



# Energy efficiency in buildings: EPC and SRI as enablers of future renovations<sup>☆</sup>

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## ARTICLE INFO

### Keywords:

Energy performance certificate  
Smart readiness indicator  
Energy efficiency  
Renewable energy  
Buildings

## ABSTRACT

In line with European climate-neutrality goals, buildings are increasingly understood not as static, isolated structures, but as active components of a wider built environment that also includes energy and transport infrastructure. This shift highlights the need for traditional, static Energy Performance Certificates (EPCs) to evolve into more dynamic and holistic instruments. Future EPCs are expected to assess not only the building envelope and technical systems, but also the performance of key subsystems such as automation and control technologies, and their interaction with the external environment.

In parallel, the Smart Readiness Indicator (SRI) has emerged as a complementary tool designed to evaluate a building's ability to respond to occupant needs, improve energy efficiency, and support grid stability through demand response signals. However, despite their relevance, EPCs and SRI are not currently reaching their full potential, revealing an important research and policy gap.

This paper provides an objective analysis of EPC and SRI, examining their respective strengths, weaknesses, and possible roles in shaping future renovation programmes through a case study of Slovenia. A mixed-methods approach was adopted, combining qualitative and quantitative techniques to explore the complex dimensions of EPC and SRI implementation and impact. To identify key challenges and opportunities, a problem tree is developed, highlighting barriers such as inconsistent implementation, performance gaps, and limited stakeholder engagement. Based on these findings, an objective tree is proposed, outlining policy interventions and measures to improve the effectiveness, usability, and integration of EPC and SRI in future building renovation strategies.

## 1. Introduction

For many years, energy efficiency has been a cornerstone of the European Union's (EU) climate and energy policy. Latest revision of the Energy Efficiency Directive (EED) [1] significantly raises the EU's ambition on energy efficiency and obliged all Member States to consider energy efficiency in all relevant policy and major investment decisions taken in the energy and non-energy sectors.

When it comes to buildings, the EU has recognized that improving the energy performance of buildings is essential for achieving climate neutrality by 2050, as committed under the European Green Deal [2]. To address this challenge, the EU has initiated a series of legislative and strategic measures aimed at accelerating the decarbonisation of the building stock. Central among these is the revised Energy Performance

of Buildings Directive (EPBD) [3]. It promotes a more ambitious and coordinated approach to improving building energy performance, integrating digital tools, and hopefully triggering large-scale renovations. It also introduces important enhancements to the framework of Energy Performance Certificates (EPC). The enhanced EPC is envisioned not only as a compliance tool but also as an enabler of targeted renovation measures, financing mechanisms, and energy efficiency investments. In this context, the Member States may allow for the comprehensive renovation passports to be drawn up and issued jointly with the EPC [3]. It is positive that Smart Readiness Indicator (SRI), that was introduced in 2018, is further elaborated in this recast of the EPBD, and complements EPCs by assessing a building's capacity to integrate smart technologies [3]. Also, it is important to mention that the SRI is being officially tested in 16 EU countries, including Slovenia, with support from various EU-funded projects to prepare for its large-scale

<sup>☆</sup> This article is part of a special issue entitled: 'ENB\_Smart Built Environment' published in Energy & Buildings.

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## Nomenclature

API	Application Programming Interface	et al.	<i>et alii</i> – and others
BEM	Building Energy Modelling	EU	European Union
BIM	Building Information Modelling	EV	Electric Vehicle
BRP	Building Renovation Passport	GHG	Greenhouse Gas
cEPC	Calculated Energy Performance Certificate	HVAC	Heating, Ventilation, and Air Conditioning
DEC	Display Energy Certificate	LED	Light-Emitting Diode
DLB	Digital Building Logbook	mEPC	Measured Energy Performance Certificate
DSM	Demand Side Management	NECP	National Energy and Climate Plan
EED	Energy Efficiency Directive	PO	Policy Option
e.g.	<i>exempli gratia</i> – for example	PV	Photovoltaic
EMS	Energy Management System	RES	Renewable Energy Sources
EPBD	Energy Performance of Buildings Directive	SMART	Specific, Measurable, Achievable, Relevant, and Time-bound
EPC	Energy Performance Certificate	SME	Small and Medium Enterprise
ESCO	Energy Service Company	SRI	Smart Readiness Indicator
		VSD	Variable-Speed Drive

implementation [4]. In the context of national energy and climate policy, the updated Slovenian National Energy and Climate Plan (NECP) [5] positions energy efficiency in buildings as a key pillar for achieving its climate targets. Further enhancements of the existing EPC scheme are also foreseen.

Even though significant policy efforts have been invested in visualizing the energy performance of buildings, the research presented by Zahaib *et al.* [6] revealed that current EPCs are not tailored to the needs of end-users, and that displaying only the energy performance of a building provides limited benefits to most people. According to Piro *et al.* [7], there is a lack of harmonization especially in the energy certificate data, methodologies applied to assess the energy performance of the building, independent controls, EPC database controls, misalignments on the EPC cost, and minimum qualification level of the energy certifier. This is also in line with findings from Sesana *et al.* [8], which identified substantial variations among EPC schemes, as well as inconsistent compliance levels for EPC indicators, reflecting the diverse methodologies currently applied across EU Member States. Few *et al.* [9] underlined that discrepancies between EPC-based estimates and actual measured energy consumption may have important implications for policy-making, and industry practice, especially EPCs tend to overestimate primary energy use intensity by approximately 8% for properties rated in band C, with the overestimation rising to about 48% for those classified in bands F and G. To address current shortcomings of EPC, Kaczmarczyk [10] introduced a three-dimensional evaluation framework that integrates primary energy consumption, the final-to-useful energy ratio, and equivalent emissions into a unified comparative structure termed the Energy Environmental Matrix.

Similar challenges also apply to energy flexibility. De Borja-Torrejón *et al.* [11] found that incorporating monitored data into energy flexibility assessments can yield more realistic estimates of achievable performance. However, they also emphasized the difficulty of identifying days with sufficiently comparable weather conditions to construct reliable baselines, which are essential for verifying performance after the implementation of corrective actions.

When it comes to SRI, research work conducted by Garzia *et al.* [12], revealed that there is no specific correlation between smart readiness and energy performance classification, indicating that the adoption of the SRI is necessary to provide a more comprehensive assessment of overall building performance. Also, Person *et al.* [13] noticed substantial divergence from both the efficiencies predicted by the SRI and the forecast coefficients defined in EN ISO 52120. They demonstrated that, in its current implementation, the SRI has limited capacity to predict the impact of smart technologies, particularly when making comparisons between different services. EN ISO 52120 is a standard that specifies how building automation, controls, and building management

contribute to the energy performance of buildings, including methods for assessing their impact on building efficiency and operation [14]. Ramezani *et al.* [15] clearly pointed that the current SRI methodology is not fully able to recognise the influence of all implemented energy improvement actions. However, Xenakis *et al.* [16], demonstrated the potential of SRI to function as a practical framework for assessing building intelligence, facilitating the identification of specific improvements that simultaneously increase smart readiness and energy efficiency. Also, according to Hernández *et al.* [17], the SRI has a potential to positively contribute to the evolution of EPCs from static to dynamic, incorporating real-time data for more accurate EPC certification. Kourgiouzou *et al.* [18] developed an approach to assess the smart readiness level of building stocks based on data obtained from Display Energy Certificates (DEC). However, they noted that the approach is inherently limited because DECs (and similar schemes, such as EPCs) primarily assess energy efficiency and therefore do not provide coverage of several SRI domains.

Based on the above discussed problems with available tolls related to energy efficiency in buildings and additionally motivated by the recommendations of Hwang *et al.* [19], who emphasized the need for systematic and ongoing evaluation of existing policy instruments in light of the EU's digital and green transition objectives, this paper examines strengths and limitations of EPC and SRI, with particular focus on their potential to guide and support future renovation strategies. The analysis explores how these tools capture and reflect the energy performance and smart capabilities of buildings, and how, when effectively combined and properly updated, they can serve as catalysts for deep renovations, reducing carbon emissions while enhancing occupant comfort and system efficiency. The following two research questions that arise in this context are:

- How can EPCs and SRIs be effectively combined and updated to better support deep renovation strategies and accelerate the energy transition in Slovenia (and by extension other EU Member States)?
- To what extent do current EPC and SRI frameworks accurately capture and reflect the real energy performance and smart capabilities of buildings, and what are their main methodological and implementation limitations (e.g., data reliability, harmonisation, stakeholder involvement)?

Within the scope of the presented research, to better understand the structural and operational barriers to the widespread implementation of EPC and SRI, a series of surveys was conducted and a problem tree was developed, highlighting issues such as inconsistent application, gaps in data reliability, and limited stakeholder involvement. Building on this diagnostic framework, the paper introduces an objective tree outlining

targeted policy interventions and strategic measures aimed at strengthening the practical impact and integration of EPC and SRI tools within the energy efficiency framework, as demonstrated through the case of Slovenia.

## 2. Methodology

This chapter presents the methodological framework adopted for the evaluation of EPCs and the SRI, with a particular focus on enhancing their effectiveness, consistency, and policy integration. A mixed-methods approach was employed, combining qualitative and quantitative techniques to capture the multifaceted nature of EPC and SRI implementation and impact. The methodology is structured around five key pillars: literature review and policy mapping, surveys with key stakeholders in order to assess the EPC generation process, field work and case studies that includes SRI calculation, development of the problem and objective trees, and identification of strategic policy measures. Outline of the applied methodology is given in Fig. 1.

The research process started with a comprehensive review of existing academic literature, policy reports, and regulatory documents at both EU and Member State levels. The objective of this stage was twofold: first, to contextualize the EPC and SRI within the broader framework of EU energy efficiency and climate policies; and second, to identify implementation gaps, challenges, and best practices. A policy mapping exercise was also undertaken to assess the degree of alignment between current Slovenian regulatory frameworks and the strategic goals of the updated National Energy and Climate Plan [5].

To assess the EPC generation process, the first survey was designed with four general and fifteen technical questions, with most of them having answers on a Likert scale, with grades from 1 to 5, where 1 means Completely unaware/Not agree/Completely not understandable, 2 Mostly unaware/Mostly not agree/Mostly not understandable, 3 Neutral, 4 Partly aware/Partly agree/Partly understandable, 5 Completely aware/Completely agree/Completely understandable. The full list of questions from the first survey is provided in Supplementary Material 1 of this manuscript.

The second survey was created to assess readiness for the Renovation Wave Strategy [20]. The main objective of this survey was to understand the knowledge gaps, the potential barriers that the target groups are foreseeing, and their needs for overcoming such barriers. The full list of questions from the second survey is provided in Supplementary Material 2 of this manuscript.

The third survey was designed to get more information from key target groups about understanding and upgrading EPC, databases and tools, SRI development and deployment and integration of instruments. This survey was focused on capturing awareness, perceptions, and experiences with EPCs and SRIs from identified target groups. In particular, this survey explored themes such as the credibility of the certificates, usability in real estate transactions, influence on renovation decisions, and the practical challenges of implementation. The full list of questions from the third survey is provided in Supplementary Material 3

of this manuscript.

In the last step, targeted interviews were conducted with selected key experts from the responsible state ministry, local energy agency, academia, and professional practice to discuss the main decision factors, including the barriers and challenges related with EPC and SRI. A semi-structured qualitative interview protocol was developed to explore these barriers, challenges, and their underlying causes. The interviewer used open-ended questions addressing the topic under investigation. When responses were unclear or raised particularly relevant issues, follow-up questions were asked to ensure depth and maintain the focus of the discussion. The list of predefined questions is provided in Supplementary Material 4 of this manuscript.

In all three surveys and the interview the following target groups were addressed:

- Professionals (certifiers, designers (engineer, architects, etc.), and energy auditors).
- Public Bodies (energy agencies, national, regional and local public authorities).
- Market operators (Energy Service Companies (ESCO), real estate agencies, construction companies, energy-related product companies).

In parallel with surveys and interviews, field work and case studies that includes SRI calculation were conducted. In the framework of the SRI calculation a detailed assessment method B was employed. Detailed descriptions of this method are given in [21]. The main objective of this part of the methodological approach was to investigate the human, technical, and institutional factors shaping the performance of SRIs on the ground. These insights added a critical layer of qualitative depth and grounded the research work in lived practice.

In the next step, the results of SRI assessments were once again assessed and in that process a use-case approach that focuses on the following end-users was used:

- Demand-Side-Management-aware facility manager.
- Sustainability-supporting owner.
- Informed ESCO.
- Informed utility.

The use-case approach represents a method for identifying the potential advantages of a tested tool from the perspective of its intended users. End-users refer to the stakeholders who may apply or benefit from the SRI. At this stage, the assessors assumed the role of end-users and re-evaluated the SRI calculation outcomes, taking into account the primary needs associated with the selected user profile. All remarks documented within the SRI calculation spreadsheet were analyzed to identify potential measures aimed at improving energy efficiency and system flexibility. An example of the structure of the adopted use-case approach for the selected end-user, Demand-Side-Management-aware (DSM) facility manager, is presented the Table 1.

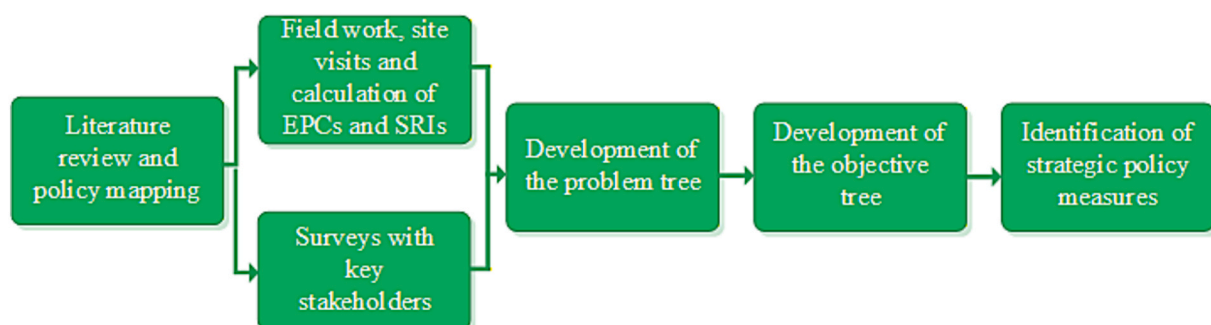


Fig. 1. Outline of the applied methodology.

**Table 1**  
Structure of the adopted use-case approach – an example for the demand-side-management-aware facility manager.

End-user	Demand-side-management-aware facility manager
End-user expectations / needs	A DSM-aware facility manager who works with a large state-owned building needs to objectively evaluate the building's flexibility potential and identify interesting DSM projects. The facility manager would like to propose tailor-made energy efficiency projects with a special emphasis on energy flexibility.
Results of SRI rating process	A reliable list of potential DSM projects that can be implemented through energy-performance contracting or a similar funding scheme.
Comments made by SRI evaluator	The selection criteria for potential DSM projects should be clearly defined, including factors such as energy efficiency, cost savings and user comfort. In addition, independent and context-sensitive variables, such as occupancy, scheduling, and weather conditions, should be identified. The key inputs required for the report, which will contain the list of potential projects to be implemented in the selected building, should include a detailed analysis of the building's energy consumption and usage patterns.

The next step of the proposed approach involved development of the problem and objective trees. In accordance with the EU Better Regulation Guidelines and Toolbox [22], a structured analytical process was employed to define the problem space and guide the formulation of policy interventions. This began with the development of a problem tree, which mapped the root causes, immediate drivers, and broader consequences of identified deficiencies in the EPC and SRI generation and exploitation pathways. This diagnostic framework served as the basis for creating an objective tree, which reframed the identified problems into positive goals. The objective tree provided a visual and logical structure that linked operational objectives to overarching policy aims, such as improving energy performance data reliability, increasing user confidence, and stimulating investment in building upgrades.

The final methodological step involved the translation of objectives into strategic measures and policy recommendations. This included the assessment of potential interventions in terms of their feasibility, stakeholder support, and alignment with EU energy and climate goals. The process of designing the policy options included identification of the baseline and combining the policy measures from all pillars with various degrees of ambition. Policy options with varying level of ambition that could be adopted to enhance building energy efficiency and smart readiness are called Policy Option 1 (basic), Policy Option 2 (advanced), and Policy Option 3 (comprehensive). These options represent different degrees of intervention, scope, and regulatory requirements. The level of ambition increases progressively across the options, with each one encompassing more stringent measures and broader impacts. The ambition level directly influences the extent to which key components such as EPC, SRI, and other relevant national strategies are implemented. Finally, the quantitative part of the impact assessment presents quantifiable effectiveness and efficiency and the cost-benefit analysis which aims to measure the effects of each policy options among a unique matrix transposing impacts into monetary terms. tunES project has developed an Impact Assessment Tool which allows to compare identified policy options towards the baseline scenario in multiple pillars (Understanding EPC, Upgrading EPC, Databases and Tools, Integration of Instruments, SRI Development and Deployment) [23].

For each policy option, the analysis considered the expected impacts on energy efficiency in buildings and translated them into a structured matrix of costs and benefits, including EPC-, BRP- and SRI-related costs, training needs, public-sector implementation costs, avoided energy costs, and avoided external costs associated with Greenhouse Gas (GHG) emissions. This approach supports transparent comparison of the policy options and provides a basis for future replication in other national contexts, provided that equivalent baseline conditions, data availability,

and policy assumptions are defined. The assessment is ex-ante in nature and is intended to support policy design by comparing options with different levels of ambition.

### 2.1. Use case: current status of EPC and SRI in slovenia

In Slovenia, the Ministry of Environment, Climate and Energy is responsible for developing and carrying out Slovenia's energy policy. The Ministry also takes care about the EPC database. At the moment, the EPC database is linked to two external databases: (1) Cadaster database, and (2) Geographical database. Special and customized Application Programming Interfaces (API) are used to provide the communication between the databases. It is very positive that Slovenia is already working on enhancing interoperability between different data systems. It has started the creation of a national database that would house all building-related and energy performance data in Slovenia. This database would facilitate better data sharing and decision-making for energy efficiency upgrades in building sector [24]. During the entire research work described in this paper, the Ministry has provided the full support and open access to all requested data for the validation of the proposed methodological framework combining field work, surveys, creation of problem and objective trees, and identification of strategic policy measures. According to Eisenhardt and Graebner [25], this represents opportunity with the unusual research access.

In Slovenia, EPCs are issued by an authorized organization and carried out by a licensed expert. The EPC must be obtained by the property owners (whole building or building unit) in case of selling or renting their property for a period longer than one year. However, there are some exceptions, and an EPC is not required in cases where a contract is to be signed with the tenant for a period less than one year. In the majority of cases, the EPC's validity is checked primarily by notaries during the sale. Building owners who do not sell or rent their properties do not need an EPC.

An EPC must also be obtained for all new buildings. For newly constructed and renovated buildings, the EPC generation process is linked to the controls in place to establish whether a building meets the minimum requirements for energy performance.

The energy certificate is necessary for all buildings owned or used by public-sector entities with a total usable floor area of more than 250 m<sup>2</sup>, and a valid EPC must be placed in a visible location. The EPC is also necessary for all buildings that are not owned or used by the public-sector entities but have a total usable floor area of more than 500 m<sup>2</sup> and are often used by the public. In this case the EPC must also be placed in a visible location.

There are two types of EPCs in Slovenia, calculated EPC (cEPC) and measured EPC (mEPC). A cEPC can be generated and issued for each building. It is prescribed for residential buildings and for all new buildings. The calculation methodology is the same as for the calculation of the building's energy consumption when obtaining a building permit. Several software tools are available for this purpose. In the case of missing project documentation, which is often the case for old residential buildings, the experts must collect the necessary data on-site with measurements and a visual inspection of the installed materials, thicknesses, technical systems, etc.

An mEPC is intended only for existing non-residential buildings, and it is determined on the basis of the actual energy consumption of the building. The basis for the generation of the measured energy certificate is the actual, measured values of the energy consumption in the building or an individual part of the building. Data about the supplied energy and general data about the building are provided by the property owner, for example, in the form of invoices or other reports.

In march 2023 Slovenia started with the analysis and testing of SRI in its national context. Initial goal is to explore the potentials and opportunities for SRI implementation in the context of our energy policy development [4]. Proposal of new Act on Energy Efficiency [26] in its Article 40, introduces SRI and defines that any buildings may voluntarily

obtain an SRI based on the needs and wishes of the owner or investor. This indicator can be used in energy audits, EPCs, reports on technical building systems, or other energy-related reports and analyses.

## 2.2. Creation of policy options for Slovenia

Based on the evaluation of existing situation, three policy options (Policy Option 1, Policy Option 2, Policy Option 3) with varying levels of ambition were defined. The Basic Level of Ambition (Policy Option 1) lays the foundation for aligning Slovenia's framework with the recast EPBD. It consolidates existing provisions in national rules and adds the mandatory requirements needed for full compliance. The focus is on making EPCs clearer and more useful for the public, establishing a single authoritative data environment, and preparing the SRI for orderly deployment without imposing complex new obligations. In practical terms, this option represents an immediately deliverable package of measures that prioritises user communication, essential methodological updates, and baseline governance for data and quality assurance. It is designed to be feasible within the current institutional capacity and to dovetail with the national timetable for transposition and secondary legislation. Within this policy option, 100 specific requirements in national legislation and practice are planned for implementation, thereby securing alignment with the EPBD and creating a solid platform for subsequent upgrades. The list of specific requirements related to Policy Option 1 is provided in Supplementary Material 5.

The Advanced Level of Ambition (Policy Option 2) fine-tunes Slovenia's framework in line with the recast EPBD and builds on Policy Option 1 through targeted enhancements. An additional 40 requirements associated to Policy Option 2 were identified (see Supplementary Material 6 for the list of specific requirements related to Policy Option 2). These enhancements improve usefulness, comparability, and uptake. This option also retains all provisions consistent with the Directive, implements the mandatory elements, and adds selected policy measures that raise the quality and impact of EPCs while preparing the SRI for meaningful deployment. The implementation plan is organised across five thematic areas: Understanding EPCs, Upgrading EPCs, Databases and Tools, Integration of Instruments, and SRI Development and Deployment.

The Comprehensive Level of Ambition (Policy Option 3) further optimises Slovenia's framework by building on Policy Option 2 and introducing a focused set of high-impact measures. In total, 19 additional requirements were identified to be operationalised into 19 measures beyond the Advanced Level (see Supplementary Material 7 for the list of specific requirements related to Policy Option 3). It retains all provisions aligned with the recast EPBD, implements both mandatory and advanced elements, and introduces additional policy options that fully integrate EPCs, the Building Renovation Passport (BRP), the SRI, and data systems. The aim is to establish a mature, data-driven system that delivers high-quality certificates, strong market signalling, and measurable improvements in renovation outcomes.

## 3. Results and discussion

The first survey about the EPC generation process was distributed among selected target groups to establish direct contact with potential future training audiences and to better understand their needs and expectations. All together 70 responses were received. The majority of respondents (60%) indicated that they have participated in the process of EPC generation. Regarding the price for the EPCs, the respondents clearly outlined that the current level of prices for the generation of an EPC for a building in Slovenia is not sustainable, and it does not provide an appropriate framework for achieving the necessary quality. Unfortunately, there are a lot of experts in the market that issue EPCs of questionable quality for an unreasonably low price. This also indicates that there are problems with inefficient inspections and low quality of the input data. It is a positive feature that there are state subsidies for

carrying out energy audits in small and medium enterprises (SMEs) and buildings, but unfortunately there is relatively low interest for these activities on the demand side (SME and building owners).

Regarding the usefulness of the information provided by the EPC for the extensive renovation of buildings, more than 45% clearly indicated that they are not convinced that the current EPC contains useful information for a major renovation of buildings. In their comments, respondents stated that energy-efficiency recommendations presented on the EPC were too general and without any real usefulness. This finding is in line with the conclusions from [6]. In the case of the energy renovation of existing buildings, a logical step forward to overcome this obstacle is to connect the generation of EPCs with the energy auditing of buildings and to make the energy-audit report part of the documentation necessary for the application for state subsidies. Also, automation of a building's technical systems opens an additional door for the automatic update of the EPC with information from control and management systems, which should be the first step towards a dynamic EPC.

More than 63% of respondents indicated that the EPC does not contain the necessary key performance indicators for a proper understanding of the energy efficiency of technical building's energy systems. The majority of respondents (more than 80%) considered positive to share data on the technical systems of the building and the actual energy consumption of the building with the certified energy-performance assessor during an energy assessment of a building. However, personal data protection rules must be respected. More than 65% of Slovenian respondents agreed on making the EPC mandatory for the entire building stock. In this context it must be added that the majority of respondents think that an EPC is useful for protecting buyers or tenants.

The second survey to assess readiness for the Renovation Wave Strategy was distributed among the same stakeholders but this time 122 responses were collected. It was positive that this time also the majority of respondents (57%) were professionals, while 24% of them were representing public authorities and 19% market operators. Respondents indicated that top three topics of interest are Building Information Modelling (BIM), building smartness assessment, and building renovation passport procedures. Regarding the tools and methods, more than three quarters of respondents think they would need simplified methods to support the assessment procedures, BIM tools, and easier access to open data portals. Among the 122 respondents, 87% declared that they would need training and support to acquire new skills. Regarding the type of support, the respondents preferred training activities (around 40%), but also guidelines (32%) as well as consultancy (24%) were selected as types of support.

The third survey was conducted one year after the second survey among 20 preselected participants to get more information about understanding and upgrading EPC, databases and tools, SRI development and deployment and integration of instruments. As no significant differences were observed among professionals, public bodies, and market operators in the main survey findings, the results are presented in aggregated form to highlight the common priorities identified across stakeholder groups. The main findings from this survey regarding understanding EPC are outlined in Fig. 2. For each topic, the percentages do not sum to 100%, since "I don't know" responses are excluded from Fig. 2.

From the 20 participants in the third survey, four interviewees were selected through purposive sampling to ensure balanced coverage of the main stakeholder perspectives relevant to the Slovenian EPC and SRI implementation framework. The in-depth interviews were used as a qualitative follow-up to deepen and validate the survey findings rather than to provide statistical representativeness. The third survey and in-depth interviews confirmed that EPCs were recognized as important, but doubts persisted regarding their reliability, ease of use, and the robustness of the underlying data. The findings reaffirmed that implementing EPCs based on dynamic data and dynamic calculation methods could substantially enhance the precision and practical relevance of energy performance evaluations. Nevertheless, the transition to these

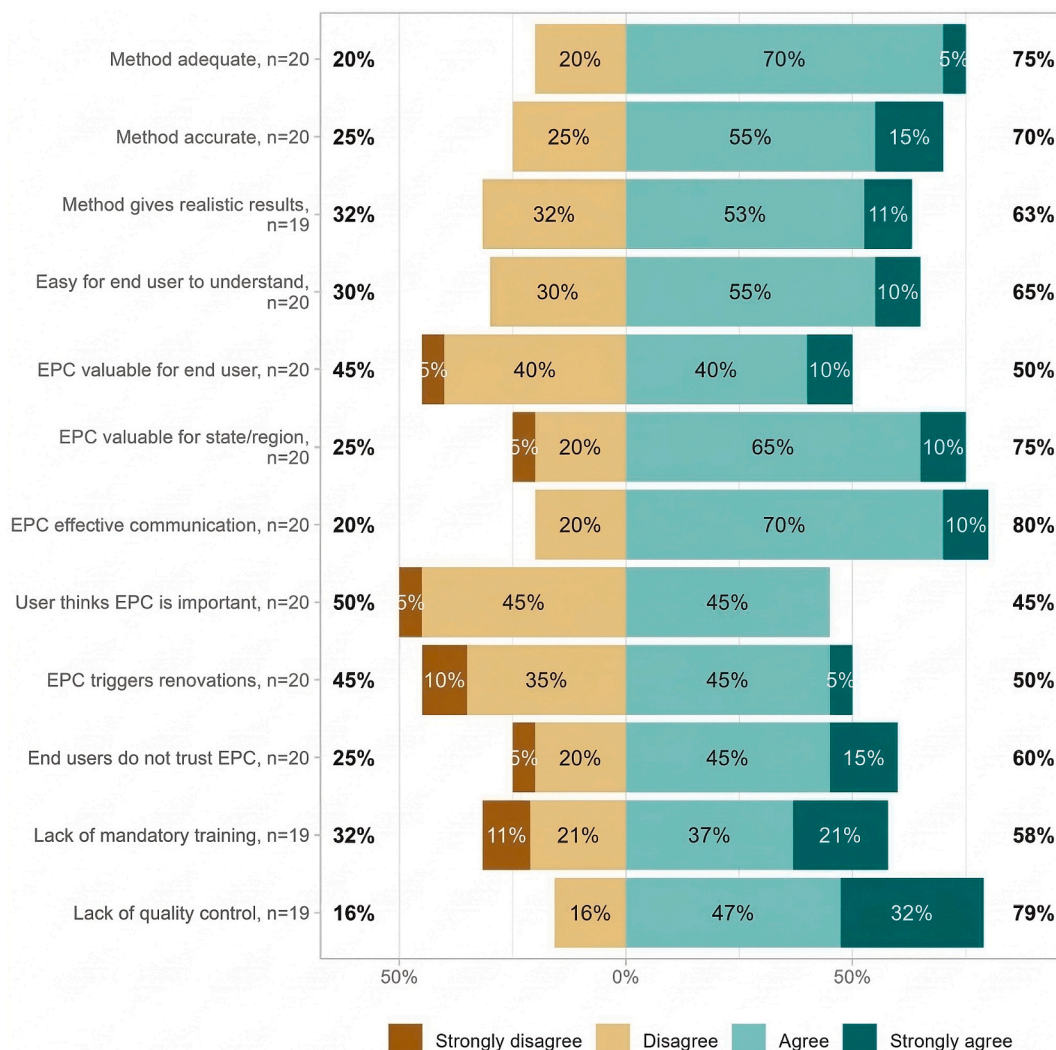


Fig. 2. Outline of the results of third survey regarding the understanding of the EPC.

advanced approaches presents several obstacles, such as technical complexities, the requirement for specialized training, and the need to integrate EPC frameworks with financial incentive mechanisms.

Slovenian respondents expressed strong support for establishing a comprehensive national energy-related database that would include all EPCs as well as the data used to develop them. This provided clear confirmation for the Ministry that the new database, which will contain all building-related and energy performance data in Slovenia, will increase transparency, strengthen quality assurance processes, and offer meaningful support for the further development of EPC frameworks.

As expected, the respondents were less familiar with the key elements of the SRI framework. However, they also recognised that SRI has significant potential to accelerate the digitalisation of buildings in Slovenia and recommended aligning SRI calculations with energy audits.

Regarding the integration of instruments, it was recognized that it should be done in phases starting with combining activities of energy performance assessment, SRI calculation and energy auditing. The key issue lies in integrating the most beneficial features of the identified tools and methodologies while avoiding excessive complexity and additional costs in the EPC generation process for end-users.

In parallel with survey, field work and data collection for the SRI calculation was done. During this phase smart readiness of 20 non-residential buildings across Slovenia were assessed. The main characteristics of assessed buildings are given in the Table 2. On-site

investigations further demonstrated that, without precise and comprehensive data, the calculations may fail to accurately represent the building’s true smartness and performance. SRI assessors recognized the following data sources that were used for assessing smartness:

- Site visits.
- Interviews with owners and facility managers.
- EPC and BIM and Building Energy Modelling (BEM) if available.
- Energy audit reports and energy consumption data.

In line with the EU SRI methodology, the assessment is structured around technical domains and impact criteria, while the results presented in Table 3 are additionally interpreted through the overall SRI score and the three key functionalities of smart-ready buildings: energy performance, responsiveness to occupant needs, and responsiveness to grid signals. In this context, these are referred to as “Building,” “User needs,” and “Grid,” respectively.

The resulting SRI scores are generally moderate, primarily affected by the building’s construction date and the timing of its most recent renovations. The obtained results also confirmed the findings of Ramezani et al. [15], who noted that the SRI methodology is still not fully capable of adequately capturing the impact of all implemented energy efficiency measures. It can also be recognized that the key functionality related to the grid integration receives relatively lower scores because smart grid technologies are still relatively expensive, and there are no

**Table 2**  
Overview of the main characteristics of assessed buildings.

Type	Total area [m <sup>2</sup> ]	Year of construction	Renovated
Non-residential 1 – School	1000–10000	1960–1990	No
Non-residential 2 – Healthcare Centre	1000–10000	1960–1990	Yes
Non-residential 3 – Office Building	500–1000	<1960	Yes
Non-residential 4 – Office Building	500–1000	<1960	No
Non-residential 5 – School	1000–10000	<1960	No
Non-residential 6 – School	500–1000	<1960	Yes
Non-residential 7 – Kindergarten	200–500	1960–1990	No
Non-residential 8 – School	1000–10000	<1960	Yes
Non-residential 9 – Culture Centre	200–500	1960–1990	Yes
Non-residential 10 – School	200–500	1960–1990	Yes
Non-residential 12 – Office Building	500–1000	1960–1990	Yes
Non-residential 13 – Office Building	200–500	<1960	Yes
Non-residential 14 – Office Building	500–1000	<1960	Yes
Non-residential 15 – Healthcare	500–1000	<1960	No
Non-residential 16 – Office Building	>25000	>2010	No
Non-residential 17 – Healthcare	1000–10000	1960–1990	Yes
Non-residential 18 – School	1000–10000	1960–1990	No
Non-residential 19 – Office Building	1000–10000	1960–1990	Yes
Non-residential 20 – School	500–1000	<1960	No

**Table 3**  
Overview of the main results of SRI assessment.

Type	Key functionalities			Overall SRI score
	Building	User needs	Grid	
Non-residential 1 – School	12%	14%	0%	10%
Non-residential 2 – Healthcare Centre	21%	21%	4%	18%
Non-residential 3 – Office Building	17%	24%	8%	16%
Non-residential 4 – Office Building	10%	29%	0%	12%
Non-residential 5 – School	7%	9%	0%	5%
Non-residential 6 – School	25%	18%	8%	17%
Non-residential 7 – Kindergarten	18%	16%	5%	13%
Non-residential 8 – School	23%	27%	9%	20%
Non-residential 9 – Culture Centre	27%	32%	8%	22%
Non-residential 10 – School	26%	34%	12% %	24%
Non-residential 12 – Office Building	19%	18%	8%	15%
Non-residential 13 – Office Building	31%	15%	9%	18%
Non-residential 14 – Office Building	21%	20%	8%	16%
Non-residential 15 – Healthcare	9%	11%	4%	8%
Non-residential 16 – Office Building	54%	45%	16%	38%
Non-residential 17 – Healthcare	26%	32%	8%	22%
Non-residential 18 – School	10%	18%	5%	11%
Non-residential 19 – Office Building	41%	46%	15%	34%
Non-residential 20 – School	9%	9%	4%	7%

well-functioning markets for flexibility services in buildings. However, recent changes in Slovenia's electricity tariff system over the past months have created a more favourable environment for leveraging flexibility opportunities within the market. This positive development has the potential to improve the SRI scores in future assessments by enabling buildings to better integrate with and contribute to grid flexibility.

The next phase involved the use-case approach for the analysis of the results of the SRI rating. In this context, the use-case approach was used to capture potential energy-efficiency and flexibility measures from data collected during the process of the SRI rating. Table 4 summarizes all the identified energy-efficiency and flexibility measures and relates them to the specific end-user. To avoid ambiguity, it should be noted that the end-users presented in Table 4 are not the same persons as the interview participants. They represent predefined user profiles used in the use-case approach to analyse the outcomes of the SRI rating from the perspective of potential beneficiaries.

It is clear that each end-user has a different perspective and expectations from the SRI rating. However, a single energy-efficiency and flexibility measure can benefit multiple end-users. For instance, the potential installation of a battery-storage system is of interest to all four envisioned end-users: the DSM-aware facility manager, the sustainability supporting owner, the informed ESCO, and the informed utility.

For each identified energy-efficiency and flexibility measure, the SRI auditor should provide an indicative estimate of the associated energy and economic benefits. This implies that, to achieve cost-effectiveness, SRI and energy performance evaluations should be conducted alongside a comprehensive energy audit.

Based on the Slovenian experiences, it has to be noticed that some of the owners are concerned about pure dependence on technology. With smart technology controlling various aspects of a building, there is increased dependence on these systems. If they fail or malfunction, it could have a significant impact on the building's operations and the comfort of its occupants.

The results of the SRI rating will not be useful for different end-users if they are not stored in repositories that enable different advanced functionalities. Current approaches that use building-related data solely for single or dedicated purposes are unsustainable and do not support the enhancement of EPCs. It is essential to ensure interoperability between existing databases, previously developed models (such as BIM), and historical energy audit reports. This information should be made accessible to building professionals—including energy and facility managers, EPC assessors, designers, and others—in a way that allows the new EPC to leverage existing data. Such an approach is the only way to achieve cost-effectiveness for the client. Analysing past performance is critical for identifying tailored, building-specific measures that improve both energy efficiency and operational flexibility. This approach is in line with the recast EPBD and the recognized need to create the Digital Building Logbook (DLB) that consolidates all relevant building data and ensures that authorized personnel have access to accurate information for each specific building [3].

In the next phase, and based on previously obtained results, a problem tree for EPC and SRI was created. The problem tree visually maps out the issues related to EPCs and SRIs at three levels: drivers, core problems, and consequences. This framework clarifies the critical factors leading to the overarching issues and their broader societal and environmental impact. Key elements include:

1. Drivers (Root Causes): Systemic challenges and external factors influencing the effective implementation of EPCs and SRIs.
2. Core Problems: Specific challenges that arise from these drivers, negatively impacting the deployment, quality, and usage of EPCs and SRIs.
3. Consequences: The broader impacts of these problems on energy efficiency, market confidence, and environmental sustainability.

**Table 4**  
Outcomes of the use-case approach based on results of SRI rating.

End-user	Outcomes of the use-case approach based on results of SRI rating
DSM-aware facility manager	<ul style="list-style-type: none"> <li>•Installation of new or upgrade of existing energy management system (EMS)</li> <li>•Enhancing the control system allowing demand/response functionalities</li> <li>•Installation of a high-efficiency, modern heat pump</li> <li>•Deployment of a photovoltaic (PV) system</li> <li>•Integration of a battery storage system with advanced grid-interaction capabilities</li> <li>•Installation of new or upgrade of existing electric vehicle (EV) charging station with advanced control systems</li> </ul>
Sustainability supporting owner	<ul style="list-style-type: none"> <li>•Renovation of façade and insulation of roof, including windows and mechanical ventilation with heat recovery</li> <li>•Enabling individual room control with optimizing function (heating and cooling)</li> <li>•Installation of PV system</li> <li>•Integration of a battery storage system with advanced grid-interaction capabilities</li> <li>•Implementation of new control components and sensors for heating, cooling, and ventilation systems</li> <li>•Deployment of variable-speed pump units</li> <li>•Installation of an upgraded light-emitting diode (LED) lighting system equipped with occupancy sensors and dimming functionality</li> <li>•Deployment of new or upgrade of existing EV-charging station with advanced control systems</li> <li>•Installation of EMS with demand/response functionalities</li> <li>•Substitution of the existing heat generator with heat pumps or other system based on renewable energy sources (RES)</li> <li>•Installation of new and smart heating, ventilation, and air conditioning (HVAC) system with advanced control systems</li> </ul>
Informed ESCO	<ul style="list-style-type: none"> <li>•Separation of space heating and domestic hot-water production</li> <li>•Enabling individual room control with optimizing function (heating and cooling)</li> <li>•Deployment of variable-speed pump units</li> <li>•Installation of an upgraded LED lighting system equipped with occupancy sensors and dimming functionality</li> <li>•Implementation of new control components and sensors for heating, cooling, and ventilation systems</li> <li>•Substitution of the existing heat generator with heat pumps or other system based on RESs</li> <li>•Installation of new or upgrade of existing EMS with demand/response functionalities</li> <li>•Full modernization of the HVAC system, including the installation of a new heat pump for both heating and cooling, integration of variable-speed drive (VSD) pumps, and implementation of advanced control systems for optimized heating and cooling management</li> <li>•Installation of new and smart HVAC system with advanced control systems</li> <li>•Deployment of PV panels combined with a battery storage system featuring advanced grid-integration capabilities</li> <li>•Implementation of a battery energy storage system designed for peak load management, backup power supply, and optimization of on-site PV generation</li> <li>•Installation of new or upgrade of existing EV-charging station with advanced control systems</li> </ul>
Informed utility	<ul style="list-style-type: none"> <li>•Deployment of a PV installation combined with a battery storage system enabling advanced grid interaction and maximizing on-site energy self-consumption</li> <li>•Deployment of a new EV-charging station equipped with advanced control functionalities and comprehensive system reporting capabilities</li> </ul>

**Table 4 (continued)**

End-user	Outcomes of the use-case approach based on results of SRI rating
	<ul style="list-style-type: none"> <li>•Installation of new or upgrade of existing EV-charging station with advanced control systems</li> <li>•Enhancing the control systems allowing demand/response functionalities</li> <li>•Implementation of a new, or upgrade of an existing, EMS with demand-response capabilities and real-time occupant feedback</li> </ul>

4. Problem tree addressing key challenges in EPC implementation in given in Fig. 3.

The consequences of low-quality EPCs in Slovenia are far-reaching. One of the most immediate impacts is the erosion of trust in the EPC system. EPCs are intended to provide a reliable assessment of a building's energy performance, but when the information they contain is inaccurate, property owners, buyers, and tenants are left with little confidence in the certificate's value. This undermines the role of EPCs in driving energy efficiency improvements and building renovations. Attia et al. [27] report that a similar issue is present in many other European countries.

The low quality of EPCs in Slovenia can be attributed to several factors, with one of the main reasons being inconsistent data collection. EPCs are based on a set of key data inputs, such as building dimensions, insulation levels, heating systems, and overall energy consumption patterns. In many cases, the data used to calculate EPCs in Slovenia is either outdated, incomplete, or inaccurate. These inaccuracies are often the result of a lack of access to real-time operational data or reliance on estimates instead of actual measurements.

Also, the qualifications of assessors vary significantly, and while some may be well-versed in energy performance assessments, others may lack the necessary expertise or have received insufficient training on the latest technologies. All this may result in a significant gap between the building's actual energy consumption and the performance that has been calculated by inexperienced assessor. This also leads towards inaccurate EPCs which can mislead property owners and potential buyers, making it difficult to trust the results and recommendations provided by the certificate.

In line with the Better Regulation Guidelines and Toolbox [22], the policy objectives derive directly from the needs and problem assessment. Therefore, the objective tree that mirrors the problem tree is presented in Fig. 4. The specific objectives align with the drivers and problems, while the general objectives reflect the broader consequences of addressed issues.

The specific objectives relate to the distinct domain and the nature of the intervention considered. They have been defined in a way that they are broad enough to allow consideration of a wide variety of options while remaining in line with the problems that need to be addressed. For example, driver 2 (Operational consumption data is not utilized) from the problem tree, (see Fig. 3) is translated into following specific objective in objective tree (see Fig. 4): Implement systems to efficiently use operational consumption data for energy planning and efficiency improvements. This is further disaggregated into following actionable and operational targets that are specific, measurable, achievable, relevant, and time-bound (SMART):

- Specific: Create customized energy efficiency recommendations for each building based on its specific characteristics and operational data.
- Measurable: Ensure that 70% of new EPCs include tailored recommendations within the next three years.
- Achievable: Use enhanced data collection and analysis tools, and provide training for assessors to generate building-specific recommendations.

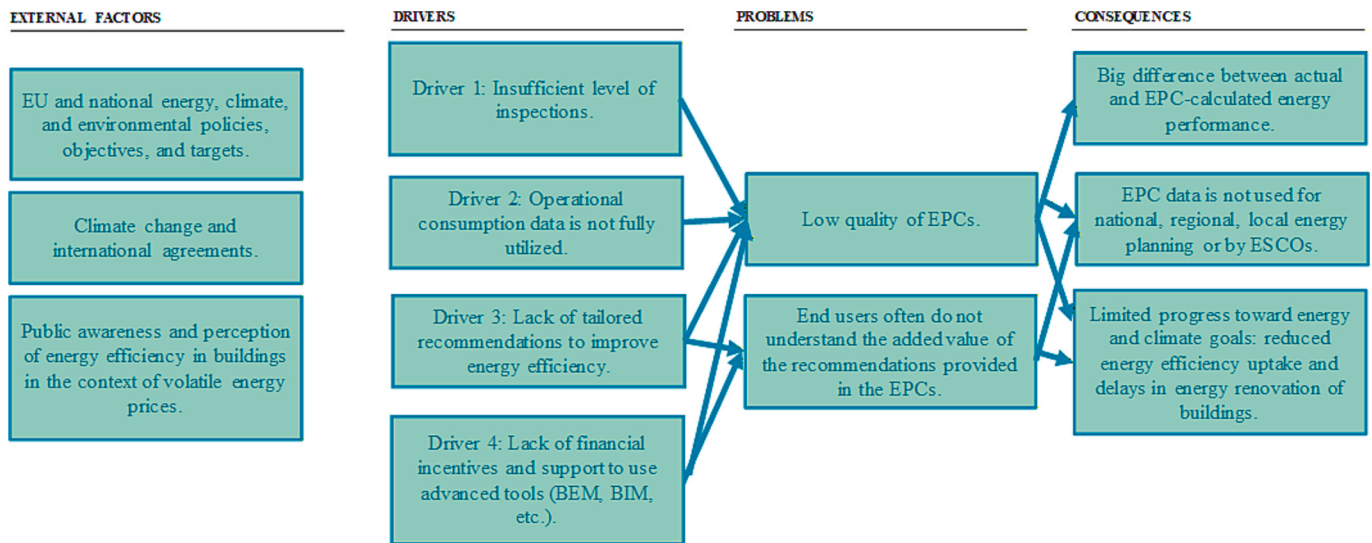


Fig. 3. Overview of the problem tree addressing key challenges in EPC implementation.

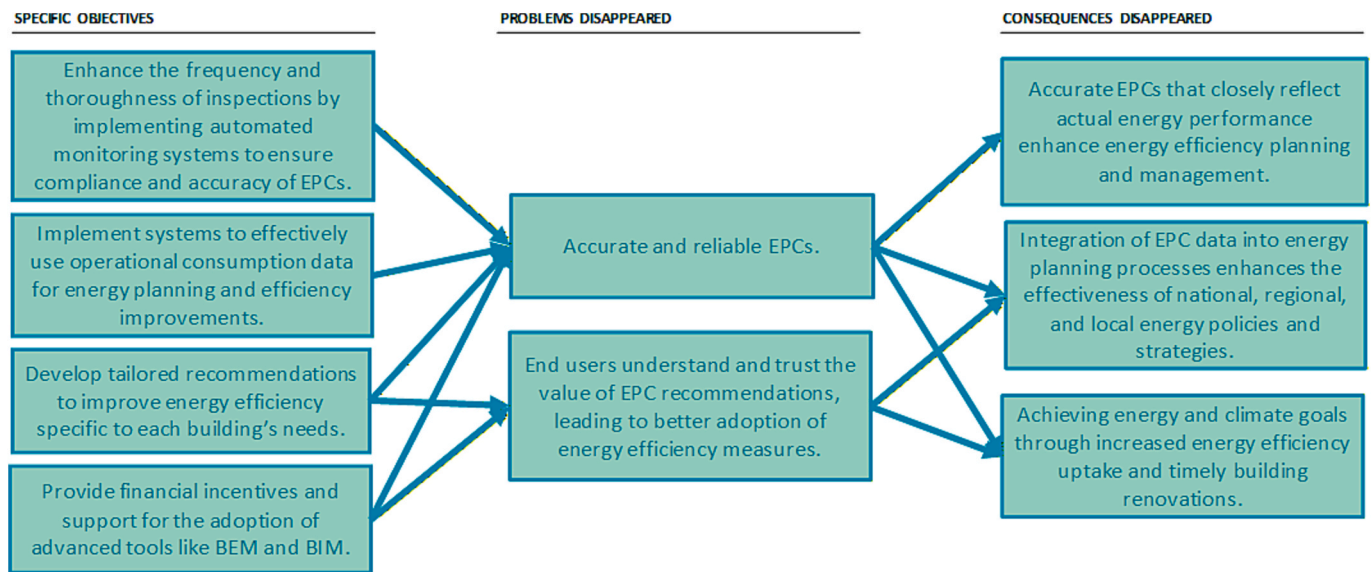


Fig. 4. Overview of the objective tree addressing key challenges in EPC implementation.

- Relevant: Addresses the driver of generic and non-specific recommendations in current EPCs.
- Time-bound: Full implementation within four years, with progress reviews conducted after the third year.

The goal is to move from a recognized deficiency (lack of use of operational consumption data) to an implemented solution (effective energy planning and improved EPC outputs). In this context the following strategic policy measures can be identified:

- Develop and deploy digital systems and frameworks that allow the systematic collection, processing, and use of operational energy consumption data at the building level.
- Mandate the generation of building-specific EPC recommendations, using both static and operational data to enhance accuracy and usefulness.
- Set regulatory benchmarks, e.g., requiring that a defined percentage (e.g., 70%) of new EPCs include data-driven, tailored energy efficiency suggestions within a specific timeframe.

- Support digital infrastructure upgrades and professional training, including:
  - Adoption of advanced data analysis tools,
  - Continuous capacity-building programs for EPC assessors,
  - Standardization of data collection protocols.
- Introduce a phased implementation plan, with:
  - A full rollout goal (within four years),
  - Intermediate progress reviews (after three years),
  - Feedback loops to refine the approach based on observed outcomes.

The presented strategic policy measures inferred from the addressed specific objective aim to transform EPCs from static, generic instruments into dynamic, building-specific tools supported by real-time data and modern analytical capabilities. They address both technical and institutional dimensions: improving data systems, enhancing professional competencies, and setting clear, enforceable policy milestones.

Based on this problems and objectives, three policy options were investigated (Policy Option 1 (PO1), Policy Option 2 (PO2) and Policy Option 3 (PO3)) by use of Impact Assessment Tool developed in frame of

tunES project. This tool allows to compare identified policy options towards the baseline scenario (see Table 5).

The estimation of costs and benefits was based on assumptions derived from the Slovenian National Energy and Climate Plan, national policy documents, stakeholder input, and data processed through the tunES Impact Assessment Tool. In addition, the Ministry of Environment, Climate and Energy provided full institutional support and access to the requested data used for validation of the methodological framework. The reported energy-savings values for PO1, PO2 and PO3 were estimated using the tunES Impact Assessment Tool, which was applied to compare each policy option against a baseline scenario. The estimation was informed by the mixed-method framework developed in this study, including stakeholder surveys and interviews, field work, SRI case studies, available energy-consumption and operational data, and national policy inputs relevant to the Slovenian building stock.

Overall, it is clear that benefits increase with ambition. Also, the majority of costs will be borne by building owners (investment and operational measures). Public sector expenditures are also significant, including subsidies, database development, quality control, regulatory adaptation, and information campaigns. Benefits accrue primarily to building owners through avoided energy costs, with additional societal benefits resulting from avoided external costs associated with GHG emissions.

PO1 has a positive cost-benefit balance up to 2050. The increase compared to the baseline is moderate: total benefits amount to €22.97 million, while total costs reach €10.19 million, resulting in a net benefit of €12.78 million.

PO2 involves higher costs (€19.72 million) than PO1 due to larger investments in EPC and BRP, expanded training and quality control activities, and increased programme management requirements. However, it also delivers higher benefits (€42.18 million), resulting in a net benefit of €22.46 million.

PO3 has the highest costs (€34.49 million) owing to the digital integration of EPC, BRP, and SRI, the establishment and operation of databases, strengthened quality control, and regulatory adaptation. Nevertheless, it also delivers the highest benefits (€64.37 million) and therefore the largest net benefit (€29.88 million).

The relevant impact areas in the EPC and SRI domain include the efficiency of public authorities and businesses (including administrative burden), as well as energy savings and resulting reductions in energy costs. An efficient EPC system lowers administrative costs for building owners and policymakers by streamlining certification procedures and centralising access to data. This reduces time, paperwork, and costs for building owners. For policymakers, it improves data quality, simplifies enforcement, and supports better-targeted policies, thereby reducing

administrative burdens and resource use. The digitalisation of processes enhances services, saves money, and ensures transparency. In addition, digitalisation may facilitate governance of energy efficiency strategies.

For households and property owners, the main cost drivers are the expected increase in EPC prices and the introduction of complementary instruments such as the BRP and the SRI. As these documents become more comprehensive and the associated procedures more demanding, certification costs are expected to rise accordingly. This provides further confirmation that these activities should be integrated, combining the preparation of EPC, SRI, and BRP with energy auditing. For experts involved in assessments (e.g. energy auditors), the trend is clear: the more demanding the requirements, the higher the costs, reflecting the need for higher qualifications and specialised knowledge. Public authorities face a similar pattern, as more advanced databases and monitoring instruments must be developed. Furthermore, accompanying financial incentives (such as subsidies) are necessary to ensure broad uptake of new tools such as the BRP and SRI.

Compared with the baseline, Policy Option 1 achieves these impacts to some extent, with estimated energy savings of approximately 38 GWh. Policy Option 2 contributes more strongly by fostering deeper renovation through tailored, costed recommendations and one-stop-shop support, resulting in energy savings of approximately 70 GWh. The measures considered under Policy Option 3 enable the most extensive contribution and deliver the highest impacts, with energy savings of approximately 107 GWh.

Based on this, an additional qualitative evaluation of the proposed policy options was carried out to highlight their main advantages and disadvantages. PO1 is characterised by quick wins at relatively low incremental cost, the easiest adaptation among the policy options, and limited additional regulatory burden. However, it delivers the lowest energy savings among the analysed options. PO2 can be considered a balanced approach between costs and savings, but it entails higher costs for owners and the state than PO1. Finally, PO3 is characterised by the strongest long-term efficiency gains, the largest energy savings, and the strongest contribution to innovation and green job creation. At the same time, it has the highest incremental costs, is the most challenging to implement, and requires significant institutional capacity for monitoring and enforcement.

#### 4. Conclusions and future work

The presented results confirmed that the proposed mixed-methods approach enables a comprehensive and integrative evaluation of EPC and SRI frameworks. By combining desk research, empirical data collection, stakeholder engagement, and structured problem-solving

**Table 5**  
Summary of estimated costs and benefits per policy option compared to the baseline.

Summary of the Cost-Benefit Analysis			Against baseline (baseline should always be zero) – all monetary values are expressed in million €			
Stakeholder	Type	Item	Baseline	Policy option 1	Policy option 2	Policy option 3
Building Owner	Costs	EPC costs	0.00	5.14	10.25	19.69
Building Owner	Costs	BRP costs	0.00	0.80	2.46	5.14
Building Owner	Costs	SRI costs	0.00	0.58	0.95	3.80
Building Owner	Benefit	Avoided energy costs	0.00	21.47	39.43	60.17
Experts	Costs	Training	0.00	0.04	0.08	0.11
State	Costs	EPC subsidy costs	0.00	0.00	0.95	0.98
State	Costs	BRP subsidy costs	0.00	0.02	0.10	0.22
State	Costs	SRI subsidy costs	0.00	0.00	0.00	0.00
State	Costs	EPC database costs	0.00	2.20	3.01	2.15
State	Costs	Communication costs	0.00	0.08	0.17	0.17
State	Costs	EPC quality control	0.00	0.48	0.49	0.53
State	Costs	Regulatory adaptation	0.00	0.84	1.27	1.69
Society	Benefit	Avoided external costs associated with GHG emissions	0.00	1.50	2.76	4.20
Sum of costs			0.00	10.19	19.72	34.49
Sum of benefits			0.00	22.97	42.18	64.37
Total			0.00	12.78	22.46	29.88

tools, the methodology provides a robust foundation for strengthening the role of EPCs and SRIs within the Slovenian energy transition pathway.

Based on the limited Slovenian experience available to date, EPCs enhanced with operational data and complemented by the SRI can be particularly valuable for professionals involved in the management, operation, auditing, and renovation of buildings. When properly assessed, the SRI has the potential to provide a clear and standardised set of insights regarding a building's readiness for smart technologies and sustainability. This can support stakeholders in making more informed decisions and improving the performance of the buildings they work with, thereby facilitating the transition towards smarter and more energy-efficient building stock.

Energy and facility managers, in particular, can use the enhanced EPC and SRI to identify and prioritise opportunities for energy efficiency improvements through smart and sustainable technologies. If operational data are properly integrated, the enhanced EPC and SRI can also be used to track improvements over time and to demonstrate the benefits of investments in energy efficiency, digitalisation, and smart technologies to building owners and other stakeholders.

However, it should be noted that the enhancement of EPCs through the integration of smart readiness features and operational data is a relatively recent development, introduced in the latest recast of the EPBD. While this represents an important step forward, further testing and methodological refinement will be necessary to ensure robust and reliable implementation. Additional policy development will also be required to fully embed these innovations into national frameworks and to support the effective integration of the SRI into the EPC scheme. Strengthening regulatory alignment, standardising assessment procedures, and ensuring data interoperability will be critical to unlocking the full potential of enhanced EPCs as dynamic and future-proof policy instruments for driving both energy efficiency and digital transformation in buildings.

Based on these findings, three policy options were proposed and analysed from an economic perspective. The combination of measures within each option contributes to the desired actions by addressing key drivers of the identified problems and supporting the achievement of both specific and general objectives. The total estimated implementation costs of the analysed policy options amount to €10.19 million, €19.72 million, and €34.49 million for PO1, PO2, and PO3, respectively. In parallel, the estimated economic benefits associated with the potential implementation of these policy options amount to €22.97 million, €42.18 million, and €64.37 million for PO1, PO2, and PO3, respectively.

Embedding the enhanced EPC and SRI within comprehensive assessments under the EPBD, as well as within national renovation plans and local energy planning processes, can support a practical and evidence-based sequencing of measures. At the same time, the proposed mixed-method approach can be further extended and strengthened. Future work should focus on validating the proposed framework through ex-post assessment of implemented policy measures and on quantifying their real-world effects on renovation rates, energy savings, renewable energy integration, storage deployment, comfort, resilience, and affordability. Additional research is also needed to refine the methodology for integrating operational data and SRI indicators into EPC schemes, improve interoperability between databases and digital building tools, and assess the transferability of the proposed approach to other EU Member States. This would enable the development of more effective measures and support a more successful transition towards smarter and more energy-efficient buildings, while improving comfort, resilience, and affordability.

#### Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve language and readability. After using this tool/service,

the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

#### CRedit authorship contribution statement

**Boris Sučić:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Goran Matesić:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Georg Vogt:** Writing – original draft, Validation, Methodology, Conceptualization. **Tomasz Cholewa:** Writing – original draft, Methodology, Formal analysis, Conceptualization.

#### 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.

#### Acknowledgments

The authors would like to thank the European Commission and the partners of the European Union's Horizon 2020 research and innovation programme project »TIMEPAC - Towards innovative methods for energy performance assessment and certification of buildings« (<https://cordis.europa.eu/project/id/101033819>) for their support. The TIMEPAC project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 101033819 as part of the call "LC-SC3-B4E-4-2020 – Next-generation of Energy Performance Assessment and Certification".

The authors would like to thank the European Commission and the partners of the European Union's LIFE Clean Energy Transition Programme project »tunES – Tuning EPC and SRI instruments to deliver full potential« for their support. The tunES project has received funding from the European Union's LIFE Programme under grant agreement No. 101120926.

#### Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.enbuild.2026.117502>.

#### Data availability

Data will be made available on request.

#### References

- [1] Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast), Official Journal of the European Union L 231, pp. 1-111, 2023, [Online]. Available: <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023L1791> (accessed on 9 January 2026).
- [2] European Commission, The European Green Deal: Striving to be the first climate-neutral continent, [Online]. Available: [https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal\\_en](https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en) (accessed on 12 January 2026).
- [3] Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings (recast), Official Journal of the European Union L 2024/1275, pp. 1-68, 2024, [Online]. Available: <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L.202401275> (accessed on 22 January 2026).
- [4] European Commission, SRI in EU countries, [Online]. Available: [https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/smart-readiness-indicator/sri-eu-countries\\_en](https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/smart-readiness-indicator/sri-eu-countries_en) (accessed on 9 February 2026).
- [5] Government of the Republic of Slovenia, Integrated national energy and climate plan for the Republic of Slovenia, [Online]. Available: [https://commission.europa.eu/document/download/19e1a8df-ca9a-4a37-9e3e-8d360b75d06c\\_en?file\\_name=SI%20%E2%80%93%20\\_FINAL%20UPDATED%20NECP%202021-2030%20%28\\_English%29.pdf](https://commission.europa.eu/document/download/19e1a8df-ca9a-4a37-9e3e-8d360b75d06c_en?file_name=SI%20%E2%80%93%20_FINAL%20UPDATED%20NECP%202021-2030%20%28_English%29.pdf) (accessed on 4 February 2026).

- [6] S. Zuhair, S. Schmatzberger, J. Volt, Z. Toth, L. Kranzl, I.E. Noronha Maia, J. Verheyen, G. Borrágán, C. Sousa Monteiro, N. Mateus, R. Fragoso, J. Kwiatkowski, Next-generation energy performance certificates: end-user needs and expectations, *Energy Policy* 161 (2022), <https://doi.org/10.1016/j.enpol.2021.112723>.
- [7] M. Piro, F. Bianco Mauthe Degerfeld, I. Ballarini, V. Corrado, The challenges for a holistic, flexible and through-life updated energy performance certificate, *Sustain. Energy Technol. Assess.* 69 (2024), <https://doi.org/10.1016/j.seta.2024.103922>.
- [8] M.M. Sesana, G. Salvalai, N. Della Valle, G. Melica, Paolo Bertoldi, Towards harmonising energy performance certificate indicators in Europe, *J. Build. Eng.* 95 (2024), <https://doi.org/10.1016/j.jobee.2024.110323>.
- [9] J. Few, D. Manouseli, E. McKenna, M. Pullinger, E. Zapata-Webb, S. Elam, D. Shipworth, T. Oreszczyn, The over-prediction of energy use by EPCs in Great Britain: a comparison of EPC-modelled and metered primary energy use intensity, *Energy Build.* 288 (2023), <https://doi.org/10.1016/j.enbuild.2023.113024>.
- [10] M. Kaczmarczyk, Energy environmental matrix for buildings energy performance certificate evaluation, *Energy Build.* 341 (2025), <https://doi.org/10.1016/j.enbuild.2025.115859>.
- [11] M. De-Borja-Torrejon, G. Mor, J. Cipriano, A.-L. Leon-Rodriguez, T. Auer, J. Crawley, Closing the energy flexibility gap: enriching flexibility performance rating of buildings with monitored data, *Energy Build.* 311 (2024), <https://doi.org/10.1016/j.enbuild.2024.114141>.
- [12] F. Garzia, G. Pernigotto, D. Menegon, L. Finozzi, U. Klammsteiner, A. Gasparella, Assessment of the potential correlation between Smart Readiness Indicator and energy performance in a dataset of buildings in South Tyrol, *Energy Build.* 321 (2024), <https://doi.org/10.1016/j.enbuild.2024.114623>.
- [13] L. Person, T. Emich, L. Spatafora, V. Hagenmeyer, K. Lennerts, Validation of the smart readiness indicator on real test buildings - energy efficiency of heat generators, *Energy Build.* 346 (2025), <https://doi.org/10.1016/j.enbuild.2025.116128>.
- [14] EN ISO 52120-1:2022. Energy performance of buildings – Contribution of building automation, controls and building management – Part 1: General framework and procedures.
- [15] B. Ramezani, M. Gameiro da Silva, N. Simões, Application of smart readiness indicator for Mediterranean buildings in retrofitting actions, *Energy Build.* 249 (2021), <https://doi.org/10.1016/j.enbuild.2021.111173>.
- [16] A. Xenakis, A. Arsenopoulos, I. Papias, F. Serepas, S. Rizou, J. Psarras, Advancing smart building upgrades through an innovative decision support framework for smart readiness indicator implementation: a Greek case study, *Build. Environ.* 281 (2025), <https://doi.org/10.1016/j.buildenv.2025.113189>.
- [17] J.L. Hernández, I. de Miguel, F. Vélez, A. Vasallo, Challenges and opportunities in European smart buildings energy management: a critical review, *Renew. Sustain. Energy Rev.* 199 (2024), <https://doi.org/10.1016/j.rser.2024.114472>.
- [18] V. Kourgiouzou, D.G. Shimizu, M. Dowson, A. Commin, R. Tang, D. Rovas, D. Mumovic, A new method for estimating the smart readiness of building stock data using display energy Certificate data, *Energy Build.* 301 (2023), <https://doi.org/10.1016/j.enbuild.2023.113673>.
- [19] S.A. Hwang, S. Çetin, H. Visscher, A. Straub, Advancing energy renovations through digitalisation: a critical review of EU policies and instruments, *Energy Build.* 336 (2025), <https://doi.org/10.1016/j.enbuild.2025.115627>.
- [20] European Commission, A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives, [Online]. Available: <https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020DC0662> (accessed on 3 February 2026).
- [21] S. Verbeke, D. Aerts, G. Reynders, Y. Ma, P. Waide, Final report on the technical support to the development of a Smart Readiness Indicator for buildings - Summary, Directorate-General for Energy, Directorate C - Renewables, Research and Innovation, Energy Efficiency, Unit C4 - Energy Efficiency: Buildings and Products. European Commission, 2020, [Online]. Available: <https://op.europa.eu/en/publication-detail/-/publication/bed75757-fbb4-11ea-b44f-01aa75ed71a1/language-en> (accessed on 6 February 2026).
- [22] European Commission, Better regulation: guidelines and toolbox, [Online]. Available: [https://commission.europa.eu/law/law-making-process/better-regulation/better-regulation-guidelines-and-toolbox\\_en](https://commission.europa.eu/law/law-making-process/better-regulation/better-regulation-guidelines-and-toolbox_en) (accessed on 12 February 2026).
- [23] LIFE Clean Energy Transition Programme, tunES project, Tuning EPC and SRI instruments to deliver full potential, [Online]. Available: <https://empirica.com/tunes/> (accessed on 20 March 2026).
- [24] B. Sučić, L. Madrazo, Á. Sicilia, I. Ballarini, V. Corrado, M. Bišćan, S. M. Vryonidi, Deliverable 4.9: Guidelines for EPC enhancement at EU level through TIMEPAC Academy, [Online]. Available: <https://timepac.eu/reports/guidelines-for-epc-enhancement-at-eu-level-through-timepac-academy/> (accessed on 11 February 2026).
- [25] K.M. Eisenhardt, M.E. Graebner, Theory building from cases: opportunities and challenges, *Acad. Manag. J.* 50 (1) (2007), <https://doi.org/10.5465/AMJ.2007.24160888>.
- [26] Ministry of Environment, Climate and Energy, Proposal of new Energy Efficiency Act, [Online]. Available: [https://www.energetika-portal.si/fileadmin/dokumenti/zakonodajna/energetika/zure/zure-1\\_jo\\_okt2024.pdf](https://www.energetika-portal.si/fileadmin/dokumenti/zakonodajna/energetika/zure/zure-1_jo_okt2024.pdf) (accessed on 12 February 2026).
- [27] S. Attia, J. Kurnitski, P. Kosiński, A. Borodinecs, Z. Deme Belafi, I. Kistelegdi, H. Krstić, M. Moldovan, I. Visa, N. Mihailov, B. Evstatiev, K. Banionis, M. Čekon, S. Vilčeková, K. Struhala, R. Brzoň, O. Laurent, Overview and future challenges of nearly zero-energy building (nZEB) design in Eastern Europe, *Energy Build.* 267 (2022), <https://doi.org/10.1016/j.enbuild.2022.112165>.