

Assessing cost-optimal energy performance in EU buildings: insights from the third calculation round

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Abstract. The building sector plays a crucial role in achieving the European Union's objective of a zero-emission and fully decarbonised building stock by 2050. The Energy Performance of Buildings Directive introduced the cost-optimal methodology as a key instrument for defining cost-effective minimum energy performance requirements for both new and existing buildings. Within this framework, Member States are required to perform cost-optimal calculations every five years to verify and update national regulatory requirements where necessary. This paper provides insights into the most recent national cost-optimal reports submitted in 2023 (third calculation round). The results show the cost-optimal energy performance levels at building level (primary energy demand and global costs) as well as at building element level (cost-optimal U-values). The analysis indicates a positive evolution in the application of the methodology with the cost-optimal primary energy for new building below 100 kWh/(m²y) and for existing buildings below 150 kWh/(m²y) in most cases. The global costs vary widely, but with most values below 1000 EUR/m² for new buildings and below 800 EUR/m² for existing buildings. Significant variations are observed across macro-climatic zones, particularly for new buildings, due to differences in climatic conditions, calculation approaches, and economic assumptions. Given the current climate and energy challenges, the cost-optimal methodology remains a critical policy instrument for supporting the progressive improvement of building energy performance and advancing the decarbonisation of the European building stock.

1 Introduction

Accounting for approximately 40% of final energy consumption and 36% of energy-related greenhouse gas (GHG) emissions in the European Union (EU), the building sector plays a central role in achieving EU climate and energy objectives [1]. In response to the climate crisis, the *European Green Deal*, launched in 2019, established a comprehensive and cross-

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sectoral strategy aimed at achieving climate neutrality by 2050 [2]. Within this framework, the *Fit for 55* legislative package emphasised the importance of accelerating the renovation of the building stock and introduced measures to support the transition towards more sustainable practices, including improved building energy efficiency, the deployment of clean heating and cooling technologies, and the increased integration of renewable energy sources. More recently, the *REPowerEU* plan further highlighted the strategic role of buildings in strengthening the EU's energy security and reducing dependence on imported fossil fuels [3].

A main legislative framework guiding the decarbonisation of the EU building stock is the Energy Performance of Buildings Directive (EPBD) [4]. The Directive establishes policies and measures to support Member States in improving the energy performance of buildings, including requirements for highly energy-efficient new buildings and strategies to promote the renovation of the existing building stock [5, 6].

The 2024 recast of the EPBD [7] further strengthens the decarbonisation pathway of the building sector, with the ultimate objective of achieving a zero-emission building stock across the EU by 2050 [8]. Within this regulatory framework, the cost-optimal methodology represents a key policy instrument for defining minimum energy performance requirements that balance energy efficiency improvements with economic feasibility over the building lifecycle. The revised Directive emphasises that the building sector is responsible for about half of primary fine particulate matter with great impact on health and the revised cost-optimal methodology, published in 2025, considers the environmental and health externalities of energy use [9].

Over the past years, the cost-optimal methodology has been extensively studied. Several studies in the literature focus on the analysis of building archetypes to identify the cost-optimal level [10, 11, 12]. Many developed specific models to represent building physics and the related energy needs and demand, enabling the comparison of alternative packages of energy efficiency measures and renewable energy systems over the building lifecycle [13, 14]. These approaches typically combine dynamic or quasi-steady-state energy simulations with global cost calculations in order to determine the combination of measures that minimizes costs while achieving high energy performance [15]. Through the use of representative archetypes [16], the methodology allows researchers and policymakers to assess the impact of design options across different building types [17], climatic conditions [18], and national contexts [19], thus supporting the implementation of the EPBD cost-optimal framework and the definition of more ambitious performance requirements [20].

Moreover, previous assessments of the cost-optimal methodology have examined the first and second calculation rounds (2013 and 2018) conducted by Member States. These assessments highlighted the overall compliance of Member States with the EPBD requirements while also identifying significant differences in national approaches, calculation assumptions, and ambition levels [21]. This paper provides the first insights on the most recent national reports submitted between 2023 and 2025. It provides the cost-optimal primary energy demand and global costs, examines differences across macro-climatic zones, and identifies key technological solutions emerging in cost-optimal packages for residential buildings. By providing the first consolidated insight into the third calculation round, the paper contributes to the understanding of how Member States are progressing in improving building energy performance requirements and supports the ongoing policy debate about findings the right balance between reducing energy and GHG emissions and managing costs effectively.

1.1 The cost-optimal framework

The calculation framework for determining cost-optimal energy performance levels for buildings was established by the European Commission in 2012 to enable Member States to benchmark national building standards [22, 23]. The methodology is based on a cost–benefit analysis carried out from two economic perspectives: a financial perspective, which includes taxes and reflects market conditions, and a macroeconomic perspective, which excludes taxes but accounts for the cost of GHG emissions and typically applies a lower discount rate.

The calculation procedure involves several key steps, as shown in Figure 1.

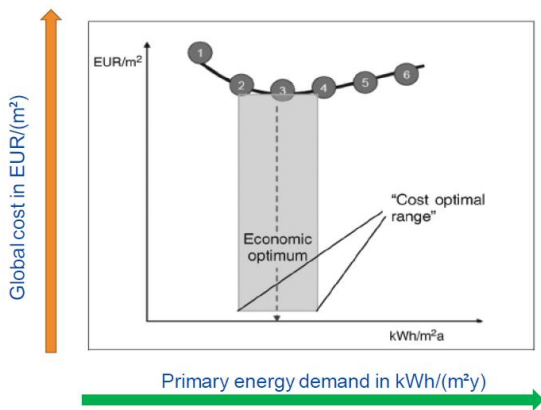


Fig. 1. The cost-optimal range within the curve of global costs and primary energy demand.

First, Member States define representative reference buildings that reflect the national building stock across four categories such as single-family houses, multi-family buildings, offices and at least one another category of non-residential buildings, for both new and existing buildings. Second, energy efficiency and renewable energy measures are identified and combined into packages to evaluate different performance levels. Third, the primary energy consumption of each building variant is calculated using national or CEN-based methodologies under defined boundary conditions such as climate data, system performance, and primary energy factors. Fourth, the global cost of each configuration is determined using a net present value approach over a calculation period of typically 30 years for residential buildings and 20 years for non-residential buildings, including investment, operational, maintenance, replacement, and disposal costs, as well as carbon costs in the macroeconomic perspective.

Cost-optimal energy performance levels are then identified as the combination of measures that minimize global costs while achieving high energy performance (low demand). These levels are expressed in primary energy consumption (kWh/m²y) and correspond to the minimum point of the cost–energy curve. Member States must calculate cost-optimal levels of performance for building elements or derive those from calculation at building level. Finally, the calculated cost-optimal levels are compared with minimum energy performance requirements for building or building elements. If the deviation exceeds 15%, Member States must justify the gap or outline a plan to reduce it.

In accordance with the EPBD timeline, the first cost-optimal calculations were submitted in 2013. The initial assessment indicated generally satisfactory compliance, although it also highlighted the need for more ambitious requirements to further reduce primary energy consumption and life-cycle costs. The second round, submitted in 2018 showed progress in

aligning national building standards with cost-optimal levels [21, 24]. This paper reports on the progress of the last round of calculation reports submitted by Member States.

2 Methodology

The third calculation round was carried out under the framework of former Directive and regulation [22]. In total, 30 reports were submitted by Member States to the European Commission between 2023 and 2025, as follows: 26 Member States, 3 regions in Belgium (Brussels capital regions, Flanders and Wallonia) and Aaland, the autonomous region of Finland. The reports are publicly accessible on the European Commission website [25].

The methodology to evaluate the third round of calculation of cost-optimal levels of minimum energy performance requirements relies on three main phases:

- i) Data collection from the national reports using an assessment template to ensure a similar granularity level.
- ii) Compliance check with the Delegated Regulation 144/2012 [22] and the plausibility check of the input data, methodological choices and results of each individual report.
- iii) Results synthesization to provide cross-country statistics and analyses, and to derive general conclusions and recommendations.

The results are presented and discussed in relation to main macro climatic zones in which EU Member States can be grouped [26]: Nordic (Denmark, Estonia, Finland including Aaland, Latvia, Lithuania, Sweden), Continental (Austria, Bulgaria, Poland, Czech Republic, Romania, Slovakia, Slovenia, Hungary), Oceanic (Belgium, France, Germany, Ireland, Luxembourg, Netherland), Mediterranean (Cyprus, Croatia, Greece, Italy, Malta, Portugal, Spain) (Figure 2).

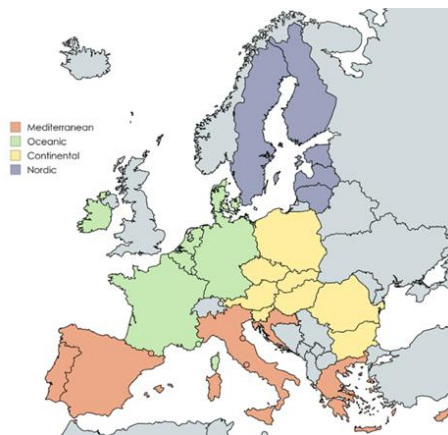


Fig.2. EU macro climatic zones.

3 Results

In the third calculation round of cost-optimal energy performance levels for buildings, Member States provided more detailed reports with clearer input data and more rigorously established cost-optimal levels compared to previous rounds, reflecting increasing proficiency with the methodology.

3.1 Primary energy demand

Figure 3 provides the 2023 cost-optimal level of primary energy and global costs for new buildings, by climatic zones. Each country/region is represented by maximum 4 data points: 1. single-family building, 2. multi-family building, 3. offices and 4. other non-residential building, depending on the completeness of the calculation (not all reports provided the calculation for all reference buildings). The primary energy refers to the net primary energy meaning that on-site generated energy from renewable sources is not included in the final values and the conversion from delivered to primary energy is performed using national/regional primary energy factors.

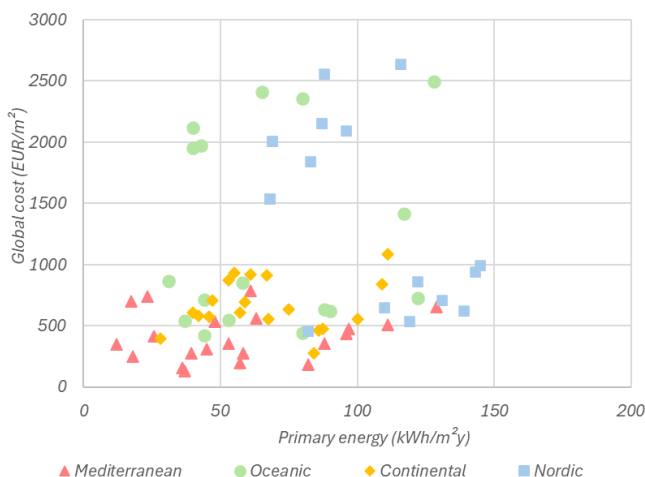


Fig. 3. Cost-optimal primary energy in new buildings by climatic zones (residential and non-residential).

It is observed that results vary widely, in terms of both primary energy and global costs. The primary energy ranges from 12 and 145 kWh/(m²y) for new buildings. The global costs – calculated over the expected economic lifetime of the reference buildings, 20 or 30 years – range from 155 and 2639 EUR/m².

It is noted that Mediterranean countries have the lowest values, averaging 55 kWh/(m²y), followed by Oceanic and Continental, both at 67 kWh/(m²y). Nordic countries have the highest values, with an average of 100 kWh/(m²y). At the same time, Mediterranean countries show higher variability, while Nordic countries lower variability.

Significant differences are observed in global costs. Mediterranean countries have the lowest global costs, with most values below 500 EUR/m² and an average of 426 EUR/m². In Continental countries, all values except one are below 1000 EUR/m² with an average of 668 EUR/m². Ocean and Nordic countries show greater variability in costs with values ranging from as low as 500 EUR/m² to over 2500 EUR/m². The averages are 1351 EUR/m² for Oceanic and 1459 EUR/m² for Nordic countries.

Wide ranges with outliers explained by differences in end-uses, primary energy factors, calculation method, climatic conditions, energy prices, omissions of some cost categories, or considering full cost approach.

Figure 4 provides the cost-optimal levels for existing buildings by macro climatic zone.

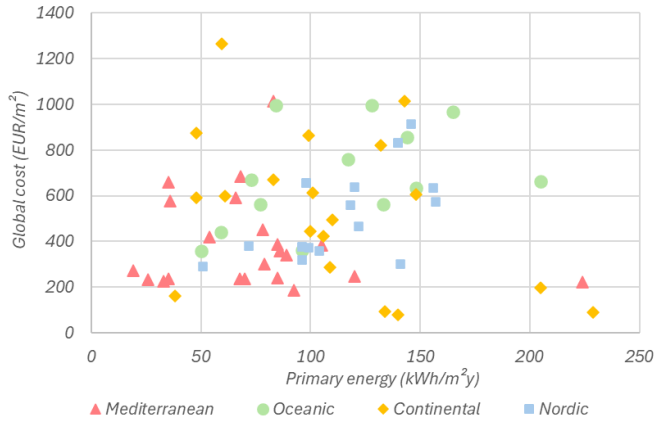


Fig.4. Cost-optimal primary energy in existing buildings by climatic zones (residential and non-residential).

Results vary widely across all climatic zones with not obvious trend in the case of existing buildings, compared to new buildings. The primary energy ranges from 19 and 229 kWh/(m²y), while the global cost ranges from 78 and 1265 EUR/m².

It is noted that Mediterranean countries have lower cost-optimal levels of primary energy demand and global costs at 79 kWh/(m²y) and 404 EUR/m², Continental 110 kWh/(m²y) and 536 EUR/m², Oceanic 129 kWh/(m²y) and 660 EUR/m² and Nordic 118 kWh/(m²y) and 530 EUR/m².

On average, new buildings show around 30% lower primary energy demand than existing buildings, but their global costs are approximately 80% higher.

However, primary energy demand and global costs cannot be not directly compared across countries. Differences in primary energy demand arise from variations in calculation methodologies (e.g., monthly, hourly, or dynamic simulations), adopted standards (e.g., heating and cooling setpoints), the accounted energy uses (heating, domestic hot water, ventilation, cooling, lighting), primary energy factors, and climatic conditions. These underlying factors can lead to different primary energy levels even when the level of ambition is similar. Similarly, global cost calculations vary due to differences in methodological assumptions, including the exclusion or inclusion of specific cost categories (e.g., maintenance or replacement costs), the treatment of non-energy-related investments (particularly in new buildings), discount rates, and national or regional energy prices. As a result, also global costs are not fully comparable across countries.

3.2 Thermal transmittances (U-value)

The cost-optimal level for minimum performance requirements for building elements is generally calculated for walls, roofs, floors and windows and expressed in U-value W/(m²K).

Figure 5 shows the U-value for (a) walls, (b) roofs, (c) floor and (d) windows, by macro-climatic zone for both new and existing building.

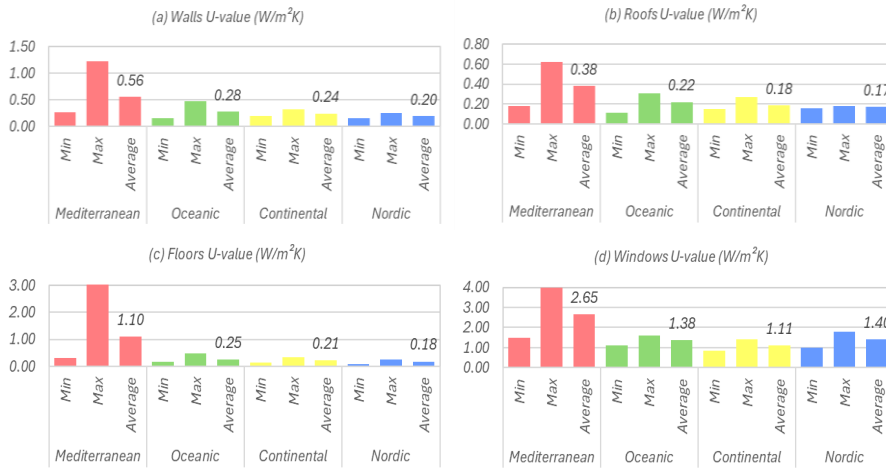


Fig. 5. Cost-optimal U-values for building elements by climatic zone (a) walls, (b) roofs, (c) floors and (d) windows.

The cost-optimal thermal transmittance (U-value) of building envelope components vary greatly across climatic zones. Mediterranean countries generally show the highest U-values and also the greatest variability looking at minimum and maximum U-values across the four building elements. The averages are double than those observed in Nordic countries (e.g., 0.56 vs 0.20 W/(m²K) for walls, 0.38 vs 0.17 W/(m²K) for roofs, 1.1 vs 0.19 W/(m²K) for floors) reflecting milder heating demand and different cost-optimal insulation levels. This partially explains why global costs are lower in Mediterranean countries. Oceanic and Continental countries show relatively similar U-values, with Continental countries having slightly lower which aligns with the more severe winter and summer conditions they experience compared to the milder average conditions found in Oceanic countries. Nordic countries achieve the lowest U-values overall, reflecting the more stringent thermal insulation standards required by colder climates.

3.3 Cost-optimal technologies for heating

Another important element in the assessment of the cost-optimal calculations, is the identification of the technical building systems (type, fuel, efficiency) that lead to the cost-optimal level of primary energy demand. The distribution of technological solutions for the heating system in residential buildings is illustrated in Figure 8, by macro-climatic zone.

Across all reports, air-to-water heat pumps emerge as the most frequently identified technology for heating in the cost-optimal package for residential buildings, in particular for Oceanic and Continental countries. These are generally characterised by a coefficient of performance of 3.0 with some variation across countries. Their widespread consideration reflects their high efficiency and their alignment with EU strategies aimed at electrifying heating and reducing fossil fuel dependence.

District heating is the second most popular choice in the cost-optimal solutions, especially for Oceanic, Nordic and Continental countries. These systems are generally characterised by high system efficiencies, often exceeding 90%, particularly when integrated with cogeneration or renewable heat sources.

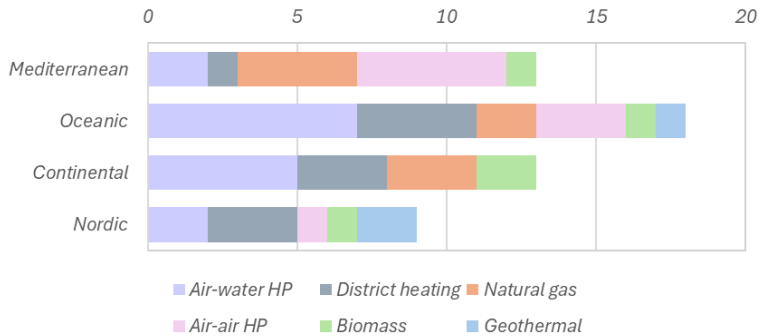


Fig. 6. Main heating technologies in residential buildings, both new and existing, by climatic zone.

Natural gas boilers are the third most common options, still identified as cost-optimal solution particularly in existing residential buildings in Mediterranean and Continental countries, where infrastructure is widespread or where electrification solutions are still developing. These are usually condensing boilers with high efficiency (above 95%). Air source heat pumps are common in Mediterranean often coupled with photovoltaics. Biomass boilers are identified in less reports but show a more even distribution across climatic zones. Heating systems using geothermal energy are less frequently chosen as cost-optimal, and mainly found in Nordic and Oceanic countries, where are more prevalent due to the natural availability of geothermal resources.

Overall, the distribution of heating technologies across climatic zones reflects both climatic conditions and the availability of infrastructure, with heat pumps and district heating emerging as the dominant solutions in many cost-optimal packages, supporting the ongoing transition towards more efficient and lower-carbon heating systems in the European building sector.

CONCLUSIONS

The European Union aims to lead global efforts to address climate change while ensuring a socially fair transition that supports innovation and economic competitiveness. Within this context, the building sector plays a central role in achieving the objective of a zero-emission building stock by 2050. The cost-optimal methodology represents a key policy instrument to guide Member States in setting minimum energy performance requirements that maximise energy efficiency while remaining economically justified over the building lifecycle.

In the third cost-optimal calculation round most new buildings reach cost-optimal levels below 100 kWh/(m²y) of primary energy, while existing buildings generally remain below 150 kWh/(m²y). Global costs vary widely, but with most values below 1000 EUR/m² for new buildings and below 800 EUR/m² for existing buildings. Significant variations in both primary energy demand and global costs are noted across macro-climatic zones, reflecting differences in optimal configuration of packages of energy savings and renewables measures. On average, new buildings show 30% lower requirements (primary energy demand) compared to existing buildings, confirming the impact of progressively stricter energy performance requirements and the implementation of nearly zero-energy building standards in the Member States.

Primary energy demand and global costs are not fully comparable across countries. Different calculation methods, methodological choices such as energy end-uses included, primary energy factors lead to varying results. Regarding global costs, inclusion or exclusion of

certain cost categories lead to outliers. These disparities make it challenging to directly compare energy and cost data across countries.

Looking at the cost-optimal U-values for envelope elements, variations are observed across the macroclimatic zones. Mediterranean countries show higher values (i.e. less thermal insulation), which is aligned with the lower global costs, while Oceanic, Continental and Nordic countries show lower U-values. In particular the Nordic countries have identified 0.2 W/(m²K) or below the cost-optimal U-value for walls, roofs and floors. These values provide useful benchmarks for improving the energy performance of building envelopes while maintaining cost-effectiveness.

The calculations reveal that cost-effectiveness of heating technologies varies by climate zone: Mediterranean countries typically find air-air heat pumps and natural gas boilers to be cost-effective; Oceanic and Continental countries see air-water heat pumps and district heating as viable options (and Continental also natural gas); while Nordic countries identify geothermal systems and district heating as the most cost-effective solutions.

The findings show that the energy performance requirements for buildings and their components have improved due to the cost-optimal approach with significant differences across the different climatic conditions. Moreover, differences in calculation approaches, assumptions, and economic parameters does not allow comparability across regions and countries. The next round of calculation, due by June 2028, will use the revised methodology that includes externalities and co-benefits such as environmental and health impact. This approach will help identify the measures that have the greatest positive impact on society and promote the decarbonization of the European building stock.

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