Article

Review of the Cost-Optimal Methodology Implementation in Member States in Compliance with the Energy Performance of Buildings Directive

Paolo Zangheri [1] **, Delia D'Agostino** [2,*] **, Roberto Armani** [3] **and Paolo Bertoldi** [2]

[1] ENEA, 21027 Ispra, Italy
[2] European Commission, Joint Research Centre, 21027 Ispra, Italy
[3] Dipartimento di Energia, Politecnico di Milano, 20156 Milano, Italy
* Correspondence: delia.dagostino@ec.europa.eu; Tel.: +39-0332-78-3512

Abstract: The building sector has a central role in achieving the European goals of a zero-emission and fully decarbonized stock by 2050. Among the provisions of the Energy Performance of Buildings Directive (EPBD) recast, the implementation of the cost-optimal methodology marked a novel approach in the establishment of minimum energy performance requirements for new and existing buildings. Member States must develop cost-optimal calculations every 5 years to verify and accordingly update the national requirements in force. This paper analyses the latest national cost-optimal reports, providing an updated assessment of the implementation of the cost-optimal methodology throughout Europe. It quantifies the progress in reaching cost-optimal levels in comparison with the previous assessment. It focuses on the conformity and plausibility of calculations in compliance with the policy framework. Furthermore, it evaluates the gap with national requirements, showing that the gap is higher than 15% only in a few Member States. The results provide a comprehensive review of the European progress towards cost-optimality in both the residential sector (average cost-optimal level 80 kWh/m²y for new, 130 kWh/m²y for existing buildings) and the non-residential sector (140 kWh/m²y for new, 180 kWh/m²y for existing buildings). An overall positive development can be inferred from the analysis of the Member States' progress in the methodology's implementation. The review also gives inputs for the cost-optimal methodology update foreseen for 2026 (e.g., cost-optimality for districts and historical buildings). The outcomes assume a crucial relevance for the ambitious energy efficiency targets established by Europe.

Keywords: cost-optimal methodology; cost-optimal analysis; nearly zero-energy buildings; energy policy; energy efficiency; building decarbonization; European Member States; Energy Performance of Buildings Directive

1. Introduction

Accounting for approximately 40% of total energy consumption and significantly contributing to global warming [1], buildings are at the core of the European strategy towards a zero-emission and fully decarbonized stock by 2050 [2]. The European Green Deal and the Renovation Wave further point to the strategic role of buildings in creating jobs, improving security, boosting green technologies, and fostering a circular economy [3,4]. The strategy foresees regulatory and financing measures that will at least double the annual energy renovation rate of buildings by 2030 and foster deep energy retrofit [5]. Within that framework, comprehensive energy and climate policy packages are progressively making the EU energy performance of buildings more efficient [6]. In particular, the Energy Performance of Buildings Directive recast (2010/31/EU—EPBD [7]) and its recent revision [8] comprise important provisions for a long-term improvement of the EU building stock [9]. Among them is the stipulation that Member States must calculate and establish cost-optimal levels of minimum energy performance requirements for new and existing

buildings following the established comparative methodology framework [10] and related Guidelines [11].

The EPBD also requires Member States to develop appropriate policies and provide the necessary financing measures to foster the transition to nearly zero-energy buildings (NZEBs) [12,13], a status mandatory for all new buildings since 2021 [14,15]. The EPBD does not advocate a uniform approach for implementing NZEBs throughout Europe, requiring Member States to draw up national roadmaps that account for the variety of building types and climates [16–19].

In this context, the cost-optimal methodology appears very effective both for upgrading the energy performance requirements in force at national level and for assessing the effects of policy measures to achieve the NZEB targets [20]. A previous study [12] showed that the majority of Member States seem to adopt the cost-optimal approach in appropriate ways and use it to define NZEB requirements.

However, since the release of the cost-optimal methodology, different debates have arisen around the approach [21]. Reference building definition [22], energy performance assessment and optimization variables [23,24], uncertainty, and sensitivity analysis [25] are among the most commonly discussed topics in the literature. Recently, the importance of including the indoor environmental quality and the interactions between the building, its systems, and its occupants became evident as a way to complement energy efficiency, as conceived by the cost benefit analysis [26].

Although it has been pointed out that the methodology has mainly spread theoretically at government and scientific levels, but has not yet disseminated sufficiently among professionals [27], its introduction unquestionably signifies an important milestone towards the renovation of the existing building stock and a substantial transformation towards a zero-carbon society.

From an early assessment of the cost-optimal methodology, a heterogeneous situation was evident in European countries, as each building type and climate presented varying cost-optimal levels [21]. Regardless of comparison issues among cost-optimal levels and a non-uniform application across Europe [28], it is generally agreed that it represents an efficient and complete decision-making tool for building design that considers both energy and economic evaluations. Several literature studies focus on a specific climate or building type [28–44], but a thorough overview of the cost-optimal methodology is still missing and undoubtedly necessary.

Accordingly, this paper aims to provide a comprehensive review of the implementation of the cost-optimal methodology in Member States to assess its progress, its strengths and weaknesses, and possible future developments in the light of the recent policy developments. To accomplish this goal, the most recent cost-optimal reports (link provided in the Supplementary material section) submitted by Member States have been considered as data sources for this policy analysis [45].

After describing the methodology (Section 1.1), this paper reports the criteria adopted to assess the cost-optimal reports (Section 2), and it provides the main assessment results in Section 3. Discussion and conclusions are presented in Sections 4 and 5, respectively.

1.1. The Cost-Optimal Methodology

The calculation framework of cost-optimal levels to be used by Member States to benchmark their building standards was defined in 2012 by the European Commission [10]. It is based on the principle of the cost-benefit analysis, and it is calculated from two economic perspectives: the financial and the macroeconomic, which refer to different discount rates (lower in the macroeconomic one) and cost items [46]. While the financial perspective includes taxes, the macroeconomic perspective considers greenhouse gas emission costs [47]. The calculation approach can be summarized in the following steps [6]:

1. Establishment of reference buildings. Real or virtual buildings representing the building stock must be selected. Member States must define at least three categories, for both new and existing buildings (residential single-family, residential multi-family, of-

fices). According to [10] (Annex I), Member States must also define reference buildings for other building categories, for which specific energy performance requirements exist. For new buildings, the standard energy performance in force can be assumed as base case. For the existing stock, at least two reference buildings must be considered, which can be established on the basis of size, age, cost, structure, construction material, use pattern, or climatic zone.

2. Identification of energy efficiency and renewable measures. These must be implemented in new or existing buildings, including different packages of measures or measures of different levels (e.g., from lower to higher insulation levels), which must respect the EU and national legislation. The impact of applying packages of measures on reference buildings (starting with the current requirements and beyond, including the NZEB level) should be estimated in the cost-optimal calculation in terms of energy and financial performance.

3. Calculation of the (net) primary energy consumption. The energy performance calculation must be based on the current national or CEN standard methodologies for each selected building variant. Framework conditions for the calculations must be defined in terms of climate data, performance of energy systems, primary energy factors, and indoor air quality.

4. Calculation of the global cost. The net present value (NPV) should be used at each step, based on 30 years for residential and 20 years for non-residential buildings. The included cost categories are: initial investment costs, running costs (i.e., energy, operational, maintenance, replacement costs), disposal costs, final value, and the cost associated with CO_2 emissions (only for the macroeconomic perspective). For the assessment of the financial performance (global costs) of the chosen combinations of packages, the European Standards EN 15459 is suggested as reference [48]. This method results in a discounted value of all costs (present and future) for a defined period of calculation. The global cost formula can be written as in Equation (1)):

$$C_G(\tau) = C_I + \sum_j \left[\sum_{i=1\dots\tau} (C_{a,i}(j) \times R_d(i) + C_{C,i}(j)) - V_{f,\tau}(j) \right] \tag{1}$$

where $C_G(\tau)$ corresponds to the global cost referred to starting year τ_0 C_I is the initial investment cost; $C_{a,i}(j)$ is the annual cost for component j at the year i (including running costs and replacement costs); $R_d(i)$ is the discount rate for year i; $V_{f,\tau}(j)$ is the final value of the component j at the end of the calculation period (referring to the starting year τ_0).

5. Identification of cost-optimal levels. This should be expressed in primary energy consumption (in kWh/m^2 per year) for each reference building. The cost-optimal configuration presents the lowest costs maintaining a high performance. It can be identified in the lower part of the curve that reports global costs (Eur/m^2) and energy consumption (kWh/m^{2}y) (Figure 1).

6. Evaluation of the shortfall against current minimum energy performance requirements. If the difference is higher than 15%, Member States must justify the gap or define a plan to reduce it. The national benchmark related to the final outcome of the cost-optimal calculations can be calculated for a financial or a macroeconomic perspective.

Sensitivity analysis can help in evaluating the robustness of key parameters, such as discount/interest rate, the annual increase in energy prices, and primary energy factors associated with different fuels.

Relevant additional information is given in the official Guidelines [11], as stated in Annex III [7]. They give methods for establishing reference building types and subcategories, reducing package combinations, gathering cost data, and deriving cost-optimal levels. They provide a list of CEN standards, cost categorization, indications for sensitivity analysis, equations for the calculation of shortfalls against current requirements, indoor air quality, and comfort. They also clarify the full cost approach, calculation period, replacement, energy and disposal costs, taxation, subsidies, and feed-in tariffs.
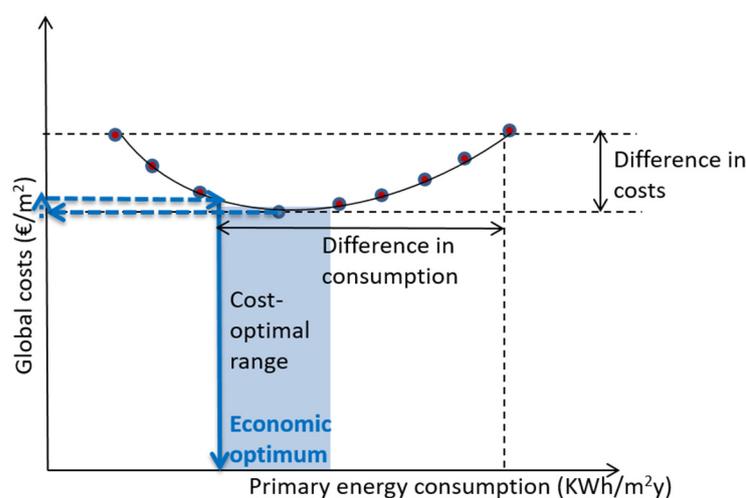
Figure 1. Different variants within the graph and position of the cost-optimal range.

Figure 2 shows the timeline of EPBD recast to implement cost-optimal calculations and NZEB requirements.

Figure 2. Timeline for cost-optimal and NZEB requirements.

In line with the EPBD timeline (Figure 2), the first cost-optimal calculations were due by 2013. According to the first assessment of 2015 [28], apart from a few cases, the overall picture seemed rather positive in terms of compliance with the EPBD requirements. Although reports were mainly assessed as plausible, energy performance levels showed space for potential improvement towards more stringent requirements to reduce primary energy use and life-cycle costs. A joint, consistent, and comparable level of ambition was desirable after the first assessment [49]. The second cost-optimal reports were submitted in 2020. Accordingly, this paper reviews the Member States' progress in reaching cost-optimal levels of minimum energy performance requirements.

2. Methodology

The methods of this cost-optimal implementation review were divided into the following main steps. In the first step, reports were collected and officially translated. Then, the template for data collection was developed and the reports analyzed (total lengths: around 6000 pages of reports and 4000 pages of annexes). Clarifications and additional information were often requested from Member States in cases of missing or non-extractable information, frequently due to unclear translations, units, tables, figures or explained methodology.

As detailed in Section 1.1, the cost-optimal methodology can be divided into different steps, to which the reference categories of Table 1 correspond. The key assessed topics developed to collect data and information for each reference category, assess the cost-optimal calculations, and guide the report evaluation are also reported in Table 1.

Table 1. Reference categories.

Number	Reference category	Assessed topics	Reference
0	Scope of report		Art. 4 [7]
1	Establishment of reference buildings	• Reference buildings and related data sources and databases • Considered climatic conditions • Established new and existing building types and properties (e.g., floor area, primary energy, reference age, climate, typical heating, and cooling systems)	Annex 1, point 1 [6]
2	Identification of energy efficiency measures, measures based on renewable energy sources, and/or packages and variants of such measures for each reference building	• Current, future/coming, and NZEB requirements for new and existing buildings • Established packages of measures and/or building variants to the different building types • Details on the measures considered for both new and existing residential and non-residential buildings	Annex 1, point 2 [6]
3a	Calculation of the primary energy demand	• Details on the performed calculations (e.g., multi-stage optimization, dynamic method, starting year, accounted energy uses) and energy demands (referring to the energy scheme of the Regulation) • Specifics on the used weather data, indoor (operative) temperature, primary energy factors	Annex 1, point 3 [6]
3b	Calculation of the global cost in terms of net present value for each reference building	• Cost categories defined in the global cost calculation • Details on the calculations performed (e.g., financial and macroeconomic perspectives, data sources for construction and renovation costs, full cost approach for cost quantification, omitted cost items, technology costs) • Specifics on main calculation parameters (e.g., calculation period, discount rate, real interest rate, energy prices, annual increase in energy prices, CO_2 emissions costs)	Annex 1, point 4 [6]
4	Sensitivity analysis	• Details on the sensitivity analyses carried out and related outcomes	Annex 1, point 5 [10]
5	Derivation of a cost-optimal level of energy performance for each reference building	• Identification of the cost-optimal levels for the different (new, existing) building types • Definition of a cost-optimal range selecting the optimal variants • Analysis of the requirements resulting in a lower use of primary energy (left border of the cost-optimal range) and of the economic perspectives (financial and macroeconomic) used to derive the cost-optimal levels and related differences	Annex 1, point 6 [6]
6	Plan to reduce the gap	• Comparison between the current/future/NZEB requirements and the identified cost-optimal levels • Identification of the gaps between current/future/NZEBs energy requirements and the cost-optimal levels for new and existing buildings • Analysis of the plan and appropriate steps to reduce the gaps	Art. 5(3) [7]; Art. 6(2) [6]

The methodology included the analysis and comparison of key input parameters (discount rate, energy prices, annual increase in energy prices) both for residential and non-residential buildings. Then, the cost-optimal levels were derived in terms of primary energy consumptions and global costs. Gaps between current requirements and cost-optimal levels were also checked, both in terms of primary energy and U-value of building elements. A comparison with previously cost-optimal reports was also made. Finally, an analysis of the conformity with the common methodology as well as of the plausibility of the input parameters and calculated cost-optimal levels was carried out to verify the calculation compliance with the cost-optimal framework based on the policy requirements [6,7]. The most recent cost-optimal reports are publicly available [45]. This review takes into account 30 cost-optimal reports, which were delivered by: Austria (AT), Belgium-Brussels (BEbru), Belgium-Flanders (BEfla), Belgium-Wallonia (BEwal), Cyprus (CY), Czech Republic (CZ), Germany (DE), Denmark (DK), Estonia (EE), Greece (EL), Spain (ES), Finland (FI), France (FR), Hungary (HU), Ireland (IE), Italy (IT), Lithuania (LT), Latvia (LV), Luxembourg (LU), Malta (MT), the Netherlands (NL), Poland (PL), Portugal (PT), Romania (RO), Sweden (SE), Slovenia (SI), Slovakia (SK), and the United Kingdom (UK).

3. Results

The results obtained are discussed in the following sections, as follows:

- Section 3.1: analysis and comparison of key input parameters (discount rate, energy prices for both residential and non-residential buildings, annual increase in energy prices for both residential and non-residential buildings).
- Section 3.2: analysis of cost-optimal levels (primary energy consumption and global costs).
- Section 3.3: comparison with first cost-optimal levels (2013) and consolidated version.
- Section 3.4: gaps between current requirements and cost-optimal levels.

### 3.1. Input Parameters Analysis and Comparison

The applied primary energy factors (PEF), the discount rate, the energy prices, and their development over the calculation period have significant impact on the outputs of the cost-optimal calculations. Under the EPBD framework, Member States can adapt them to their context. Figure 3 shows and compares their choices, and provides some key statistics.
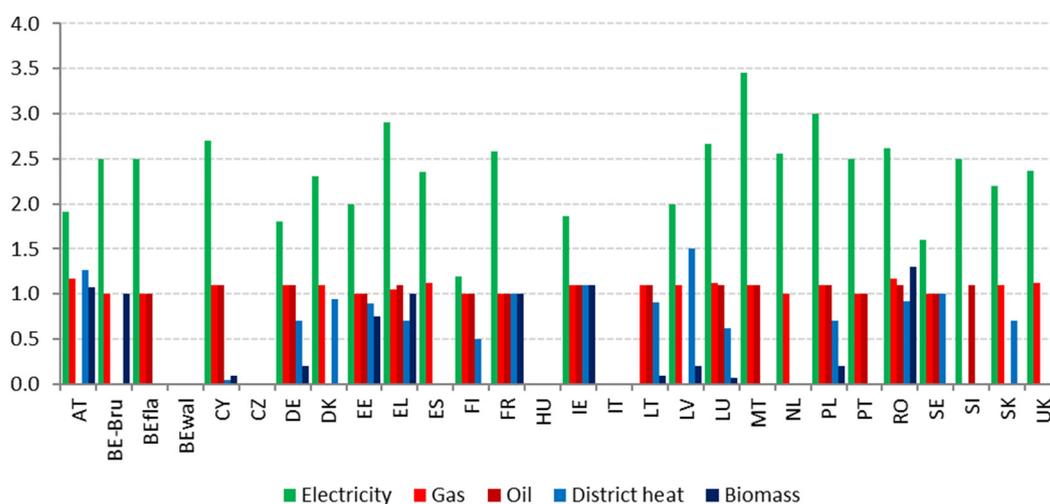
	Electricity	Gas	Oil	District Heat	Biomass
Min	1.20	1.00	1.00	0.05	0.07
Max	4.03	1.22	1.10	1.50	1.30
Average	2.39	1.08	1.06	0.85	0.67
Median	2.50	1.10	1.10	0.91	1.00

Figure 3. Primary energy factors used by Member States and associated statistics.

Regarding the Primary Energy Factors applied for the main energy fuels (Figure 3), the main differences refer to electricity, with a maximum of 3.5 (Malta) and a minimum of 1.2 (Finland). We also observed good variation for biomass, which some Member States (Cyprus, Germany, Lithuania, Latvia, Luxembourg, and Poland) considered almost fully renewable (PEF close to zero), and some others (Austria, Estonia, Greece, France, Ireland, Romania) assimilated into fossil fuels (PEF close to 1). Discount rates (DR) are reported in Figure 4.
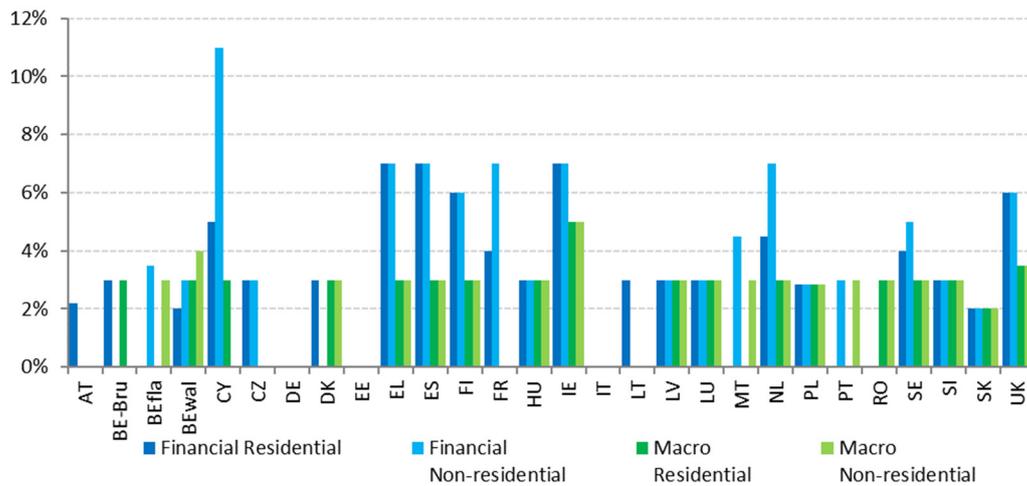
	Financial Residential	Financial Non-Residential	Macro-residential	Macro-non-Residential
Min	2%	2%	2%	2%
Max	7%	11%	5%	5%
Average	4%	5%	3%	3%
Median	3%	5%	3%	3%

Figure 4. Discount rate used by Member States and associated statistics.

As shown in Figure 4, almost all Member States (with a few exceptions) made the same choices for the macro-economic perspective (DR = 3%), following the indication of the official Guidelines [11]. The picture for the financial perspective is more heterogeneous, with an average of 4% for the residential and 5% of the non-residential sector.

The energy prices and the annual increase in energy price applied by Member States for residential and non-residential building types are shown in Figures 5 and 6. Minimum, maximum, average, and median values are reported for both residential and non-residential sectors in Tables 2 and 3.
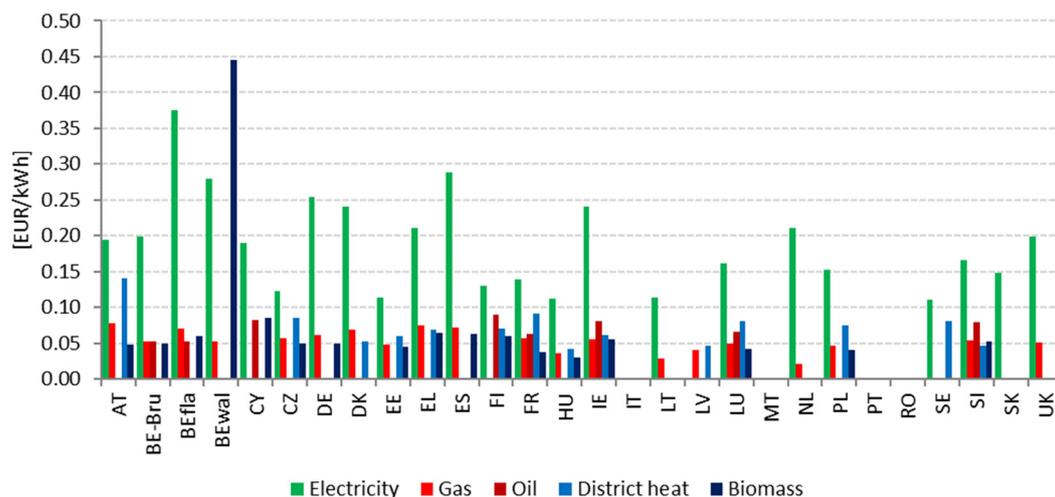

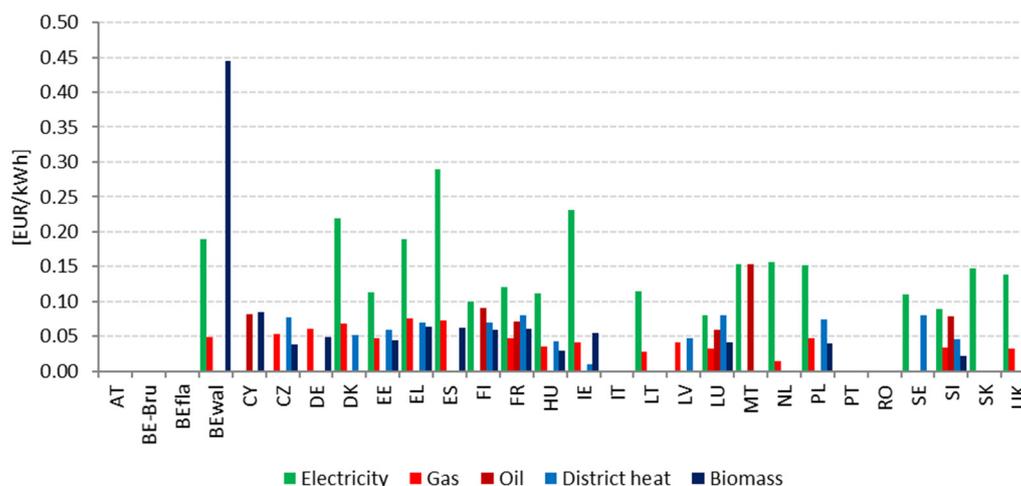**Figure 5.** Energy prices used by Member States for residential sector.

Figure 6. Annual increase in energy prices used by Member States for non-residential sector.

Table 2. Statistics about the energy prices selected for residential (Res) and non-residential (N-Res) buildings.

	Electricity		Gas		Oil		District Heat		Biomass	
	Res	N-Res	Res	N-Res	Res	N-Res	Res	N-Res	Res	N-Res
Min	0.110	0.080	0.021	0.014	0.053	0.059	0.043	0.010	0.030	0.023
Max	0.375	0.311	0.078	0.075	0.090	0.154	0.140	0.081	0.445	0.445
Average	0.191	0.156	0.054	0.046	0.070	0.089	0.071	0.061	0.075	0.079
Median	0.190	0.143	0.054	0.047	0.072	0.081	0.070	0.069	0.050	0.052

Table 3. Statistics about the annual increase in energy prices used for residential (Res) and non-residential (N-Res) buildings.

	Electricity		Gas		Oil		District Heat		Biomass	
	Res	N-Res	Res	N-Res	Res	N-Res	Res	N-Res	Res	N-Res
Min	0.2%	0.2%	1.0%	1.0%	1.2%	1.2%	0.6%	1.0%	0.7%	0.7%
Max	5.4%	2.8%	3.6%	2.8%	3.0%	5.3%	2.8%	2.8%	2.8%	2.8%
Average	1.7%	1.4%	1.9%	1.8%	2.4%	2.9%	1.6%	1.8%	1.7%	1.8%
Median	1.6%	1.5%	1.8%	1.8%	2.5%	2.6%	1.5%	1.9%	2.0%	2.0%

The figures demonstrate that the divergences are not as relevant for energy prices. Only a few cases (e.g., Flanders, Belgium for electricity and Wallonia, Belgium for biomass) referred to values not close to the averages.

The analysis of the annual increase in energy prices (Figure 6, Table 3) showed that the average of the Member States' values for electricity was closer than gas to the indication of the European Commission (For the estimation of fuels and electricity price development trends, the Commission reference data to Member States: https://ec.europa.eu/energy/en/data-analysis/market-analysis, https://ec.europa.eu/energy/en/news/reference-scenario-energy, accessed on 10 June 2022) (respectively 1.4% and 2.8%). However the deviation is quite high for all energy vectors, especially for electricity in the residential sector. For instance, here, Brussels applied only 0.2% against 5.4% for the Netherlands.

3.2. Cost-Optimal Level Assessment

From the reports analyzed, it was not possible to extract all the cost-optimal levels for all Member States, as half of them did not derive them in a clear and complete way. Plotting the values collected in the primary energy/global cost domain (Figures 7 and 8),

an overall picture was obtained for new and existing buildings. The values pertain to single family houses (SFH), multi-family houses (MFH), and offices and other non-residential (N-R) buildings. The latter is the least-covered category, for which Member States are free to select the reference type. In some cases, these results refer to a particular type (often an educational building), in others to an average among different building types (e.g., school, commercial and hospital). For this reason, the comparison between countries cannot be fully consistent.
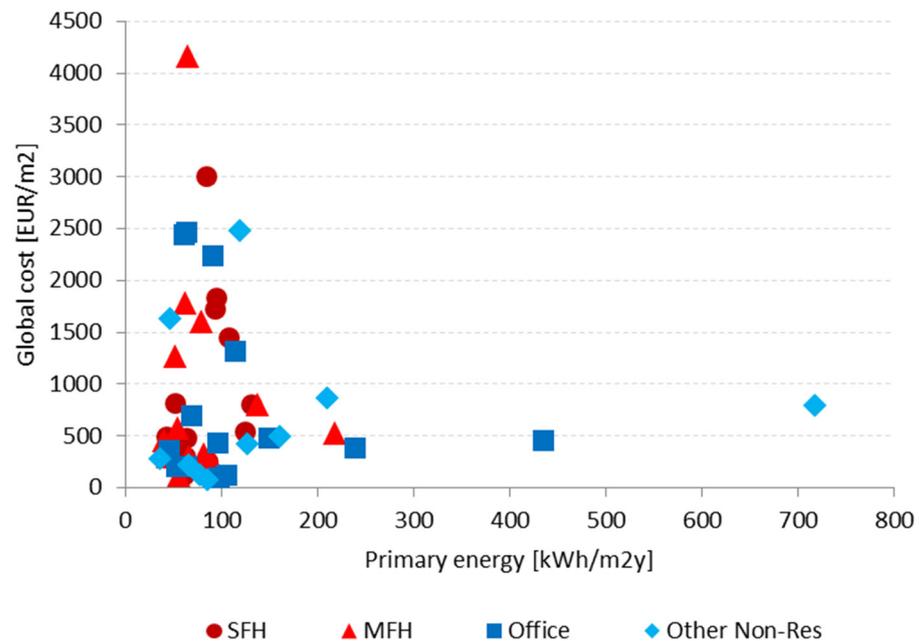

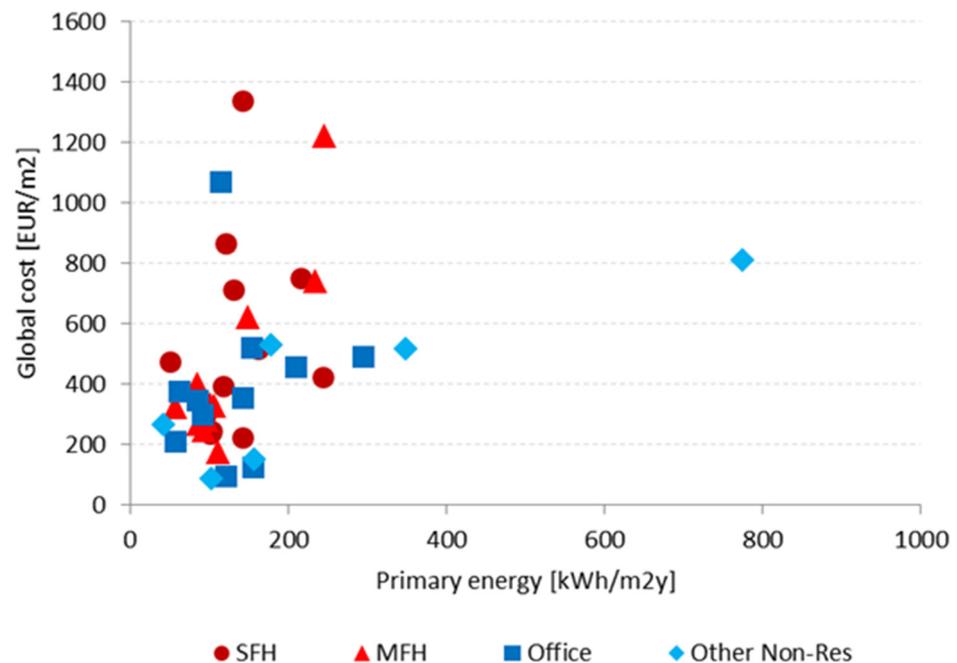**Figure 7.** Cost-optimal levels for new buildings.

Figure 8. Cost-optimal levels for existing buildings.

For new buildings, the majority of cost-optimal points fell between 50 and 100 kWh/m²y, with an average of 80 kWh/m²y for the residential sector and 140 kWh/m²y for the non-

residential sector. Associated global costs were often lower than 1500 EUR/m^2, with an average of 925 EUR/m^2 for the residential and 800 EUR/m^2 for the non-residential sector.

For existing buildings, the majority of cost-optimal levels fell between 75 and 175 kWh/m^{2}y, with an average of 130 kWh/m^{2}y for the residential and 180 kWh/m^{2}y for the non-residential sector. For existing buildings, the global costs were generally lower than 600 EUR/m^2, with an average of 500 EUR/m^2 for the residential and 385 EUR/m^2 for the non-residential sector.

An additional analysis grouped countries per climate zone (Tables 4 and 5) [50]. We applied an official approach [51], including:

- Mediterranean zone: Cyprus, Greece, Spain, Italy, Malta, and Portugal;
- Oceanic zone: Belgium, France, Ireland, Luxembourg, the Netherlands, and the UK;
- Continental zone: Austria, Czech Republic, Estonia, Germany, Hungary, Lithuania, Latvia, Poland, Romania, Slovenia, and Slovakia;
- Nordic zone: Denmark, Finland, and Sweden.

Table 4. Average cost-optimal levels (PE: Primary Energy and GC: Global Cost) for new buildings per climatic condition.

Climate Zone	New SFH		New MFH		New Office		New Other n-R	
	PE [kWh/m^{2}y]	GC [EUR/m^2]	PE [kWh/m^{2}y]	GC [EUR/m^2]	PE [kWh/m^{2}y]	GC [EUR/m^2]	PE [kWh/m^{2}y]	GC [EUR/m^2]
Mediter.	81	887	105	698	221	648	423	607
Oceanic	86	760	66	746	94	1214	140	992
Continental	81	419	93	356	80	157	67	173
Nordic	77	1882	62	2076	66	1681	120	2481

Table 5. Average cost-optimal levels (PE: Primary Energy and GC: Global Cost) for existing buildings per climatic condition.

Climate Zone	Existing SFH		Existing MFH		Existing Office		Existing Other n-R	
	PE [kWh/m^{2}y]	GC [EUR/m^2]	PE [kWh/m^{2}y]	GC [EUR/m^2]	PE [kWh/m^{2}y]	GC [EUR/m^2]	PE [kWh/m^{2}y]	GC [EUR/m^2]
Mediter.	161	500	148	467	175	396	775 *	808 *
Oceanic	124	670	142	628	160	682	264	522
Continental	97	329	100	237	112	143	102	166
Nordic	183	643	77	303	78	336	122	236

* Available only for Malta (average of values obtained for schools, hotels, restaurants, shops, elderly centers and sport complex).

From this comparison, it is interesting to observe that in in all cases the primary energy consumption associated with cost-optimal levels is lower in the cold zones. Global costs are lower in the Continental zone, which includes the States of Eastern Europe.

3.3. Comparison with First Cost-Optimal Levels (2013)

Table 6 shows a comparison between the primary energy consumption associated with the cost-optimal levels of 2013 and 2020, when both these values were available. A reduction in primary energy consumption associated with the cost-optimal levels (negative percentage) can be observed for almost all building types: about −20% for the residential (new and existing) and new office buildings.

Table 6. Comparison between cost-optimal levels obtained Member States in 2020 and 2013.

MS	New SFH	New MFH	New Office	Existing SFH	Existing MFH	Existing Office
AT	−53%	−47%		−55%		
BEwal	−27%	−44%				
DE	−60%	−36%	−36%			
DK	−13%	−26%	−11%	−23%	−21%	−43%
EE	−46%	−39%	−44%	11%	−24%	−11%
ES	−12%	6%	35%	−9%	−17%	16%
FI	−38%	−32%	−44%	−17%	−38%	−24%
FR	−18%	−10%	−2%	66%	52%	108%
HU	−1%	4%	26%	21%	−22%	−19%
IE	56%	−4%	−10%			
LT	15%	16%	18%	9%	17%	12%
LU	0%	−1%	1%	0%	0%	−7%
PL	−26%	−21%		−1%	−8%	
RO	−48%	−60%	−5%	−46%	−25%	11%
SE	57%	35%	−28%			
SI	−100%	−100%	−100%	−100%	−100%	−100%
SK	−71%	−68%	−38%	−83%	−68%	−44%
UK	−32%	−41%	−17%			
Average	−23%	−23%	−17%	−17%	−21%	−9%

Table 7 displays a consolidated version of cost-optimal energy levels that considers 2013 levels when 2020 ones are missing, for all eight building types previously discussed. Only two Member States (Bulgaria and the Netherlands) did not provide a clear cost-optimal requirement.

Table 7. Consolidated version of cost-optimal levels in kWh/m^{2}y (considering both 2020 and 2013 results).

MS	New SFH	New MFH	New Office	New Other n-R	Existing SFH	Existing MFH	Existing Office	Existing Other n-R
AT	41	41	291	n/a	44	44	n/a	n/a
BEbru	64	55	n/a	n/a	119	149	n/a	n/a
BEfla	n/a	n/a	63	46	n/a	n/a	71	51
BEwal	82	63	64	48	143	246	115	n/a
BG	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
CY	156	217	280	n/a	160	178	252	n/a
CZ	84	95	210	n/a	144	78	193	n/a
DE	38	44	110	110	n/a	n/a	n/a	n/a
DK	52	40	46	n/a	121	58	63	n/a
EE	87	103	93	n/a	250	130	160	n/a
EL	109	52	114	n/a	163	107	143	n/a
ES	53	45	96	n/a	78	70	86	n/a
FI	92	82	86	117	233	102	93	130
FR	76	60	109	112	178	166	141	208
HR	84	105	62	n/a	79	144	55	n/a
HU	132	138	106	86	141	113	156	158
IE	52	66	69	211	104	88	210	260
IT	66	32	46	n/a	n/a	n/a	n/a	n/a
LT	141	154	127	118	156	168	140	131
LV	74	75	93	n/a	114	84	93	n/a
LU	125	82	150	180	131	85	150	192
MT	32	15	436	844	23	15	n/a	908
NL	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
PL	89	83	97	79	89	83	97	79
PT	40	29	n/a	128	61	48	n/a	n/a
RO	70	40	50	64	105	63	90	135
SE	85	65	62	n/a	89	115	99	n/a
SI	86	92	64	66	96	94	121	104
SK	29	29	71	n/a	24	27	46	n/a
UK	96	77	105	201	n/a	n/a	n/a	n/a

3.4. Gaps between Current Requirements and Cost-Optimal Levels

The evaluation of the gaps between cost-optimal levels and current requirements is a relevant step in the calculation, since it should provide useful indications for the update of existing energy performance regulations. National minimum energy performance requirements should not be higher than 15% compared to the outcome of the cost-optimal levels. A plan should be defined to reduce the gaps that cannot be strongly justified.

The gap quantification allows the comparison of results among countries, reference building types, and requirements for renovation of building or components. Therefore, it is important to note that the results are not fully comparable among Member States, since they are free to choose the macroeconomic or financial perspective for deriving the cost-optimal levels and to apply different national standards to calculate the energy performance of buildings. Other differences (e.g., related to investment costs) should reflect national market conditions, and are thus not a limit to, but an integral part of the comparison.

The comparison between the levels assessed in 2013 and 2020 can also be extended to the shortfall against minimum energy performance requirements in force. Tables 8 and 9 collect the available information, providing the gap evolution when data are available from both the 2013 and 2020 reports. A negative percentage means that the analyzed energy requirement is lower than the cost-optimal level. We report a single gap value for cases that were assessed only in a calculation round (by indicating the reference year), and both gap values when available. The Member States for which it was not possible to derive clear figures for any building types are not included in the tables.

Table 8. Consolidated version of shortfalls against minimum energy performance requirements for new buildings, with comparisons between the 2013 and 2020 values when available. A negative gap means that the requirement is lower than the cost-optimal level.

MS	New SFH	New MFH	New Office	New Other N-R
AT	48% (2013)	55% (2013)	6% (2013)	n/a
BEbru	−30% (2020)	−18% (2020)	n/a	n/a
BEwal	from 15% to 40%	from 15% to 83%	n/a	n/a
CY	33% (2013)	−2% (2013)	−7% (2013)	n/a
DE	0% (2013)	0% (2013)	0% (2013)	n/a
DK	from −10% to −22%	from −11% to −15%	from 33% to −11%	n/a
EE	from 0% to 46%	from −12% to 31%	from −3% to 42%	n/a
ES	from 8% to 14%	from 7% to 21%	7% (2013)	n/a
FI	from 15% to 14%	from 0% to 9%	from 3% to 13%	14% (2020)
FR	from −46% to −24%	from −6% to 2%	from −13% to 3%	from −13% to −10%
HR	49% (2013)	n/a	n/a	n/a
HU	from 67% to −32%	from 26% to −38%	from 60% to −6%	−1% (2020)
IE	from 51% to −5%	from −11% to −35%	from 299% to 9%	−9% (2020)
IT	31% (2013)	80% (2013)	−22% (2013)	n/a
LT	from 20% to −10%	from 11% to −4%	from 21% to 1%	2% (2020)
LU	from 0% to −21%	from 0% to −18%	from 16% to 0%	−21% (2020)
MT	172% (2013)	680% (2013)	61% (2020)	from 63% to 30%
NL	5% (2020)	5% (2020)	−3% (2020)	−3% (2020)
PL	from 17% to 7%	from 43% to 3%	−38% (2020)	−24% (2020)
PT	−10% (2013)	−12% (2013)	n/a	25% (2020)
RO	from 102% to 120%	from 33% to 195%	from 16% to 20%	77% (2020)
SE	from 35% to 6%	from 52% to 24%	from −6% to 23%	n/a
SI	14% (2013)	14% (2013)	20% (2013)	8% (2020)
SK	116% (2013)	43% (2013)	35% (2013)	n/a
UK	from −21% to −3%	from −21% to 19%	−5% (2013)	−12% (2020)

Table 9. Consolidated version of shortfalls against minimum energy performance requirements for existing buildings, with comparison between 2013 and 2020 values when available.

MS	Existing SFH	Existing MFH	Existing Office	Existing Other N-R
AT	54% (2013)	45% (2013)	n/a	n/a
BEbru	−54% (2020)	−61% (2020)	n/a	n/a
CY	n/a	n/a	−7% (2013)	n/a
DK	from 1% to 10%	from 3% to 63%	from −3% to 39%	n/a
EE	from −7% to 16%	from 6% to 38%	from 17% to 31%	n/a
ES	−29% (2013)	−27% (2013)	−6% (2013)	n/a
FI	from 19% to 8%	from 1% to 4%	from 11% to 0%	10% (2020)
FR	from 10% to 1%	from 10% to −5%	from 49% to −34%	from 49% to 6%
HR	59% (2013)	n/a	n/a	n/a
HU	from 71% to −6%	from −15% to 4%	from −31% to −10%	−30% (2020)
IE	23% (2020)	42% (2020)	−28% (2020)	82% (2020)
LT	from 54% to 7%	from 56% to 5%	from 80% to 10%	10% (2020)
LU	from 8% to 8%	from 7% to 8%	from 5% to 14%	−16% (2020)
MT	270% (2013)	680% (2013)	n/a	from 74% to 27%
PL	from 79% to 7%	from 92% to 3%	−38% (2020)	−24% (2020)
PT	1% (2013)	−2% (2013)	n/a	n/a
RO	from 65% to 46%	from 58% to 115%	from 40% to −33%	−16% (2020)
SE	2% (2020)	−35% (2020)	−24% (2020)	n/a
SI	15% (2013)	19% (2013)	−37% (2013)	−17% (2020)
SK	48% (2013)	49% (2013)	85% (2013)	n/a

Focusing on Member States for which data from both 2013 and 2020 are available, it can be observed that in some cases the gaps decreased, and in others they increased with the second calculation round. This progress can be assessed as quite positive, especially for existing buildings. A key implication of this aspect for a future revision of the methodology is accounting for the developments of the construction market as well as the technological innovation of building products, considering the evolution of energy prices, primary energy factors, and materials. Another important implication is the identification of the most suitable renovation packages that Member States should consider to achieve ZEBs.

4. Discussion

The cost-optimal methodology appears to be currently entrenched at government and scientific levels. It represents a well-established tool that includes both energy and economic evaluations. Progress is clearly assessed in Member States in relation to the analyzed categories. In support of future reviews of the cost-optimal methodology implementation, the following proposals are elaborated.

- A common template to collect data

A future common template would be useful to collect key input data and outputs. A large number of input data may impact final results (e.g., implemented technology costs, normally collected from databases or construction projects), while a common template would allow easier and comparable methodology implementation, and consequently coordinated assessment.

- Increase the number of variants

Considering a higher number of variants could be useful, as the current number (10 packages/variants plus the reference case) may not guarantee a comprehensive coverage of applicable technologies. A number of 20 packages/variants appears suitable, as some Member States and other studies [52–55] have already shown this figure as feasible.

- Guidance for historical buildings

Indications could be provided for historical buildings. Normally the selected existing building types date from the years 1960s–1980s, and a few Member States also considered

historical buildings. Guidance for selecting energy efficiency measures in heritage buildings could be useful [56].

- Indications on indoor air quality and comfort

Currently, a few Member States considered comfort and indoor air quality within their cost-optimal framework, probably due to the complexity of their inclusion in the calculations. Summer comfort is particularly overlooked, and an active air conditioning system is not often included among the selected efficiency measures. One possible procedure would refer to the operative indoor temperature provided by Standard EN 16798 [57], which replaced EN 15251. According to this set-point, the energy demand for cooling should be calculated for all building variants, and an active cooling system should be considered for variants with an energy demand higher than a certain limit (e.g., 3 or 5 kWh/month).

- Introduction of a base refurbishment level

The cost-optimal framework could take into account additional variables, such as the increase in the building value due to better energy performance, as well as further co-benefits deriving from the application of energy efficiency measures and the use of renewable sources, such as improved comfort, noise reduction, and indoor air quality.

The introduction of a "base refurbishment level" for existing buildings would take these factors into account. It would represent the lower renovation level to be compared with more efficient ones. This base level should comprise building façade and roof rehabilitation, old windows and heating/cooling system replacement, active cooling installation. Its definition would allow the obtainment of harmonized building variants in terms of functionality, aesthetics, and liveability, would recognize which costs could be omitted, and would fix the end-life of the original building components (normally older than 40 years). An example of how the base refurbishment level can be applied with good results is given in the Entranze project [20].

- Additional co-benefits of better performing buildings

Member States are free to extend the methodology to full life-cycle costs, although none of them have. As recently discussed [58], the global cost calculation could follow a revised formula, which includes new savings related to the environmental impacts (C_{EN}), economic impacts (C_{EC}, i.e., the change in GDP and the cost savings due to improved energy security), and social impacts (C_{SO}), as shown in equation 2:

$$C_G(\tau) = C_I - C_{EN} - C_{EC} - C_{SO} + \sum_j \left[\sum_{i=1...\tau} (C_{a,i}(j) \times R_d(i) + C_{C,i}(j)) - V_{f,\tau}(j) \right] \quad (2)$$

where:
$C_G(\tau)$ is the life-cycle cost including environmental, economic, and social indicators [€];
C_I is the sum of initial investment costs;
$C_{a,i}(j)$ is the annual cost for component j at the year i;
$R_d(i)$ is the discount term for year i;
$C_{c,i}(j)$ means carbon cost per measure or set of measures j during year i (not included in the financial perspective methodology);
$V_{f,\tau}(j)$ is the final value of component j at the end of the calculation period.
The inclusion of this approach in the cost-optimal calculation would be relevant to the wider benefits of energy efficiency and policy decisions that shape the market transition.

- Derivation of the cost-optimal level

In relation to the cost-optimal level identification, two aspects deserve more attention:
- the application of the "cost-optimal range" is too often ignored, despite affecting the final results;
- the choices related to the averaging operation applied to the cost-optimal levels (derived for different building types) to quantify the shortfall against current requirements should always be thoroughly discussed and motivated.

The first point also relates to the wider benefits of energy efficiency previously discussed. If this effect is not explicitly considered in the optimization method, it becomes more important to select the optimum level in a non-conservative way. That is, by applying a tolerance on global costs (3%–5%) and choosing the lowest energy level (in the so called "left border of the cost-optimal range").

- Enhancing sensitivity

The selection of input parameters highly influences results. Consequently, sensitivity analysis is of a key importance in controlling their impact and the robustness of related outcomes. This allows quantification of the uncertainty of the data, especially those derived from databases. Two approaches are possible: changing parameters one by one (as done by Member States) or assigning a probabilistic function (e.g., Monte Carlo simulation) to input parameters and obtaining more precise distributions of outcomes. This approach takes into account more fully the heterogeneity of the different data sources, providing results based on intervals. As example of this approach, a study from Becchio et al. [59] considered, for each identified parameter, a minimum, average, and maximum value in a triangular distribution.

- Cost-optimality at district level

It would be useful to define a cost-optimal approach focused to the district level, where environmental and social impacts are considered in terms of the co-benefits linked to the environment and the involved community [60]. This could also encourage the development of decarbonization strategies for reducing environmental impacts at local level [61].

Finally, it is worth underlining that, in compliance with Article 6 of [8] (ex-Article 5 of the EPBD), the calculation of cost-optimal levels falls within the core of the Green Deal [3], as costs of greenhouse gas allowances as well as environmental and health aspects of energy use will have to be considered in order to derive the lowest costs [62]. This is also in line with the update of the NZEB definitions, the introduction of energy requirements and incentive mechanisms for renovation [63], as stated in the Renovation Wave [4], and the environmental targets for the building sector. The cost-optimal level shall lie within the range of performance levels where the cost benefit analysis calculated over the estimated economic lifecycle is positive.

5. Conclusions

Reducing the energy demand in buildings is a prerequisite for meeting Europe's energy efficiency and GHG-emission reduction targets. The cost-optimal and NZEB implementation can support this process and provide useful references to develop policy and incentive measures to retrofit the existing building stock.

This paper gives a comprehensive assessment of the cost-optimal methodology in Member States based on latest reports. This review appears necessary in order to assess the implementation progress and outline weak and strong points as well as future developments. The review outputs highlight how cost-optimality is currently a well-established concept in Member States, and an overall positive development can be acknowledged. Based on the collected data, some statistics can be presented. The average cost-optimal level is assessed at 80 kWh/m^{2}y for the new residential sector and 140 kWh/m^{2}y for the new non-residential sector, while it is 130 kWh/m^{2}yr for the existing residential sector and 180 kWh/m^{2}y for existing non-residential sector. For almost all building types, the primary energy consumptions associated with cost-optimal levels were lower in cold regions, while global costs are normally lower in countries with a warm and mild climate.

The positive assessment achieved by Member States in implementing the cost-optimal methodology implies its potential for adaptation toward the gradual introduction of zero-emission buildings (ZEBs), for both new and existing buildings and at building element level.

The comparison with cost-optimal levels of the previous calculation round (2013) shows that for almost all building types, lower values were obtained in 2020. Looking at

the consolidated cost-optimal levels, only two Member States did not clearly provide any cost-optimal requirement. Regarding conformity to the EU policy framework, some gaps can be highlighted:

- almost two-thirds of the Member States failed to cover one or more objectives, such as a required building type or the cost-optimal levels for building elements installed in existing buildings.
- almost half of the Member States applied derivation methodologies that did not fully conform or did not provide sufficient information to allow assessment of this calculation step.
- many Member States did not provide convincing explanations about the existing gaps or clear plans to reduce them, or did not even discuss the shortfalls against current requirements. Only in a few cases was a comparison with NZEB requirements available.

However, the situation looks positive with regard to the plausibility of input parameters and results obtained. As a consequence, the identified areas for improvement of the cost-optimal methodology include modalities of adapting to ZEBs to better enlighten the environmental and externalities aspects. The implications of such adaptations will have to be tested in terms of calculation robustness, confidence level, and sensitivity analysis.

The future cost-optimal framework will enable the calculation of both energy and emission performance, taking into account environmental and health externalities, as well as the emissions trading system (ETS) extension and carbon prices. The update of the calculations of cost-optimal levels will have to be monitored while also considering:

- the update of the NZEB definitions for new and renovated buildings;
- the introduction of energy requirements and incentive mechanisms for existing buildings in line with the Renovation Wave Strategy;
- the environmental targets for 2030 and the carbon neutrality goal for 2050 for the building sector as a whole.

This review also details suggestions on the points that could be considered in the future cost-optimal methodology that will be reviewed by 2026. Among the implications of the results of this review are the introduction of cost-optimality at district level and historical buildings; the use of a common template to collect data; harmonization of results and streamlining of the administrative aspect. A base refurbishment level could be useful to take into account the increased value of energy efficiency implementation in building retrofit. Enhanced importance could be placed on comfort and indoor air quality, as well as on the inclusion of wider energy efficiency benefits, such as a reduced import dependency and a positive impact on the economy (e.g., job creation). In this way, the global cost concept could be more in line with a complete life-cycle assessment that would take into account all environmental impacts throughout the life-cycle. In particular, the introduction of socioeconomic benefits could fulfil ambitious requirements and unlock higher energy and monetary savings. From this perspective, the outcomes of this cost-optimal review assume a strategic value, since they allow a comprehensive comparison among Member States for assessing progress and related strengths and weaknesses. Its future development and implementation will be crucial for the renovation of existing buildings and the achievement of a zero-carbon society in 2050.

Author Contributions: Conceptualization, P.Z., D.D., R.A. and P.B.; methodology, P.Z., D.D. and R.A.; software, P.Z., D.D. and R.A.; formal analysis, P.Z., D.D. and R.A.; investigation, P.Z., D.D. and R.A.; data curation, P.Z., D.D. and R.A.; writing—original draft preparation, P.Z. and D.D.; writing—review and editing, D.D.; visualization, P.Z. and D.D.; project administration, P.B. All authors have read and agreed to the published version of the manuscript.

List of Abbreviations and Definitions

EPBD	Energy Performance of Buildings Directive
EED	Energy Efficiency Directive
MFH	Multi-family house
n-R	Non-residential
NZEB	Nearly zero-energy building
EE	Energy efficiency
RES	Renewable energy systems
SFH	Single-family house

References

1. Economidou, M.; Todeschi, V.; Bertoldi, P.; D'Agostino, D.; Zangheri, P.; Castellazzi, L. Review of 50 years of EU energy efficiency policies for buildings. *Energy Build.* **2020**, *225*, 110322. [CrossRef]
2. EC, A Clean Planet for All, COM. 773 Final, A Clean Planet for All a European Strategic Long-Term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy. 2018. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0773&from=EN (accessed on 4 May 2022).
3. EC, the European Green Deal, COM (2019) 640 Final, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. Available online: https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf (accessed on 8 June 2022).
4. EC, A Renovation Wave for Europe—Greening our Buildings, Creating Jobs, Improving, COM (2020) 662 Final. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1603122220757&uri=CELEX:52020DC0662 (accessed on 29 June 2022).
5. EC 2013, Green Paper, A 2030 Framework for Climate and Energy Policies, COM (2013) 169 Final. Available online: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2013:0169:FIN:en:PDF (accessed on 5 July 2022).
6. Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0001.01.ENG&toc=OJ:L:2018:328:FULL (accessed on 17 May 2022).
7. European Parliament. EPBD Recast, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (Recast). *Official Journal of the European Union*, 18 June 2010; L 153/13.
8. Revision of the Directive of the European Parliament and of the Council on the Energy Performance of Buildings (Recast), COM (2021) 802 Final. Available online: https://ec.europa.eu/energy/sites/default/files/proposal-recast-energy-performance-buildings-directive.pdf (accessed on 19 May 2022).
9. EC. Commission Staff Working Document, Good Practice in Energy Efficiency, Accompanying the Document: Energy efficiency for a Sustainable, Safer and More Competitive Europe (Communication from the Commission to the European Parliament and the Council). 27 April 2017. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52014DC0520 (accessed on 1 August 2022).
10. European Parliament. Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 Supplementing Directive 2010/31/EU of the European Parliament and of the Council on the Energy Performance of Buildings by Establishing a Comparative Methodology Framework for Calculating Cost-Optimal Levels of Minimum Energy Performance Requirements for Buildings and Building elements. *Off. J. Eur. Union* **2012**, *136*, 18–36. Available online: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:081:0018:0036:EN:PDF (accessed on 15 September 2022).

11.   European Parliament. Guidelines accompanying Commission Delegated Regulation (EU) No. 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements. *Off. J. Eur. Union* **2012**. Available online: https://op.europa.eu/en/publication-detail/-/publication/b6d03fa4-b936-43f1-9120-10b027c04e3a/language-en (accessed on 15 September 2022).
12.   D'Agostino, D.; Tzeiranaki, S.T.; Zangheri, P.; Bertoldi, P. Assessing Nearly Zero Energy Buildings (NZ EBs) development in Europe. *Energy Strat. Rev.* **2021**, *36*, 100680. [CrossRef]
13.   D'Agostino, D.; Parker, D.; Epifani, I.; Crawley, D.; Lawrie, L. How will future climate impact the design and performance of nearly zero energy buildings (NZEBs)? *Energy* **2021**, *240*, 122479. [CrossRef]
14.   D'Agostino, D.; Mazzarella, L. What is a Nearly zero energy building? Overview, implementation and comparison of definitions. *J. Build. Eng.* **2018**, *21*, 200–212. [CrossRef]
15.   Pikas, E.; Thalfeldt, M.; Kurnitski, J. Cost optimal and nearly zero energy building solutions for office buildings. *Energy Build.* **2014**, *74*, 30–42. [CrossRef]
16.   D'Agostino, D.; Mazzarella, L. Data on energy consumption and Nearly zero energy buildings (NZEBs) in Europe. *Data Brief* **2018**, *21*, 2470–2474. [CrossRef]
17.   Kurnitski, J.; Kuusk, K.; Tark, T.; Uutar, A.; Kalamees, T.; Pikas, E. Energy and investment intensity of integrated renovation and 2030 cost optimal savings. *Energy Build.* **2014**, *75*, 51–59. [CrossRef]
18.   Buso, T.; Becchio, C.; Corgnati, S.P. NZEB, cost- and comfort-optimal retrofit solutions for an Italian Reference Hotel. *Energy Procedia* **2017**, *140*, 217–230. [CrossRef]
19.   Ashrafian, T.; Yilmaz, A.Z.; Corgnati, S.P.; Moazzen, N. Methodology to define cost-optimal level of architectural measures for energy efficient retrofits of existing detached residential buildings in Turkey. *Energy Build.* **2016**, *120*, 58–77. [CrossRef]
20.   Zangheri, P.; Armani, R.; Pietrobon, M.; Pagliano, L. Identification of cost-optimal and NZEB refurbishment levels for representative climates and building typologies across Europe. *Energy Effic.* **2017**, *11*, 337–369. [CrossRef]
21.   CA EPBD, Concerted Action EPBD: Implementing the Energy Performance of Buildings Directive (EPBD). Information of the Joint Initiative of EU Member States and the European Commission. Available online: http://www.epbd-ca.eu/themes/cost-optimum (accessed on 19 July 2022).
22.   Corgnati, S.P.; Fabrizio, E.; Filippi, M.; Monetti, V. Reference buildings for cost optimal analysis: Method of definition and application. *Appl. Energy* **2013**, *102*, 983–993. [CrossRef]
23.   Longo, S.; Montana, S.L.F.; Sanseverino, E.R. A review on optimization and cost-optimal methodologies in low-energy buildings design and environmental considerations. *Sustain. Cities Soc.* **2018**, *45*, 87–104. [CrossRef]
24.   Ferrara, M.; Monetti, V.; Fabrizio, E. Cost-Optimal Analysis for Nearly Zero Energy Buildings Design and Optimization: A Critical Review. *Energies* **2018**, *11*, 1478. [CrossRef]
25.   Østergård, T.; Jensen, R.L.; Maagaard, S.E. Building simulations supporting decision making in early design—A review. *Renew. Sustain. Energy Rev.* **2016**, *61*, 187–201. [CrossRef]
26.   Becchio, C.; Bottero, M.C.; Corgnati, S.P.; Dell'Anna, F. Decision making for sustainable urban energy planning: An integrated evaluation framework of alternative solutions for a NZED (Net Zero-Energy District) in Turin. *Land Use Policy* **2018**, *78*, 803–817. [CrossRef]
27.   Becchio, C.; Ferrando, D.G.; Fregonara, E.; Milani, N.; Quercia, C.; Serra, V. The cost-optimal methodology for the energy retrofit of an ex-industrial building located in Northern Italy. *Energy Build.* **2016**, *127*, 590–602. [CrossRef]
28.   Zacà, I.; D'Agostino, D.; Congedo, P.M.; Baglivo, C. Data of cost-optimality and technical solutions for high energy performance buildings in warm climate. *Data Brief* **2015**, *4*, 222–225. [CrossRef]
29.   D'Agostino, D.; Parker, D.; Melià, P.; Dotelli, G. Optimizing photovoltaic electric generation and roof insulation in existing residential buildings. *Energy Build.* **2022**, *255*, 111652. [CrossRef]
30.   Becchio, C.; Ferrando, D.; Fregonara, E.; Milani, N.; Quercia, C.; Serra, V. The Cost Optimal Methodology for Evaluating the Energy Retrofit of an ex-industrial Building in Turin. *Energy Procedia* **2015**, *78*, 1039–1044. [CrossRef]
31.   Baglivo, C.; Congedo, P.M.; D'Agostino, D.; Zacà, I. Cost-optimal analysis and technical comparison between standard and high efficient mono-residential buildings in a warm climate. *Energy* **2015**, *83*, 560–575. [CrossRef]
32.   Corrado, V.; Ballarini, I.; Paduos, S. Assessment of Cost-optimal Energy Performance Requirements for the Italian Residential Building Stock. *Energy Procedia* **2014**, *45*, 443–452. [CrossRef]
33.   D'Agostino, D.; Parker, D. A framework for the cost-optimal design of nearly zero energy buildings (NZEBs) in representative climates across Europe. *Energy* **2018**, *149*, 814–829. [CrossRef]
34.   D'Agostino, D.; Parker, D. Data on cost-optimal Nearly Zero Energy Buildings (NZEBs) across Europe. *Data Brief* **2018**, *17*, 1168–1174. [CrossRef] [PubMed]
35.   Ferrara, M.; Fabrizio, E.; Virgone, J.; Filippi, M. A simulation-based optimization method for cost-optimal analysis of nearly Zero Energy Buildings. *Energy Build.* **2014**, *84*, 442–457. [CrossRef]
36.   Fokaides, P.A.; Papadopoulos, A.M. Cost-optimal insulation thickness in dry and mesothermal climates: Existing models and their improvement. *Energy Build.* **2014**, *68*, 203–212. [CrossRef]
37.   Aste, N.; Adhikari, R.S.; Manfren, M. Cost optimal analysis of heat pump technology adoption in residential reference buildings. *Renew. Energy* **2013**, *60*, 615–624. [CrossRef]

38. Teodoriu, G.; Balan, M.; Șerbănoiu, I.; Verdeș, M. Cost-optimal analysis of performance relation thermal insulation—Hydronic heating system applied to Romanian residential buildings. *Procedia Technol.* **2014**, *12*, 583–590. [CrossRef]

39. Pikas, E.; Kurnitski, J.; Liias, R.; Thalfeldt, M. Quantification of economic benefits of renovation of apartment buildings as a basis for cost optimal 2030 energy efficiency strategies. *Energy Build.* **2015**, *86*, 151–160. [CrossRef]

40. Schimschar, S.; Blok, K.; Boermans, T.; Hermelink, A. Germany's path towards nearly zero-energy buildings—Enabling the greenhouse gas mitigation potential in the building stock. *Energy Policy* **2011**, *39*, 3346–3360. [CrossRef]

41. Ballarini, I.; Corgnati, S.P.; Corrado, V. Use of reference buildings to assess the energy saving potentials of the residential building stock: The experience of TABULA project. *Energy Policy* **2014**, *68*, 273–284. [CrossRef]

42. Kurnitski, J.; Saari, A.; Kalamees, T.; Vuolle, M.; Niemelä, J.; Tark, T. Cost optimal and nearly zero energy performance requirements for buildings in Estonia. *Est. J. Eng.* **2013**, *19*, 183–202. [CrossRef]

43. D'Agostino, D.; Zacà, I.; Baglivo, C.; Congedo, P.M. Economic and thermal evaluation of different uses of an existing structure in a warm climate. *Energies* **2017**, *10*, 658. [CrossRef]

44. D'Agostino, D.; Cuniberti, B.; Bertoldi, P. Data on European non-residential buildings. *Data Brief* **2017**, *14*, 759–762. [CrossRef]

45. EC. EU Countries' Cost-Optimal Reports. 2018. Available online: https://ec.europa.eu/energy/topics/energy-efficiency/energy-performance-of-buildings/energy-performance-buildings-directive/eu-countries-2018-cost-optimal-reports_en?redir=1 (accessed on 28 April 2022).

46. ECOFYS. *Assessment of Cost Optimal Calculations in the Context of the EPBD (ENER/C3/2013-414)*; Final Report; Ecofys: Brussles, Belgium, 2015.

47. EC. Report from the Commission to the European Parliament and the Council—Progress by Member States in Reaching Cost-Optimal Levels of Minimum Energy Performance Requirements. COM(2016) 464 final of 29 July 2016. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52016DC0464 (accessed on 1 August 2022).

48. *EN 15459:2007*; Energy Performance of Buildings—Economic Evaluation Procedure for Energy Systems in Buildings. CEN: 2007; CEN: Tallinn, Estonia, 2007.

49. BPIE (Buildings Performance Institute Europe). *Implementing the Cost-Optimal Methodology in EU Countries*; pp. 1–82, ISBN 9789491143083. Available online: http://bpie.eu/costoptimalmethodology.html (accessed on 26 May 2022).

50. D'Agostino, D.; Parker, D.; Epifani, I.; Crawley, D.; Lawrie, L. Datasets on Energy Simulations of Standard and Optimized Buildings under Current and Future Weather Conditions across Europe. *Data* **2022**, *7*, 66. [CrossRef]

51. Recommendation (EU) 2016/1318 Commission Recommendation (EU) 2016/1318 of 29 July 2016 on guidelines for the promotion of nearly zero-energy buildings and best practices to ensure that, by 2020, all new buildings are nearly zero-energy buildings. *Off. J. Eur. Union* **2016**, L 208/46. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32016H1318 (accessed on 15 September 2022).

52. Hamdy, M.; Hasan, A.; Siren, K. A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010. *Energy Build.* **2013**, *56*, 189–203. [CrossRef]

53. de Vasconcelos, A.B.; Pinheiro, M.D.; Manso, A.; Cabaço, A. EPBD cost-optimal methodology: Application to the thermal rehabilitation of the building envelope of a Portuguese residential reference building. *Energy Build.* **2016**, *111*, 12–25. [CrossRef]

54. Ortiz, J.; Fonseca i Casas, A.; Salom, J.; Garrido Soriano, N.; Fonseca i Casas, P. Cost-effective analysis for selecting energy efficiency measures for refurbishment of residential buildings in Catalonia. *Energy Build.* **2016**, *128*, 442–457. [CrossRef]

55. Kona, A.; Economidou, M.; Zangheri, P. *Analysis of the Annual Reports 2017 under the Energy Efficiency Directive—Summary Report*; EUR 28922 EN; Publications Office of the European Union: Luxembourg, 2017; ISBN 978-92-79-77040-1. [CrossRef]

56. Ascione, F.; Cheche, N.; De Masi, R.F.; Minichiello, F.; Vanoli, G.P. Design the refurbishment of historic buildings with the cost-optimal methodology: The case study of a XV century Italian building. *Energy Build.* **2015**, *99*, 162–176. [CrossRef]

57. *EN 16798-1:201*; Energy Performance of Buildings—Ventilation for Buildings—Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics. Available online: http://store.uni.com/catalogo/uni-en-16798-1-2019 (accessed on 15 June 2022).

58. Shnapp, S.; Paci, D.; Bertoldi, P. *Untapping Multiple Benefits: Hidden Values in Environmental and Building Policies*; EUR 30280 EN, Publications Office of the European Union: Luxembourg, 2020; ISBN 978-92-76-19983-0. [CrossRef]

59. Becchio, C.; Bertoncini, M.; Boggio, A.; Bottero, M.; Corgnati, S.P.; Dell'Anna, F. *The Impact of Users' Lifestyle in Zero-Energy and Emission Buildings: An Application of Cost-Benefit Analysis*; Springer Nature: Berlin/Heidelberg, Germany, 2019. [CrossRef]

60. Congedo, P.M.; Baglivo, C.; Zacà, I.; D'Agostino, D. High performance solutions and data for nZEBs offices located in warm climates. *Data Brief* **2015**, *5*, 502–505. [CrossRef]

61. D'Agostino, D.; Parker, D.; Melià, P.; Dotelli, G. Data on roof renovation and photovoltaic energy production including energy storage in existing residential buildings. *Data Brief* **2022**, *41*, 107874. [CrossRef] [PubMed]

62. D'Agostino, D.; Cuniberti, B.; Maschio, I. Criteria and structure of a harmonised data collection for NZEBs retrofit buildings in Europe. *Energy Procedia* **2017**, *140*, 170–181. [CrossRef]

63. D'Agostino, D.; Tzeiranaki, S.T.; Zangheri, P.; Bertoldi, P. Data on nearly zero energy buildings (NZEBs) projects and best practices in Europe. *Data Brief* **2021**, *39*, 107641. [CrossRef] [PubMed]