Journal of Building Engineering 95 (2024) 110323

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Towards harmonising energy performance certificate indicators in Europe

Marta Maria Sesana[a,*], Graziano Salvalai[b], Nives Della Valle[c], Giulia Melica[c], Paolo Bertoldi[c]

[a] Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, 25123, Brescia, Italy
[b] Department of Architecture, Built Environment and Construction Engineering (ABC), Politecnico di Milano, 20133, Milano, Italy
[c] European Commission, Joint Research Centre, Ispra, Italy

ARTICLE INFO

Keywords:
Energy performance certificate
Indicator assessment methodology
European green deal
Qualitative-quantitative analysis
Decarbonisation of building stock

ABSTRACT

Achieving the European Union's ambitious goal of transforming buildings into carbon-neutral assets is crucial for combating climate change and improving energy efficiency. The harmonization of Energy Performance Certificates (EPCs) plays a vital role in this effort. It can provide a standardized measure of building energy performance, which is crucial for benchmarking and improving energy efficiency across Member States. In the context of the recast Energy Performance of Buildings Directive (EPBD) of 2024, this study examines the progress made by EU Member States in standardizing EPCs. The research aims to evaluate the implementation of EPC indicators, focusing on data quality, calculation methods, and costs. The methodological procedure followed for the study led to the development of a dedicated Cross Comparative Matrix (CCM) to assess the implementation of EPC indicators across 27 EU Member States and their reading feature allowed the declination into three scenarios for different EPC data analysis: qualitative, quantitative and burden costs. The findings reveal significant disparities, particularly in areas such as thermal comfort and smart readiness, due to the lack of a common methodology and local regulatory differences. While key indicators like energy performance class and primary energy use are widely implemented, compliance with EU standards varies. The study concludes by recommending standardized methodologies and enhanced assessor training to improve EPC quality, harmonization, and effectiveness. This research contributes to policy discussions by offering a comprehensive framework for EPC evaluation and insights into improving data quality, reliability, and accessibility. The originality of this study lies in its cross-national analysis, highlighting the need for a unified EPC scheme to promote building sustainability across the EU.

* Corresponding author.
E-mail address: marta.sesana@unibs.it (M.M. Sesana).

https://doi.org/10.1016/j.jobe.2024.110323
Received 19 March 2024; Received in revised form 21 June 2024; Accepted 27 July 2024
Available online 28 July 2024
2352-7102/

Abbreviations

CCM	Cross Comparative Matrix
BC	Burden Costs
BT	Building Technology
CS	Compliance Score
E	Energy
EC	European Commission
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
EU	European Union
GHG	Greenhouse Gas
GWP	Global Warming Potential
IAQ	Indoor Air Quality
MEPS	Minimum Energy Performance Standard
MS	Member State
RES	Renewable Energy Sources
SRI	Smart Readiness Indicator
STC	Summer Thermal Comfort
TDS	Tool and Data Source

1. Introduction

Buildings account for 40 % of final energy consumption in the European Union (EU) and 36 % of its energy-related greenhouse gas emissions while 75 % of buildings in Europe are still energy-inefficient [1]. These emissions result partly from the direct use of fossil fuels in buildings (e.g., oil and gas used in boilers for heating) and partly from the production of electricity and heat for use in buildings (e.g., electricity consumed by water heaters, lighting, electrical devices, cooling systems, etc.) [2].

According to the European Climate Neutrality Observatory report [3], between 2005 and 2021, the direct GreenHouse Gas (GHG) emissions from buildings in the EU decreased by 20 %. The reduction in GHG emissions has primarily taken place within the past two decades alongside a gradual strengthening of policies to reduce them. Concerning the whole life cycle, the European Environment Agency attributed the overall decrease to the shifts in energy production methods, notably a significant decline in coal usage and growth in the adoption of renewable energy sources coupled with a modest reduction in total energy consumption, and substantial decreases in GHG emissions linked to specific industrial production processes. This trend reflects the EU's decarbonisation strategies which include the improvement of energy efficiency and the electrification of end-uses and it is remarked also by the recently published Directive 2024/1275 of the European Parliament and Council of April 24, 2024 on the Energy Performance of Buildings (EPBD recast) [1], proposed in 2021 in the context of "Fit for 55" legislative package to deliver on the EU's 2030 climate targets [4]. This revision of the EPBD [5] has also represented a key component of the Renovation Wave initiative [6], aiming specifically to boost the renovation rate of buildings in Europe, to achieve a zero-emission building stock by 2050 [7,8].

So far, Member States have faced challenges implementing the provisions of EPBD, resulting in significant gaps in key instruments like the Energy Performance Certificate (EPC) [9]. Introduced in 2002 with the Directive 2002/91/EC [10], reinforced in 2010 with the recast 2010/31/EU [11], and also in 2018 with the Directive 2018/844 [12], the EPC serves as a vital tool for data exchange between owners, investors, and policymakers, enhancing awareness of energy savings in real-estate market transactions [13,14]. As an example, in Member States (MSs), where the EPC schemes have a long tradition and their implementation is properly done, the positive impact of the EPC on the real estate market is tangible [15]. However, only a minority of financial institutions use EPCs as a basic benchmark of a building's general condition [16], EPCs also include recommendations for the cost-effective improvement of the energy performance of the building. They can also be used to monitor the overall energy performance of the building stock [17]. There is a consensus [18] that EPCs, particularly in accessible databases, can enhance transparency and inform about building-level energy performance, renewable share, energy costs, and potential energy efficiency improvements [19].

At the same time, EPC scheme implementation varies across the EU, due to contextual factors, technical capacities to support the implementation, as well as the characteristics of the construction sector and buildings market in general [20].

The Horizon 2020 call in 2008 for the "Next-generation of Energy Performance Assessment and Certification" aimed to enhance the reliability of energy performance assessment and certification, as well as their compliance with relevant EU standards and the Energy Performance of Buildings Directive. Considering this, the Directive (EU) 2024/1275 [1] introduces measures to make EPCs clearer, more reliable and visible, with easy-to-understand information on energy performance and other key indicators.

Moreover, it covers a broader range of policies and incentives to support building renovation, such as the introduction of Minimum Energy Performance Standards (MEPSs) and it provides a clearer definition of a good-quality EPC, its purpose, and how it should be issued (e.g. through control mechanisms and enhanced visibility in property advertisements). In particular, the EPC template of Annex V introduces different indicators, like energy and GHG emissions, charging points, indoor air quality, and the building's life-cycle carbon emissions.

Against this policy background, recent scientific research [21–24] underlines that although the EPC is a mandatory tool, some voluntary certification schemes (such as LEED, BREEAMS, Well) are globally more accepted and trusted by the market to certify the building performances and sustainability levels. Some other studies [25–28] attempted to provide where MSs stand in terms of EPC implementation through reviews and comparative analysis. This research stream (to name a few examples of the latest in Europe) sheds light on existing applications of EPC and unveils how EPBD is differently interpreted and assessed by various methodologies and parameters across Europe. Further studies [29–33] primarily evaluated the assessment methods and EPC data feature, auxiliary input data, application domain and temporal distribution, and underlined that EPC data are mainly used to map building energy performance through energy consumption analysis. They also highlight the lack of data quality and comparability across Europe. In addition, recent literature [34–37]also acknowledges the energy performance gap between actual energy use and the EPC values.

Those statements combined with the lack of data availability or limitations (weak quality assessment method, input data, or assessors' skills), and the limited country focus, identify the research gap of a comprehensive framework to assess the current state of the EPC scheme implementation, but also the clear identification of which are the key indicators for assessing the building energy performance.

The present study was conducted during the EPBD revision negotiation process with the aim to cover this gap, by providing a comprehensive analysis of EPC schemes across all the 27 EU Member States considering the EPC template presented in the proposal for a recast of the EPBD Annex V [38,39].

To achieve this goal, the study defined a novel methodology to evaluate qualitatively and quantitatively the implementation of the EPC schemes across Europe, by developing a dedicated tool called Cross Comparative Matrix (CCM).

In particular, the instrument assesses and takes into account the indicators (both mandatory and suggested, as listed in the EPBD recast) of the EPC template to identify good practices in making EPC data reliable, accessible, and reusable by the building's community (i.e. real estate, building owners, tenants, experts, policymakers, etc.)

The study has been structured into 5 main sections: after the first introduction on the topic and the European regulatory framework concerning the EPC definition and implementation, section 2 presents the methodological procedure based on the first outcome of the overall work: the so-called Cross Comparative Matrix (CCM). This is the tool used to conduct the whole analysis of the EPC indicators, which is described in detail together with the other outcomes of the study in section 3. Section 4 focuses on the discussion of the data collected and presented in the previous section and finally, in section 5 the main conclusions of the study are summarised.

2. Methodology

The main contribution of this paper is the development of a new methodology to comprehensively analyze the EPCs indicators listed in the EPBD recast Annex V [39].

This novel methodological framework has been defined to perform a cross-country comparison between EU Member States and identify potential gaps in the implementation of EPC indicators in the respective EPC national schemes.

Considering the complexity of the activity to evaluate each single indicator per all the European EPC schemes in term of data collection, analysis, interactions and availability, the authors developed a dedicated methodology to fulfil the identified research gap.

As a result, a Cross Comparative Matrix (CCM) was chosen to serve as a structured methodological tool to analyze different scopes of analysis within different boundary conditions (i.e. topic or area of interest, list of indicators, geographical context, output, and type of the analysis).

This methodology is graphically summarised in Fig. 1 including the CCM structure definition, the selected boundary conditions, the data sources, and flow foreseen for the population of such tool, and the reached outputs.

The starting point considered (step 1 in Fig. 1) for the CCM development is the complete list of indicators of the EPC template provided by Annex V of the EPBD recast proposal clustered according to two main types of indicators: mandatory (Art 1, Annex V "On its front page, the energy performance certificate shall display") and suggested (Art 2, Annex V "In addition, the energy performance certificate may include"). This first distinction between mandatory and suggested indicators, remarks the need to further cluster the indicators per main categories to characterize deeply the analysis per topics of interest. It was specifically implemented following the approaches in related studies [40–46] and validated by the authors based on their expertise. Step 2 thus resulted in the identification of seven categories of indicators: Energy (E); Emissions (GHG); Tool and Data Source (TDS); Building Technology (BT); Summer Thermal Comfort (STC); Indoor Air Quality (IAQ); Smart Readiness Indicator (SRI). Table 1 summarizes these categories and the list of EPC indicators from Annex V. To further define the CCM an additional step was needed: Step 3. This step enabled to define the geographical context, namely the 27 EU Member States (MSs). In Step 4, the main ingredients of the CCM were identified, respectively the rows and the columns of the matrix, and an addition to a final column to allow for a global picture of the analysis at EU level.

Finally, in Step 5 the matrix was populated according to the three scenarios identified with the ~~scope~~ aim to analyze the EPC indicators listed by Annex V EPBD recast in terms of qualitative, quantitative, and burden costs points of view. A key aspect to consider in this process was the identification of reliable data necessary to populate the matrix. To account for this, the tool was designed to allow for multifunctional use and multiple-data reading. Overall, this study adopted three types of analysis.

The first two (Step~~s~~ 5, scenarios A and B) correspond to a qualitative and quantitative analysis of the EPC indicators across the EU. For these two analyses, different data sources have been considered to gather all the necessary information starting from the regulatory framework (EU legislations, directives, and standards) [47], the concerted action reports [48,49], and the national, regional, and local regulations and standards (for example the Long-Term Renovation Strategies implemented in each MSs) [50–59].

In addition, Horizon 2020 projects' public deliverables (Appendix D), as well as technical reports and scientific publications

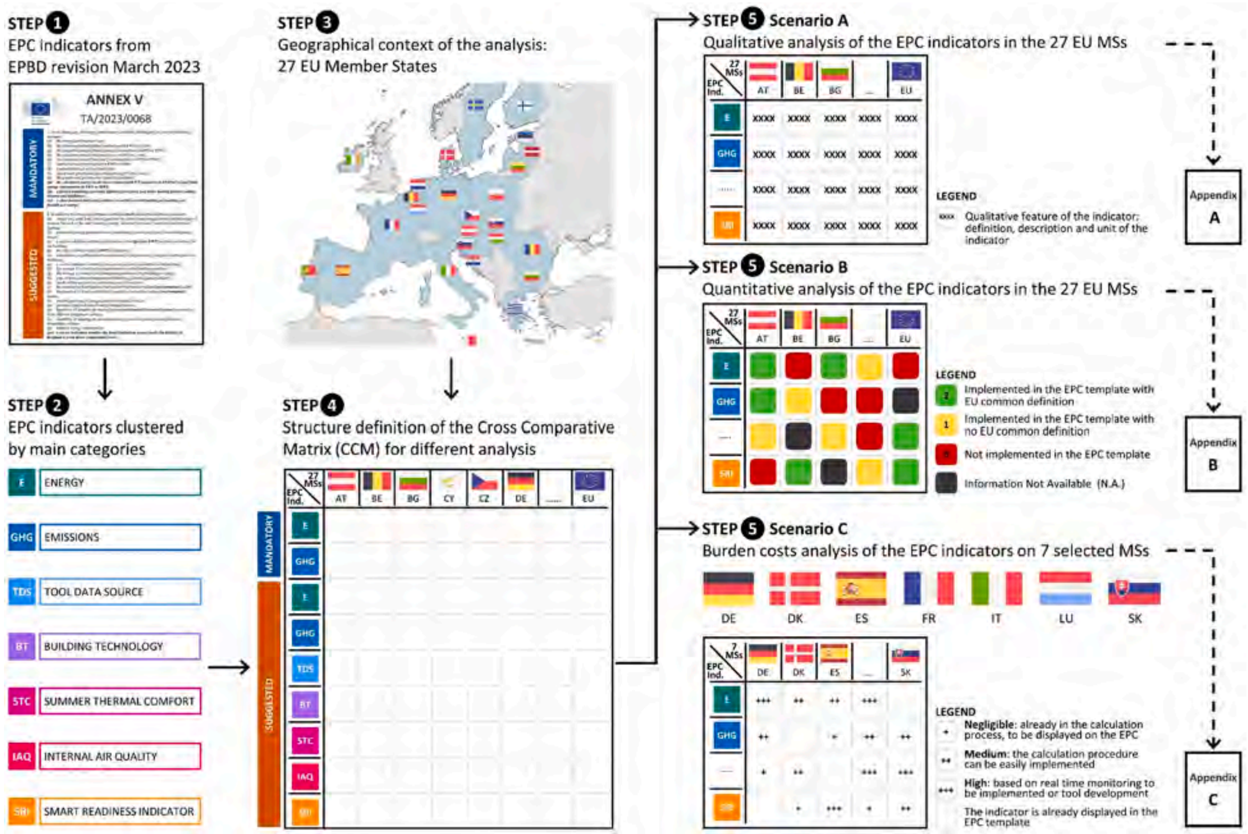

Fig. 1. Graphical abstract of the study's methodology developed for the analysis of the EPC indicators across Europe.

[60–62] served as sources to complete the overview and the data collection. The third analysis (Step 5, scenario C) focused on the burden cost of the EPC indicators implementation on selected MSs.

3. Outcomes of the study

Three are the main outcomes of the present work, resulting from the steps of the methodology, developed by the authors, to study and analyze the EPC indicators across Europe.

At Step 4 in Fig. 1, the creation and definition of the Cross Comparative Matrix (CCM) correspond to the first outcome. The CCM is the core tool used to critically compare and review the EPC indicators along different aspects, uses, and contents.

The three derived analyses on EPC indicators (qualitative, quantitative and burden costs), conducted in the final step 5 with the use of the CCM, correspond to the second outcome of the study, identified respectively as the three main scenarios: A, B and C (Fig. 1).

The third outcome is the critical review and comparison of the overall results across EU collected and analyzed using the previous outcomes. The CCM in fact offers not only the possibility to understand, compare and cluster EPC data, but also to evaluate their implementation as well as potential barriers that limit their introduction or calculation into the EPC scheme.

3.1. The Cross Comparative Matrix

The Cross Comparative Matrix (CCM) is on one hand the first outcome of the study, on the other it is also the core instrument used to conduct the EPC indicators analyses which correspond to the other following outcomes.

The basic structure of the CCM, as anticipated, is composed by rows and columns, which correspond respectively to EPC indicators and EU Member States, completed by an additional final column to provide a global picture of the analysis at the EU level.

The added value, which offer the EPC data collection within a matrix, is the possibility to understand, compare and cluster them in a unique tool to deeply evaluate their implementation, to correlate and compare them easily, and even to identify eventually barriers and/or constraints that limit their introduction or calculation into the EPC scheme.

3.2. Three scenarios for the EPC data analysis

The second outcome of the study corresponds to the three main scenarios of the EPC data analysis, derived from the use of the CCM and declined at step 5 respectively into three possible reading features of the methodological framework: i) Scenario A Qualitative analysis, ii) Scenario B Quantitative analysis, and iii) Scenario C Burden Costs analysis.

Table 1
Overview of the EPC template indicators according to the recast of the EPBD in Annex V with the integration of code category and number defined by the study.

	NO.	CATEGORY		INDICATOR NAME
MANDATORY	1	E	1	Energy performance class
	2	E	2	Calculated annual primary energy use in kWh/m^2year
	3	E	3	Calculated annual primary energy consumption in kWh or MWh
	4	E	4	Calculated annual final energy use in kWh/m^2year
	5	E	5	Calculated annual final energy consumption in kWh or MWh
	6	E	6	Renewable energy production in kWh or MWh
	7	E	7	Renewable energy in % of energy use
	8	GHG	1	Operational greenhouse gas emissions (kg CO_2/m^2year)
	9	GHG	2	Greenhouse gas emission class (if applicable)
SUGGESTED	10	E	8	Energy use, peak load, size of generator or system, main energy carrier, and main type of element for each of the uses: heating, cooling, domestic hot water, ventilation, and in-built lighting
	11	E	9	Renewable energy produced on-site, main energy carrier, and type of renewable energy source
	12	GHG	3	Yes/no indication whether a calculation of the Global Warming Potential has been carried out for the building
	13	GHG	4	Value of life-cycle Global Warming Potential (if available)
	14	GHG	5	Information on carbon removals associated with the temporary storage of carbon in or on buildings
	15	TDS	1	Yes/no indication whether a renovation passport is available for the building
	16	BT	1	Average U-value for the opaque elements of the building envelope
	17	BT	2	Average U-value for the transparent elements of the building envelope
	18	BT	3	Type of most common transparent element (e.g., double-glazed window)
	19	STC	1	Results of the analysis on overheating risk (if available)
	20	IAQ	1	Presence of fixed sensors that monitor the levels of indoor air quality
	21	IAQ	2	Presence of fixed controls that respond to the levels of indoor air quality
	22	SRI	1	Number and type of charging points for electric vehicles
	23	SRI	2	Presence, type, and size of energy storage systems
	24	SRI	3	Feasibility of adapting the heating system to operate at more efficient temperature settings
	25	SRI	4	Feasibility of adapting the air conditioning system to operate at more efficient temperature settings
	26	SRI	5	Metered energy consumption
	27	IAQ	3	Operational fine particulate matter (PM2.5) emissions
	28	SRI	6	Yes/no indication whether a smart readiness assessment has been carried out for the building
	29	SRI	7	Value of the smart readiness assessment (if available)
	30	TDS	2	Yes/no indication whether a Digital Building Logbook is available for the building

The first two scenarios A and B, corresponding to the qualitative and quantitative analysis, allow a final comparison of the indicators through the EU MSs as well as the estimation of the Compliance Score (CS), as graphically shown in Fig. 2.

The third scenario C focuses only on the Burden Cost analysis based on dedicated metrics to facilitate the results' reading and the price quantification for the EPC indicators. Those scenarios A, B, and C are explained in detail, in the following subsections.

3.2.1. Scenario A: qualitative analysis

Step 5 Scenario A is the first outcome and the first possible CCM reading feature declined from the general CCM structure and it provides a qualitative analysis of the EPC indicators.

The data that populated the matrix provided properties, characteristics, and details per every single indicator per each EU Member State, according to the data collected from the available data sources and the existing literature (Appendix A).

Due to the lack of a unique European repository for the EPCs, a common harmonized language, and structure of the certificates and classes, various types of sources were used, ranging from official EU documents, national, regional and local regulations and standards, project deliverables, technical reports, and scientific publications, to stakeholders and expert interviews.

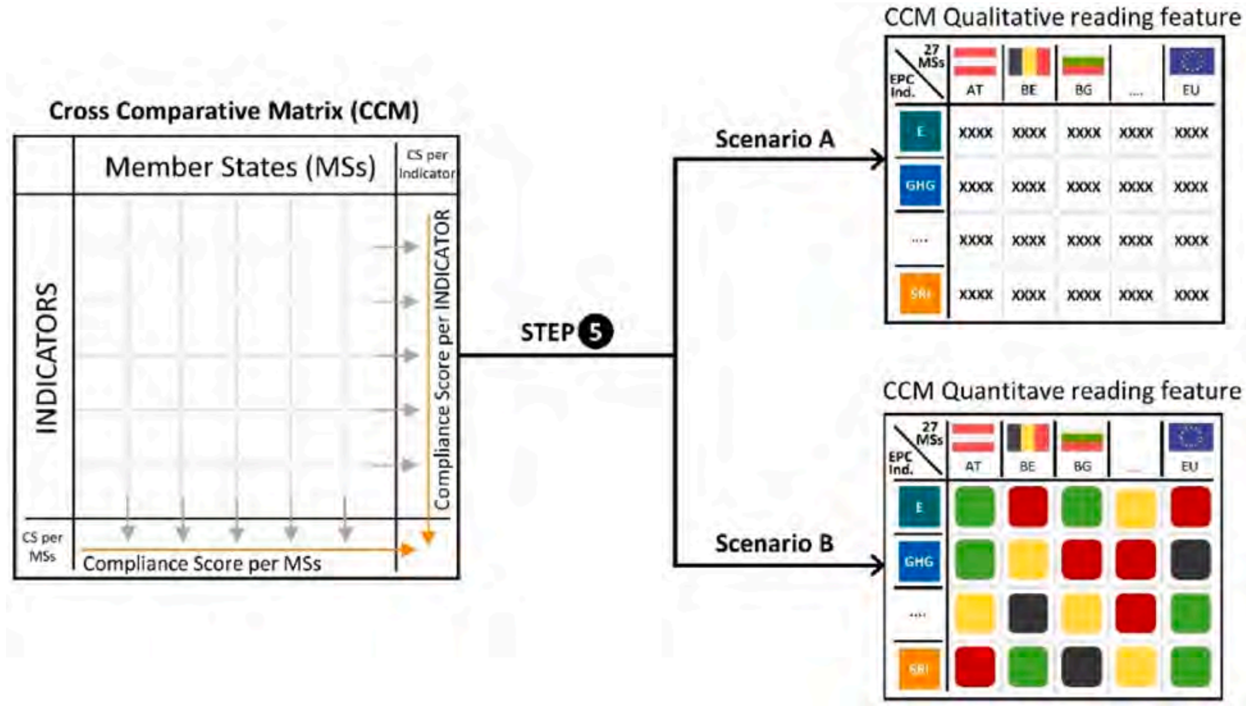

Fig. 2. Graphical scheme of the Step 5 scenarios A and B for the Cross Comparative Matrix for the visualization of the qualitative and quantitative analysis results and the Compliance Score definition per MSs (by columns) or per indicators (by rows).

The data collection has been a fundamental step of the methodology to frame a complete overview of the topic and to populate the Cross Comparative Matrix. For example, the Concerted Actions reports have been the initial data source for the state of the art in each MS. This is considered a valuable document, given that it describes the progress per country on EPC implementation, including issues of compliance, use of databases, and training of assessors. Public deliverables and presentations of research projects' outcomes, funded by the European Commission under the Horizon 2020 Energy Efficiency Programme during the three years from 2018 to 2020, provided further insight into the EPC indicators, exploring current and future ways to implement certification of buildings' energy performance. The main EU research projects used as data sources have been listed in alphabetic order with respective details about: the period, the funding programme, the countries involved in the consortium, the objectives, and deliverables or other technical reports from which data and inputs have been collected (Appendix D).

3.2.2. *Scenario B: quantitative analysis*

Step 5 Scenario B is the second outcome and CCM reading feature which provides in this case a quantitative analysis. In this scenario, the quantitative values populate the tool to enable the evaluation of not only the Compliance Score (CS) of each indicator in Europe, comparing the 27 EU Member States, but also the CS of all the EPC indicators listed in Annex V of the EPBD recast in each EU MS.

A heat map was chosen to best portray the results of this quantitative analysis (Appendix B). In this graphical representation of data, values are depicted by color, making it easier to visualize complex data. By aggregating results, the heat-map gives a snapshot allowing to identify trends, optimize, and increase the comprehension of the current implementation of the indicators across MSs. The legend for the quantitative analysis - based on a 0–2 point-scale rating coupled with colors - has been chosen to enhance the impact and the user-friendly reading level of the matrix.

Step 5 Scenario B, graphically presented in Fig. 1, provides the legend of the quantitative data analysis where: black cells stand for information Not Available (N.A.), green and yellow cells represent an indicator already implemented in the EPC template: green specifies that the indicator has been implemented in the EPC template with a common European definition (i.e. in line with existing EU regulations or standards); yellow applies to indicators implemented with no EU common definition, but with specific definition and/or calculation method defined by its own MS based for example on local regulations, or other requirements, such as climate conditions, declined specifically from the EU common one. Finally, red cells apply to indicators not yet implemented in the EPC template. Besides the specific analysis of each indicator in each MS, an overall vision of the EPC indicators implementation is provided by the Compliance Score indicator. Its value indicates both the state of implementation of the single indicator concerning the 27 MSs (values in the last column of the CCM), but also the state of progress of implementation into the EPC template for each MS of all the 30 listed indicators (values in the last row of the CCM). This simple point-scale rating allows to highlight which indicators have been already implemented and in how many countries. The value of the CS indicator has been calculated based on a scale rating (from 0, meaning not

Table 2
Legend of the cross comparative matrix for burden costs.

Burden Cost level	Motivation	Score
Negligible	The indicator is already in the calculation process, it has only to be displayed on the EPC.	+
Medium	The calculation procedure for the specific indicator can be easily implemented.	++
High	The indicator is based on real time monitoring that need to be implemented or tool development.	+++
-	The indicator is already displayed in the EPC template.	

implemented or information Not Available (N.A.), to 2, meaning implemented with a common European definition) corresponding to the colors (from red to green) of the CCM quantitative feature.

3.2.3. Scenario C: burden costs analysis

Step 5 Scenario C is the third outcome of the study which focuses on the analysis of the additional burden costs necessary for the EPC indicators' implementation into the EPC scheme. These costs may increase the overall costs for both assessors and building owners. The Burden Cost (BC) analysis is the consequential result of the CCM step 4, which allows a sectorial evaluation of the additional burden costs due to the introduction of novel indicators in the EPC template as listed in the Annex V of EPBD to further investigate their feasibility implementation. Due to the availability of data, which also depended on access to data from directly known experts, the scenario C focuses only on a selection of EU countries (Appendix C).

In fact, alternative access, e.g. from the literature, was often difficult, being a topic still unexplored in the literature. In any case, the selection of countries was confirmed by the few available resources, namely deliverables or technical factsheets from EU funding projects (Appendix D) referring to the countries of the consortium partners. Finally, to strengthen the data reliability, the authors have conducted online interviews with experts from the selected countries that are currently involved in projects related to building energy efficiency certification such as the ongoing sister projects on the Next generation of EPC. In particular, the interviews have been conducted involving first the partners/experts of the EPCRECAST project and then enlarging the discussion with all the sister projects expert funded under the call: Next-generation of Energy Performance Assessment and Certification (CrossCert, EUSuper Hub, iBRoad2EPC projects). The authors involved also in the interview experts of the public authorities and stakeholders participating to the EPC RECAST project, including a total of 20 experts from France, Italy, Germany, Spain, Portugal, Belgium). Despite being focused only on some selected countries; the main findings of the analysis could set a valid initial benchmark for all MSs to learn from other MSs' practices. Fig. 1 at Step 5 Scenario C graphically summarizes the steps followed for the population of this CCM feature on Burden Costs. The starting point is, as anticipated, a selection of EU countries (Denmark, France, Germany, Italy, Luxembourg, Slovakia and Spain – step 2).

As for the other matrixes, a dedicated legend has been defined to facilitate the reading and to limit the margin of inadequacy and inaccuracy error in quantifying the price. The Burden Cost levels identified in Table 2 are three: negligible, medium, and high, represented in the CCM for Burden Costs with an incremental number of symbols "+", respectively with 1, 2, and 3, and in case the indicator has been already implemented in the EPC template, leaving empty the cell.

3.3. Results of the scenarios A, B and C

The overall results, collected and derived from the analysis conducted using the CCM for the three presented scenarios A, B and C, correspond, as anticipated, to the third main outcome of the study.

Starting from scenario A, Fig. 3 graphically summarizes the results obtained by the qualitative analysis conducted to evaluate the status of the EPC indicators' implementation in the EU Member States using the code and number defined in Table 1.

The graphic clearly outlines that only 2 out of 20 indicators are fully implemented in all Member States, the Energy performance class (E1) and the Calculated primary energy use (E2), both considered mandatory indicators in Annex V of the EPBD revision. Those two indicators stem from the EPBD 2010, which introduced a requirement to express the energy performance of buildings through an energy performance indicator and a numeric indicator of primary energy use. However, the yellow bar indicates that less than 30 % of the countries implemented those indicators with an EU common definition [47,63,64], so a high number of MSs have implemented them with an independent framework, often related to national, regional, or local standards and regulations.

The other suggested indicators (numbered from 10 to 30 in Table 1) by the EPBD recast have a limited implementation mostly related to Energy (10-E8; 11-E9) and Building Technology categories (16-BT1; 17-BT2; 18-BT3 and represented by colored dots in the respective indicators' bars. The indicators from 12 to 15 and from 27 to 30 have not been found in any European EPC template.

In particular, the indicators related to the Emissions category (12-GHG3; 13-GHG4; 14-GHG5) focus on the Global Warming Potential, a new indicator which requires a dedicated software for whole life cycle emissions evaluation, currently not in use in common practice concerning EPCs. In literature and common practice referring to most widespread green building certification procedures (e.g., BREEAM and LEED), there are different software pre-programmed with calculation routines for the evaluations of emissions referring mainly to the standard EN15978 [65] based on the Life Cycle Assessment (LCA) for building level.

This approach aims to assess the potential environmental of buildings over the complete life cycle, from materials production to the end-of-life and management of waste disposal, which correspond to the 3 modules (A, B and C) defined by CEN TC350 standard, respectively subdivided into the following stages: product, process, use and the end-of-life.

The other not implemented indicators belong respectively to the following categories.

- Indoor Air Quality (indicator no. 27 - Operational fine particulate matter (PM2.5) emissions);

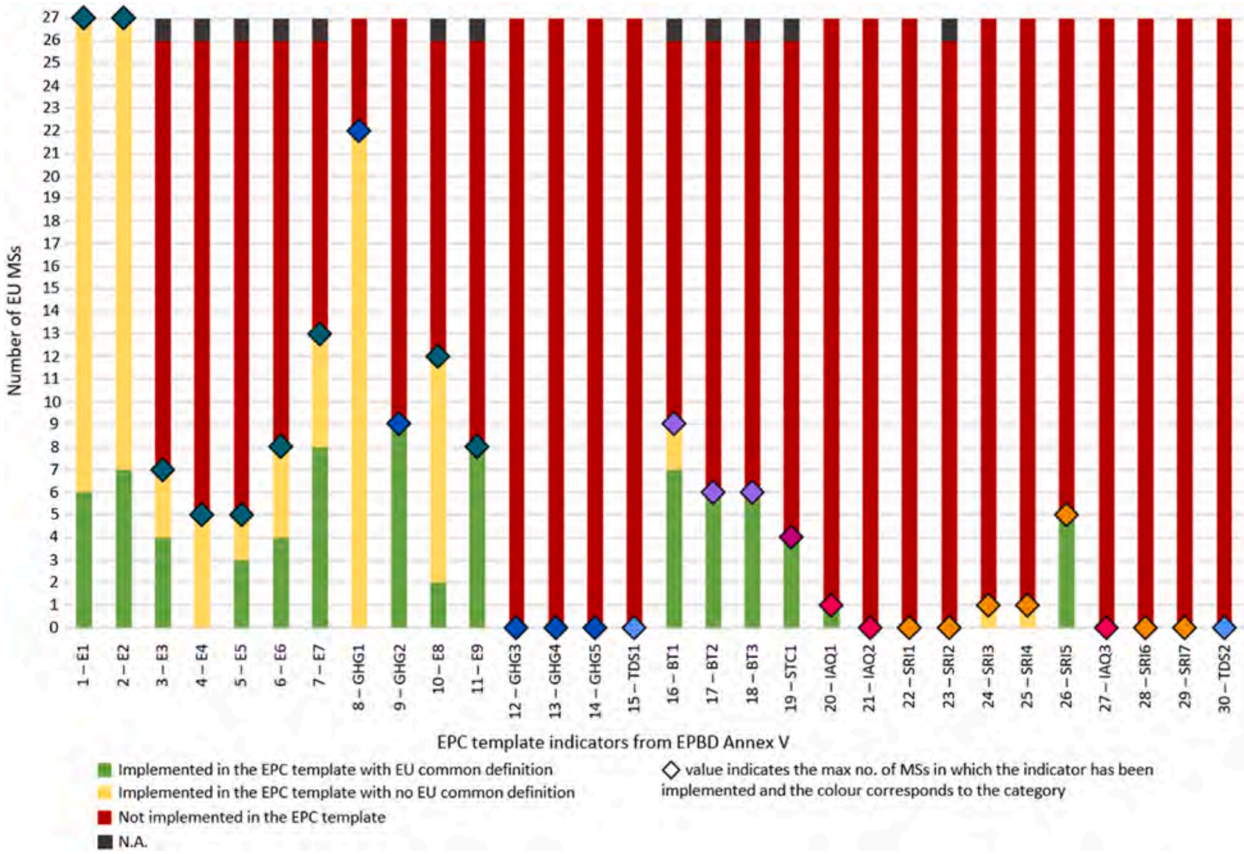

Fig. 3. EPC indicators' implementation status in the EU Member States.

- Smart Readiness Indicators (indicator no. 28 - Yes/no indication whether a smart readiness assessment has been carried out for the building and indicator no. 29 - Value of the smart readiness assessment (if available));
- Tools and data sharing (indicator no. 30 - Yes/no indication whether a Digital Building Logbook is available for the building).

In general, those indicators require a specific methodology and assessment tool for their effective integration into the current EPC schemes.

Fig. 4 reports, differently from the previous analysis per indicators of Fig. 3, the implementation level per each single Member State of all the EPC indicators listed in the recast of EPBD Annex V [39]. Only two MSs (Belgium and Spain) have implemented more than 10 EPC indicators in their current EPC scheme in comparison with the 30 indicated and in both cases, most of the implemented indicators referred to an EU common definition (green bar in Fig. 4).

The majority, 17 out of 27 MSs (Austria, Bulgaria, Croatia, Czechia, France, Germany, Greece, Ireland, Italy, Latvia, Luxembourg, Malta, Netherlands, Polonia, Portugal, Slovakia, and Sweden), have implemented between 5 and 10 EPC indicators, with (green bar) and without an EU common definition (yellow bar). Finally, 8 out of 27 MSs (Cyprus, Denmark, Estonia, Finland, Hungary, Lithuania, Romania, and Slovenia) have implemented less than 5 indicators out of 30. It is remarkable to notice that the MSs, which register a medium level of implementation, have mainly implemented indicators with different definitions from the EU common ones. A final overview of the implementation level of the EPC indicators has been graphically represented with the Compliance Score in Fig. 5, with an axis range from 0 to 54, corresponding to the range values that the 27 MSs can reach considering the legend defined at Step 5 Scenario A qualitative analysis of the methodological procedure (Fig. 1), which assigns a maximum score of 2 for the implemented indicators.

The graphic of Fig. 5 summarizes the results of the quantitative analysis and it highlights a predominance, at the European level, of the Energy category for the indicators' implementation (with a peak for E1 and E2 indicators) followed by Emissions, Building Technology, and Summer Thermal Comfort. It has to be remarked that for the Emissions category, only two indicators have been implemented (8-GHG1; 9-GHG2), while the other three indicators indicated by Annex V and related to the Emissions registered a null implementation (12-GHG3; 13-GHG4; 14-GHG5). Tools and Data Source category is the only one with all the listed indicators not implemented (15-TDS1; 30-TDS2) being related mainly to Building Passport and Digital Logbook that at the moment of the analysis were a voluntary tool. Indoor Air Quality and Smart Readiness Indicators are the categories with most of the indicators with Compliance Score null, although some of their respective indicators have been implemented (20-IAQ1; 24-SRI3; 25-SRI4; 26-SRI5), underlining a growing interest around this topic within the EPC scheme. Finally, the results of the CCM on Burden Costs Scenario

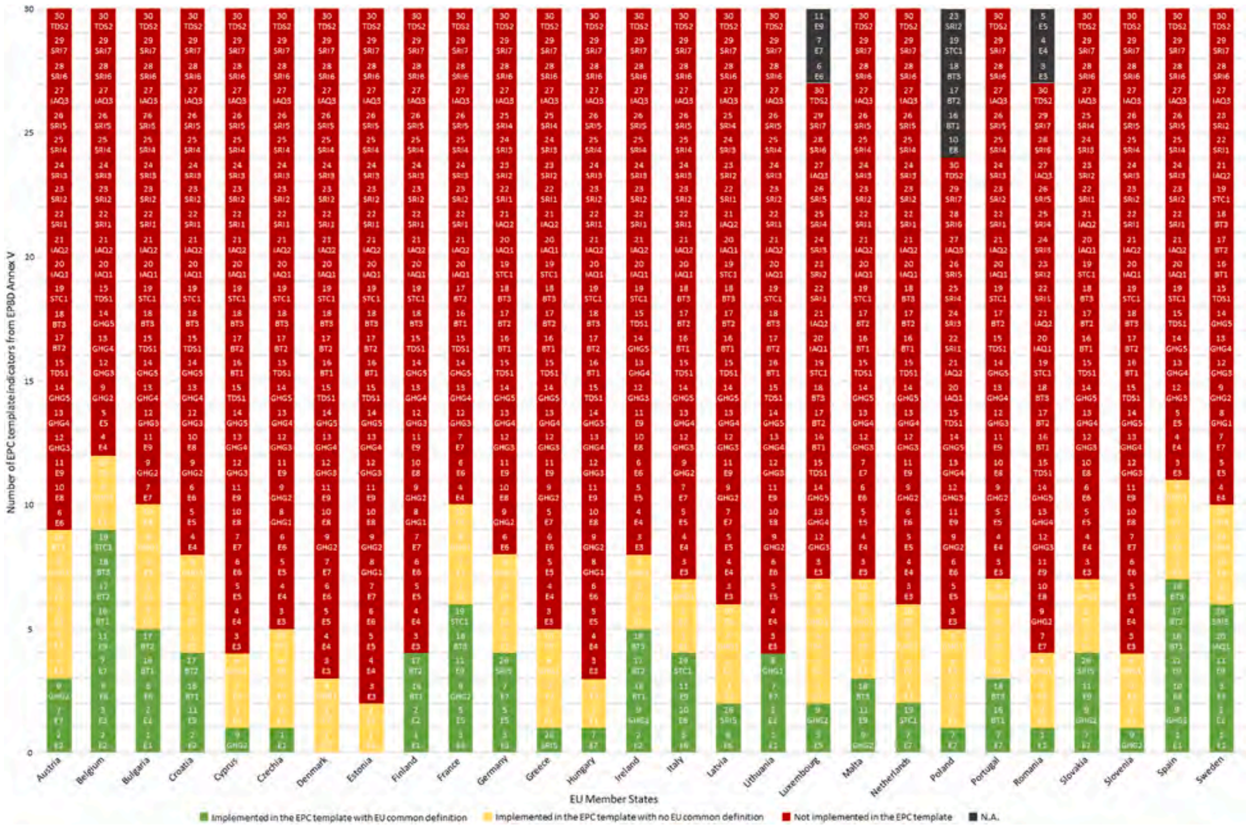

Fig. 4. Overview of the implementation of the EPC indicators listed in Annex V of EPBD recast across the EU MSs.

C have been analyzed and critically revised to complete the study on the EPC indicators. The EPC price for a single-family house of an average size of 85 m^2, according to the Building Stock Observatory, ranges from a minimum of 100€ for an online certification in Germany to 1250€ in the Flemish region [66], due to several aspects such as.

- labor cost;
- workload required for calculation;
- number of competing actors on the market;
- cost of EPC software;
- calculation method (i.e., asset rating or operational rating);
- involvement of trained experts;
- on-site inspection;
- effort for data acquisition (i.e., demand-based EPC or consumption-based EPC);
- verification by an independent organization;
- registration or not in a national EPC database.

Regarding the certification procedure, in countries where the EPCs are issued automatically via online tools (e.g. in the Netherlands), the costs are low due to the low level of involvement of trained experts (no needs of specific software and on-site visits). The building characteristics play a big role in the price definition, in particular the main influencing features are.

- type, size and complexity of the building;
- location of the building;
- use of the building (i.e., residential or non-residential);
- age of the building (i.e., new or in use);
- existence and level of detail of plans and building-related documents;
- characteristics and complexity of the building envelope;
- characteristics and complexity of plant systems and renewable energies;
- need of on-site measurements;
- measured energy use data;
- dynamic simulation due to the presence of plant systems;

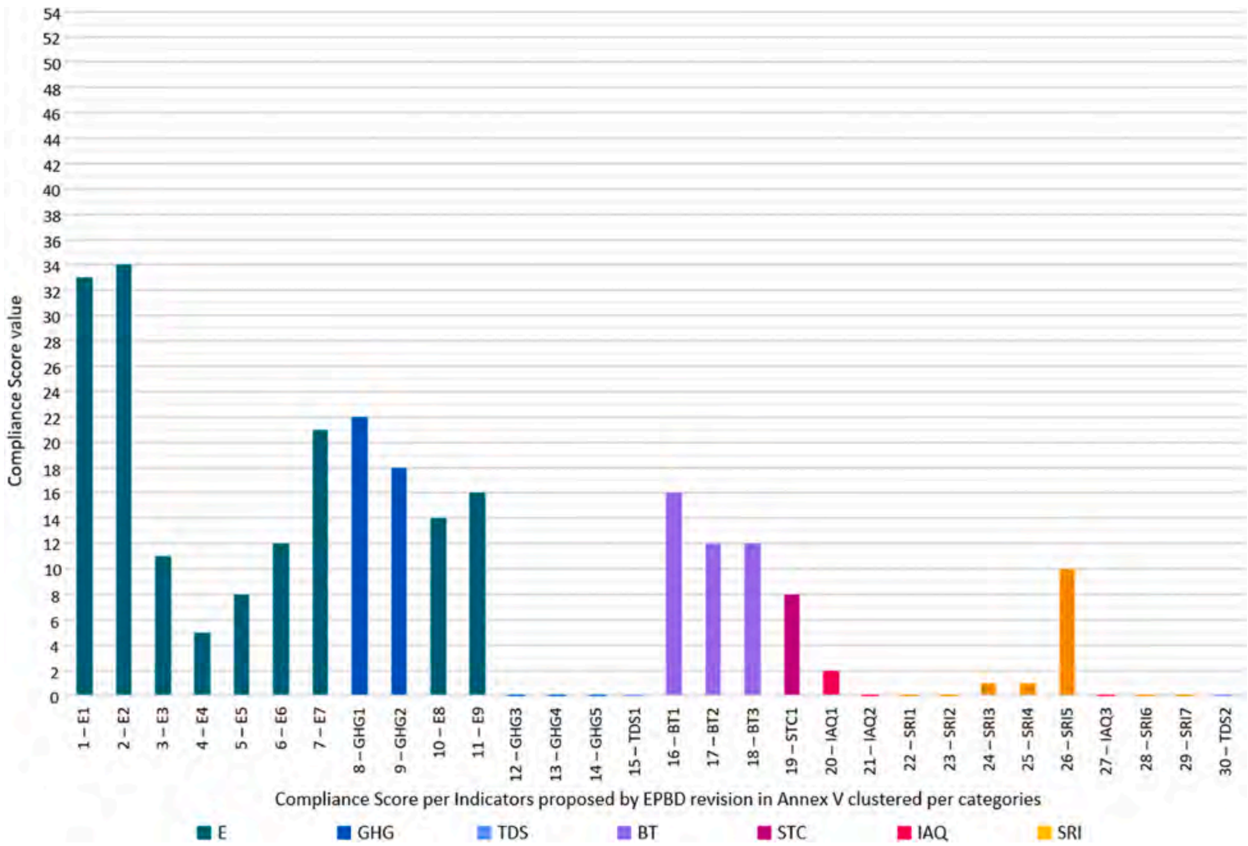

Fig. 5. Compliance Score graphic per indicator, referring to the maximum CS value of 54, corresponding to the implementation level with no EU common definition.

Depending on the factors mentioned above, very low costs for issuing an EPC can call into question the integrity, quality and reliability of the EPC, but on the other hand keeping prices affordable for end-users may increase the public acceptability and uptake of the certification scheme. It is therefore important to guarantee good quality with high affordability of the EPCs to avoid the use of default values to minimize costs. The increasing complexity and reliability of the calculation methodologies and of the efforts for the assessors are causing a general increase in the EPCs' cost assessment. As for the integration of additional indicators into the EPCs, the cost can vary according to the effort needed for their implementation.

Fig. 6 shows the additional burden costs score per indicator, referring to the required level (negligible, medium and high) of effort for its implementation.

The results underlined that the indicators already implemented in the EPC template (only 3 out of 30) do not require additional burden costs. The categories with a lower score are Energy, Tool and Data Source, and Building Technology, while the higher scores are associated with the categories related to newly defined indicators (i.e., Emissions, Summer Thermal Comfort, IAQ and SRI).

Moreover, 9 indicators (out of 30) register a burden cost score higher than 12, due to the lack of a common definition across EU, or calculation methods or instruments for data collection. They mainly refer to the categories of GHG (life cycle GWP and carbon removals), STC, IAQ and SRI, which require certifiers with specific expertise or skills and new instruments (e.g., smart meters or building management service for real time monitoring service).

4. Discussion

The present study provides an extensive and deep analysis of the implementation of the 30 indicators listed in Annex V of the recast of EPBD [39] in the EPCs schemes across Europe performed with a flexible and modular matrix. This matrix, called CCM, was developed with the intention to be reused and adapted to other contexts. The analysis of the CCM was defined along three specific features (qualitative, quantitative and burden costs). Results revealed not only significant differences between the EPC schemes, but also a non-homogeneous level of compliance for the EPC indicators, considering different approaches currently used across the EU MSs. Moreover, it highlighted that the heterogeneous level of implementation depends mainly on the local regulatory and policy contexts, the available technical capacities of assessors to support the indicators' implementation, and the knowledge and expertise in more recently introduced areas, such as Level(s), SRI and life-cycle Global Warming Potential (GWP). At the same time, results clearly point out that 16 out of 30 indicators analyzed register a high integration into the EPC template of MSs and 9 of those correspond to the

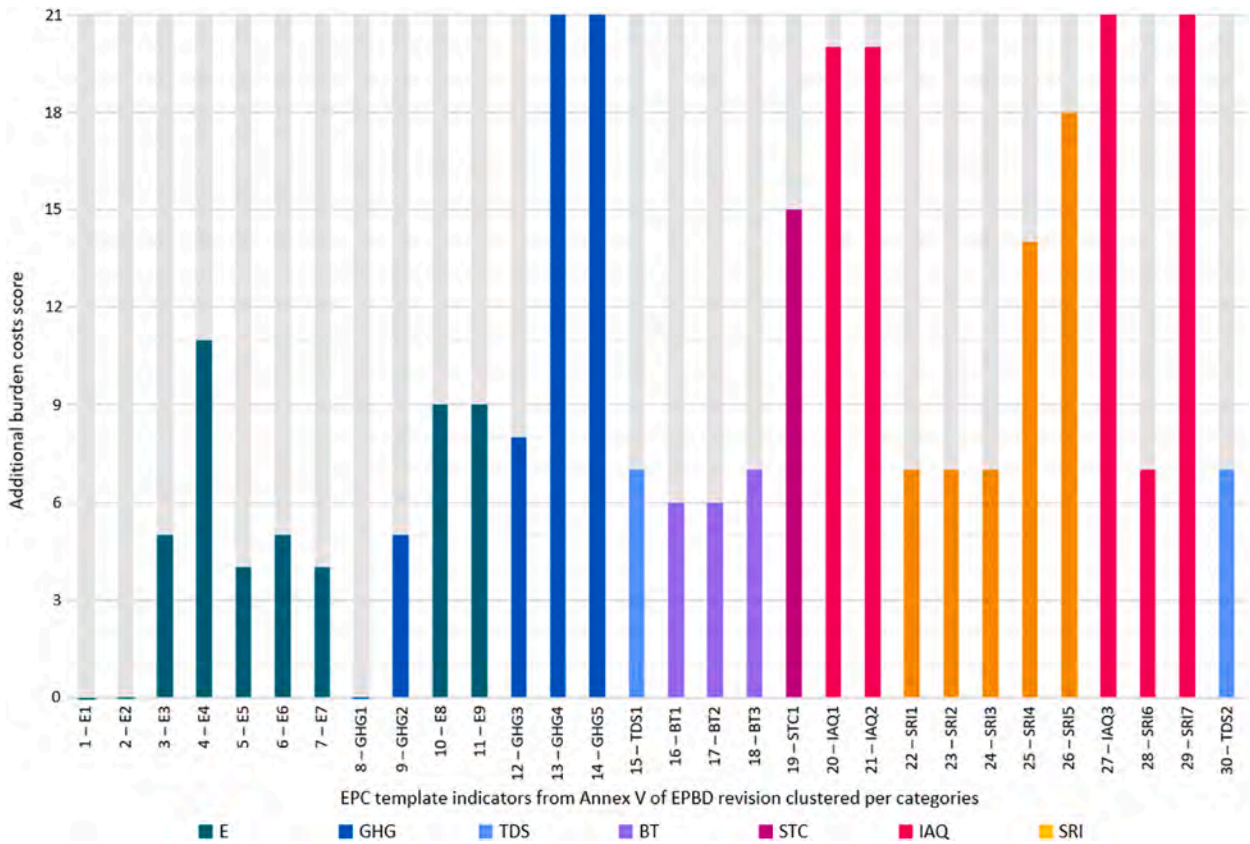

Fig. 6. Additional burden cost score for EPC indicators' implementation for the 7 selected MSs clustered per categories.

first 9 indicators listed in Annex V of the recast of the EPBD [39].

Results also suggest that currently most of the EU Member States have not yet implemented all the mandatory indicators (indicators from 1 to 9 in Table 1) set by the EPBD recast, and those indicators are mainly related to Energy and Emissions categories. The other suggested indicators (numbered from 10 to 30 in Table 1) have a limited implementation: most of them are related to Building Technology category (BT 16 – BT 17 – BT 18) and integrated only in 9 countries (AT, BE, BG, HR, IE, CZ, FI, PT, ES).

The energy performance class (E1) and the calculated primary energy use in kWh/m^{2}year (E2) are the only 2 out of 30 indicators implemented in all the EPC templates across Europe. However, most countries have implemented them without a definition fully compliant with EU regulation, preferring instead to use their own developed independent and national standards.

The Summer Thermal Comfort (STC) category - identified in the work - presents only one indicator, named "Results of the analysis on overheating risk", which has been implemented in 4 countries (BE, FR, IT, NL), underlying the increasing relevance of this topic in the energy efficiency discourse, despite the absence of a common definition and rating. The choice of the authors, to categorize this indicator into the Summer Thermal Comfort (STC) even if the overheating can occur also in winter, is due to the limited frequency and intensity in that season, respect to the summer one and considering also the increasing CDD registered all over Europe. Moreover, the winter overheating in residential buildings can easily be solved by applying natural ventilation or adapting the coatings temporarily.

Moving from results per indicator to the country-by-country analysis, the Compliance Score value (reported in Appendix B) of the Cross Comparative Matrix shows that there are 11 MSs (AT, BE, BG, FR, DE, IE, IT, ES, SK, SE) which register a value greater than 11. This demonstrates that only one-third of the EU Member States have implemented at least one-third of the indicators listed by the recast EPBD [39], but with not an EU common definition.

Regarding indoor air quality, 3 out of 30 EPC indicators belong to this category, as suggested indicators: the presence of fixed sensors that monitor the levels of indoor air quality (indicator no. 20 - IAQ 1); the presence of fixed controls that respond to the levels of indoor air quality (indicator no. 21 - IAQ 2); and operational fine particulate matter (PM2.5) emissions (indicator no. 27 - IAQ 3).

IAQ 1 is the unique IAQ indicator already implemented only in the Swedish EPC template for monitoring the radon level. The other 2 indicators on IAQ are not implemented in any country.

Sometimes the implementation difficulties experienced are inherent in the complexity of the indicator assessment, the lack of a common definition or calculation method, and the non-homogeneous building features and typologies. Those facts have contributed to the significant differences in EPC indicators' implementation among EU MSs described in this study. Achieving harmonization at the EU level would benefit from the provision of assessment or calculation methodologies at least for mandatory indicators and would require developing and strengthening the skills of technicians dealing with EPCs across Member States.

These results also emphasize the need for an evidence-based approach to enhance the outreach and effectiveness of EPCs across European contexts. Integrating behavioral economic insights into the design and implementation of EPCs is one of such evidence-based approaches that could enable to maximize the effectiveness of EPCs [42]. This approach enables the development of information tools that resonate with individuals, tapping into their motivations and accounting for their cognitive biases [40]. Relying on the experimental method, this approach enables to assess the effectiveness of different information (i.e. which indicators to show and how) on the target population enables policymakers to refine and tailor EPCs [41]. By enabling to design EPCs that better align with how individuals process information and make decisions, such as simplifying information presentation, framing energy-related benefits, and providing meaningful reference points, policymakers can more effectively steer individuals towards energy-efficient choices.

The results of the additional burden cost analysis revealed that higher increments are expected for 3 categories related to: Emissions, IAQ, and SRI, since related indicators require dedicated training (GHG 4 and GHG 5 indicators) or expertise by assessors in managing additional tools and sensors to monitor and gather real consumptions (IAQ 1, IAQ 2, SRI 5 and SRI 7).

5. Conclusions

This article provides a comprehensive evaluation of the implementation of EPC indicators as outlined in the recast EPBD across the 27 EU Member States. Developing and utilizing a Cross Comparative Matrix (CCM), our analysis reveals considerable variability in the adoption and integration of EPC indicators. One of the major findings is the non-homogeneous level of compliance with some indicators, particularly in areas like thermal comfort and smart readiness, due to varying local regulations, technical capacities, and assessor expertise.

Overcoming these discrepancies is paramount to achieving a harmonized approach to EPC implementation across Europe. Standardizing methodologies and enhancing training programs for assessors are critical steps toward achieving harmonization.

Moreover, the study highlights the potential benefits of integrating behavioral economic insights into EPC design. By aligning EPCs more closely with how individuals process information and make decisions, policymakers can enhance the impact of EPCs on encouraging energy-efficient dwelling adoption.

In conclusion, the article provides a comprehensive analysis of EPC indicators, as identified by the latest EPBD recast, observing the need to promote a more harmonized approach across Europe, coupled with the cost-optimal methodology assessment [67] to boost EPC development and implementation and a further investigation on the emerging topic IAQ comfort [68]. Further research could aim to complete the burden cost analysis in the remaining MSs and focus on other geographical contexts to evaluate worldwide the EPC potentialities starting from the recent studies [69,70] performed singularly to correlate the results also to the climatic context.

Disclaimer

The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

CRediT authorship contribution statement

Marta Maria Sesana: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Graziano Salvalai:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Nives Della Valle:** Writing – review & editing, Supervision. **Giulia Melica:** Validation, Supervision. **Paolo Bertoldi:** Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgments

The authors sincerely acknowledge the Next Generation Energy Performance Certificates cluster of sister projects, funded by the Horizon 2020 research and innovation programmes and their partners/experts, for the cooperation and assistance given in providing the data and necessary feedback during the interviews of this study.

Appendix A. Cross Comparative Matrix: qualitative data feature

INDICATOR	NO.	CATEGORY		AT	BE	BG	HR	CY	CZ	DK	EE	FI	FR	DE	EL	HU	IE	IT	LV	LT	LU	MT	NL	PL	PT	RO	SK	SI	ES	SE
RECOMMENDED	1	E	1	Additional classes above A	Classification in seven classes from A+ to F	✓	additional class above A	division of class B in two sub-classes	✓	classification in ten classes from A2020 to G	classification in eight classes from A to H only for non-residential buildings	✓	classification in nine classes from A to I only for non-residential buildings	classification in nine classes from A+ to H	classification in nine classes from A+ to G with subdivision also for class B	classification in twelve classes from AA++ to JJ	classification in fifteen classes with subdivision also for classes B, C, D and E	division of class A in four sub-classes	no division in specific classes	additional classes above A	classification in nine classes from A+ to I	no division in specific classes for residential buildings	additional classes above A	no division in specific classes	classification in eight classes with subdivision also for class B	✓	division of class A in three sub-classes	classification in seven classes with subdivision also for class B	✓	✓
				A++ - G	A+ - F	A - G	A+ - G	A - G	A - G	A2020, 2015, 2010 levels - G	A - H	A - G	A - G residential; A - I non-residential	A+ - H	A+ - G	AA++ - JJ	A1 - G	A4 - G	Sliding scale	A++ - G	A+ - I	sliding scale dwellings A - G non-dwellings	A++++ - G	Sliding scale	A+ - F	A - G	A0 - G	A1 - G	A - G	A - G
	2	E	2	✓	✓	✓	✓	defined as primary energy consumption	only non-renewable primary energy	defined as calculated energy use	defined as weighted specific energy use	✓	defined as primary energy consumption	defined as primary energy demand	only non-renewable primary energy	defined as primary energy consumption	✓	only non-renewable primary energy	in the sliding scale only primary energy for heating	defined as primary energy consumption	defined as total primary energy requirement	defined as energy use (no specification if primary energy)	defined as primary fossil energy consumption	only non-renewable primary energy demand	defined as primary energy needs	defined as annual specific energy consumption (no specification if primary energy)	defined as global primary energy	only non-renewable primary energy	only non-renewable primary energy	✓
				kWh/m²year	kWh/m²year	kWh/m²	kWh/m²year	kWh/m²year	kWh/m²year	kWh/m²year	kWh/m²year	kWh/m²year	kWh/m²year	kWh/m²year	kWh/m²year	kWh/m²year	kWh/m²year	kWh/m²year	kWh/m²year	kWh/m²year	kWh/m²year	kWh/m²year	kWh/m²year	kWh/m²year	ratio between evaluated building and reference building in %	kWh/m²year	kWh/m²year	kWh/m²year	kWh/m²year	kWh/m²year
	3	E	3	defined as primary energy requirements	✓	defined as energy consumption	defined as required energy (no specification if primary energy)	not in use	not in use	not in use	not in use	not in use	✓	✓	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	N.A.	not in use	not in use	not in use	✓
				kWh/year	kWh/year	MWh	kWh/year	not in use	not in use	not in use	not in use	not in use	kWh	kWh	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	N.A.	not in use	not in use	not in use	kWh
	4	E	4	defined as final energy demand	not in use	defined as specific energy consumption for required energy (no specification if final energy)	not in use	not in use	not in use	not in use	not in use	not in use	not in use	defined as final energy demand	not in use	not in use	not in use	not in use	not in use	not in use	only for heating and domestic hot water	not in use	not in use	defined as final energy demand	not in use	N.A.	not in use	not in use	not in use	not in use
				kWh/year	not in use	kWh/m²	not in use	not in use	not in use	not in use	not in use	not in use	not in use	kWh/m²year	not in use	not in use	not in use	not in use	not in use	not in use	kWh/m²year	not in use	not in use	kWh/m²year	not in use	N.A.	not in use	not in use	not in use	not in use
	5	E	5	defined as final energy requirement	not in use	defined as energy consumption for required energy (no specification if final energy)	not in use	not in use	not in use	not in use	not in use	not in use	✓	✓	not in use	not in use	not in use	not in use	not in use	not in use	✓	not in use	not in use	not in use	not in use	N.A.	not in use	not in use	not in use	not in use
				kWh/year	not in use	MWh	not in use	not in use	not in use	not in use	not in use	not in use	kWh	kWh	not in use	not in use	not in use	not in use	not in use	not in use	kWh	not in use	not in use	not in use	not in use	N.A.	not in use	not in use	not in use	not in use
	6	E	6	not in use	✓	✓	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	✓	✓	not in use	N.A.	not in use	not in use	not in use	divided in energy produced for regulated uses and other uses	defined as energy consumption from renewable sources	not in use	not in use	only for electric energy	for solar heating and solar cell systems
				not in use	-	MWh	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	kWh	kWh/m²year	not in use	N.A.	not in use	not in use	not in use	kWh/year	kWh/m²year	not in use	not in use	kWh/year	kWh/year
	7	E	7	✓	✓	not in use	share of renewable energy in total delivered energy	not in use	sun and environment energy	not in use	not in use	not in use	not in use	✓	not in use	✓	only in the potential impact of the recommended energy upgrades	not in use	not in use	defined as ratio between renewable and non-renewable energy consumption	N.A.	not in use	✓	✓	✓	not in use	✓	not in use	only for thermal energy	not in use
				%	%	not in use	%	not in use	%	not in use	not in use	not in use	not in use	%	not in use	%	%	not in use	not in use	-	N.A.	not in use	%	%	%	not in use	%	not in use	%	not in use
	8	GHG	1	defined as equivalent CO_2 emissions	defined as CO_2 emissions	defined as CO_2 emissions	defined as specific annual emission	defined as CO_2 emissions	not in use	defined as calculated CO_2 emissions	not in use	not in use	defined as CO_2 emissions	defined as greenhouse gas emissions	defined as CO_2 emissions (calculated and actual)	not in use	defined as calculated annual CO_2 emissions	defined as CO_2 emissions	defined as CO_2 emissions	defined as CO_2 emissions	defined as CO_2 emissions	defined as CO_2 emissions	defined as CO_2 emissions	defined as CO_2 emissions	defined as CO_2 emissions	defined as equivalent CO_2 index	defined as CO_2 emissions	defined as CO_2 emissions	defined as CO_2 emissions	not in use
				kg/m²year	kg/year	t/year	kg/m²year	kgCO_2/m²year	not in use	-	not in use	not in use	kgCO_2/m²year	kg$CO_{2,eq}$/m²year	kg/m²	not in use	kgCO_2/m²year	kg/m²year	kgCO_2/m²year	kgCO_2/m²year	kgCO_2/m²year	kg/m²year	kgCO_2/m²year	-	t/year	kgCO_2/m²year	kg/m²year	kg/m²year	kgCO_2/m²year	not in use
	9	GHG	2	✓	not in use	not in use	not in use	✓	not in use	not in use	not in use	not in use	✓	not in use	not in use	not in use	✓	not in use	not in use	not in use	✓	✓	not in use	not in use	not in use	not in use	✓	✓	✓	not in use
				A++ - G	not in use	not in use	not in use	Sliding scale	not in use	not in use	not in use	not in use	A - G	not in use	not in use	not in use	Sliding scale	not in use	not in use	not in use	A+ - I	Sliding scale dwellings A - G non-dwellings	not in use	not in use	not in use	not in use	Sliding scale	Sliding scale	A - G	not in use
SUGGESTED	10	E	[illegible]	not in use	main energy carrier and main type of element	energy use, main energy carrier and main type of element	not in use	not in use	main energy carrier	not in use	not in use	not in use	main type of element	not in use	energy use and energy carrier	not in use	not in use	everything apart from peak load	main type of element	not in use	energy use, main energy carrier and main type of element	main type of element	main type of element	N.A.	not in use	not in use	not in use	not in use	everything apart from peak load	main energy carrier
				not in use	-	-	not in use	not in use	-	not in use	not in use	not in use	-	not in use	-	not in use	not in use	-	-	not in use	-	-	-	N.A.	not in use	not in use	not in use	not in use	-	-
	11	E	[illegible]	not in use	type of renewable energy production system	not in use	type of renewable energy production system	not in use	not in use	not in use	not in use	not in use	type of renewable energy production system	not in use	not in use	not in use	not in use	type of renewable energy production system and main energy carrier	not in use	not in use	N.A.	type of renewable energy production system	not in use	not in use	not in use	not in use	type of renewable energy source	not in use	type of renewable energy production system	type of renewable energy production system
				not in use	-	not in use	-	not in use	not in use	not in use	not in use	not in use	-	not in use	not in use	not in use	not in use	-	not in use	not in use	N.A.	-	not in use	not in use	not in use	not in use	-	not in use	-	-
	12	GHG	3	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use
				not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use
	13	GHG	4	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use
				not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use
	14	GHG	5	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use
				not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use
	15	TDS	1	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use
				not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use
	16	BT	1	defined as medium U-value (no specification if only opaque)	✓	✓	✓	not in use	defined as building envelope U-value (no specification if only opaque)	not in use	not in use	✓	not in use	not in use	not in use	not in use	✓	not in use	not in use	not in use	not in use	not in use	not in use	N.A.	✓	not in use	not in use	not in use	✓	not in use
				W/m²K	W/m²K	W/m²K	W/m²K	not in use	W/m²K	not in use	not in use	W/m²K	not in use	not in use	not in use	not in use	W/m²K	not in use	not in use	not in use	not in use	not in use	not in use	N.A.	W/m²K	not in use	not in use	not in use	W/m²K	not in use
	17	BT	2	not in use	✓	✓	✓	not in use	not in use	not in use	not in use	✓	not in use	not in use	not in use	not in use	✓	not in use	not in use	not in use	not in use	not in use	not in use	N.A.	not in use	not in use	not in use	not in use	✓	not in use
				not in use	W/m²K	W/m²K	W/m²K	not in use	not in use	not in use	not in use	W/m²K	not in use	not in use	not in use	not in use	W/m²K	not in use	not in use	not in use	not in use	not in use	not in use	N.A.	not in use	not in use	not in use	not in use	W/m²K	not in use
	18	BT	3	not in use	✓	not in use	not in use	not in use	not in use	not in use	not in use	not in use	✓	not in use	not in use	not in use	✓	not in use	not in use	not in use	not in use	✓	not in use	N.A.	✓	not in use	not in use	not in use	✓	not in use
				not in use	-	not in use	not in use	not in use	not in use	not in use	not in use	not in use	-	not in use	not in use	not in use	-	not in use	not in use	not in use	not in use	-	not in use	N.A.	-	not in use	not in use	not in use	-	not in use
	19	STC	1	not in use	✓	not in use	not in use	not in use	not in use	not in use	not in use	not in use	✓	not in use	not in use	not in use	not in use	✓	not in use	not in use	not in use	not in use	✓	N.A.	not in use	not in use	not in use	not in use	not in use	not in use
				not in use	-	not in use	not in use	not in use	not in use	not in use	not in use	not in use	-	not in use	not in use	not in use	not in use	-	not in use	not in use	not in use	not in use	-	N.A.	not in use	not in use	not in use	not in use	not in use	not in use
	20	IAQ	1	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	radon measurements
				not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	-
	21	IAQ	2	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use
				not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use
	22	SRI	1	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use
				not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use
	23	SRI	2	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	N.A.	not in use	not in use	not in use	not in use	not in use	not in use
				not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	N.A.	not in use	not in use	not in use	not in use	not in use	not in use
	24	SRI	3	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	in recommendation measures
				not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	-
	25	SRI	4	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	in recommendation measures
				not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	-
	26	SRI	5	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	for heating and domestic hot water	electric, thermal and total energy	not in use	not in use	not in use	defined as energy accounting for heating and domestic hot water	not in use	not in use	not in use	not in use	not in use	not in use	not in use	for heating	not in use	not in use	for heating, cooling and domestic hot water
				not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	kWh	kWh/m²year	not in use	not in use	not in use	kWh/m²year	not in use	not in use	not in use	not in use	not in use	not in use	not in use	kWh/m²year	not in use	not in use	kWh
	27	IAQ	3	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use
				not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use
	28	SRI	6	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use
				not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use
	29	SRI	7	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use
				not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use
	30	TDS	2	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use
				not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use	not in use

Appendix B. Cross Comparative Matrix: quantitative data feature

INDICATORS	NO.	CATEGORY		AT	BE	BG	HR	CY	CZ	DK	EE	FI	FR	DE	EL	HU	IE	IT	LV	LT	LU	MT	NL	PL	PT	RO	SK	SI	ES	SE	CS per indicator	N.A.
RECOMMENDED	1	E	1																												33	0
	2	E	2																												34	0
	3	E	3																												11	1
	4	E	4																												5	1
	5	E	5																												8	1
	6	E	6																												12	1
	7	E	7																												21	1
	8	GHG	1																												22	0
	9	GHG	2																												18	0
SUGGESTED	10	E	8																												14	1
	11	E	9																												16	1
	12	GHG	3																												0	0
	13	GHG	4																												0	0
	14	GHG	5																												0	0
	15	TDS	1																												0	0
	16	BT	1																												16	1
	17	BT	2																												12	1
	18	BT	3																												12	1
	19	STC	1																												8	1
	20	IAQ	1																												2	0
	21	IAQ	2																												0	0
	22	SRI	1																												0	0
	23	SRI	2																												0	1
	24	SRI	3																												1	0
	25	SRI	4																												1	0
	26	SRI	5																												10	0
	27	IAQ	3																												0	0
	28	SRI	6																												0	0
	29	SRI	7																												0	0
	30	TDS	2																												0	0
	CS per MS			12	21	15	12	5	6	3	2	8	16	12	6	4	13	11	8	4	9	10	8	6	10	5	11	5	18	16	256	/
	N.A.			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	6	0	3	0	0	0	0	/	12

Appendix C. Cross Comparative Matrix on Burden Costs

INDICATORS	SELECTED EU MEMBER STATES									
	NO.	CATEGORY		DK	FR	DE	IT	LU	SK	ES
RECOMMENDED	1	E	1							
	2	E	2							
	3	E	3	+			+	+	+	+
	4	E	4	++	++		++	+	++	++
	5	E	5	+			+		+	+
	6	E	6	+	+	+		+	+	
	7	E	7	+	+		+	+		
	8	GHG	1							
	9	GHG	2		+	+	++		+	
SUGGESTED	10	E	8	++	++	+	+	+	+	+
	11	E	9	+	+	+	+	+	++	++
	12	GHG	3	+	+	+	++	+	+	+
	13	GHG	4	+++	+++	+++	+++	+++	+++	+++
	14	GHG	5	+++	+++	+++	+++	+++	+++	+++
	15	TDS	1	+	+	+	+	+	+	+
	16	BT	1	+	+	+	+	+	+	
	17	BT	2	+	+	+	+	+	+	
	18	BT	3	+	+	+	+	+	+	+
	19	STC	1	+++		+++		+++	+++	+++
	20	IAQ	1	+++	+++	+++	++	+++	+++	+++
	21	IAQ	2	+++	+++	+++	++	+++	+++	+++
	22	SRI	1	+	+	+	+	+	+	+
	23	SRI	2	+	+	+	+	+	+	+
	24	SRI	3	+	+	+	+	+	+	+
	25	SRI	4	++	++	++	++	++	++	++
	26	SRI	5	++	+++	++	+++	+++	++	+++
	27	IAQ	3	+++	+++	+++	+++	+++	+++	+++
	28	SRI	6	+	+	+	+	+	+	+
	29	SRI	7	+++	+++	+++	+++	+++	+++	+++
	30	TDS	2	+	+	+	+	+	+	+

Appendix D. Summary of the research projects considered as sources for the analysis

Project name and period	EU funding programme	Consortium partners' countries	Objective and main outcomes	Reference documents
crossCert - Cross Assessment of Energy Certificates in Europe (2021–2024) [71].	Horizon 2020 - LC-SC3-B4E-4-2020 - Next-generation of Energy Performance Assessment and Certification.	AT; BG; HR; DK; DE; EL; MT; PL; SI; ES; UK.	The crossCert project aims at creating a product **testing methodology for new EPC approaches** to improve accuracy and usability of the EPCs, people-centric designs, and homogeneity across Europe. The crossCert project is based on a bottom-up approach which uses test cases, compare and analyze the results between different approaches, elaborate policy recommendations and engage networks and alliances for analysis and for outreach. crossCert will also use the cross-assessment exercise to conduct research and issue guidelines on: training and education, EPC promotion and marketing, adapting EPCs investor needs, linking next-generation of EPCs to energy audits, logbooks and Building Renovation Passports and EPCs and one-stop shops for building renovation.	D2.4 EPC cross-testing procedure.
E-DYCE - Energy flexible DYnamic building Certification (2020–2023) [72].	Horizon 2020 - LC-SC3-EE-5-2018-2019-2020 - Next-generation of Energy Performance Assessment and Certification.	DK; DE; EL; IT; CH.	E-DYCE will combine innovative approaches with established and widely available tools to create a methodology capable of implementing **scalable and adaptable dynamic energy performance certification (DEPC)** through a technology neutral methodology for dynamic labelling adaptable to any type of building. The project includes communication with the final user and validation in pilot buildings. E-DYCE will be compatible to existing and emerging EPC methods, or can function as a stand-alone DEPC labelling process.	D1.1 EPC regional report.
ePANACEA - Smart European Energy Performance AssessmeNT And CErtificAtion (2020–2023) [73].	Horizon 2020 - LC-SC3-EE-5-2018-2019-2020 - Next-generation of Energy Performance Assessment and Certification.	AT; BE; FI; DE; EL; ES.	The objective of the ePANACEA project is to develop a **holistic methodology for energy performance assessment and certification of buildings**. ePANACEA comprises the creation of a prototype making use of the most advanced techniques in dynamic and automated simulation modelling, big data analysis and machine learning, inverse modelling or the estimation of potential energy savings and economic viability check. The project will also involve the end-user through thematic workshops and demonstrate the methodology through case studies.	Next generation of EPCs and Quality Convergence across the EU: Implementation of Innovative Certification Schemes.
EPC Recast - Energy Performance Certificate Recast (2020–2023) [74].	Horizon 2020 - LC-SC3-EE-5-2018-2019-2020 - Next-generation of Energy Performance Assessment and Certification.	BE; FR; DE; IT; LU; SI; ES.	To reach the EU decarbonisation objectives, it is urgent to trigger more investments targeting energy retrofit for buildings. Energy Performance Certificates (EPCs) represent a relevant instrument supposed to be strongly structuring for the assessment of buildings energy performance, decision support regarding energy retrofit projects, development and articulation of financing instruments (public and private), benchmark of building assets and market value recognition. EPC RECAST project will set a **well-structured process and a toolbox supporting the development,**	D1.10 EPC RECAST Certificate and Renovation Roadmap.

(continued on next page)

(*continued*)

Project name and period	EU funding programme	Consortium partners' countries	Objective and main outcomes	Reference documents
			implementation and validation of a new generation of Energy Performance Assessment and Certification, with a deliberate focus on residential buildings, more specifically existing ones, for which retrofit is one of the most challenging and pressing issue.	
EUB SuperHub - European Building Sustainability performance and energy certification Hub (2021–2024) [75].	Horizon 2020 - LC-SC3-B4E-4-2020 - Next-generation of Energy Performance Assessment and Certification.	AT; HR; FR; DE; HU; IE; IT.	The EUB SuperHub project will support the evolvement of the certification process in the EU by development of a **scalable methodology to view, assess and monitor the buildings through their lifecycle** (embedded energy, costs etc.). Energy performance assessments and certificates of buildings need to evolve to reflect the technological development, the needs of the society, and within the EU, they must be consistent throughout Member States. Holistic view of buildings, social and technological shifts in the society require a change in the way we observe and handle the built environment helping incentives to yield in energy efficiency and investments.	Quality, usability and visibility of energy and sustainability certificates in the real estate market.
iBRoad - Individual Building (Renovation) Roadmaps (2017–2020) [76].	Horizon 2020 - EE-11-2016-17 - Overcoming market barriers and promoting deep renovation of buildings.	AT; BE; BG; DE; EL; PL; PT; RO; SE.	iBROAD intends to explore, design, develop and demonstrate the concept of individual building renovation roadmaps, as a tool outlining **deep step-by-step renovation plans with customised recommendations for individual buildings**, combined with a repository of building-related information. The project will develop an integrated concept, and produce modular tools, suitable for differing national conditions. The iBROAD innovative concept and tools will be tested in some partner. iBROAD's implementation, beyond the project duration, will strongly support building owners in step-by-step deep renovation, while avoiding lock-in effects.	Factsheet for EU countries (Poland, Portugal and Romania). Current use of EPCs and potential links to iBRoad.
IDEAL EPBD - Improving Dwellings by Enhancing Actions on Labelling for the EPBD (–) [77].	Intelligent Energy Europe Programme.	–	In countries where the EPBD directive has been implemented for a while, the energy label seems to have little motivational impact on people to improve the energy performance of their home. IDEAL-EPBD aims to **investigate why the response of households towards the energy label has been limited**, in particular trying to determine: the reasons behind whether or not homeowners take the energy label into account, the reasons behind whether or not homeowners take up the additional proposed measures. The results of the investigations are being used to **develop policy recommendations and action plans** for improving the effectiveness of the energy certificates and other activity in the field of energy savings in the residential sector.	Deliverable 3.1 Country Specific Factors - Report of Findings in WP3.
QualDeEPC - High-quality Energy Performance Assessment and	Horizon 2020 - LC-SC3-EE-5-2018-2019-2020 - Next-generation of Energy	BE; BG; DE; EL; HU; LV; ES; SE.	The QualDeEPC project is aiming to both **improve quality and cross-EU convergence of Energy Performance**	D4.2 Development of Standard EPC.

(*continued on next page*)

(*continued*)

Project name and period	EU funding programme	Consortium partners' countries	Objective and main outcomes	Reference documents
Certification in Europe Accelerating Deep Energy Renovation (2019–2023) [78].	Performance Assessment and Certification.		**Certificate (EPC) schemes, and the link between EPCs and deep renovation**. The objective of the project is to improve the practical implementation of the assessment, issuance, design, and use of EPCs as well as their renovation recommendations, in the participating countries and beyond. The project will include the analysis of existing EPC schemes and the development and testing of concrete proposals and tools for enhanced EPC assessment The QualDeEPC project will stimulate changes by intensive dialogue involving the important stakeholders at all levels from the very beginning and by disseminating its findings among the relevant target audiences in Europe.	
TIMEPAC - Towards Innovative Methods for Energy Performance Assessment and Certification of Buildings (2021–2024) [79].	Horizon 2020 - LC-SC3-B4E-4-2020 - Next-generation of Energy Performance Assessment and Certification.	AT; HR; CY; DE; IT; SI; ES.	TIMEPAC will contribute to improving existing energy certification processes, **moving from a single, static certification to more holistic and dynamic approaches** that consider: the data generated in the overall energy performance certification process and throughout all the building lifecycle; buildings as part of a built environment, connected to energy distribution and transport networks and buildings as dynamic entities, continuously changing over time. TIMEPAC will demonstrate the feasibility of combining EPC databases with other data sources to make certification more effective and reliable and will validate the methodology in six countries.	Deliverable 1.1 Context analysis of EPC generation.
X-tendo - eXTENDing the energy performance assessment and certification schemes via a mOdular approach (2019–2022) [80].	Horizon 2020 - LC-SC3-EE-5-2018-2019-2020 - Next-generation of Energy Performance Assessment and Certification.	AT; BE; DK; EE; EL; IT; PL; PT; RO; UK.	X-tendo will support public authorities to transition to **next-generation energy performance certification (EPC) schemes**, including improved compliance, reliability, usability and convergence. The X-tendo toolbox will contain 10 innovative EPC features ranging from a smartness and a comfort indicator to building logbooks and how to improve EPC databases. A selection of twenty-nine test projects in nine different member states will demonstrate the potential of each feature as part of more reliable next-generation EPC schemes across the EU.	Energy Performance Certificates. Assessing their status and potential.

References

[1] European Parliament, Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings (recast) (Text with EEA relevance) https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202401275&pk_keyword=Energy&pk_content=Directive (accessed May 2024).

[2] European Environment Agency (EEA), Greenhouse gas emissions from energy use in buildings in Europe. https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-energy, Published 24 Oct 2023 (accessed May 2024).

[3] S. Lalieu, J. Pestiaux, M. Hagemann, S. Jackson, A. Lefebvre, A. Śniegocki, A. Stefańczyk, Net zero risk in European climate planning, report of European Climate Neutrality Observatory. https://climateobservatory.eu/sites/default/files/2024-02/ECNO_NECPAssessment_Report.pdf, January 2024. May 2024.

[4] A. Wilson, Revision of the Energy Performance of Buildings Directive: Fit for 55 package. Briefing EU Legislation in Progress, European Parliament. https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/698901/EPRS_BRI(2022)698901_EN.pdf. (accessed May 2024).

[5] European Parliament legislative resolution of 12 March 2024 on the proposal for a directive of the European Parliament and of the Council on the energy performance of buildings (recast) (COM(2021)0802 – C9-0469/2021 – 2021/0426(COD)) https://www.europarl.europa.eu/doceo/document/TA-9-2024-0129_EN.html (accessed May 2024).

[6] COM(2020)662 – Communication Renovation Wave for Europe - greening our buildings, creating jobs, improving lives, COM/2020/662 final, published on 14 October 2020, https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX:52020DC0662 (accessed May 2024).
[7] European Commission, Communication from the commission to the European parliament, the Council, the European economic and social committee and the committee of the regions. An EU-wide assessment of national energy and climate plans, Driving forward the green transition and promoting economic recovery through integrated energy and climate planning (2020). COM(2020) 564 final, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0564&qid=1665388701923&from=EN. May 2024.
[8] C. Maduta, G. Melica G, D. D'Agostino, P. Bertoldi, Towards a decarbonised building stock by 2050: the meaning and the role of zero emission buildings (ZEBs) in Europe, Energy Strategy Rev. 44 (2022) 101009, https://doi.org/10.1016/j.esr.2022.101009.
[9] C. Maduta, D. D'Agostino, S. Tsemekidi-Tzeinaraki, L. Castellazzi, G. Melica, P. Bertoldi, Towards climate neutrality within the European union: assessment of the energy performance of buildings directive implementation in member states, Energy Build. 301 (2023) 113716, https://doi.org/10.1016/j.enbuild.2023.113716.
[10] European Commission, Directive 2002/91/EC of the European parliament and of the Council of 16 december 2002 on the energy performance of buildings, 2002/91/EC. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32002L0091, 2002. May 2024.
[11] European Commission, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). https://eur-lex.europa.eu/eli/dir/2010/31/oj, 2010. May 2024.
[12] 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. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0844&from=EN, 2018. May 2024.
[13] D. Heidenthaler, M. Leeb, P. Reindl, L. Kranzl, T. Bednar, M. Moltinger, Building stock characteristics of residential buildings in Salzburg, Austria based on a structured analysis of energy performance certificates, Energy Build. 273 (2022) 112401, https://doi.org/10.1016/J.ENBUILD.2022.112401.
[14] M. Economidou, V. Todeschi, P. Bertoldi, D. D'Agostino, P. Zangheri, L. Castellazzi, Review of 50 years of EU energy efficiency policies for buildings, Energy Build. 225 (2020) 110322, https://doi.org/10.1016/j.enbuild.2020.110322.
[15] P. Zancanella, P. Bertoldi, B. Boza-Kiss, Energy Efficiency, the Value of Buildings and the Payment Default Risk, EUR 29471 EN, Publications Office of the European Union, Luxembourg, 2018. ISBN 978-92-79-97751-0, https://publications.jrc.ec.europa.eu/repository/handle/JRC113215. May 2024.
[16] J. Stromback, D. Hobson, E. Streng, T. Serrenho, P. Bertoldi, Advanced Quality and Use of Energy Performance Certificates (EPCs) by Investors and Financial Institutions, EUR 30886 EN, Publications Office of the European Union, Luxembourg, 2021, https://doi.org/10.2760/151167.
[17] A. Arcipowska, F. Anagnostopoulos, F. Mariottini, S. Kunkel, Energy Performance Certificates across the EU. A Mapping of National Approaches, Building Performance Institute Europe, 2014. ISBN: 9789491143106. (accessed May 2024).
[18] F. Pagliaro, F. Hugony, F. Zanghirella, R. Basili, M. Misceo, L. Colasuonno, V. Del Fatto, Assessing building energy performance and energy policy impact through the combined analysis of EPC data – the Italian case study of SIAPE, Energy Pol. 159 (2021) 112609, https://doi.org/10.1016/j.enpol.2021.112609.
[19] A. Gonzalez-Caceres, A.K. Lassen, T.R. Nielsen, Barriers and challenges of the recommendation list of measures under the EPBD scheme: a critical review, Energy Build. 223 (2020) 110065, https://doi.org/10.1016/j.enbuild.2022.112267.
[20] S. Zuhaib, S. Schmatzberger, J. Volt, Z. Toth, L. Kranzl, I.E.N. Maia, J. Verheyen, G. Borragán, C.S. Monteiro, N. Mateus, R. Fragoso, J. Kwiatkowski, Next-generation energy performance certificates: end-user needs and expectations, Energy Pol. 161 (2022) 112723, https://doi.org/10.1016/j.enpol.2021.112723.
[21] C. Jiménez-Pulido, A. Jiménez-Rivero, J. García-Navarro, Improved sustainability certification systems to respond to building renovation challenges based on a literature review, J. Build. Eng. 45 (2022) 103575, https://doi.org/10.1016/j.jobe.2021.103575.
[22] S. Vosoughkhosravi, L. Dixon-Grasso, A. Jafari, The impact of LEED certification on energy performance and occupant satisfaction: a case study of residential college buildings, J. Build. Eng. 59 (2022) 105097, https://doi.org/10.1016/j.jobe.2022.105097.
[23] A. Ferreira, M.D. Pinheiro, J. de Brito, R. Mateus, A critical analysis of LEED, BREEAM and DGNB as sustainability assessment methods for retail buildings, J. Build. Eng. 66 (2023) 112751, https://doi.org/10.1016/j.jobe.2023.105825.
[24] O. Awadh, Sustainability and green building rating systems: LEED, BREEAM, GSAS and Estidama critical analysis, J. Build. Eng. 11 (2017) 25–29, https://doi.org/10.1016/j.jobe.2017.03.010.
[25] J. Volt, S. Zuhaib, S. Schmatzberger, Z. Toth, Energy Performance Certificated - Assessing Their Status and Potential (2020) X-Tendo Project (H2020), Brussels (BE). (accessed May 2024).
[26] P. Olasolo-Alonso, L.M. López-Ochoa, J. Las-Heras-Casas, L.M. López-González, Energy performance of buildings directive implementation in southern European countries: a review, Energy Build. 281 (2023) 112751, https://doi.org/10.1016/J.ENBUILD.2022.112751.
[27] S. Semple, D. Jenkins, Variation of energy performance certificate assessments in the European Union, Energy Pol. 137 (2020) 111127, https://doi.org/10.1016/j.enpol.2019.111127.
[28] I. Flores-Abascal, P. Hernandez-Cruz, M. Odriozola-Maritorena, M. Almeida, B. Onety, J. Nicolle, F. Allard, J. Le Dréau, E. Suárez, A novel multicriteria methodology to assess the renovation of social buildings, J. Build. Eng. 77 (2023) 107505, https://doi.org/10.1016/j.jobe.2023.107505.
[29] G. Salvalai, M.M. Sesana, I. Isacco, New generation Energy Performance Certificate: development and application in an Italian case study as an EU proof of concept, E3S Web of Conferences 523 (2024) 06001, https://doi.org/10.1051/e3sconf/202452306001.
[30] R. Cichowicz, T. Jerominko, Comparison of calculation and consumption methods for determining Energy Performance Certificates (EPC) in the case of multi-family residential buildings in Poland, Energy 282 (2023) 128393, https://doi.org/10.1016/j.energy.2023.128393.
[31] G. Salvalai, M.M. Sesana, Long-term monitoring strategies for increasing EPCs reliability, Environ. Sci. Proc. 11 (2021) 16, https://doi.org/10.3390/environsciproc2021011016.
[32] S. Cozza, J. Chambers, J.L. Scartezzini, A. Schlüter, M.K. Patel, Do energy performance certificates allow reliable predictions of actual energy consumption and savings? Learning from the Swiss national database, Energy Build. 224 (2020) 110235, https://doi.org/10.1016/J.ENBUILD.2020.110235.
[33] A. Figueiredo, J. Kämpf, R. Vicente, R. Oliveira, T. Silva, Comparison between monitored and simulated data using evolutionary algorithms: reducing the performance gap in dynamic building simulation, J. Build. Eng. 17 (2018) 96–106, https://doi.org/10.1016/j.jobe.2018.02.003.
[34] B. Coyne, E. Denny, Mind the energy performance gap: testing the accuracy of building energy performance certificates in Ireland, Energy Efficiency 14 (2021) 57, https://doi.org/10.1007/s12053-021-09960-1.
[35] S. Cozza, J. Chambers, M.K. Patel, Measuring the thermal Energy Performance Gap of labelled residential buildings in Switzerland, Energy Pol. 137 (2020) 111085, https://doi.org/10.1016/j.enpol.2019.111085.
[36] P.X.W. Zou, X. Xu, J. Sanjayan, J. Wang, Review of 10 years research on building energy performance gap: life-cycle and stakeholder perspectives, Energy Build. 178 (2018) 165–181, https://doi.org/10.1016/j.enbuild.2018.08.040.
[37] L. Xiang, Y. Junqi, Z. Anjun, H. Shuai, M. Yun, Time series prediction method based on sub-metering in building energy performance evaluation, J. Build. Eng. 72 (2023) 106638, https://doi.org/10.1016/j.jobe.2023.106638.
[38] European Commission, Proposal for a Directive of the European Parliament and of the Council on the energy performance of buildings (recast), COM(2021) 802 final. https://eur-lex.europa.eu/resource.html?uri=cellar:c51fe6d1-5da2-11ec-9c6c-01aa75ed71a1.0001.02/DOC_1&format=PDF, 2021. May 2024.
[39] European Commission, Annexes to the Proposal for a Directive of the European Parliament and of the Council on the energy performance of buildings (recast), COM(2021) 802 final. https://eur-lex.europa.eu/resource.html?uri=cellar:c51fe6d1-5da2-11ec-9c6c-01aa75ed71a1.0001.02/DOC_2&format=PDF, 2021. May 2024.
[40] N. Della Valle, P. Bertoldi, Mobilizing Citizens to Invest in Energy Efficiency, EUR 30675 EN, Publications Office of the European Union, Luxembourg, 2021, https://doi.org/10.2760/137315. ISBN 978-92-76-36152-7.
[41] V. Taranu, G. Verbeeck, A closer look into the European Energy Performance Certificates under the lenses of behavioural insights—a comparative analysis, Energy Efficiency 11 (2018) 1745–1761, https://doi.org/10.1007/s12053-017-9576-6.
[42] X. Troussard, R. van Bavel, How can behavioural insights Be used to improve EU policy? Intereconomics: Review of European Economic Policy, Springer; ZBW - Leibniz Information Centre for Economics; Centre for European Policy Studies (CEPS) 53 (1) (2018) 8–12, https://doi.org/10.1007/s10272-018-0711-1.

[43] M. Arbulu, X. Oregi, L. Etxepare, R.J. Hernández-Minguillón, Barriers and challenges of the assessment framework of the Commission Recommendation (EU) 2019/786 on building renovation by European RTD projects, Energy Build. 269 (2022) 112267, https://doi.org/10.1016/j.enbuild.2022.112267.
[44] M. Gómez-Gil, M.M. Sesana, G. Salvalai, A. Espinosa-Fernández, B. López-Mesa, The Digital Building Logbook as a gateway linked to existing national data sources: the cases of Spain and Italy, Journal of Building Engineering 63 Part A (2023) 105461, https://doi.org/10.1016/j.jobe.2022.105461.
[45] Y. Li, S. Kubicki, A. Guerriero, Y. Rezgui, Review of building energy performance certification schemes towards future improvement, Renew. Sustain. Energy Rev. 113 (2019) 109244, https://doi.org/10.1016/j.rser.2019.109244.
[46] K. Võsa, A. Ferrantelli, D. Tzanev, K. Simeonov, P. Carnero, C. Espigares, M. Navarro Escudero, P. Vicente Quiles, T. Andrieu, F. Battezzati, K. Cordeiro, F. Allard, Z. Zoltan Magyar, G. Turturiello, L. Piterà, S. d'Oca, E. Willems, P.V. Op't, A. Lițiu, C. Lungu, T. Catalina, J. Kurnitski, Building performance indicators and IEQ assessment procedure for the next generation of EPC-s, E3S Web Conf. Cold Climate HVAC & Energy 246 (2021) 13003, https://doi.org/10.1051/e3sconf/202124613003.
[47] United Nations Economic Commission for Europe, Joint task force on energy efficiency standards in buildings, mapping of existing energy efficiency standards and technologies in buildings in the UNECE region, May 2024, https://unece.org/fileadmin/DAM/hlm/Meetings/2018/09_05-07_St._Petersburg/EE_Standards_in_Buildings_full_version.ENG.pdf, 2018.
[48] Concerted Action Energy Performance of Buildings, Implementing the Energy Performance of Buildings Directive (EPBD) Country Reports, 2018. Copenhagen, 2019. ISBN 978-87-93180-43-7.
[49] Concerted Action Energy Performance of Buildings, Implementing the Energy Performance of Buildings Directive (EPBD) Thematic Reports, 2018. Copenhagen, 2019. ISBN 978-87-93180-44-4.
[50] DAMCAR Properties Unite, Energy Performance Certificate. https://damcarproperties.com/Buying/EnergyPerformanceCertificate (accessed May 2024).
[51] Energetsko Certificiranje, Energetski Certifikat. https://www.energo-certificiranje.com/energetski-certifikat/(accessed May 2024).
[52] European Commission, National long-term renovation strategies 2020, Country factsheet. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/long-term-renovation-strategies_en#national-long-term-renovation-strategies-2020. (accessed May 2024).
[53] Enerdata, Evolution of households energy consumption patterns across the EU. https://www.enerdata.net/publications/executive-briefing/households-energy-efficiency.html (accessed May 2024).
[54] Journal Officiel du Grand-Duché de Luxembourg, Règlement grand-ducal du 9 juin 2021 concernant la performance énergétique des bâtiments. https://legilux.public.lu/eli/etat/leg/rgd/2021/06/09/a439/jo, 2021. May 2024.
[55] L'Observatoire DPE Diagnostic de Performance Énergetique, Outil statistique DPE. https://observatoire-dpe-audit.ademe.fr/statistiques/outil (accessed May 2024).
[56] Rijksdienst voor Ondernemend Nederland. https://www.rvo.nl/sites/default/files/2021/08/energielabel-voorbeeld-woningen.pdf (accessed May 2024).
[57] Sustainable Energy Authority of Ireland (SEAI), Building Energy Rating (BER). https://www.seai.ie/home-energy/building-energy-rating-ber/understand-a-ber-rating/Sample-BER-Cert.pdf (accessed May 2024).
[58] TECHNICKÝ A ZKUŠEBNÍ ÚSTAV STAVEBNÍ PRAHA, S.P., Průkazy energetické náročnosti budov. https://www.tzus.cz/sluzby/certifikace-budov/energeticke-stitky-prukazy-audity/prukazy-energeticke-narocnosti-budov (accessed May 2024).
[59] Vlaanderen verbeelding werkt, Energieprestatiecertificaat. https://assets.vlaanderen.be/image/upload/v1664179812/VoorbeeldEPCvanafjanuari2019_nieuw_sg5wa0.pdf (accessed May 2024).
[60] T. Constantinescu, Energy Performance Certificates across Europe. From Design to Implementation, Building Performance Institute Europe (BPIE), Brussels, 2010.
[61] R. Norvaisiene, J. Karbauskaite, P. Bruzgevicius, Energy performance certification in Lithuanian building sector. 40th IAHS World Congress on Housing. Sustainable Housing Construction, Funchal, 2014. ISBN:978-989-98949-0-7, https://www.researchgate.net/profile/Rosita-Norvaisiene/publication/271701773_Energy_Performance_Certification_in_Lithuanian_building_sectorBook_of_Abstracts/links/5c4977e3a6fdccd6b5c447d7/Energy-Performance-Certification-in-Lithuanian-building-sectorBook-of-Abstracts.pdf.
[62] Riigi Teataja, Nõuded energiamärgise andmisele ja energiamärgisele. https://www.riigiteataja.ee/akt/106052015002 (accessed May 2024).
[63] CA EPBD, Quality assurance for energy performance certificates, available at: www.epbd-ca.eu, 2011.
[64] E.P.B.D. Ca, Implementing the energy performance of buildings directive – featuring country reports 2012, available at: www.epbd-ca.eu, 2013.
[65] EN 15978:2011, Sustainability of Construction Works. Assessment of Environmental Performance of Buildings. Calculation method.
[66] CA EPBD, The price of energy performance certificates, available at: www.epbd-ca.eu, 2011.
[67] A. Shady, P. Kosiński, R. Wójcik, P. Węglarz, D. Koc, O. Laurent, Energy efficiency in the polish residential building stock: a literature review, J. Build. Eng. 45 (2022) 103461, https://doi.org/10.1016/j.jobe.2021.103461.
[68] M. Pourkiaei, A.C. Romain, Scoping review of indoor air quality indexes: characterization and applications, J. Build. Eng. 75 (2023) 106703, https://doi.org/10.1016/j.jobe.2023.106703.
[69] F. Re Cecconi, A. Khodabakhshian, L. Rampini, Data-driven decision support system for building stocks energy retrofit policy, J. Build. Eng. 54 (2022) 104633, https://doi.org/10.1016/j.jobe.2022.104633.
[70] T. Hai, A.S. El-Shafay, A. Alizadeh, K. Kulshreshtha, S.F. Almojil, A.I. Almohana, A.F. Alali, Improved locust swarm optimization algorithm applied for building retrofitting based on the green policy of buildings, J. Build. Eng. 70 (2023) 106274, https://doi.org/10.1016/j.jobe.2023.106274.
[71] crossCert: Cross Assessment of Energy Certificates in Europe (2021-2024), Grant Agreement (GA) No: 101033778, 2022. D2.4 EPC cross-testing procedure. https://www.crosscert.eu/fileadmin/user_upload/D2-4_EPC_cross-testing_procedure_v2-9.pdf (accessed May 2024).
[72] E-DYCE: Energy flexible Dynamic building Certification (2020-2023), Grant Agreement (GA) No: 893945, 2020. D1.1 EPC regional report. https://edyce.eu/wp-content/uploads/2021/01/E-DYCE_D1.1_EPC_regional_report_18.12.2020_Final.pdf. (accessed May 2024).
[73] ePANACEA: Smart European Energy Performance AssessmeNt And CErtificAtion (2020-2023), Grant Agreement (GA) No: 892421, 2020. Next Generation of EPCs and Quality Convergence across the EU: Implementation of Innovative Certification Schemes. https://epanacea.eu/results/.
[74] EPC Recast: Energy Performance Certificate Recast (2020-2023), Grant Agreement (GA) No: 893118. https://epc-recast.eu/(accessed May 2024).
[75] EUB SuperHub: European Building Sustainability performance and energy certification Hub (2021-2024), Grant Agreement (GA) No: 101033916, 2021. Quality, usability and visibility of energy and sustainability certificates in the real estate market. https://eubsuperhub.eu/assets/content/Deliverables/EUBSuperHub_D1.1.pdf. (accessed May 2024).
[76] iBRoad: Individual Building Renovation Roadmaps (2017-2020), Grant Agreement (GA) No: 754045, 2017. Factsheet for EU countries (Poland, Portugal and Romania). Current use of EPCs and potential links to iBRoad. https://ibroad-project.eu/news/8-country-factsheets/. (accessed May 2024).
[77] IDEAL EPBD: Improving Dwellings by Enhancing Actions on Labelling for the EPBD, Agreement: IEE/07/600/SI2 499426, 2009. Deliverable 3.1 Country Specific Factors – Report of Findings in WP3. https://publications.tno.nl/publication/34632143/Xp4s13/o11083.pdf (accessed May 2024).
[78] QualDeEPC: High-quality Energy Performance Assessment and Certification in Europe Accelerating Deep Energy Renovation (2019-2023), Grant Agreement (GA) No: 847100, 2022. D4.2 Development of Standard EPC. https://qualdeepc.eu/wp-content/uploads/2022/07/QualDeEPC_D4.2_standard_EPCs_02062022_final-komprimiert.pdf. (accessed May 2024).
[79] TIMEPAC: Towards Innovative Methods for Energy Performance Assessment and Certification of Buildings (2021-2024), Grant Agreement (GA) No: 101033819, 2022. Deliverable 1.1 Context analysis of EPC generation. https://timepac.eu/reports/context-analysis-of-epc-generation/. (accessed May 2024).
[80] X-tendo: eXTENDing the energy performance assessment and certification schemes via a mOdular approach (2019-2022), Grant Agreement (GA) No: 847056, 2020. Energy Performance Certificates. Assessing their status and potential. https://x-tendo.eu/toolbox/background-material/. (accessed May 2024).