spots)

Table 8
Market Prices of *Scenario A* and *Scenario B* interventions.

Area	Interventions	Market Prices
Heating	a) Condensing boiler with compensated control according to ambient outside temperature (irrelevant of fuel) b) District heating with heat exchanger (where applicable) c) heat pumps (air to water or air to air)	a) SFH: 800 – 1700 € (for $25kW_{th}$) MFH: 1700 – 3400 € (max $50kW_{th}$) b) 7000 - 8000 € (District Heat, 2022) c) 300 - 500 €/kW_{th}
Ventilation	Ventilation system with heat recovery	19 - 40 €/m^2
DHW	a) Solar thermal system with hot water storage tank b) Existing heating system coupled with hot water storage tank	a) 150–500 €/person depending on location b) 300 – 1000 € per building
Generation/ Storage	a) PV system (BAPV/BIPV) b) V2G system (bi-directional EV charging spots)	a) SFH: 3500–6000 € (for $5kW_{el}$) (Martinopoulos, 2020) MFH: 19,000–30,000 € (max $30kW_{el}$) b) SFH: 5000 € MFH: 15,000 €
Building Automation	Building management system (BMS) to control the HVAC system, lighting, and load for the produced renewable electricity, including sensors	25 – 80 €/m^2

typologies (i.e. SFH and MFH), was retrieved from the TABULA Web Tool (TABULA, 2022), which was developed in the framework of Energy Europe projects "TABULA" (IEE Project TABULA, 2009) and "EPISCOPE" (IEE Project EPISCOPE, 2013) with a main goal to disseminate typical national residential building typologies to building experts in Europe and for tracking the energy performance of buildings with regard to energy savings and climate targets. The same scenarios for both the SFH and MFH were adopted with a view to support benchmarking purposes as well as to align the scope of the study with TABULA recommendations and national regulations. The interventions were selected by capitalising TABULA recommendations and the respective EPBD requirements as well as determining the specific needs of the building in relation with its type, climate zone/country, operational needs and prior state.

The process of applying the SRI methodology for the various scenarios was divided in three working steps, followed by the identification of the cost per intervention in each scenario. Analytically the steps and the information regarding the buildings selected for the analysis, are described in the following sections.

3.1. Step 1: definition and SRI assessment of the baseline scenario

Initially, the SRI assessment was completed for both the SFH and MFH for the baseline scenario, which represents the national minimum requirements for the typologies selected in the five countries. The key characteristics of the buildings selected are shown in Tables 3 and 4 below. The countries are selected in a way so that they represent all five climate zones according to the SRI methodology.

3.2. Step 2: definition and SRI assessment of scenario a

The next step included the application of the SRI methodology to the same types of buildings taking into consideration that retrofitting *Scenario A* has been applied. In *Scenario A* we consider interventions that can be accounted for retrofitting the building towards Nearly Zero Energy Building (NZEB) (BPIE (Buildings Performance Institute Europe) 2011, Directive 2010, IEA SHC - Task 40, 2014), as introduced by the EPBD. Therefore, retrofitting interventions considered, aim at rendering the building into grid-connected building with a very high energy performance, and the nearly zero or very low amount of energy required to be covered by RES, including RES produced on-site or nearby (dependant on nZEB regulation for each country). Table 5 and Table 6 present

Table 9
Total SRI scores and SRI class for different scenarios and methods applied.

Total SRI score (%) – SRI class (A-G)	Baseline		Scenario A		Scenario B	
	Method A	Method B	Method A	Method B	Method A	Method B
Single-Family Houses						
Denmark	7% (G)	7% (G)	37% (E)	32% (F)	70% (C)	68% (C)
Czech Republic	8% (G)	4% (G)	33% (F)	27% (F)	70% (C)	66% (C)
Greece	16% (G)	9% (G)	41% (E)	31% (F)	73% (C)	69% (C)
Bulgaria	4% (G)	2% (G)	28% (F)	26% (F)	66% (C)	64% (D)
Austria	5% (G)	4% (G)	29% (F)	23% (F)	68% (C)	67% (C)
Av. score (SFH)	8%	5%	34%	28%	70%	67%
Multi-Family Houses						
Denmark		8% (G)		30% (F)		65% (C)
Czech Republic		4% (G)		27% (F)		65% (C)
Greece		12% (G)		30% (F)		65% (C)
Bulgaria		5% (G)		24% (F)		60% (D)
Austria		5% (G)		27% (F)		69% (C)
Av. score (MFH)		7%		28%		65%

Table 10
Aggregate scores for the 3 key functionalities, for different scenarios and methods applied.

Key functionality scores (%) (*1: optimize energy efficiency and overall in-use performance; 2: adapt operation to the needs of the occupant; 3: adapt to signals from the grid*)	Baseline					Scenario A					Scenario B				
	Denmark	Czech Rep	Greece	Bulgaria	Austria	Denmark	Czech Rep	Greece	Bulgaria	Austria	Denmark	Czech Rep	Greece	Bulgaria	Austria
Method A – SFH															
Key functionality 1 – Building	7	7	11	3	4	43	38	46	35	34	61	59	58	55	58
Key functionality 2 – User	22	22	28	18	18	54	46	60	47	47	82	82	78	82	82
Key functionality 3 – Grid	0	0	15	0	0	0	0	17	0	0	77	80	88	72	76
Method B – SFH															
Key functionality 1 – Building	10	6	7	2	5	41	37	41	35	34	60	59	58	56	59
Key functionality 2 – User	10	10	17	8	8	46	42	46	36	36	73	73	72	73	73
Key functionality 3 – Grid	0	0	5	0	0	10	7	13	12	7	67	63	70	62	66
Method B – MFH															
Key functionality 1 – Building	10	6	12	6	7	38	38	40	35	37	64	63	61	58	63
Key functionality 2 – User	10	7	19	10	10	47	37	45	37	38	72	72	70	69	73
Key functionality 3 – Grid	0	0	5	0	0	8	7	12	8	9	54	55	59	51	66

the characteristics of the interventions considered for *Scenario A* related to SFH and MFH respectively. In general, interventions considered for *Scenario A* focus on the smartification of the building and not so much on the drastic retrofit of the energy systems in order to evaluate mainly retrofits that can cause buildings smartification.

3.3. Step 3: definition and SRI assessment of scenario B

Step 3 included the application of the SRI methodology to the buildings selected taking into consideration that a consecutive retrofitting scenario (*Scenario B)* is applied. In *Scenario B* we consider retrofitting interventions that can be used in order to offer higher grid flexibility, if the buildings produce more energy than they consume, leaving users with extra energy to employ in other ways i.e., powering mobile devices, electric tools or electric cars i.e. retrofitting the buildings towards a Positive Energy Building (PEB) (Cole & Fedoruk, 2015), (Magrini, Lentini, Cuman, Bodrato, & Marenco, 2020). However, the main goal of the retrofit for *Scenario B* aims at primarily increasing smartness, and therefore interventions were selected to be applied upon the lowest possible cost to be incurred. The specific types of interventions considered for *Scenario B* are provided in Table 7 and apply to both SFH and MFH in all countries.

3.4. Market prices of scenarios A and B

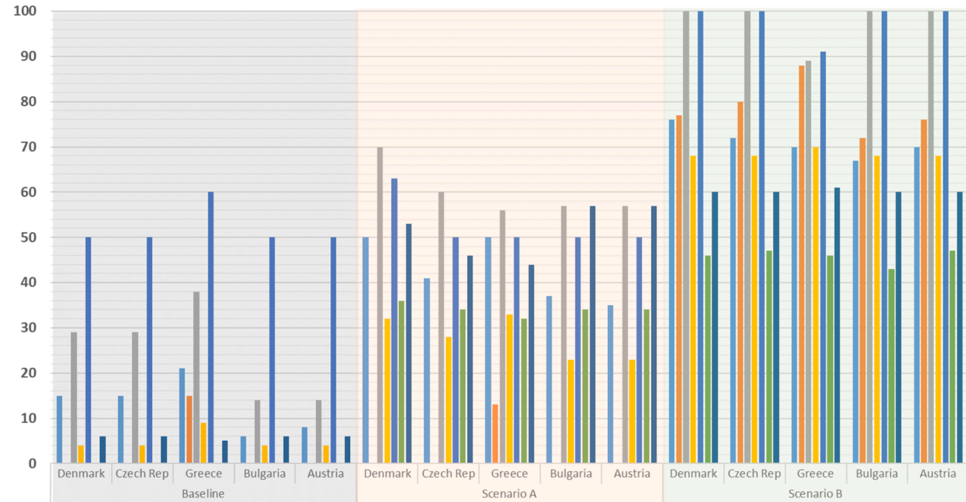
The identification of the cost for all interventions is based on a systematic collection, analysis and information assessment of current market prices. The proposed solutions are adapted in terms of capacity/dimensioning and subsequently intervention cost to the load profile and needs of the building type. Table 8 lists the identified market prices for the interventions of *Scenario A* and *Scenario B* respectively.

4. Results

This section is dedicated to the analysis of the SRI results for the selected building typologies and climate zones. First, the effect of the smart retrofit scenarios on increasing the smartness levels of the buildings and the resulting SRI score is examined, and, second, a cost estimation of the proposed smart interventions for different retrofitting scenarios, scenarios A and B, follows, towards evaluating their cost-effectiveness in relation with the total SRI improvement. Data and results generated using the calculation spreadsheet are available upon request. SRI scores obtained for each country and for the different scenarios and methods are presented in Table 9.

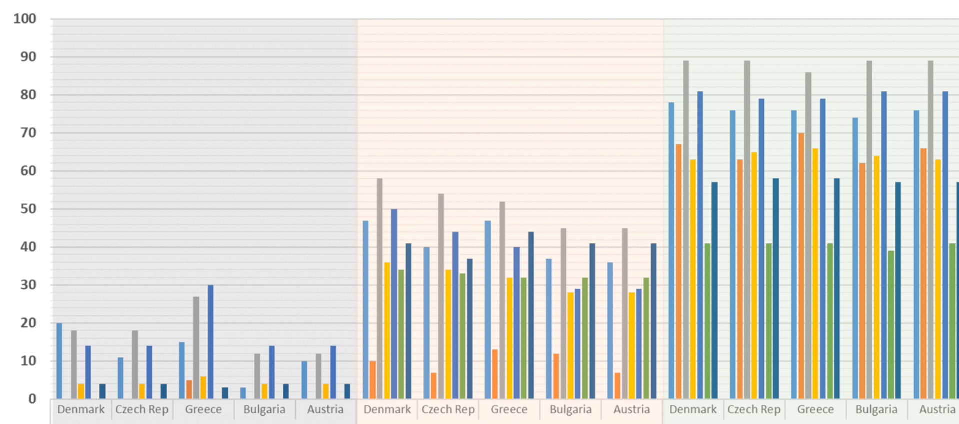
According to results, the minimum national requirements in compliance with EPBD requirements generally lead to a *Class G* for SFHs and an average SRI score of 8% and 5% for Method A and B respectively. Similarly, the average SRI score obtained for the MFHs is 7% (*Class G*) for Method B, since Method A is not applied for the MFHs (Directorate-General for Energy (European Commission) 2020). More specifically, the SRI assessment of the baseline status led to scores that range from 2% to 9% in the case of SFH and from 4% to 12% in the case of MFH (Method B). When using Method A, SRI scores obtained for the SFH are between 4% and 16%. In Greece, the SRI score is higher for the baseline scenario (16% for Method A, and 9% for Method B), when compared to the other countries mainly due to the solar thermal system covering 60% of the DHW, and the highly efficient, low carbon air-to-air heat pump that provides both heating and cooling. In general, the application of the SRI methodology for the two different building typologies examined (i.e., SFH, MFH) indicate that buildings built after the application of the EPBD, i.e., buildings constructed within the period of 2009- 2018, obtain similar SRI scores regardless of the climate zone.

After applying retrofitting *Scenario A*, with an average cost of 103€/m^2 for SFHs and 91€/m^2 for MFHs, the proposed interventions improved the smartness of buildings leading to SRI scores ranging from 23% to 41% depending on the method applied and the building typology



	Baseline Denmark	Baseline Czech Rep	Baseline Greece	Baseline Bulgaria	Baseline Austria	Scenario A Denmark	Scenario A Czech Rep	Scenario A Greece	Scenario A Bulgaria	Scenario A Austria	Scenario B Denmark	Scenario B Czech Rep	Scenario B Greece	Scenario B Bulgaria	Scenario B Austria
Energy efficiency	15	15	21	6	8	50	41	50	37	35	76	72	70	67	70
Energy flexibility and storage	0	0	15	0	0	0	0	13	0	0	77	80	88	72	76
Comfort	29	29	38	14	14	70	60	56	57	57	100	100	89	100	100
Convenience	4	4	9	4	4	32	28	33	23	23	68	68	70	68	68
Health, well-being and accessibility	50	50	60	50	50	63	50	50	50	50	100	100	91	100	100
Maintenance and fault prediction	0	0	0	0	0	36	34	32	34	34	46	47	46	43	47
Information to occupants	6	6	5	6	6	53	46	44	57	57	60	60	61	60	60

Fig. 2. Aggregate scores for the 7 impacts – Method A – SFHs.



	Baseline Denmark	Baseline Czech Rep	Baseline Greece	Baseline Bulgaria	Baseline Austria	Scenario A Denmark	Scenario A Czech Rep	Scenario A Greece	Scenario A Bulgaria	Scenario A Austria	Scenario B Denmark	Scenario B Czech Rep	Scenario B Greece	Scenario B Bulgaria	Scenario B Austria
Energy efficiency	20	11	15	3	10	47	40	47	37	36	78	76	76	74	76
Energy flexibility and storage	0	0	5	0	0	10	7	13	12	7	67	63	70	62	66
Comfort	18	18	27	12	12	58	54	52	45	45	89	89	86	89	89
Convenience	4	4	6	4	4	36	34	32	28	28	63	65	66	64	63
Health, well-being and accessibility	14	14	30	14	14	50	44	40	29	29	81	79	79	81	81
Maintenance and fault prediction	0	0	0	0	0	34	33	32	32	32	41	41	41	39	41
Information to occupants	4	4	3	4	4	41	37	44	41	41	57	58	58	57	57

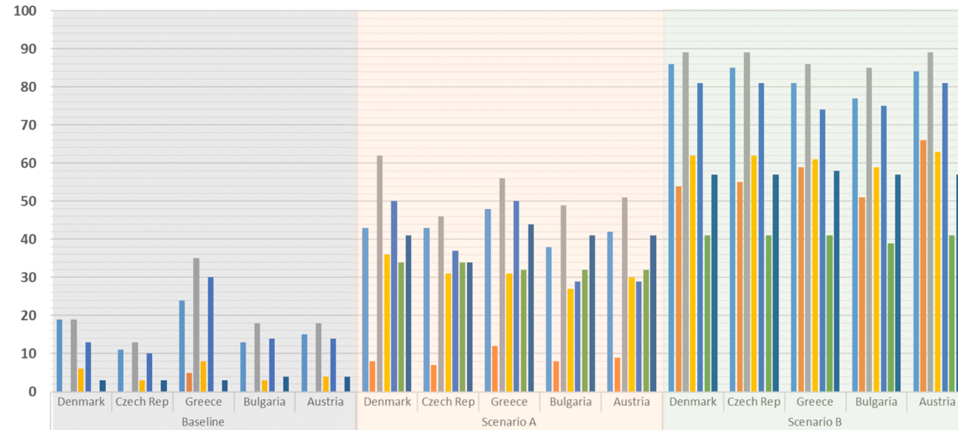
Fig. 3. Aggregate scores for the 7 impacts – Method B - SFHs.

examined. The SRI scores obtained for the SFHs are on average 34% and 28% (*Class F*) for Method A and Method B respectively, and 28% for the MFHs (Method B).

Retrofitting *Scenario B*, with an average cost 210 €/m^2 for SFHs and 134 €/m^2 for MFHs resulted in SRI scores of 70%, and 67% for Methods A and B respectively, leading to *Class C*, while for the MFH, the SRI score obtained was on average 65%. The application of Method B generally results in lower SRI scores in all cases mainly because a wider range of smart services are evaluated. The final SRI scores obtained in the typical buildings of the five countries differ slightly, reaching a minimum and maximum score of 64% and 69% in the case of SFH, and of 60% and 69% in the case MFH respectively, when Method B applied.

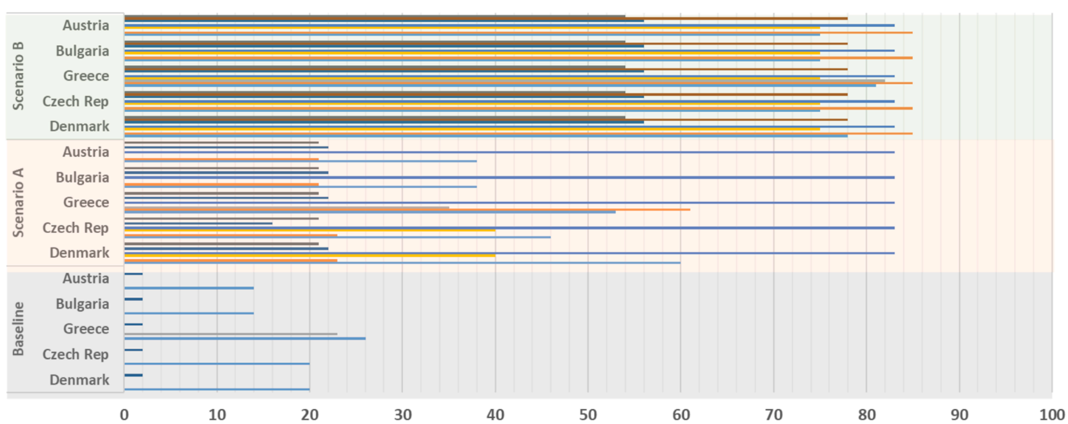
Overall, the maximum SRI class reached with the retrofits proposed in Scenarios A and B is *"Class C"* after scenario B implemented. To achieve a higher SRI class a much higher retrofitting cost is required.

The aggregate scores for the three key functionalities: a) *optimize energy efficiency and overall, in-use performance*; b) *adapt operation to the needs of the occupant*; c) *adapt to signals from the grid,* are presented in Table 10. The functionality related to *'the adaptation of the building to the needs of the occupants'* has obtained a higher score almost in all countries, for both the SFHs and the MFHs. Buildings with national minimum requirements, and in compliance with the EPBD around Europe are more smart-ready to adapt their operation according to the user requirements, than optimize their energy efficiency and overall in-use performance, or adapt to signals from the grid. When applying retrofitting interventions of *Scenario A*, there is an increase in the aggregate score towards energy efficiency optimization. Whereas, when applying the retrofitting interventions of Scenario B, there is considerable increase in the aggregated scores related to the adaptation of the buildings to signals from the grid. At the same time, there is also a considerable but comparably lower increase towards optimizing energy efficiency leading to the assumption that the optimization of energy efficiency requires higher investment



	Baseline					Scenario A					Scenario B				
	Denmark	Czech Rep	Greece	Bulgaria	Austria	Denmark	Czech Rep	Greece	Bulgaria	Austria	Denmark	Czech Rep	Greece	Bulgaria	Austria
Energy efficiency	19	11	24	13	15	43	43	48	38	42	86	85	81	77	84
Energy flexibility and storage	0	0	5	0	0	8	7	12	8	9	54	55	59	51	66
Comfort	19	13	35	18	18	62	46	56	49	51	89	89	86	85	89
Convenience	6	3	8	3	4	36	31	31	27	30	62	62	61	59	63
Health, well-being and accessibility	13	10	30	14	14	50	37	50	29	29	81	81	74	75	81
Maintenance and fault prediction	0	0	0	0	0	34	34	32	32	32	41	41	41	39	41
Information to occupants	3	3	3	4	4	41	34	44	41	41	57	57	58	57	57

Fig. 4. Aggregate scores for the 7 impacts – Method B - MFHs.



	Baseline					Scenario A					Scenario B				
	Denmark	Czech Rep	Greece	Bulgaria	Austria	Denmark	Czech Rep	Greece	Bulgaria	Austria	Denmark	Czech Rep	Greece	Bulgaria	Austria
Monitoring and control	0	0	0	0	0	21	21	21	21	21	54	54	54	54	54
Electric vehicle charging	0	0	0	0	0	0	0	0	0	0	78	78	78	78	78
Electricity	2	2	2	2	2	22	16	22	22	22	56	56	56	56	56
Dynamic building envelope	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lighting	0	0	0	0	0	83	83	83	83	83	83	83	83	83	83
Ventilation	0	0	0	0	0	40	40	0	0	0	75	75	75	75	75
Cooling	0	0	23	0	0	0	0	35	0	0	0	0	82	0	0
Domestic hot water	0	0	0	0	0	23	23	61	21	21	85	85	85	85	85
Heating	20	20	26	14	14	60	46	53	38	38	78	75	81	75	75

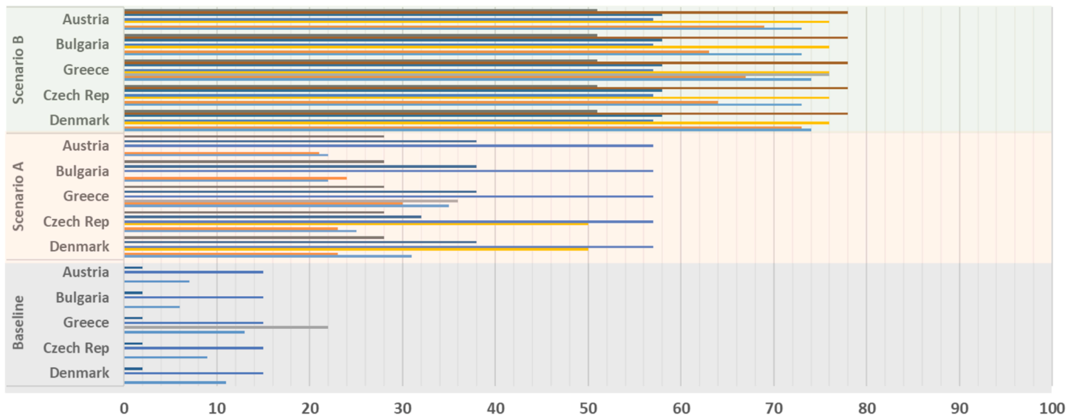
Fig. 5. Aggregate scores for the 9 domains – Method A - SFHs.

cost. The increase in key functionality 3 is mainly due to the installation of EV chargers and flexible storage with V2G applied in Scenario B.

The smart-ready potential to adapt the operation of buildings according to user needs is increased for both Scenarios, but a higher increase is achieved with Scenario B. However, in Greece there is a higher aggregated score for the functionality related to the adaptation to signals from the grid (*key functionality 3*), which is mainly due to the electrified load for cooling during summer and heating during winter served by the air-to-air heat pump. Similarly, a higher score is observed for this country for the key functionality 1 because of the highly efficient, and low carbon heating/cooling solution.

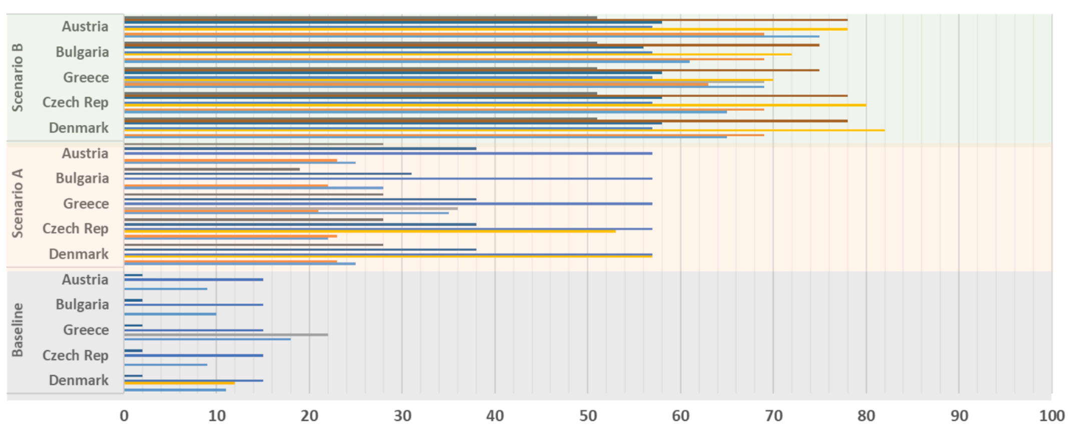
The aggregate scores for the 7 impacts defined by the SRI, for the different scenarios and methods applied, are presented in Figs. 2-4. The impact categories for which the buildings performed better were "Health, well-being and accessibility" and "Comfort", both considering the baselines scores and the improvement achieved from the implementation of scenarios (in some cases i.e., Denmark, Czech Republic and Austria even reaching a maximum score of 100%). Smart-orientated interventions proposed in this study, can achieve very high scores in these two categories, pinpointing that smartness in buildings is mostly perceived as a way to satisfy user needs in a rather anthropocentric than energy-orientated way. Another interpretation of this outcome is that lower cost interventions can more efficiently address these issues, in contrast with achieving exemplar levels of energy efficiency where heavy upfront costs are usually necessary for deep renovation.

On the other hand, all buildings performed poorly (0%), at their current state, in "Maintenance and fault prediction" and "Energy flexibility and storage". Indeed, these are aspects that until recently, were only considered relevant and cost efficient for very large, mostly tertiary buildings, thus it is unusual to find relevant technologies installed in



	Baseline					Scenario A					Scenario B				
	Denmark	Czech Rep	Greece	Bulgaria	Austria	Denmark	Czech Rep	Greece	Bulgaria	Austria	Denmark	Czech Rep	Greece	Bulgaria	Austria
Monitoring and control	0	0	0	0	0	28	28	28	28	28	51	51	51	51	51
Electric vehicle charging	0	0	0	0	0	0	0	0	0	0	78	78	78	78	78
Electricity	2	2	2	2	2	38	32	38	38	38	58	58	58	58	58
Dynamic building envelope	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lighting	15	15	15	15	15	57	57	57	57	57	57	57	57	57	57
Ventilation	0	0	0	0	0	50	50	0	0	0	76	76	76	76	76
Cooling	0	0	22	0	0	0	0	36	0	0	0	0	76	0	0
Domestic hot water	0	0	0	0	0	23	23	30	24	21	73	64	67	63	69
Heating	11	9	13	6	7	31	25	35	22	22	74	73	74	73	73

Fig. 6. Aggregate scores for the 9 domains – Method B - SFHs.



	Baseline					Scenario A					Scenario B				
	Denmark	Czech Rep	Greece	Bulgaria	Austria	Denmark	Czech Rep	Greece	Bulgaria	Austria	Denmark	Czech Rep	Greece	Bulgaria	Austria
Monitoring and control	0	0	0	0	0	28	28	28	19	28	51	51	51	51	51
Electric vehicle charging	0	0	0	0	0	0	0	0	0	0	78	78	75	75	78
Electricity	2	2	2	2	2	38	38	38	31	38	58	58	58	56	58
Dynamic building envelope	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lighting	15	15	15	15	15	57	57	57	57	57	57	57	57	57	57
Ventilation	12	0	0	0	0	57	53	0	0	0	82	80	70	72	78
Cooling	0	0	22	0	0	0	0	36	0	0	0	0	69	0	0
Domestic hot water	0	0	0	0	0	23	23	21	22	23	69	69	63	69	69
Heating	11	9	18	10	9	25	22	35	28	25	65	65	69	61	75

Fig. 7. Aggregate scores for the 9 domains – Method B - MFHs.

residential buildings. The only exception is the building in Greece, for which some points (15% for the case of Method A for SFH and 5% for the case of Method B for both SFH and MFH) were assigned to energy flexibility and storage since smart ready services such as heat generator control (for heat pumps) and cooling emission control, are positively affected by the presence of the new noncondensing fuel oil boiler with outdoor temp compensation and individual split type heat pump units. These two impacts exhibited an increased performance in Scenario B, for which its interaction with the grid is increased. The installation of BMS significantly contributed to the improvement of, not only the before mentioned impacts, but also to the “information to occupants” domain since there are several smart ready services dealing with communication of information (see Annex 1). As expected, considering the overall SRI scores presented before, Method B results in lower scores for all impact categories in comparison with Method A.

Similar to the impact-orientated analysis presented before, results were further evaluated per SRI domain. The domain-orientated results are summarized in Figs. 5-7. The best-performing domains for the baseline were “Heating”, “Cooling” (for the case of Greek buildings) and “Lighting” (for Method B only), whereas all the other domains received the minimum or a very low score. It should be mentioned that the “Cooling” domain was only considered for the case of Greek buildings,

Table 11
SRI-Cost analysis for Scenario A.

Scenario A	Total Intervention Cost (in €)	Relative Cost (in €/m^2)	Achieved SRI improvement (%)		Achieved SRI improvement (%) per 5000€ invested	
			Method A	Method B	Method A	Method B
Denmark SFH	23,035 €	153 €/m^2	+30%	+25%	+6.51%	+4.46%
Czech Republic SFH	14,823 €	141 €/m^2	+25%	+23%	+8.43%	+4.29%
Greece SFH	10,020 €	78 €/m^2	+25%	+22%	+12.48%	+4.11%
Bulgaria SFH	7130 €	64 €/m^2	+24%	+24%	+16.83%	+5.24%
Austria SFH	12,385 €	81 €/m^2	+24%	+19%	+9.69%	+3.23%
Average (SFH)	13,478 €	103 €/m^2	+26%	+23%	+10.8%	+4.3%
Denmark MFH	90,272 €	138 €/m^2		+22%		+1.04%
Czech Republic MFH	180,142 €	96 €/m^2		+23%		+0.59%
Greece MFH	47,320 €	74€/m^2		+18%		+0.95%
Bulgaria MFH	23,210 €	60€/m^2		+22%		+2.22%
Austria MFH	77,170 €	85€/m^2		+22%		+0.93%
Average (MFH)	83,623 €	91€/m^2		+21%		+1.04%

Table 12
SRI-Cost analysis for Scenario B.

Scenario B	Total Intervention Cost (in €)	Relative Cost (in €/m^2)	Achieved SRI improvement (%): i) compared to Baseline; ii) compared to Scenario A		Achieved SRI improvement (%) per 5000€ invested: i) compared to Baseline; ii) compared to Scenario A	
			Method A	Method B	Method A	Method B
Denmark SFH	28,035 €	186€/m^2	i) +63% ii) +33%	i) +61% ii) +36%	i) +13.68% ii) +7.16%	i) +10.88% ii) +6.42%
Czech Republic SFH	26,823 €	255€/m^2	i) +62% ii) +37%	i) +62% ii) +39%	i) +20.91% ii) +12.48%	i) +11.56% ii) +7.27%
Greece SFH	26,796 €	209€/m^2	i) +57% ii) +32%	i) +60% ii) +38%	i) +28.44% ii) +15.97%	i) +11.20% ii) +7.09%
Bulgaria SFH	22,905 €	206€/m^2	i) +62% ii) +38%	i) +62% ii) +38%	i) +43.48% ii) +26.65%	i) +13.53% ii) +8.30%
Austria SFH	29,399 €	192€/m^2	i) +63% ii) +39%	i) +63% ii) +44%	i) +25.43% ii) +15.74%	i) +10.71% ii) +7.48%
Average (SFH)	26,971 €	210€/m^2	i) +61% ii) +36%	i) +61% ii) +39%	i) +26.39% ii) +15.60%	i) +11.58% ii) +7.31%
Denmark MFH	105,272 €	160€/m^2		i) +57% ii) +35%		i) +2.71% ii) +1.66%
Czech Republic MFH	195,142 €	104€/m^2		i) +61% ii) +38%		i) +1.56% ii) +0.97%
Greece MFH	94,641 €	148€/m^2		i) +53% ii) +35%		i) +2.80% ii) +1.85%
Bulgaria MFH	49,627 €	128€/m^2		i) +55% ii) +36%		i) +5.54% ii) +3.63%
Austria MFH	118,897 €	131€/m^2		i) +64% ii) +42%		i) +2.69% ii) +1.77%
Average (MFH)	112,716 €	134€/m^2		i) +58% ii) +37%		i) +3.06% ii) +1.98%

where there are significant cooling needs whereas for the rest of the countries cooling was assumed to be irrelevant (consistent with TABULA that does not provide a cooling system either). Additionally, the domain "Dynamic building envelope" was not considered since, as mentioned in Section 3, renovation of the building envelope was out of scope due to the typology of the buildings selected. The domain "Electric vehicle charging" was also assumed to be irrelevant for the baseline and Scenario A, since this domain is absent and not mandatory yet, for renovated residential buildings. These assumptions are reflected in the results where no score was assigned for the three pre-mentioned domains.

The scenarios proposed significantly increased the score in all domains (achieving a performance of >50% for Scenario B). For Scenario B, most of the results between different countries coincide, indicating that the SRI scores are mostly affected by the installed systems, whereas climate zones and respective pre-defined weights are not having a significant impact in the final scores. The performance of Greek buildings in the "heating" domain was slightly better due to two reasons: a) the fact that the Greek buildings utilize apart from a heating system, air-to-air heat pumps (to cover cooling demand), which offer more controllability in comparison with district heating; b) slightly lower weight values were applied in Northern climatic zones in this domain by the current SRI methodology, e.g. a weighting factor of 0.30 is assigned for Denmark instead of 0.32 for Greece. In any case this result rises some questions on whether the utilization of district heating networks is properly considered in the SRI, an issue that was also mentioned in other similar studies (Janhunen, Pulkka, Säynäjoki, & Junnila, 2019). The introduction of mechanical ventilation with heat recovery in Scenario A for Denmark and Czech Republic, offering additional automated and central control services when installed for all buildings in Scenario B, significantly improves the performance of the buildings in this domain. It is worth mentioning that even with the EPBD (where the envelope is fully insulated, and windows have very low U values) – mechanical ventilation is nonexistent in almost all countries (in the baseline) impacting somewhat energy efficiency.

Once again, the utilization of Method B leads to lower or similar

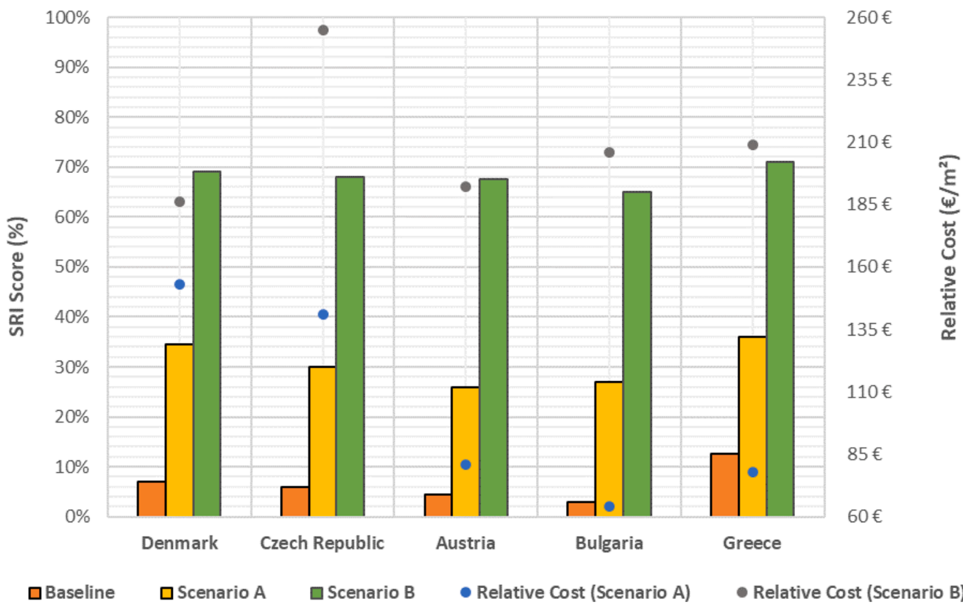


Fig. 8. SRI score in relation with intervention cost - SFHs.

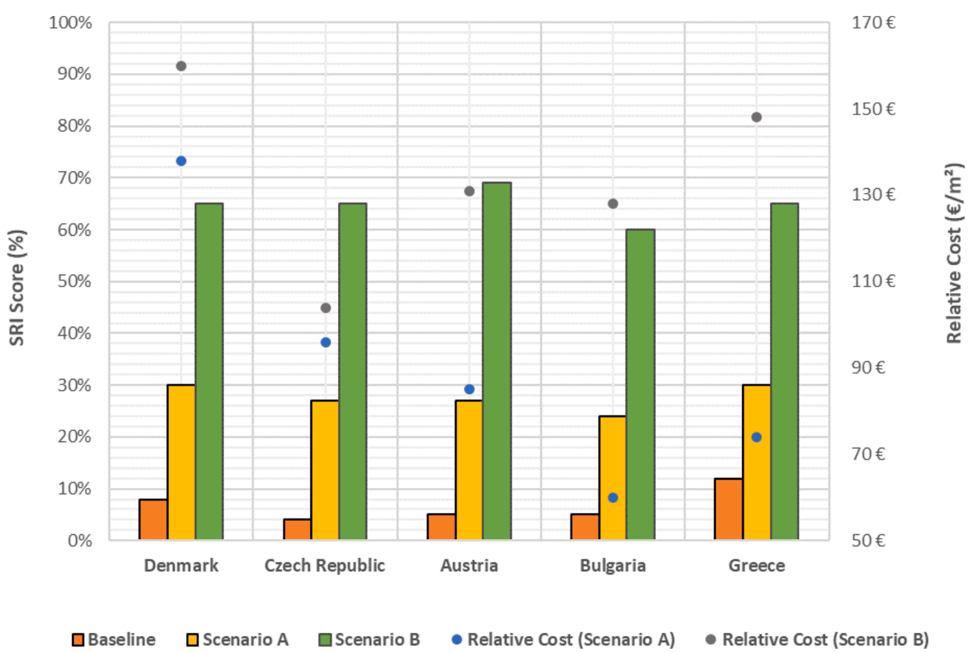


Fig. 9. SRI score in relation with intervention cost - MFHs.

scores in most domains for SFHs. Some exceptions were observed though i.e., for the domain "Lighting" the utilization of Method B unlocked an extra smart-ready service (control artificial lighting power) which had a positive effect on the results since all building have manual control per room (which is better in comparison with central on/off). This was also the case for the domains "Ventilation", "Electricity" and "Monitoring and control". No significant differences in scores per domain were observed between SFH and MFH. Both building typologies achieved considerably good SRI scores after the implementation of all the proposed smart retrofitting interventions. This can be attributed at a large extent to the presence of smart services assisting in building interaction with the grid, by providing flexible control of heating and RE production based on grid signals and flexible energy storage due to the installation of V2G points. The utilisation of optimized heating systems and renewable electricity generation systems plays also a major role on that matter. The most impacting domains in relation with the increase of the total SRI score was in both cases those of heating and V2G charging. Although they are not the domains, which had the highest scores, they tend to have bigger importance towards improving the total smartness levels in terms of SRI, because they affect more the services related with grid flexibility.

As a next step, the interventions proposed for the two scenarios for both building typologies are evaluated in terms of cost. To that end, the values presented in Table 8 were used and the total intervention cost for each scenario is presented in Tables 11 and 12. Apart from the initial cost, the relative cost per floor area is presented, as well as the relative increase of SRI per 5 k€ invested. In Table 12, the relative improvement is provided both compared to the baseline as well as to Scenario A, as the interventions there are added to those already considered installed in Scenario A. In Scenario A, with an average cost of 103 €/m^2 an increase of 26% for Method A, and 23% for Method B is achieved for SFH buildings. Denmark has the highest performance with a higher difference to the other countries in Method A than method B. It also requires the highest cost per m^2 which leads to the lowest increase of SRI per 5 k€ invested. All the other cases have the same increase in SRI with the exception of Austria (for Method B) which achieves only a 19% increase. The low relative cost and subsequent higher values of SRI improvement per 5 k€ invested in Greece and Bulgaria, has to do with the fact that in their case no mechanical ventilation is required. The same trend is apparent for the MFH in Scenario A where the average cost drops to 91€/m^2 and the average SRI improvement is 21%. The improvement is practically the same in all cases apart from Greece, which has only an 18% increase, because of the higher baseline score that is attributed to the existence of a cooling system. The improvement to SRI and the initial cost are not correlated linearly, as it is apparent from the fact that on average for Method B the achieved SRI improvement drops from 3.23% per 5 k€ for SFH to only 1.04% for MFH, indicating that there are not economies of scale present.

In the case of Scenario B, the achieved improvement is significant higher reaching on average 61% improvement over the baseline with both Methods with an average cost of 210 €/m^2 for SFH and 58% for MFH with an average cost of 134 €/m^2. The achieved SRI improvement per initial investment in this case is in general significantly better than in scenario A (Method B) with an average of 11.58% for SFH and 3.06% for MFH. As such, if the initial capitals are available, it makes more sense (SRI wise) to implement Scenario B in all cases. It has to be noted, that probable life cycle cost gains due to the increased energy efficiency of the buildings and the use of local renewable energy generation is not taken into consideration in this analysis and will be dealt in future steps. It should also be noted that, since the selected buildings are energy efficient and relatively new, if the above scenarios were applied in older buildings along with retrofitting of the building envelope, the overall cost of the interventions would be much higher, as in this case we replace efficient systems with more efficient and flexible ones, before the end of their life cycle.

The following Figs. 8 and 9, illustrate the increase of SRI score in comparison with the relative intervention cost per floor area required for each typical building and for the two different building typologies, SFH and MFH. In the case of the SFH, an average SRI score (%) of the results extracted with the two methods (A and B) was considered.

5. Conclusions

The promotion and deployment of smart technologies and systems towards optimising building performance is now being highly promoted in the EU through the SRI framework. The current study sought to i) investigate alternative smart retrofit scenarios of two building types ii) implement the SRI methodology in five EU countries pertaining to the various SRI-defined climate zones, iii) utilise methods A and B to evaluate buildings in terms of SRI, iv) identify the potential of increasing the level of 'smartness' compared to the relative cost of the proposed interventions. The outcomes of the specific study could serve as a practical example to collect experiences across the EU for SRI implementation in accordance with the current trends of decarbonization and digitalization in the building industry.

According to the SRI assessment of the baseline status, typical buildings are classified in *Class G* having an average score of around 8% and 5% in the case of SFH (for Method A and B respectively) and 7% in the case of the MFH. The retrofitting options of Scenario A led to improved SRI scores that classify the case buildings in *Class F* of SRI. SFH score was on average 34% and 28% (depending on the method) while 28% was for the MFH. Scenario B made it possible to achieve *Class C*, for most of the buildings, with average SRI scores of 70%, and 67% for Methods A and B respectively in the case of SFH, and 65% in the case of MFH. The SRI scores are influenced primarily by the smart interventions, while the adoption of the default weights based on the SRI-defined climate zones seems to have a very low impact on the final achievable scores. Typically, BMS, heating system upgrade or replacement, as well as ventilation systems with heat recovery and V2G charging infrastructure related interventions have a significant impact on the SRI.

As a first outcome, this study indicates that buildings, constructed after the EPBD was applied in the EU, are suitable to install certain interventions with a relatively low cost towards significantly improving the achieved SRI scores. The buildings require on average 210 €/m^2 in the case of SFH and 134 €/m^2 in the case of MFH, to achieve a score of over 64% for SFH and a score of over 60% for MFH (SRI classes C and D). A second finding is that the SRI methodology resulted in slightly higher SRI scores (2–6% on average) for both scenarios in the case of SFH. This implies the need for establishing a more tailored SRI framework considering the peculiarities of the various building typologies, based on the building size, the construction date, the systems type (autonomous or centralized) and the building users' activities, a critical aspect that should be addressed in the future by the SRI rationale.

The SRI methodology considers aspects related with the classification of buildings in terms of smartness as a first step towards establishing specific requirements for the SRI levels (%), paving also the way for building certification schemes based on the SRI. In this context, the integration of energy efficiency measures accompanied by smart renovation packages in buildings could further increase energy savings. However, smart building systems need to prove their benefits in terms of investment costs by achieving desirable smartness and/or energy efficiency levels with attractive payback times. Therefore, further research on this field should define the cost-effectiveness of the various smart technologies in buildings retrofitting, according to the building typology or the year of construction. Further research should be conducted also on the effect that user-specified indicator weights may have in the SRI, considering technical and operational building characteristics. Final weighting factors need to be defined capitalizing on the implementation process. Moreover, the impact of smart retrofit on the potential energy savings is yet to be explored further.

Declaration of Competing Interest

The authors declare no conflict of interest.

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ANNEX

Annex 1 and 2

Annex 1
List of SRI smart ready services included in Methods A and B (full list considering all domains are relevant). Method B also includes all smart services of Method A.

Domain	Smart-ready services – Method A	Smart-ready services – Method B
Heating	- Heat emission control - Storage and shifting of thermal energy - Heat generator control (all except heat pumps) - Heat generator control (for heat pumps) - Report information regarding heating system performance	- Emission control for TABS (heating mode) - Control of distribution pumps in networks - Thermal Energy Storage (TES) for building heating (excluding TABS) - Sequencing in case of different heat generators Flexibility and grid interaction
Domestic hot water	- Control of DHW storage charging (with direct electric heating or integrated electric heat pump) - Control of DHW storage charging - Report information regarding domestic hot water performance	- Control of DHW storage charging (with solar collector and supplementary heat generation) - Sequencing in case of different DHW generators
Cooling	- Cooling emission control - Generator control for cooling - Report information regarding cooling system performance - Flexibility and grid interaction	- Emission control for TABS (cooling mode) - Control of distribution network chilled water temperature (supply or return) - Control of distribution pumps in networks - Interlock: avoiding simultaneous heating and cooling in the same room - Control of Thermal Energy Storage (TES) operation - Sequencing of different cooling generators
Ventilation	- Supply air flow control at the room level - Reporting information regarding IAQ	- Air flow or pressure control at the air handler level - Heat recovery control: prevention of overheating - Supply air temperature control at the air handling unit level - Free cooling with mechanical ventilation system
Lighting	- Occupancy control for indoor lighting	- Control artificial lighting power based on daylight levels
Dynamic building envelope	- Window solar shading control - Reporting information regarding performance of dynamic building envelope systems	- Window open/closed control, combined with HVAC system
Electricity	- Reporting information regarding local electricity generation - Storage of (locally generated) electricity - Reporting information regarding energy storage - Reporting information regarding electricity consumption	- Optimizing self-consumption of locally generated electricity - Control of combined heat and power plant (CHP) - Support of (micro)grid operation modes
Electric vehicle charging	- EV Charging Capacity - EV Charging Grid balancing - EV charging information and connectivity	
Monitoring and control	- Central reporting of TBS performance and energy use - Smart Grid Integration - Single platform that allows automated control & coordination between TBS + optimization of energy flow based on occupancy, weather and grid signals	- Run time management of HVAC systems - Detecting faults of technical building systems and providing support to the diagnosis of these faults - Occupancy detection: connected services - Reporting information regarding demand side management performance and operation Override of DSM control

Annex 2
SRI domain weighting factors per impact category and climate zone in the case of residential buildings.

Domain Weightings	Impacts Energy Efficiency	Energy flexibility and storage	Comfort	Convenience	Health, well-being and accessibility	Maintenance and fault prediction	Information to occupants
North Europe							
Heating	0.30	0.43	0.16	0.10	0.20	0.31	0.11
Domestic hot water	0.09	0.13	0.00	0.10	0.00	0.10	0.11
Cooling	0.00	0.00	0.16	0.10	0.20	0.00	0.11
Ventilation	0.19	0.00	0.16	0.10	0.20	0.20	0.11
Lighting	0.04	0.00	0.16	0.10	0.00	0.00	0.00
Electricity	0.13	0.19	0.00	0.10	0.00	0.14	0.11
Dynamic building envelope	0.05	0.00	0.16	0.10	0.20	0.05	0.11
Electric vehicle charging	0.00	0.05	0.00	0.10	0.00	0.00	0.11
Monitoring and control	0.20	0.20	0.20	0.20	0.20	0.20	0.20
West Europe							
Heating	0.34	0.46	0.16	0.10	0.2	0.35	0.11
Domestic hot water	0.08	0.10	0.00	0.10	0.00	0.08	0.11
Cooling	0.03	0.04	0.16	0.10	0.20	0.03	0.11
Ventilation	0.18	0.00	0.16	0.10	0.20	0.18	0.11
Lighting	0.01	0.00	0.16	0.10	0.00	0.00	0.00
Electricity	0.11	0.15	0.00	0.10	0.00	0.11	0.11
Dynamic building envelope	0.05	0.00	0.16	0.10	0.20	0.05	0.11
Electric vehicle charging	0.00	0.05	0.00	0.10	0.00	0.00	0.11
Monitoring and control	0.2	0.2	0.2	0.20	0.2	0.2	0.2

(continued on next page)

Annex 2 (*continued*)

Domain Weightings	Impacts Energy Efficiency	Energy flexibility and storage	Comfort	Convenience	Health, well-being and accessibility	Maintenance and fault prediction	Information to occupants
South Europe							
Heating	0.32	0.38	0.16	0.10	0.20	0.33	0.11
Domestic hot water	0.10	0.12	0.00	0.10	0.00	0.10	0.11
Cooling	0.07	0.08	0.16	0.10	0.20	0.07	0.11
Ventilation	0.09	0.00	0.16	0.10	0.20	0.10	0.11
Lighting	0.03	0.00	0.16	0.10	0.00	0.00	0.00
Electricity	0.15	0.17	0.00	0.10	0.00	0.15	0.11
Dynamic building envelope	0.05	0.00	0.16	0.10	0.20	0.05	0.11
Electric vehicle charging	0.00	0.05	0.00	0.10	0.00	0.00	0.11
Monitoring and control	0.20	0.20	0.20	0.20	0.20	0.20	0.20
North-East Europe							
Heating	0.30	0.41	0.16	0.10	0.20	0.31	0.11
Domestic hot water	0.14	0.19	0.00	0.10	0.00	0.14	0.11
Cooling	0.00	0.00	0.16	0.10	0.20	0.00	0.11
Ventilation	0.19	0.00	0.16	0.10	0.20	0.19	0.11
Lighting	0.01	0.00	0.16	0.10	0.00	0.00	0.00
Electricity	0.11	0.15	0.00	0.10	0.00	0.11	0.11
Dynamic building envelope	0.05	0.00	0.16	0.10	0.20	0.05	0.11
Electric vehicle charging	0.00	0.05	0.00	0.10	0.00	0.00	0.11
Monitoring and control	0.20	0.20	0.20	0.20	0.20	0.20	0.20
South-East Europe							
Heating	0.21	0.24	0.16	0.10	0.20	0.21	0.11
Domestic hot water	0.06	0.07	0.00	0.10	0.00	0.06	0.11
Cooling	0.15	0.17	0.16	0.10	0.20	0.15	0.11
Ventilation	0.11	0.00	0.16	0.10	0.20	0.11	0.11
Lighting	0.01	0.00	0.16	0.10	0.00	0.00	0.00
Electricity	0.22	0.26	0.00	0.10	0.00	0.22	0.11
Dynamic building envelope	0.05	0.00	0.16	0.10	0.20	0.05	0.11
Electric vehicle charging	0.00	0.05	0.00	0.10	0.00	0.00	0.11
Monitoring and control	0.20	0.20	0.20	0.20	0.20	0.20	0.20

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