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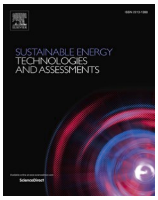

The challenges for a holistic, flexible and through-life updated energy performance certificate

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ABSTRACT

One of the strategies proposed by the recently approved version of the Energy Performance of Buildings Directive recast is to provide the Member States with more reliable, accurate, and digitalised Energy Performance Certificates (EPCs), the so-called next-generation or enhanced EPCs. Currently, end-users perceive the EPC as just an administrative obligation for buying or renting a building. The data in the certificates provide limited energy-related information and lack accuracy. Moreover, they cannot account for the continuous changes that occur throughout building lifetime.

The overcoming of the EPC limitations is the main objective of the research activity conducted within the framework of Next Generation EPC Horizon2020 cluster. At this regard, the EU-Horizon2020 TIMEPAC project is going to contribute to the enhancement of the entire process of generating, storing, analysing, and exploiting EPCs. The premise is that the building is no longer conceived as a static entity, but as an occupant-centric object, subject to continuous changes. Therefore, the enhanced EPC approach should be holistic, flexible, through-life updatable, and interoperable.

In this work, the main methodologies and tools proposed in the TIMEPAC project for the enhancement of the existing EPC schema in terms of EPC generation, exploitation, and data quality are presented and discussed.

Introduction

Background analysis and literature review

The European Directive 2002/91/EC [1], and its amendments and recasts, introduced the Energy Performance Certificate (EPC) as a mandatory document for constructed, sold, or leased buildings or building units. The primary objective of this document is to create a homogeneous framework for building energy-saving initiatives around EU Member States, aiming to achieve energy targets for the building stock. The certification process aims at providing a transparent tool in the building market to compare and assess the energy efficiency of the buildings. The EPC includes reference values such as current legal standards and benchmarks, enabling owners and tenants to evaluate the energy performance of a building or building unit.

The EPC represents a core source of information that reflects the energy performance *status* of the building stock [2–4], the fuel poverty [5], and the monitoring of national or regional energy renovation programs [6,7]. From this perspective, Conticelli et al. [8] developed a method to scale-up EPCs to track the energy efficiency of a municipality in the northern Italy. In the work of Heidenthaler et al. [9], the building stock energy performance of the Salzburg region in Austria was characterised using probabilistic archetypes built from EPCs. Indeed, Terés-Zubiaga et al. [10], utilising energy certificates, proposed a method to map the energy vulnerability at a regional scale with a three-dimensional index, highlighting the potential of public data to prioritise the deep renovation of energy-inefficient districts.

The accuracy and reliability of the EPC are strongly dependent on the quality of the input data, the methodology and applied tools, and the energy assessor's expertise [11]. Hardy et al. [12] highlighted that 27 % of the analysed certificates have at least an incorrect value. A worse outlook is reported in Iribar et al. [13] and Marinosci et al. [14] where the inconsistent EPCs are respectively 78 % and 61 %. Incorrect energy certificates influence the building economic assessment since they generate wrong energy performance labels: the more energy-efficient a building is, the more it is associated with a 'premium price' [15,16]. Moreover, the quality of energy certificates reflects Member State market laws where, in most cases, the EPC cost is not directly related to the EPC value. In this context, regulated EPC prices should be preferred

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Nomenclature

Quantities

A	area (m^2)
CR	compactness ratio (m^{-1})
$cv(RMSE)$	coefficient of variation of the root-mean-square error (–)
DPP	discounted payback period (a)
EP	energy performance indicator ($kWh \cdot m^{-2}$)
HDD	heating degree day (°C·d)
MBE	mean bias error (–)
NPV	net present value (€)
PDH	percentage of discomfort hours (–)
q	volumetric air flow rate ($l \cdot s^{-1}$)
RER	renewable energy ratio (–)
U	thermal transmittance ($W \cdot m^{-2} \cdot K^{-1}$)
V	volume (m^3)

Greek symbols

η	efficiency (–)

Subscripts/Superscripts

C	cooling
d	design
env	envelope
g	gross
gen	generation
gl	overall
H	heating
m	measured
nd	need
ngen	without generation
nren	non-renewable
op	opaque
ren	renewable
s	seasonal
use	useful
W	domestic hot water
w	window

Acronyms

BA	Building Archetype
BACS	Building Automation and Control System
BEM	Building Energy Model
BIM	Building Information Model (Modelling)
BRP	Building Renovation Passport
CAL	Calibration Against Monitored Data
CP	Construction Period
ECM	Economic Evaluation of Energy Efficiency Measures
EEM	Energy Efficiency Measure
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
IQR	Interquartile Ranges
KPI	Key Performance Indicator
NZEB	Nearly-Zero Energy Building
SRI	Smart Readiness Indicator
TBS	Technical Building System
TDS	Transversal Deployment Scenario
TEPA	Tailored Energy Performance Assessment
TIMEPAC	Towards Innovative Methods for Energy Performance Assessment and Certification of Buildings
TMY	Typical Meteorological Year
UBEM	Urban Building Energy Model
ZeB	Zero-emission Building
XML	Extensible Markup Language

over standardised tariffs, e.g., unaffected by building complexity or effort for the data collection or the energy model creation. From this perspective, Arcipowska et al. [17] compared the EPC price ranges for single-family houses across EU countries highlighting the wide range of prices and the failure of the market to stabilise the price.

The competence of the technician is the most influential aspect of the EPC quality, since it has an impact on the validation of the data, the application of the calculation method, and the use of the software. In 22 EU Member States, a minimum education requirement for the energy assessors is requested [11]. According to the round-robin test performed by Tronchin et al. [18], 70 % of the beginner's technicians correctly estimated the energy rating of the assessed building. The proposed study suggested how relevant the experience of the energy certifier is to carry out an EPC. Moreover, regarding the EPC generation stage, building energy performance simulation tools must be recognised and validated by the control body of the Country of reference.

To fill in the uncertainty gap in the EPC input data picture, the introduction of checks and rules [12,19] integrated into the EPC generation (i.e., energy simulation tool) or the uploading phase (i.e., in local, regional, or national EPC databases) plays a crucial role. Furthermore, to improve data quality, the information property should belong to a database that interact with other informative systems. This would reduce the stratification and dispersion of information in various databases. The building energy performance can be 'measured' or 'calculated' [20,21]; the latter is divided into standard and reduced-input calculations [22]. From this perspective, Cichowicz et al. [23] evaluated that the energy indicators were slightly lower applying the consumption method than using calculation method for 15 multi-family houses located in Poland.

Furthermore, the applied energy performance assessment has to allow the comparability between old and new EPCs in order to track the building stock energy efficiency over time [24,25].

The Energy Performance of Buildings Directive (EPBD)-recast [26] includes new elements to achieve a decarbonised building stock by 2050 [27] and the ambitious transition from the Nearly-Zero Energy Building (NZEB) to the Zero-emission Building (ZeB), i.e., from the energy to the environmental neutrality. The new EPC may integrate financial incentives and financing mechanisms, include strategies to increase the climate resilience of the building, and capture the building operational greenhouse gas emissions. Moreover, the EPC will be the core of the national building performance database, made interoperable, i.e., improving the data transfer, with other administrative and non-administrative informative systems [26].

In the framework of Next Generation EPC Horizon2020 cluster [28], the EU funded numerous projects to stimulate and roll-out the future of the certification scheme. This group of projects focuses on enhancing the current energy certificate to make it more reliable, user-friendly, cost-effective, of comparable good quality, and compliant with EU legislation.

EU projects like X-tendo [29], D^2EPC [30], EUB Super Hub [31], U-CERT [32], and ePANACEA [33] aim to enrich the current EPC with an inventory of new KPIs to improve the usability of next-generation EPCs. In particular, the experience gained in the EUB Super Hub led to the activation of a CEN Workshop Agreement [34] to harmonise a core set of 21 transnational indicators for comparing the performances of buildings across regions. The E-DYCE [35] and ePANACEA [33] projects tested the integration of standard energy performance assessments with the actual use of the buildings. Finally, to improve EPC data quality, X-tendo [29] developed an automated algorithm to assign a score for validating energy certificates.

The sister projects have synergy aspects with TIMEPAC (Towards Innovative Methods for Energy Performance Assessment and Certification of Buildings, 2021–2024) [36]. TIMEPAC envisages a new EPC that will result from a holistic, flexible, and through-life certification process, facilitating a continuous flow of data [37] throughout all phases of energy performance certification – generation, storage, analysis, and exploitation – enabling a more efficient and reliable EPC. The Transversal Deployment Scenarios (TDSs) are the core of the TIMEPAC project, focusing on the development of standardised procedures and tools in the six partner countries (Austria, Croatia, Cyprus, Italy, Spain, and Slovenia). TDSs are interrelated and address specific stages of the EPC process (generation, storage, analysis, and exploitation). They include different objectives, methods and involve different target groups, such as energy certifiers, energy agencies, energy auditors, architects, engineers, real estate agencies, construction companies, and public authorities. The following five TDSs are conceived: i) Generating enhanced EPCs with Building Information Modelling (BIM) data, ii) Enhancing EPC schemas through operational data integration, iii) Creating Building Renovation Passport (BRP) from data repositories, iv) Integration of SRIs and sustainability indicators in EPC, and v) Carrying out large-scale statistical analyses of EPC databases.

Research gap

Currently, the EPC is an energy-related document considered from the end-user's vision as an administrative obstacle for constructed, sold, or leased buildings or building units. The next-generation EPC, as envisioned by the new EPBD-recast [26], should go beyond the energy field; buildings should be holistically assessed from different perspectives, including economics, environment, and social aspects. The future EPC dataset has to be enriched with new Key Performance Indicators (KPIs), accompanying the standard theoretical energy performance of the assessed object with the actual use of the building. This aspect has been also emphasised in literature by Anđelković et al. [38], who compared the standard and actual energy performance of 16 buildings, highlighting the 'energy performance gap' issue.

Thus, new research lines are expected to address this topic, by improving the credibility and the application fields of future energy certificates, by showcasing potential enhancements, modernisation, and optimal integration with national or regional informative systems. Moreover, another evident issue of the existing energy certification of buildings regards the low quality of the EPC data. In most cases, a validation approach to verify the energy certificate data quality should be integrated into the building energy performance simulation tools or in the EPC databases. The current drawback in the EPC data quality negatively affects the use of the energy certificates for single-building and large-scale analyses. Especially at the city-scale, energy certificates are a pivotal source of information to rank the overall energy performance of the building stock.

While the disadvantages of energy certificates are often discussed in the literature, concrete ways to enhance the current energy certificate are less debated. To bridge this research gap, this work applies and discusses the introduction of a list of standardised procedure to increase the credibility, reliability, and usability of next-generation EPCs, as described in detail in the following section.

Aim of the research

The building, which is intended as a complex object made of building fabric, technical building systems (TBSs), and occupants, is a dynamic entity subjected to continuous changes throughout its lifetime.

The next-generation energy performance certification of buildings envisages an integrated and holistic approach centred both on different scales (e.g., from the single-building to the building stock) and on several domains (e.g., energy performance, indoor environmental quality – IEQ, environmental sustainability, cost-effectiveness, resilience, etc.)

The enhanced EPC has not to be intended as a paper-based document, but as a digital source of information. The next-generation energy performance certification will satisfy the following requirements: (i) data quality improvement, (ii) data enrichment and integration (Smart Readiness Indicator – SRI [39,40], sustainable indicators, real energy consumption data, etc.), (iii) dynamic (i.e., through-life updatable) and flexible (i.e., tailored for different purposes and target groups) EPC. The dynamicity and flexibility of the enhanced EPC should not invalidate the legal value of the document, which should capture both the standard energy performance *status* of the building or building unit, and the continuous changes throughout its lifetime. It is not probable that all the mentioned data and indicators could be included in a mandatory scheme, but more likely some of them could be drafted voluntarily. Currently, the EPC is a document mainly addressed to the end-users with limited and, in most cases, unreliable technical data. Thus, the enhanced EPC should have multiple functions becoming a central document for different target groups (e.g., end-users, energy certifiers, local, regional and national authorities, etc.). Moreover, the enhanced EPC should be part of an interconnected environment where the interoperability between different databases, such as the cadastre or the Building Information Model (BIM), facilitates users in accessing building data regardless of its application. This avoids time wastage and potential errors resulting from multiple data-gathering efforts. In this context, as presented in Fig. 1 the next-generation energy certificate, as well as other building documents like the building renovation passport (BRP) [41], could be tailored for intended audiences and final purposes, enhancing the utility of the documents, without a significant increase in calculation time.

Within the overall framework of objectives, the aim of this research embraces and concretises two pillars of the enhanced EPC perspective. The first pillar is data enrichment, achieved through standardised procedures, by describing the dynamic behaviour of the building and improving the EPC reliability with new KPIs from various domains. The second pillar is data quality improvement, accomplished by illustrating a tailored-rule score procedure and its benefit in assessing the building stock energy performance. The research here presented was developed in the context of the TIMEPAC project [36] which is aimed at creating a ground base for the next-generation EPC.

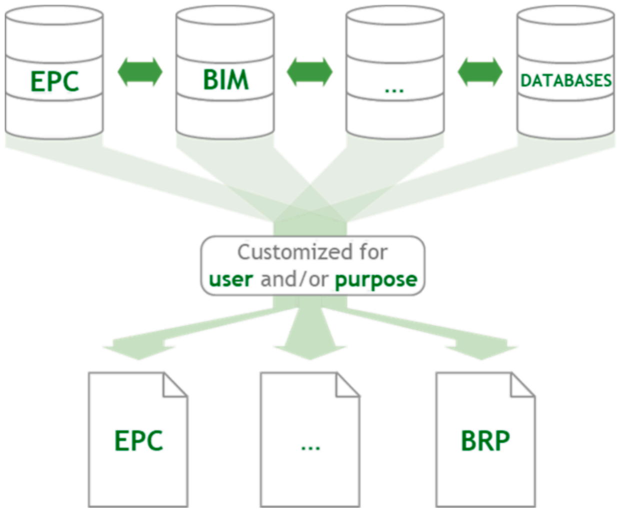

Fig. 1. Enhanced EPC architecture.

Methods

In this section, standardised methods for improving the reliability of EPCs in describing both the current performance and potential enhancements of the buildings are presented. The procedures here analysed, which are part of a wider cluster of procedures defined in the framework of the TIMEPAC project, encompass not only parameters related to energy consumption but also describe the applicability of the approaches to a group of buildings and the user-relevant factors. Additionally, procedures for EPC data integration, EPC data quality enhancement, and EPC data exploitation to improve the credibility and the fields of application of the next-generation energy certificates are analysed in the context of TIMEPAC.

Enhanced EPC generation

A major option in the EPC enhancement is related to the use of operational data. Through these data, several analyses able to enhance the spectrum of evaluations can be performed. Other procedures from the energy, economic, social, and environmental domains can also be applied to enhance and improve the EPC quality. In the following sections, two operative data approaches are analysed, namely the tailored energy performance assessment and the calibration procedure), and three different enhancement procedures are presented, i.e., the economic evaluation of the energy efficiency measures, the indoor environmental quality evaluation, and the assessment of the building and control automation system's impact on the energy performance of the building. A complete description of the procedures can be found in [42].

Tailored energy performance assessment (TEPA)

The tailored energy performance assessment is a procedure to determine the energy performance of a building using both standard and real information. While the actual and standard energy performance assessment deploys respectively actual and standard data for both user information and climate, the tailored one deploys, instead, actual user information and standard data [43].

Calibration against monitored data (CAL)

The building energy model calibration is the process of fine-tuning the simulation inputs so that the observed energy consumptions (or environmental variables) closely match those predicted by a simulation tool. In this work, a manual calibration procedure has been applied, which consists of iterative modification of model parameters affected by uncertainties; these can be modified one at a time or by combining them.

In preparation for the application of the manual calibration procedure, the available monitored data have to be analysed and, according to the type and temporal discretisation of the available monitored data, the calibration scenario is defined.

After the above-mentioned preliminary steps, the calibration scenario for the energy consumption consists of the following phases:

i. actual energy performance assessment with the same climatic data and time step as the monitored data,
ii. comparison between monitored and simulated outputs employing both statistical and graphical methods,
iii. verification of compliance with two statistical indexes: mean bias error (*MBE*), and coefficient of variation of the root-mean-square error [*cv(RMSE)*], where the limit values are defined in [44], and
iv. until the statistical indexes are verified, modification of the base energy model and repetition of steps from (i) to (iv).

Economic evaluation of energy efficiency measures (ECM)

The economic evaluation of the energy efficiency measures is carried out by analysing the building in the original state (later referred to as 'baseline') and the various scenarios of energy efficiency measures (EEMs) (later referred to as 'scenarios') following these steps: (i) determination of the general parameters, (ii) determination of the specific case parameters, and (iii) calculation of economic cost analysis indicators.

The analysis is performed with a calculation period of thirty years and the economic indicators are calculated from a financial perspective according to EN 15459–1 [45]. For all the cases, the annual costs for all the energy carriers deployed in the analysed building must be defined. For each EEM or associated technology, and each energy carrier, the annual actualised costs are calculated in the reference period. For each scenario, the annual cash flow derived from the comparison with the baseline, the sum of cash flows, the actualised Net Present Value (*NPV*), and the Discounted Payback Period (*DPP*) are determined according to ISO/TS 50044 [46].

Indoor environmental quality evaluation (IEQ)

The IEQ assessment is carried out in accordance with EN 16798–1 [47] and CEN/TR 16798–2 [48], considering thermal comfort and indoor air quality (IAQ). A preliminary activity is to select representative spaces and to identify the IEQ comfort category. The thermal comfort evaluation is based on the adaptive comfort theory. A comfort quality index that identifies the expected level of thermal comfort is defined employing the percentage of discomfort hours (*PDH*) [48], as follows: (i) if $PDH \leq 3\ \%$, then a high thermal comfort level is expected, (ii) if $3\ \% < PDH \leq 6\ \%$, then an acceptable thermal comfort level is foreseen, and (iii) if $PDH > 6\ \%$, then a non-acceptable thermal comfort level is expected.

The IAQ evaluation is carried out as a simple comparison between the external air flow rate, which can be either a measured or a design value, with the minimum value to guarantee the IAQ, following the specification of method A of EN 16798–1 [47]. The proposed KPI is a qualitative index that identifies whether the minimum air flow rate requirement for IAQ (q_{IAQ}) is met. This is defined as follows: if $q_{\mathrm{m/d}} < q_{\mathrm{IAQ}}$, where $q_{\mathrm{m/d}}$ is the design value for the external air flow rate, then the minimum air flow rate for IAQ is not met, otherwise the minimum air flow rate for IAQ is met.

Building automation and control system impact assessment (BACS)

To determine BACS impact, the proposed procedure focuses on the effect of a specific function on the building energy performance. At first, for each of the functions presented in EN ISO 52120–1 [49], it should be determined if it is installed, if it is not installed but could be, or if it cannot be installed in that specific building. Then, for the available functions, the specific level describing the BACS should be determined for each building service and the whole building. Finally, the chosen functions are analysed one-at-time, improving their BACS level by one step, and assessing the effect on the primary energy need. A percentage of reduction of the primary energy need is calculated, as the difference between the primary energy need of the building in the original state and the primary energy need with function improvement implemented, divided by the primary energy need of the building in the original state.

Enhanced EPC analysis and exploitation

Reliable and accurate energy certificates are crucial to create both the Building Energy Model (BEM) and the Urban Building Energy Model (UBEM) [2–4]. The EPC data quality checking procedure, described in detail in [50], encompasses the uncertainty evaluation of the energy certificate parameters setting quantitative confidence intervals. Then, the work continues with the probabilistic building archetypes (BAs) creation through EPC data whose reliability has been verified by applying the EPC data quality checking procedure. In Fig. 2 the steps of the employed methodology to verify the quality of the EPC data in order to create the BA is depicted.

The preliminary steps of the energy certificate quality assurance approach are (i) the EPC data selection, i.e., homogenisation of input and output metrics set between different countries, enabling cross-

Fig. 2. BA creation workflow.

country comparison, and (ii) the EPC data clustering, i.e., the grouping of buildings with similar properties and characteristics. The clustering is performed according to the following criteria: climatic zone, building use category (i.e., residential, and non-residential buildings), construction period, and building size and shape for residential buildings (i.e., single-family houses and building units in multi-housing buildings). The methodology for clustering buildings can be derived from the outcomes of the TABULA project [51], aimed at harmonising the European building typology approach.

The EPC data quality checking procedure is based on scoring the EPC against a maximum error threshold beyond which the certificate is considered *unreliable*. This methodology draws inspiration from the TIMEPAC sister project X-tendo [52], especially for the EPC rule definition and data score attribution.

Firstly, the relevant EPC data have been divided into 'critical', i.e., variables whose validity is deemed influent for the EPC exploitation phase, and 'non-critical' parameters. Moreover, an acceptability threshold value to declare the entire validity of the energy certificate has been defined.

For each of the selected EPC data, a validity rule has been associated. Three different groups of rules have been established: (i) data type checks (i.e., to define the mathematical, relational, or logical data types), (ii) physical impossibility checks (i.e., to compare the order of magnitude of EPC data comparing them with the physical admissibility set for those parameters), and (iii) (in-)consistency checks (i.e., to determine the validity of the parameter connected to the results of another).

For each rule, scores begin at zero and increase as the validity rules are not met. The score depends on the number of critical and non-critical parameters. However, the magnitude of the non-respected rule score is different between critical and non-critical parameters. The acceptability threshold value corresponds to the sum of the score of half of the EPC data considered in the analysis. The non-compliance rules for critical parameters give a score greater than the threshold value and thus every EPC data will be neglected. Moreover, the single-non-critical parameter with a non-null score (i.e., non-respected rule) will be discarded. Otherwise, whether the overall EPC data score, originating from summing the single score of each parameter, is greater than the threshold value then all the EPC data will be neglected, and they will not appear in the EPC data exploitation phase.

Multiple functions, application fields, and target groups can be involved in EPC data exploitation. In large-scale analysis huge amounts of data are needed [53] and EPCs represent an indispensable and central source of information to close the uncertainty data gap. The collected data flows in the BA generation first, and in the development of the national building renovation plan [26] afterward.

The BAs [54], prototypes [55], or building typologies [56] are 'virtual' buildings that reflect the most common geometrical characteristics, technical specifications of the building envelope, and TBS typology, representing the average situation in a market segment. The data categories selected for the BA schema definition are (i) the geometric data, such as the compactness ratio, the thermally conditioned floor area, the heated/cooled volume, and the transparent thermal envelope area on thermal envelope area, (ii) the thermal properties of the opaque and transparent building envelope, such as the mean thermal transmittance of the opaque building envelope and the mean thermal transmittance of the transparent building envelope), (iii) the typology and energy performance of the TBSs, and (iv) the energy performance indicators, such as the energy need for space heating/cooling, the non-renewable energy performance, etc.). In this context, statistical analysis has been applied to extract the most probable data to generate 'virtual' representative buildings for the specific climate zone.

Application

In this section, the application of the above-mentioned methods to improve EPC reliability in describing the current performance and the possible enhancements of buildings are described. In the context of the TIMEPAC project, procedures to enhance EPC data integration, EPC data quality, and EPC data exploitation are presented and discussed as well.

Enhanced EPC generation

The aim of the application of the methodologies was not to get numerical output values, rather to test the applicability of these procedure in different scenarios. For this reason, the result of the application of the aforementioned procedures was a qualitative analysis derived from the experience on several case studies using different building energy performance assessment tools. The proposed methodology has been applied to a cluster of 45 case studies different for country, period of construction, and building use. For each of the analysed buildings, one or more procedures presented in the methods section were applied. In Fig. 3, the country, the main building use and the applied procedure are summarised for the analysed case studies.

The main calculation options and input data are presented below.

Energy performance assessment (SEPA/TEPA)

The energy performance assessment was developed using both monthly and hourly procedures with varying level of details. In particular, quasi-steady-state monthly methods and simplified dynamic hourly procedures based on European and national standards (e.g., based on EN ISO 52000 series [43]) were deployed in the majority of cases (55 %), while detailed procedures deploying the EnergyPlus calculation engine were used in 29 % of the cases.

Calibration against monitored data (CAL)

This procedure was applied in most of the cases using monthly bills as the source of monitored data (82 % of the cases). Hourly energy consumption and indoor operative temperatures were also considered for the calibration, respectively in 45 % and 33 % of the cases. In some cases, more than one calibration scenario was applied.

Economic evaluation of energy efficiency measures (ECM)

Both the energy cost and the discount rate were assessed considering national mean cost values and historical trends. The energy efficiency measures cost was derived considering local price lists and market analyses.

Indoor environmental quality evaluation (IEQ)

For the thermal comfort evaluation, the hourly indoor operative temperatures were derived from the energy performance assessment based on typical meteorological years (TMY). In the indoor air quality assessment, the air flow rates were derived from the measured values, the standard values, or the results of the calibration, depending on the case.

Building automation and control system impact assessment (BACS)

The impact of the measures was defined using the detailed procedure described in EN ISO 52120–1 [49].

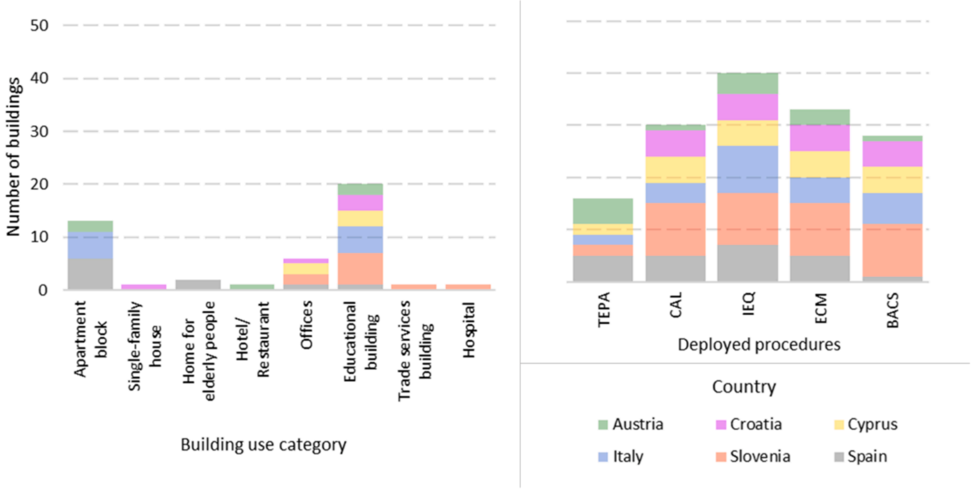

Fig. 3. Building use category (left) and deployed procedures (right) for the analysed case studies by country.

Enhanced EPC analysis and exploitation

A shared and common framework of input datasets and statistical KPIs among different TIMEPAC countries (Austria, Croatia, Cyprus, Italy, Slovenia, and Spain) to create BAs was utilised. Then, different analysis tools for the EPC data quality checking approach and BA generation were adopted by the partners, following the same procedures.

In this research, the methods were applied and validated to the entire EPC database of the Piedmont Region (Italy). Some EPC data were selected from the overall energy certificate schema, choosing parameters common for the six involved TIMEPAC countries. The energy certificates uploaded in the Piedmont Region EPC database [57] were collected and clustered according to the above-described criteria. The EPC issued for buildings located in climatic zone E (heating degree day, $HDD - 2101 \leq HDD \leq 3000$), in which most of the cities of the Piedmont Region are situated, were exploited to generate BAs. The EPCs stored in the EPC database for the considered climatic zone are just over half a million documents. Thus, climatic zone E was chosen as the most representative to summarise and describe the building technologies of the Nort-West Italian Region. The TABULA [51] eight construction periods (CPs) to cluster the EPCs are utilised and following reported: $\leq$ 1900 (CP1), 1901 – 1920 (CP2), 1921 – 1945 (CP3), 1946 – 1960 (CP4), 1961 – 1975 (CP5), 1976 – 1990 (CP6), 1991 – 2005 (CP7), $>$ 2005 (CP8). Then, for the selected 48 EPC relevant data the EPC data quality checking procedure and the statistical analysis were applied. The essential parameters are reported in the probabilistic BA schema highlighting for each of them the median and the interquartile ranges (IQRs). Finally, residential (i.e., single-family houses and building units in multi-unit housing) and non-residential (office and educational building) BAs were generated for a total of 32 BAs, representative of the Piedmont Region [50]. Instead, around the other five TIMEPAC country partners the totality of 122 BAs applying the same methods were created [50].

Results and discussions

Enhanced EPC generation

The analysis of the application of the proposed enhanced EPC procedures underlined strengths and weaknesses of the methods. TEPA relies on knowing actual occupancy and building use. Since these data are often difficult to gather and may suffer from inaccuracies, the application is not always feasible. The key information for TEPA is typically the occupancy, ventilation, lightings, and appliances profiles. Those are typically defined through building inspections or user surveys but can be retrieved from other sources. For instance, data can be collected from representative spaces within the building and then extrapolated to the entire building. Alternatively, information from buildings with similar use, size, and location can help fill gaps. These procedures, while able to produce the required data, could produce unexpected errors and therefore should be used with care. However, TEPA often presents non-negligible differences compared to standard energy performance assessment, making its inclusion in EPCs beneficial for end-users. The calibration procedure provides the possibility to significantly increase the reliability of the energy assessment results. However, the complexity of obtaining accurate and detailed real data may hinder its application. Moreover, the required information cannot be substituted, and their absence makes the procedure inapplicable. Additionally, the calibration process often demands numerous refinements of the building energy model, consuming significant simulation and implementation time, especially in the case of complex models.

The economic evaluation of energy efficiency measures stands out for its simplicity and potential effectiveness. The use of discounted indicators increases the output's effectiveness compared to the procedures currently deployed in several countries. Indoor environmental quality evaluation, instead, encounters limitations in both thermal comfort and air quality procedures. The first one is only applicable to hourly calculation procedures. The second one needs adjustments specific to each country due to enforceable National Annexes or legislation. Nevertheless, both procedures showed promising results in providing new and useful information to the end-user.

The assessment of BACS impact on the building proved to be effective in evaluating improvements. Currently, the EPC is lacking information on building control and automation systems in several countries. Moreover, given the critical role of BACS in building energy performance assessment, it is imperative to introduce new indicators in EPCs to underline their relevance and impact. Numerical results of the application of the procedures can be found in [42].

Enhanced EPC analysis and exploitation

The dataset of the BA schema is significantly influenced by the current constraints of the EPC data. Despite slight differences in the energy certification process among EU Member States, common issues include limited information, the application of a static energy performance assessment methodology, and high data uncertainty. However, the most impactful factor in achieving a high-quality EPC data level is attributable to the qualification and experience of the energy certifier.

In this research, for each cluster established to categorise EPCs, around 30 % are excluded as their overall EPC scores surpass the acceptable threshold limit. The reasons for rejection are either null values or quantities exceeding the physical or legislative limits (e.g., thermal transmittances and mean building heights). In the case of the Piedmont Region, it is not proved that the overall EPC score, derived from the sum of non-critical errors, exceeds the acceptability threshold. However, it is typical for an EPC to be rejected if it contains at least one critical error.

Table 1 reports the probabilistic BA schema for a 'virtual' residential single-family house, located in climatic zone E according to the Italian legislation, built between 1961 and 1975, taken as example. The data extracted from the EPC are reported in terms of median and interquartile ranges (i.e., $Q_3 - Q_2$ and $Q_2 - Q_1$).

The generated BA schema reflects the limitations of the current EPC configuration: limited data, static energy performance assessment, energy-related information, and low-quality parameters. Although insufficient information is reported in the current EPC, the created BA provides appealing building stock energy performance orientation regarding typical building uses. Enriching the next-generation schema with new KPIs and enhancing the EPC data quality will improve the efficiency and effectiveness of the BA in the context of the national building renovation plan.

Conclusions

In this work, the major limitations, constraints, and issues in the generation, storage, analysis, and exploitation phases of the current EPCs have been deepened and discussed. Although the European directives have been transposed by all EU countries, there are significant differences in implementation in the Member States. There is a lack of harmonisation 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. These are fundamental requirements to homogenise and align the EPC framework and content among the EU countries. Specifically, the current EPC lacks monitoring data, and the reliability of the information in the certificates is often questionable. Including real consumption data reflects the actual use of the building, improves the decision-making process for potential buyers, and enhances occupants' awareness of their energy use and potential savings. The low quality of EPC data affects large-scale energy analysis, where uncertainty is not reduced but amplified. Improving the reliability and usability of the EPC will drive the deep renovation of the existing buildings, as required by the new EPBD recast.

The fundamental pillars of the enhanced EPC in the context of the European TIMEPAC project have been investigated. The synergic aspects of the enhanced EPC envisaged by TIMEPAC with the EU funded projects within the Next Generation EPC Horizon2020 cluster have been deepened. The requirements of the TIMEPAC next-generation EPC are presented, including: (i) improvement of the EPC data quality, (ii) enrichment of the KPIs integration (SRI, sustainable indicators, real energy consumption, etc.), (iii) dynamicity, and (iv) flexibility of the energy certificate.

Five types of data analyses are presented and applied; they include tailored energy performance assessment, model calibration, economic evaluation of EEMs, IEQ evaluation, and BACS impact assessment. The results highlight the significant possibilities for improvement of the EPC with new indicators and increased data quality. In particular, the tailored energy performance assessment can give a more detailed overview of the building performance, if coupled with the standard energy performance assessment. On the other hand, the calibration gives the opportunity to refine the energy model by correcting any possible mistake and reducing the gap between the performance of the real building and of the model building. The analysis of possible building improvements was pursued with two different methodologies. The first one assesses combinations of measures to define the best solution from an economic perspective, while the second one is focused on the evaluation of the effects of the improvements of technical building systems. The IEQ domain can be also included in the EPC through the analysis of thermal comfort and IAQ.

A reliable and accurate energy certificate is a key condition to have a clear and updated picture of the energy *status* of the building stock in order to boost knowledge and awareness of energy efficiency. The improvements of the future EPC impose the introduction of quality checks in the database framework or integrated into the building energy

Table 1

Characterisation of the BA identified by statistical analysis of the EPC database. Example for single-family house in climatic zone E (Piedmont Region, Italy) built in CP5 (1961–1975).

	Data	Symbol	Unit of measure	Median	$Q_3 - Q_2$	$Q_2 - Q_1$
Geometry	Compactness ratio ($A_{env}/ V_{H;g}$)	CR	m^{-1}	0.824	0.137	0.137
	Thermally heated gross volume	$V_{H;g}$	m^3	497	200	130
	Thermally heated floor area	$A_{H;use}$	m^2	121	53	31
	Transparent thermal envelope area on thermal envelope area	A_w/A_{env}	–	6 %	2 %	1 %
Envelope	Mean thermal transmittance of the opaque building envelope	U_{op}	$W \cdot m^{-2} \cdot K^{-1}$	1.052	0.274	0.324
	Mean thermal transmittance of the transparent building envelope	U_w	$W \cdot m^{-2} \cdot K^{-1}$	2.820	1.159	1.116
Technical bldg system	Energy carrier per space heating	Natural gas = 78 %; solid biomass = 7 %; others = 15 % (of the analysed sample)				
	Energy carrier per space cooling	Electricity = 100 % (of the analysed sample)				
	Energy carrier per space domestic hot water	Natural gas = 72 %; electricity = 17 %; others = 11 % (of the analysed sample)				
	Mean seasonal efficiency of the heating generation sub-system (natural gas)	$\eta_{H;gen}$	–	0.917	0.093	0.127
	Mean seasonal efficiency of the heating generation sub-system (solid biomass)	$\eta_{H;gen}$	–	0.750	0.186	0.290
	Overall energy efficiency (without generation)	$\eta_{H;ngen}$	–	0.875	0.048	0.065
Energy indicators	Energy need for space heating per unit of conditioned floor area	$EP_{H;nd}$	$kWh \cdot m^{-2}$	166.0	69.0	59.1
	Energy need for space cooling per unit of conditioned floor area	$EP_{C;nd}$	$kWh \cdot m^{-2}$	8.2	6.8	4.9
	Energy need for space domestic hot water per unit of conditioned floor area	$EP_{W;nd}$	$kWh \cdot m^{-2}$	16.6	1.4	1.3
	Seasonal space heating energy efficiency	$\eta_{s;H}$	–	0.740	0.070	0.060
	Seasonal space cooling energy efficiency	$\eta_{s;C}$	–	1.240	1.118	0.491
	Seasonal domestic hot water energy efficiency	$\eta_{s;W}$	–	0.690	0.100	0.130
	Non-renewable energy performance for space heating	$EP_{H;nren}$	$kWh \cdot m^{-2}$	204.5	111.4	91.0
	Non-renewable energy performance for space cooling	$EP_{C;nren}$	$kWh \cdot m^{-2}$	6.9	8.0	4.1
	Non-renewable energy performance for domestic hot water	$EP_{W;nren}$	$kWh \cdot m^{-2}$	22.2	6.6	6.0
	Overall non-renewable energy performance	$EP_{gl;nren}$	$kWh \cdot m^{-2}$	228.6	115.8	95.2
	Overall renewable energy performance	$EP_{gl;ren}$	$kWh \cdot m^{-2}$	2.2	13.3	1.3
	Renewable Energy Ratio	RER	–	1 %	8 %	0

performance simulation programs during the XML-exporting phase. The analysed datasets represent a relevant part of the BA schema. BAs are extremely important elements to bridge the uncertainty gap in the development of large-scale energy analysis.

The reflections presented in this contribution suggest the need to rethink the energy performance certificate at the EU level. The future energy certificate should not be seen by the end-user just as a legal obligation, but as an opportunity to have a standard and tailored rating about its building. The introduction of enhanced indicators from other domains (environmental, social, economic, etc.) will improve credibility and interdisciplinarity, enlarging the fields of the utilisation of digital documents. The coexistence of all these elements will improve every stage of the enhanced EPC: generation, storage, analysis, and exploitation.

Future research lines regarding the enhancement of next-generation EPCs may focus on:

- Standardisation of data reporting: strengthening and harmonising the KPIs to be included in the energy certificate, extending beyond the energy field.
- Large-scale analysis: rethinking EPCs for large-scale analysis, such as disaggregating information in the recommendations section and enhancing indicators to better assess the impact of applied energy efficiency measures.
- Data quality label: improvement of the reliability of the data in the EPC, assigning a quality label to certify the accuracy and completeness of the information provided.

CRediT authorship contribution statement

Matteo Piro: Writing – original draft, Visualization, Formal analysis. **Franz Bianco Mauthe Degerfeld:** Writing – original draft, Visualization, Formal analysis. **Ilaria Ballarini:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Vincenzo Corrado:** Writing – review & editing, Validation, Supervision, Methodology, 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.

Data availability

Data will be made available on request.

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