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Simplified tool for the energy performance assessment of residential buildings

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ABSTRACT

Building sector is responsible for approximately 40% of energy consumption and 36% of CO_2 emissions in the EU. For more than a decade the Energy Performance Certification (EPC) revealed to be an effective tool to create demand for energy efficiency in buildings providing recommendations for the cost-effective upgrading of the energy performance. The EPC process is founded on a standard calculation, based on conventional climate, use, surroundings and occupant-related input data, as defined by the Technical Standard EN 15603:2008. Even if the EPC is substantially mandatory in the European Countries, differences can be found along the process in particular in terms of methodology and tools. In Italy the national regulation provides simplified methodologies that can generate results assuring a maximum deviation between + 20% and - 5% of the final non-renewable primary energy compared to the same parameters determined with the application of the national reference tool. The aim of the present article is to describe the salient features of the methodology and the technical choices necessary to guarantee the range of acceptability of the results. A case study tested the procedure and the results were compared to those of an extended calculation procedure.

1. INTRODUCTION

Building sector accounts for about 40% of final energy consumptions in the European Union (EU). EU has promoted and continues promoting energy efficiency in buildings through specific energy strategies and policy instruments [1]. The Energy Performance of Buildings Directives (EPBD, Directives 2002/91/EU and 2010/31/EU) identified the general guidelines to steer the building sector towards ambitious energy efficiency standards and increased use of renewable energy sources. A wide number of tools and methods, with different degrees in detail, has been developed to reach this goal. Among them, simplified but accurate methodologies represent an active area of investigation [2-3]. Energy Performance Certificates (EPCs) are useful tools introduced by EU directives in order to express the level of energy efficiency of buildings and increase awareness among both tenants and buyers allowing for comparison of buildings and building units in terms of energy efficiency.

Over the years the EPCs have been exploited for the definition of energy policies by the Public Administration [4]; the collected information has been used for the analysis of the current energy performance in urban areas [5-6], Regions [7] or entire Countries [8-9]. Furthermore, these analyses are used for the development of hypothetical energy refurbishment scenarios [10-11].

Despite the widespread diffusion of EPCs, the energy efficiency issues still have a limited impact on the criteria for choosing buildings and determining their market value [12].

To date all the Member States have implemented the EPBD requirements for EPCs. Differences persist about the characteristics of the adopted EPC calculation methodology [13].

Italy transposed and applied the European Directives 2002/91/EU and 2010/31/EU in 2005 (DLgs 192/2005) and 2013 (DL 63/2013) respectively. The certification procedure follows a regional approach both for accreditation and control procedures. The calculation methodology can be evaluated on the basis of the calculated (known as asset rating) or actual energy consumption (known as operational rating) and the use of public and commercial software is permitted [14]. In particular the national decrees provide the use of simplified tools for energy certification of existing residential buildings in order to promote the diffusion of the energy efficiency awareness and reduce the costs for the end users.

The present article describes the development of a simplified tool for energy certification and highlights the simplification adopted. The reliability of the tool has been verified by considering a reference residential building. The results were verified with those deriving from the use of a national reference tool.

2. METHODOLOGICAL APPROACH

In Italy, the energy certification of buildings is based on the "asset rating" methodology based on data derived from building inspection or project data, simulated energy performance calculated with standard climate conditions, standard occupancy schedules, default thermal loads, and standard HVAC systems management [15].

The certification procedure provides the definition of energy performance indicators and the assignment of a performance class to the building [16]. The EPBD (2002/91/EU) and the EPDB recast (2010/31/EU) are implemented by State, Regions and autonomous Provinces. An overall overview of the current state of the application procedures and of the diffusion of the energy certification of buildings in Italy is provided by Ref. [17]. At national level, the technical specifications UNI TS 11300 Parts 1 to 6 are recognized as references for the definition of the energy performance of buildings providing the calculation procedures of the following energy indicators:

(1) Heating and cooling needs (Part 1);

(2) Primary energy for heating, ventilation, domestic hot water and lighting (Part 2);

(3) Primary energy for cooling (Part 3);

(4) Contributions from renewable sources (thermal solar, photovoltaic, biomass) (Part 4);

(5) Energy performance for classification (Part 5)

(6) Energy needs for lifts, elevators, escalators and moving walkways (Part 6).

The global non-renewable primary energy divided by the conditioned floor area, EPgl,nren, is the energy performance (EP) indicator used for buildings classification. The EP indicator is the sum of the primary energy for each energy service, as described by equation Eq (1):

$$EP_{gl,nren} = EP_{H,nren} + EP_{W,nren} + EP_{C,nren} + EP_{V,nren} + EP_{L,nren} + EP_{T,nren} \quad (1)$$

Primary energy for lighting ($EP_{L,nren}$) and transport ($EP_{T,nren}$ – if present) of people are not mandatory for residential and industrial buildings. The energy classification is determined by comparing the actual EP indicator of the building with that of a Reference Building, defined as a building with the same geometrical and shape characteristics, identical orientation, geographical location, intended use and boundary conditions of the actual one, but with thermo-physical proprieties of the envelope and efficiencies of HVAC systems fixed by law. These properties were defined by applying the cost-optimal methodology in order to identify minimum energy performance requirements for buildings, building elements and technical building systems [18].

A specific energy class, represented by a scale of 10 levels ranging from A4 (the most efficient) to G (the least efficient), is assigned to the building.

At national level the actual laws provide the use of simplified tools for the energy certification of residential buildings with a net area lower than 200 m^2. In this field, the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) and the National Research Council of Italy (CNR) have been selected by a national inter-ministerial decree to create a simplified software to meet this requirement.

The result of the collaboration of these two research institutes is the software DOCET. This tool implements the algorithms provided by the UNI TS 11300 and the related standards; the simplifications were defined by using parametric analysis in compliance with the limits imposed by the national inter-ministerial decree, i.e. the results must be included in a range between +20% and -5% compared to the detailed calculation. The software can be applied both for the certification of a single building, such as a row house or single family house, and for single apartments.

The calculation procedure and the simplifications adopted for the tool development are described below.

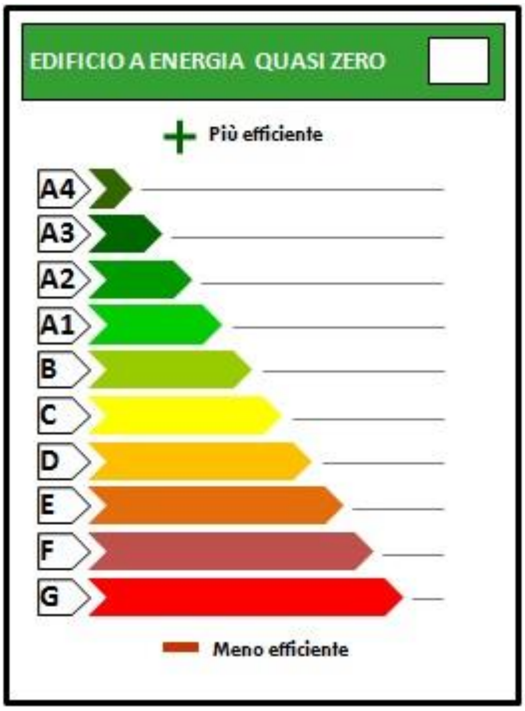

Figure 1. Energy classes (from DI 26/06/2015)

2.1 Net energy

The thermal energy need for heating ($Q_{H,nd}$) and cooling ($Q_{C,nd}$) is determined by applying a monthly steady-state balance between energy losses (by transmission, Q_{tr}, and by ventilation, Q_{ve}) and gains (solar, Q_{sol}, and internal, Q_{int}) corrected with the gain or loss utilization factor, eta_H or eta_C respectively , according to the following equations:

$$Q_{H,nd} = (Q_{tr} + Q_{ve}) - \eta_H(Q_{sol} + Q_{int}) \quad (2)$$

$$Q_{C,nd} = (Q_{sol} + Q_{int}) - \eta_C(Q_{tr} + Q_{ve}) \quad (3)$$

The parameters of the equations are function of environment conditions, geometrical and morphological characteristics of the building and thermal properties of building envelope.

2.2 Primary energy

The primary energy is defined "as the energy from renewable and non-renewable sources which has not undergone any conversion or transformation process" (Directive 2010/31/EU). Primary energy is calculated for each energy service (heating, cooling and domestic hot water, DHW, and the related electric energy), considering the energy delivered from renewable energy sources. The primary energy for each energy service is expressed by the following equation as a function of the delivered ($Q_{del,i}$) and exported (Q_{exp},i) energy by each energy carrier multiplied by their primary energy factors ($f_{p,del,i}$ and $f_{p,exp,i}$, respectively):

$$Q_p = \sum(Q_{del,i} \times f_{p,del,i}) - \sum(Q_{exp,i} \times f_{p,exp,i}) \quad (4)$$

The primary energy is expressed in terms of renewable, non-renewable and global energy. For each energy carrier a threefold primary energy factor is defined, as expressed below:

$$f_{p,tot} = f_{p,ren} + f_{p,nren} \quad (5)$$

The subscripts "ren" and "nren" refer to the renewable and non-renewable fractions, respectively. In Table 1 the primary energy factors of the most diffuse energy carriers in residential buildings are presented; for a complete overview refer to DM 26/06/2015.

Table 1. Primary energy factors for some energy carriers

Energy carrier	$f_{p,ren}$	$f_{p,nren}$
Natural gas	0	1,05
GPL	0	1,05
Solid biomass	0,80	0,20
Electric energy	0,47	1,95
District heating	1,5	0
Thermal energy from solar panels	1	0
Electric energy from photovoltaic	1	0

The global renewable or non-renewable primary energy of buildings is given by the sum of single values for each energy carrier.

2.3 Refurbishment scenario

According to the European EPBD (Energy Performance of Buildings Directive) normative framework the energy certificate shall include recommendations for the cost-optimal improvement of the energy performance of a building. These recommendations besides being technically feasible, may provide an estimate for the range of payback periods over the building's economic lifecycle.

The simple payback time is one of the most important financial indicators. It determines the time in which the initial cash outflow of an investment is expected to be recovered from the cash inflows generated by the investment, according the formula:

$$SPBT = \frac{initial\ investment}{annual\ saving} \quad (6)$$

Since this method does not evaluate the cash flow after capital recovery time and does not take into account the possible currency floating over the time, the SPBT value calculated by years needs to be compared with the expected useful life of the refurbishment. In order for the solution to be economically feasible, the SPBT must be shorter than the useful refurbishment measure's lifetime.

2.4 Simplification criteria

As already mentioned, the calculation engine is completely based on the procedure described by UNI TS 11300 technical standards. Adequate simplifications were necessary to implement the simplified tool due to the specific category of buildings to be certificated. It is often difficult to find information about existing buildings especially those related to the thermo-physical properties of building envelope. For this reason we assumed a set of simplifications both for envelope and HVAC systems. First of all the procedure takes into account a single thermal zone.

Following paragraphs show the simplifications criteria.

2.4.1 Urban context

The description of the urban context allows to take into account the presence of external obstacles that shade the building with a reduction of solar gains. These elements can be other facing buildings, trees or other external objects. The tool assumes a single obstacle for each façade of the building (eight orientations) and three possibilities to define the distance of the obstacles:

(1) isolated buildings: no shading on the façade;

(2) suburban buildings: a distance from facing building equal to 20m;

(3) city center buildings: a distance from facing building equal to 10m.

The global heights of the external obstacles are calculated as a function of the number of hypothetical floors (each 3m high). These values have to be considered from the floor level of the building unit to the rooftop of the facing building (Figure 2).

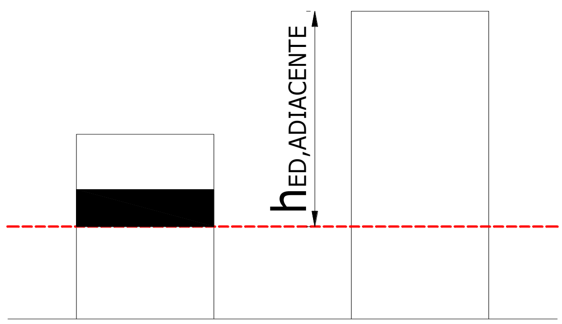

Figure 2. Height of external obstacles

2.4.2 Geometrical and morphological features

The shape of the building unit is described by the linear dimensions of each external wall considering the height cardinal orientations. The tool considers a regular section of the shape of the building that can however be manually modified by the user.

2.4.3 Opaque envelope

Each technical element of the building unit (wall, floor, basement, roof, etc.) is characterized by a single value of its thermal transmittance or thermal capacity. These values are taken from the technical standard UNI TR 11552:2014, depending from the structure considered (external wall, roof, basement floor etc), as a function of the year of construction, location, actual requirements, etc. In case of technical elements of the same typology with different composition, it is necessary to calculate average weighted values of their thermal characteristics.

The envelope is subject to solar gains. In presence of balconies, an overhang of 1,40m deep and a distance from the center of the wall equal to half of the net height of the floor are assumed.

2.4.4 Transparent envelope

The dimension of transparent envelope's elements for each orientation is determined by the number of leaf of the window. We considered a standard size window 0,70m wide and 1,40m high while 2,10m high for door windows. The transparent envelope surfaces for each orientation can still be customized by users.

The thermal transmittance derives from values provided by UNI TS 11300-1 technical standard, as a function of frame and glass typologies. The U-values are considered as the weighted average for each orientation. Solar gains through the transparent envelope are reduced by adopting two strategies: internal white curtains, fixed external overhangs and fixed vertical fins are considered for each window. The former causes a reduction of the total solar energy transmittance, g_{gl}. The latter introduces shading coefficients: balcony determines an overhang 1,40m deep, reduced at 0,20m without balcony; fins are considered 0,20m deep. Shutter boxes as wide as windows and 0,30m high are included.

A reduction of total solar energy transmittance equal to 20% and 50% in winter and summer respectively is considered in presence of fixed external shutters.

2.4.5 Thermal bridges

The computation of thermal bridges is fundamental for the calculation of the thermal performance of a building. Thermal bridges can account up to 50% of the thermal transmission. Simplified fixed values of linear thermal transmittance are assumed for each thermal bridge in compliance with UNI EN ISO 14683:2018. These values vary according to the characteristics of the technical element and the presence of thermal insulation (Table 2).

Table 2. Linear thermal transmittance [$Wm^{-1}k^{-1}$] of the thermal bridge for technical elements and insulation levels

Technical elements	Insulated [$Wm^{-1}k^{-1}$]	Not insulated [$Wm^{-1}k^{-1}$]
Pillar	0,15	0,90
Internal wall	0,20	0,10
Corner	0,10	0,15
Window	0,15	0,45
Ground floor	0,80	0,65
Internal floor	0,65	0,80
Roof	0,75	0,65

2.4.6 Unconditioned thermal zones

Unconditioned thermal zones (UTZ) are characterized by adjustment factors, b_{tr}, smaller than 1, in order to consider thermal transmission and solar gains towards these spaces. No internal gains are considered from UTZs. Pre-defined b_{tr} values are assumed in the calculation procedure, as reported in Table 3.

Table 3. Adjustment factors

UTZs	b_{tr}
Floor towards UTZs	0,65
Ground floor	0,45
Staircase or other UTZs	0,40
Ceiling towards UTZs	0,70

2.4.7 Ventilation system

Only natural ventilation with an air exchange rate equal to $0,3h^{-1}$ is assumed.

2.4.8 Heating system

Heating energy service is provided by a single thermal generator, in separated (only heating) or combined (heating and DHW) thermal production mode, autonomous or centralized; multi-generation systems are not allowed by the proposed tool. The provided generation systems are the following:

(1) Combustion systems;
(2) Biomass systems;
(3) Heat pumps;
(4) District heating.

The performance of combustion and biomass systems are calculated by considering pre-defined efficiency factors, , as a function of the characteristics of the system.

The performance of heat pumps is calculated according to the bin-method, referring only to heating mode. Electrically-driven vapour compression cycle heat pumps are considered.

The performance of district heating systems is evaluated by dividing the system into two parts: the section situated outside the building (from the generator to the building) and inside the building (the substation).

Combustion and biomass systems and district heating require the definition of the heating subsystems: emission, regulation and distribution. In centralized heating systems the length of the distribution pipes is calculated by using parametric formulas.

In buildings without a heating system, it's assumed a traditional combustion system with efficiency defined by the national decree.

2.4.9 Cooling system

The cooling service, if present, is supplied by electrically-driven vapour compression cycle heat pumps. The average monthly coefficient of performance is calculated starting from the Energy Efficiency Ratio (EER) corrected with the load factor and other coefficients function of the characteristics of the system.

2.4.10 DHW system

As already mentioned, the DHW system can be separated or combined with the heating system. In the former case, autonomous or centralized systems can be chosen: autonomous ones are electric or gas-powered boilers with or without heat storage; centralized ones are combustion or biomass systems, similar to those described for the heating service.

2.4.11 RES systems

The exploitation of Renewable Energy Sources (RES) allows a reduction in primary energy consumptions of buildings. Solar thermal (ST) and photovoltaic (PV) systems are the RES systems provided by the tool.

The electric energy produced by the PV system is subtracted from the energy of electric auxiliaries and electrical powered devices, such as the heat pumps. The excess amount of produced electric energy is not computed in primary energy calculation. A fixed inclination of 30° of the PV system and slightly-ventilated panels are considered.

The thermal energy produced by the ST panels can be exploited for heating, DHW mode or for a combined use. A ST system with a horizontal thermal storage and insulated pipes placed in heated rooms is considered.

2.5 Simplification criteria

Besides the requirements of the inter-ministerial decree further limitations are necessary for the compliance of the characteristics of the tool.

Since there has been a complex evolution of the regulatory framework on energy efficiency and certification of buildings it is necessary to specify for which existing buildings the software is applicable. We assumed for the simplified tool that existing buildings are those built before 2009 (date of the previous legislation on buildings certification).

Some constrains have already been mentioned in the text and derive from the analysis of the characteristics of Italian building stock aimed at identifying the typological aspects. For this reason, a building unit is considered as single thermal zone with natural ventilation heated with a single hydronic generator. Neither absorption heat pumps nor cogeneration are permitted as they are not diffuse in residential sector.

3. CASE STUDY

The selected case study is a multistory residential building located in Milan with a North-South principal orientation, consisting of an unconditioned ground floor where the cellars are located, three conditioned floors each with two apartments (six building units in total, C1-C6) and an unconditioned attic with a smaller surface than the floor below. The stories are connected with an internal unconditioned staircase.

The area of each apartment is about 80m^2, with a net height of 2,70m. On the south side each conditioned floor has a balcony along the entire façade. The average geometrical and thermo-physical characteristics of the envelope referred to a single apartment are shown in table 4.

Table 4. Geometrical and thermo-physical characteristics of the envelope

Building components	U-value [W m^{-2} k^{-1}]	A [m^{-2}]
External wall	0,30	55,79
Internal wall	0,90	19,25
Floor	0,26	79,32
Ceiling	0,27	39,93
Roof	0,28	39,39
Windows	1,58	11,48
Shutter box	1,00	2,80

The selected heating system consists in a combined centralized condensing boiler. The cooling system is an electrically-driven air to air heat pump. Finally, both ST and PV panels are installed for the production of thermal and electric energy, respectively. The solar systems are both south-exposed and their surfaces are 23,30m^2 for the ST and 34,56m^2 for the PV. The energy production of the ST is equally subdivided among the apartments, while that due to the PV system is subdivided according to the effective electrical need of each apartment, as shown in table 5.

Table 5. PV system area for each apartment

Apartments	A[m^{-2}]
C1	5,49
C2	5,47
C3	5,51
C4	5,50
C5	6,30
C6	6,29

The calculation of the energy performance indicators has been carried out for each apartment.

4. RESULTS

In this chapter the energy performance indicators calculated with the simplified tool are compared to the results of the detailed calculation procedure as required by UNI TS 11300 technical standards.

4.1 Thermal energy

The comparison of the results in terms of energy needs, both for heating ($Q_{H,nd}$) and cooling ($Q_{C,nd}$) are shown in table 6. The results comply with the range defined by the national inter-ministerial decree (+20%÷-5%). For each apartments, the results in heating mode are higher than those calculated with the detailed calculation procedure. The results in cooling mode are lower for the apartments placed in the second (C1, C2) and third floors (C3, C4) and higher for the other ones (C5, C6). The difference is due to the computation of the solar gains. The simplifications reduce the effect of the solar gains with an increase of the energy needs in winter and a reduction in summer.

Table 6. Thermal energy comparison

Units	$Q_{H,nd}$[kWh]	Check	$Q_{C,nd}$[kWh]	Check
C1	3612	+9%	1204	-4%
C2	3617	+9%	1200	-4%
C3	2888	+13%	1222	-1%
C4	2893	+13%	1218	-1%
C5	3982	+12%	1385	+3%
C6	3987	+12%	1381	+4%

Figure 3 shows the trend of the monthly energy need for apartment C1, for heating and cooling (red line), respect to the range defined by the national inter-ministerial decree (grey area).

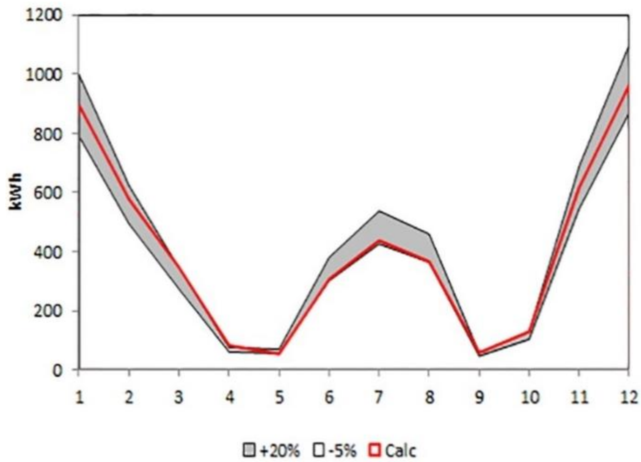

Figure 1. Monthly energy need (apartment C1)

4.2 Primary energy

The results of non-renewable primary energy (table 7) and total (sum of renewable and non-renewable, table 8) primary energy for each energy service (heating, cooling and DHW production) are in compliance with those of the previous paragraph.

Table 7. Comparison of non-renewable primary energy for each energy service (H, C, W)

Units	$EP_{H,nren}$ [kWh]	Check	$EP_{c,nren}$ [kWh]	Check	$EP_{w,nren}$ [kWh]	Check
C1	4096	+9%	241	0%	806	+8%
C2	4101	+9%	242	+2%	806	+8%
C3	3241	+13%	226	-4%	803	+8%
C4	3246	+13%	225	-4%	803	+8%
C5	4528	+12%	262	+2%	800	+7%
C6	4533	+12%	261	+3%	800	+7%

Table 8. Comparison of total primary energy for each energy service (H, C, W)

Units	$EP_{H,tot}$ [kWh]	Check	$EP_{c,tot}$ [kWh]	Check	$EP_{w,tot}$ [kWh]	Check
C1	4181	+9%	610	-4%	2330	+2%
C2	4187	+9%	609	-3%	2330	+2%
C3	3317	+14%	601	-3%	2329	+2%
C4	3323	+14%	600	-3%	2329	+2%
C5	4617	+12%	668	-1%	2326	+2%
C6	4623	+12%	687	+2%	2326	+2%

Considering the global primary energy as the sum of the indicators of each energy service, the results show how the simplified tool provides results higher than the detailed calculation with an average value of 10% in non-renewable energy, allowing a conservative energy certification.

Table 9. Comparison between global non-renewable and total primary energy

Units	EP_{nren}[kWh]	Check	EP_{tot}[kWh]	Check
C1	4747	+8%	6735	+6%
C2	4752	+8%	6738	+6%
C3	3848	+11%	5816	+7%
C4	3853	+11%	5819	+7%
C5	5058	+11%	7077	+8%
C6	5063	+10%	7080	+8%

5. CONCLUSIONS

The present paper describes the methodological approach and the technical choices to implement a simplified tool for the energy certification of existing residential buildings. The simplification criteria in the calculation procedure and in the input data are presented. The reliability of the tool in meeting the requirements defined by the national inter-ministerial decree has been checked by matching the results with those of the detailed procedure described by UNI TS 11300 technical standard.

The comparison highlights the correspondence of the results at each level of the calculation procedure.

The availability of simplified tools for the energy certification or the assessment of the energy performance of buildings is a stimulus for a growing awareness of energy and environmental issues and for the dissemination of energy saving best practices.

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NOMENCLATURE

DHW	domestic hot water
EP	energy performance, kWh m-2 a-1
EPBD	energy performance of buildings directive
EPC	energy performance certificates
fp	primary energy factor
PV	photovoltaic
Q	thermal energy
RES	renewable energy source
SP	simple payback time
ST	solar thermal
UTZ	unconditioned thermal zone

Greek symbols

η	Utilization factor, -

Subscripts

C	cooling
del	delivered
exp	exported
gl	global
H	heating
int	internal
L	lighting
nd	need
nren	non-renewable
ren	renewable
sol	solar
T	transport
tr	transmission
V	mechanical ventilation
ve	ventilation
W	hot water