Future trajectories for EPBD-aligned incentives: evidence from Italy’s Superbonus programme

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Abstract. Buildings account for around 40% of final energy demand in Europe, and the last Energy Performance of Buildings Directive (EPBD) calls for cost-optimal, performance-based renovation pathways toward a zero-emission building stock. In Italy, the Superbonus 110% has triggered an unprecedented renovation wave, but recent studies mostly address macroeconomic impacts, construction cost inflation and implementation barriers, rather than building-level cost-effectiveness and actual performance improvements. This paper analyses a sample of buildings within the average climate conditions of Italy, renovated between 2021 and 2024 through Superbonus incentives. By analysing pre- and post-retrofit energy certification data, envelope and system characteristics, and investment costs, the study derives indicators such as the cost per unit of primary energy saving and the cost per unit of CO_2 abatement, distinguishing different combinations of retrofit interventions. The results highlight the spread of cost-effectiveness among the interventions linked to the building characteristics. On this basis, the paper discusses future trajectories for EPBD-aligned incentives, providing a valuable contribution to reconcile decarbonisation objectives with economic sustainability.

1 Introduction

In the EU, buildings account for roughly 40% of energy consumption and a substantial share of greenhouse-gas emissions, largely driven by space heating and domestic hot water in an ageing and often inefficient building stock [1]. Achieving long-term climate neutrality, therefore, requires accelerating renovation rates and, crucially, ensuring that public resources are allocated to interventions that deliver robust and measurable reductions in energy use and emissions.

In Italy, the so-called “Superbonus” represented an unprecedented attempt to stimulate renovation at scale through a generous fiscal mechanism. Introduced by the Law Decree No. 34/2020 [2], it enabled beneficiaries to recover (up to) the full cost of eligible interventions through tax deductions, with widespread use of credit transfer and invoice discount options that effectively lowered, or eliminated, upfront financial barriers [3, 4]. Access to the incentive was conditional upon the execution of at least one leading measure (e.g., envelope insulation or heating-system replacement), compliance with technical requirements and

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spending caps, and, most notably, achievement of at least a two-class improvement in energy performance (or the highest achievable class), demonstrated through "conventional" pre- and post-retrofit Energy Performance Certificates (EPCs) [4]. While such rules ensured formal eligibility and expenditure control, they largely framed the programme as a compliance-based scheme centred on investment volumes and proxy targets (e.g., class jumps), rather than on the direct quantification of energy and carbon abatement per euro invested. In parallel, monitoring-based evidence highlights that actual outcomes can be strongly influenced by user behaviour and operational settings, potentially altering the realised benefits of envelope measures and, more broadly, the effectiveness achieved per euro spent [5].

The recast Energy Performance of Buildings Directive (EU) 2024/1275 [1] consolidates a shift towards performance-based incentives schemes and explicitly prioritises the transformation of the worst-performing segments of the stock, to maximise decarbonisation impact. In this context, the Directive frames deep renovation as a strategic lever and calls for enhanced financial and administrative support to foster deep renovation and to deliver a progressive improvement trajectory for the residential stock [6, 7]. However, turning these principles into effective incentive designs requires empirical data to provide the realistic orders of magnitude, distributional behaviour, and variability of abatement outcomes that arise under real-world constraints, heterogeneous building conditions, and technology choices.

This paper addresses this gap by providing building-level empirical evidence derived from the Superbonus experience to support EPBD-aligned incentive trajectories. Specifically, it provides a cost-to-benefits assessment framework based on two upfront abatement metrics, cost per unit of primary energy reduced (€/kWh) and cost per unit of CO_2 avoided (€/kgCO_2), quantifying differences and dispersions across retrofit packages and baseline performance conditions. Methodologically, the study analyses a set of residential Superbonus renovation sites under homogeneous climatic conditions, combining pre- and post-intervention EPC data with initial investment costs. Finally, suggestions for policy implications and future trajectories for outcome-based, EPBD-aligned incentive schemes are outlined.

2 Method and Material

The study relies on the analyses of residential buildings located in Central Italy within the average climate conditions of the Nation (climate zone D, characterised by a range of heating degree days between 1401 and 2100). The buildings were realised between the 1970s and 1990s and refurbished between 2021 and 2024 through the incentive process of "Superbonus". Examples of the case studies are reported in Fig.1.

Fig. 1. Examples of renovated residential buildings.

An empirical database was created by collecting information from the buildings' Energy Performance Certificates, referring to both pre- and post-intervention, and the bills of quantities produced along the incentive process. The entire renovation was coordinated by a single General Contractor, ensuring consistency in contractual terms, project management, and operational organisation. Once the data were collected, buildings were grouped according to the intervention package implemented, dividing the related overall renovation costs into direct costs (materials and labour), ancillary works and safety measures costs (AWS), as well as design and professional services costs to provide for a systematic cost breakdown. Finally, a cost characterisation and a cost abatement assessment were carried out. A flow-chart of the described method is reported in Fig. 2.

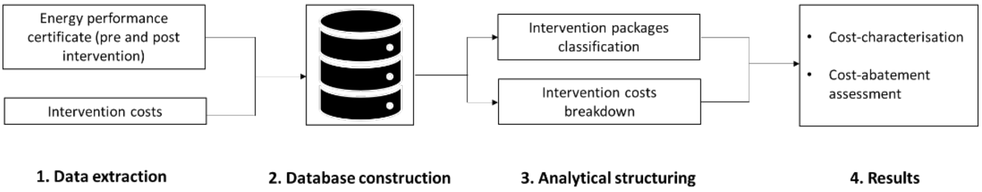

Fig. 2. Method flow chart.

2.1 Data extraction, database construction, and analytical structuring

Data were assembled from official projects and administrative documentation produced along the incentive process. For each buildings, the information base combines: (i) energy performance certificates issued before and after the retrofit, used to retrieve baseline and post-intervention energy class and energy performance indicators; and (ii) bill of quantities and initial investment cost reports including direct costs for the works, cost of ancillary works and safety, design and professional services costs, that consolidate the overall investment, disaggregated by types of intervention (e.g., envelope thermal insulation works, heating system upgrade, and installation of renewables plants). The renovation measures implemented were classified according to three retrofit packages, considering:

- Envelope refurbishment (EN): thermal insulation of the opaque envelope and windows replacement;
- Building service system upgrading (SY): replacement of standard gas-based boilers of the heating and/or domestic hot water systems with condensing boilers, and cases with air-to-water heat pumps with back-up condensing boilers (SY*);
- Renewable energy plants installation: differentiating between solar thermal plants (SL) and photovoltaic plants (PV).

In Table 1, a summary of the main features collected from the renovation sites is reported.

Table 1. Main features collected from the renovated building sites.

Site id	Heated floor area [m^2]	Pre- (Post-) Energy class	Intervention package	Initial investment cost [€]	Primary energy reduced [kWh/m^2]	CO_2 emissions reduced [kg/m^2]
1	1058.7	D (B)	EN	557,220	48.70	54.19

2	2425.0	E (C)	EN	1,757,026	55.73	78.60
3	3122.0	D (B)	EN	2,169,023	43.61	103.25
4	6761.3	E (C)	EN	4,990,361	37.22	110.44
5	8065.8	D (B)	EN	7,624,700	43.86	121.34
6	2722.3	E (C)	EN	2,219,969	60.51	75.78
7	1762.5	E (C)	EN	1,333,982	55.04	77.05
8	1004.3	F (C)	EN+ SY	495,835	79.54	32.57
9	610.4	F (D)	EN+ SY	334,715	52.06	56.17
10	1767.6	E (C)	EN+ SY	1,428,358	39.06	113.43
11	852.4	F (D)	EN+ SY	819,170	26.46	163.00
12	1215.3	F (D)	EN+ SY	651,569	61.75	45.72
13	3450.8	D (B)	EN+ SY	2,032,228	18.40	61.54
14	588.7	F (C)	EN+ SY	613,102	52.56	119.66
15	560.7	G (D)	EN+ SY	624,375	154.10	36.56
16	6671.0	G (B)	EN+ SY	3,091,652	65.03	26.49
17	820.1	F (A2)	EN+ SY	591,248	83.65	45.23
18	1064.4	E (B)	EN+ SY+ PV	1,123,756	56.64	101.55
19	2050.4	E (A2)	EN+SY*+ PV	2,353,171	63.73	71.79
20	2273.2	D (A3)	EN+ SY+ PV	1,937,800	84.13	56.08
21	2754.8	G (E)	EN+ SY+ PV	1,346,289	95.42	29.10

22	2842.7	G (E)	EN+ SY+ PV	1,454,448	81.20	37.39
23	2871.9	G (E)	EN+ SY+ PV	1,411,899	73.70	34.53
24	2780.0	G (E)	EN+ SY+ PV	1,315,229	93.74	26.47
25	1927.6	G (C)	EN+ SY+ PV	1,109,446	83.15	36.62
26	1154.5	F (A1)	EN+ SY+ PV	1,250,718	88.32	64.56
27	5312.7	D (A3)	EN+ SY+ PV	2,915,816	86.49	34.60
28	2276.4	G (E)	EN+SY*+ PV	2,357,324	39.40	114.19
29	4311.9	G (E)	EN+SY*+ PV	3,801,640	34.30	114.97
30	4311.9	G (E)	EN+SY*+ PV	3,821,313	32.10	114.51
31	435.6	G (E)	EN+ SY+ SL	351,264	108.63	38.91
32	1125.2	E (B)	EN+ SY+ SL	815,953	33.29	86.10
33	556.9	G (C)	EN+ SY+ SL	419,740	189.73	20.68
34	239.1	F (C)	EN+ SY+ SL	223,094	69.12	65.14
35	1534.9	D (A3)	EN+ SY+ SL	1,557,331	37.58	113.60
*heat pump and back-up condensing boiler						

2.2 Cost-abatement metrics and cost-breakdown

The EPBD recast frames incentive design within a cost–optimal logic, where the allocation of public support should be informed by life-cycle cost-effectiveness (i.e., global costs over a reference period, discounted cost streams, and performance outcomes). While this perspective is inherently long-term, its practical implementation critically depends on the availability of robust and realistic input data, particularly on the actual investment costs of renovation measures under real-world market and site conditions. Against this background, the primary objective of this study is to provide an empirical characterisation of cost variability observed under a large-scale incentive programme, by leveraging real, disaggregated intervention costs collected from Superbonus renovation sites. To this end, investment costs are systematically broken down by types of intervention and cost items (direct works, AWS, design and professional services costs), enabling an explicit assessment of unit-cost dispersion and cost-composition heterogeneity across retrofit packages. To assess how the variability of intervention costs could affect energy and emission outcomes, this study adopts two preliminary, upfront abatement metrics that relate initial investment costs to annual EPC-based energy and carbon reductions, limiting the analysis to the first year:

- The cost per unit of total annual primary energy reduced (€/kWh);
- The cost per unit of annual CO2 emission reduced (€/kg CO2).

Since different types of intervention could have different lifespans, it is important to highlight that the above indicators are used to quantify realistic orders of magnitude and dispersion of energy and emission reduction outcomes across retrofit packages.

3 Results and Discussion

The methodological workflow is primarily exploratory and comparative. The indicator distributions are first summarised through robust descriptive statistics and then analysed through stratified visualisations to examine (i) the dispersion of cost abatement within and across packages, and (ii) how dispersion aligns with baseline building characteristics (e.g., ante-operam energy class and size descriptors). When comparing groups, emphasis is placed on distributional shifts (changes in median and spread) rather than on mean-only comparisons, given the presence of skewness and influential points typical of real-world renovation datasets. This structure supports the central interpretation goal of the paper: linking observed variability in abatement costs to the interaction between retrofit package composition and baseline building conditions, rather than attributing outcomes to investment intensity alone.

3.1 Cost characterisation

To quantify price dispersion across sites, Table 2 reports the statistical parameters of the costs for each retrofit measure within the considered cases. EN measures costs show an interquartile dispersion normalised to the median value (IQRN) of 0.67 for the Opaque case and 0.39 for the Transparent case. The latter is plausibly mainly linked to differences in the adopted commercial products, while the former is also affected by the installation complexity of the building context, such as building site accessibility, building morphology, etc., leading to different AWS.

Table 2. Statistical parameters of the unit cost related to the retrofit measures.

Statistic	EN (Opaque)	EN (Transparent)	SY (Condensing boiler)	SY (Hybrid)	PV	SL
	[€/m^2]*	[€/m^2]**	[€/gen]	[€/gen]	[€/kWp]	[€/m^2] ***
Min	104	770	2,115	6,493	517	1,824
Q1	173	1,040	3,721	6,551	841	1,855
Median	232	1,202	5,836	7,688	1,411	2,153

Q3	330	1,512	7,713	13,292	1,734	2,850
Max	695	2,713	8,568	15,639	2,029	3,335
* of opaque envelope ** of transparent envelope *** of SL panel						

The unit costs for SY interventions are distinguished by generator typology. Hybrid solutions, being the most complex technology, are the highest-cost option, with a median value of 7688 €/apartment against 5,836 €/apartment of the condensing boiler cases. The high IQRN values of 0.87 and 0.68 of the Former and the latter case, respectively, are likely due to the variability costs related to updating the equipment of the existing central heating room, besides differences in the adopted commercial products. PV and SL costs show dispersion of 0.63 and 0.46, respectively, attributable to the variability in plant size, roof constraints, and integration with existing systems.

Fig. 3 reports the distribution of direct cost shares (%) by component within each retrofit package, together with the packages' AWS costs. Each boxplot describes how the budget is split across opaque envelope (EN-opaque), transparent envelope (EN-transparent), heating/DHW systems (SY), renewables (PV or SL), and cost of ancillary works and safety (AWS).

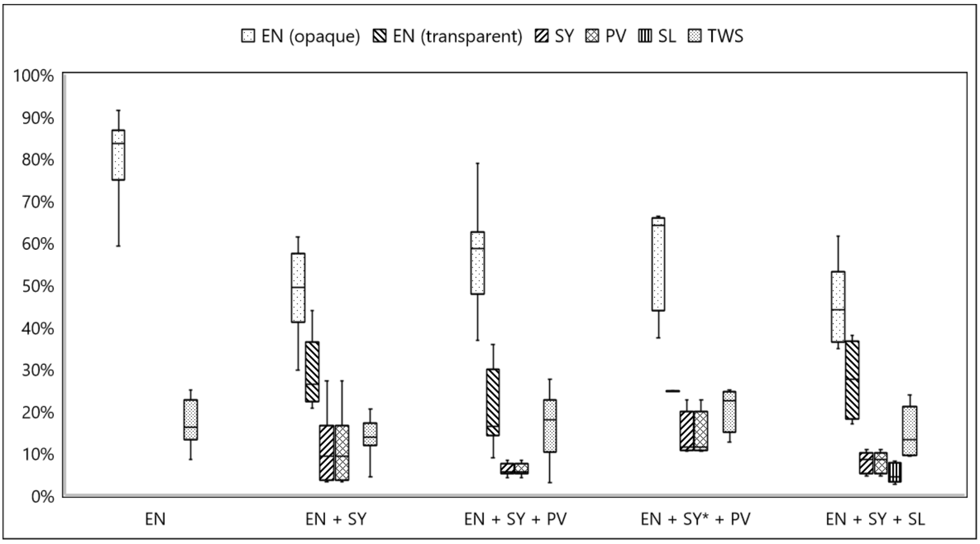

Fig. 3. Cost composition within each retrofit package.

Overall, the budget is dominated by the envelope component, both opaque and transparent, which also reveals the highest dispersions among the components in each retrofit package. Furthermore, within the same nominal package, the dispersion of shares indicates that projects can allocate costs very differently, providing a cost abatement spread. Notably, AWS costs (about 20 % of the renovation package's costs) represent a non-negligible variable overhead strongly affecting the overall cost. Nevertheless, both the unit cost variability and AWS costs are often not properly considered in cost-effectiveness analyses [8-10] and in scenario-based estimates toward the EPBD target [3, 11], which rely on reference nominal costs lower than the ones reported in the present study.

3.2 Abatement costs assessment

The boxplot in Fig. 4 synthesises the distribution of the primary-energy abatement cost for the four retrofit packages. Envelope-only interventions display a relatively compact range, with a median value of 13.7 €/kWh and first and third quartiles between roughly 13 and 18 €/kWh. When heating and DHW system upgrades are introduced (EN+SY), the median cost is reduced to 9.61 €/kWh, but both the interquartile range and the whiskers widen markedly, extending from about 6 to 32 €/kWh. This indicates that system retrofits can lead to very efficient projects, but also to clearly unfavourable ones, in line with the high dispersion observed in Fig. 3. On the other hand, the distribution related to the hybrid systems reveals a very tight range, approximately between 18.6 and 21.0 €/kWh.

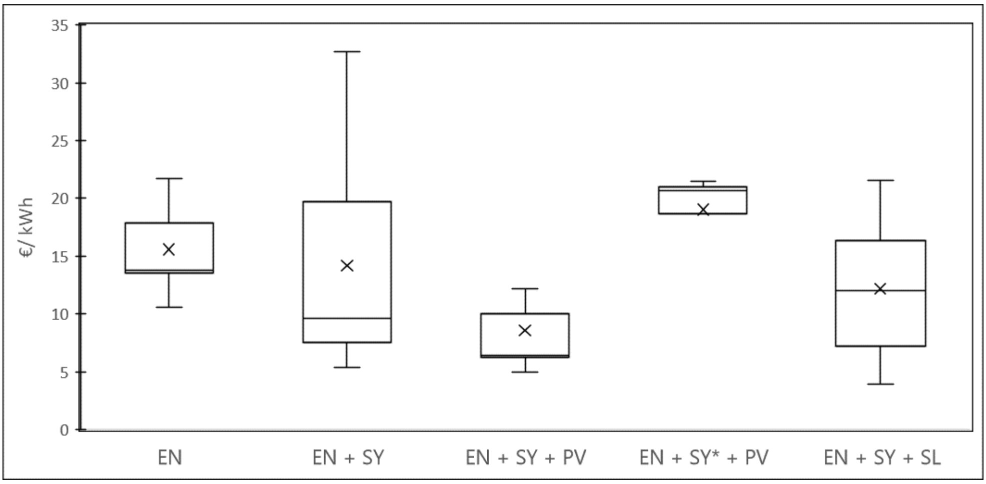

Fig. 4. Box plot of primary energy abatement cost according to retrofit packages.

Packages that combine both envelope and service systems upgrades with photovoltaic generation (EN+SY+PV) exhibit a slightly lower median (6.4 €/kWh) and a relatively limited dispersion from about 4.9 €/kWh to 12.2 €/kWh. Finally, the deep retrofit package with thermal solar (EN + SY + SL) reveals a higher and much more dispersed abatement cost than the EN+SY+PV package: median equal to 12.0 €/kWh (Q1–Q3: 7.2–16.3 €/kWh; min–max: 3.9–21.5 €/kWh).

The distribution of the CO_2 abatement cost across the four retrofit packages is reported in Fig. 5. Envelope-only interventions exhibit by far the highest and most compactly "upper-shifted" distribution, with a median around 80 €/kgCO₂ and an inter-quartile range approximately between 77 and 106 €/kgCO₂. This pattern is consistent with the limited decarbonisation leverage of envelope-side measures when the heat supply is still dominated by fossil fuel conventional boilers. In contrast, when the heating system is upgraded, a downward shift of almost all the distributions is shown. The EN+SY package presents a median value of 50.9 €/kgCO₂; however, 50% of the cases reveal values up to 163 €/kgCO₂, overcoming the IQR of the EN distribution. When renewables are added, the dispersion decreases. The EN+SY+PV package achieves the lowest central tendency (median 36.6 €/kgCO₂) and a relatively narrow spread, with an IQR between ~34.5 €/kgCO₂ and ~56.0 €/kgCO₂, suggesting consistently better decarbonisation effectiveness when PV panels are integrated with envelope and plant upgrade measures. By contrast, the variation with hybrid systems shows again the worst abatement costs, with an IQR confined between 103.6 €/kgCO₂ and 114.6 €/kgCO₂.

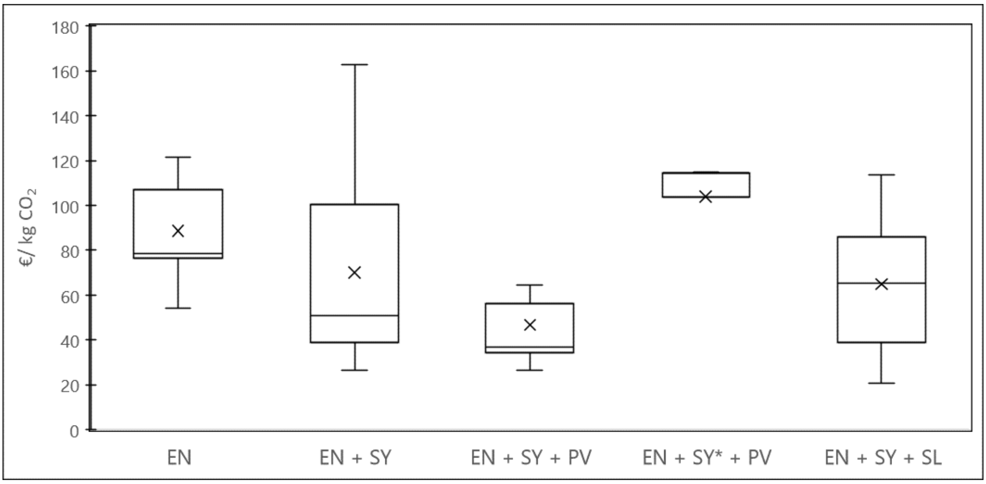

Fig. 5. Box plot of CO_2 emission abatement cost according to retrofit packages.

Overall, the evidence supports the EPBD-oriented shift toward the prioritisation of deep renovation interventions. Envelope-only measures tend to deliver lower energy and carbon cost-abatement, confirming that they are insufficient to maximise decarbonization effectiveness. In contrast, packages combining envelope upgrades with heating and DHW system replacement, and, where applicable, renewable integration, more frequently achieve lower cost-abatement profiles, although with non-negligible internal variability. Importantly, the dispersion observed in the abatement indicators is consistent with the heterogeneity highlighted by the cost analysis: both unit costs and the within-package cost breakdown vary substantially across sites, even under the same nominal retrofit package. This implies that a relevant portion of the abatement-cost spread is structurally driven by differences in cost composition and unit-price variability, rather than by the package label alone. This wide dispersion indicates that proxy requirements such as investment thresholds and energy-class jump alone are a weak policy lever. From a policy perspective, deep retrofit should be encouraged through outcome-based corridors (e.g., sliding thresholds tied to €/kgCO₂) and accompanied by de-sign/technology safeguards to reduce the risk of high-cost and low-impact projects.

3.3 Impact of the pre-renovation EPC rating

The boxplots in Fig. 6 summarise the distribution of the primary-energy abatement cost (€/kWh, left) as a function of the pre-retrofit energy class, with class G representing the least energy-efficient buildings. Overall, the chart shows a clear tendency towards lower abatement costs for poorer building energy performance, i.e., moving from class D/E to class F/G, suggesting that buildings with higher initial consumption offer larger absolute savings for a given investment and therefore yield more favourable €/kWh ratios. Specifically, the median abatement costs move from 16 €/kWh to 7 €/kWh, passing from class D to class G. As all the cases where traditional boilers were replaced by heat pumps with a back-up condensing boiler fall in class G, an additional group G* was defined to isolate the effect of specific heating system upgrading choices as it introduces substantial variability. In the filtered group G*, the €/kWh distributions become markedly more concentrated and remain at the highest end of the sample, reinforcing the interpretation that certain system configurations can substantially increase uncertainty in outcomes. From a policy perspective, these distributions provide empirical support for prioritising low-performing buildings within incentive schemes: directing resources towards classes F–G is more likely to deliver larger energy and emissions re-ductions per euro spent, thereby improving the alignment of incentives with EPBD-style, performance-based decarbonisation targets.

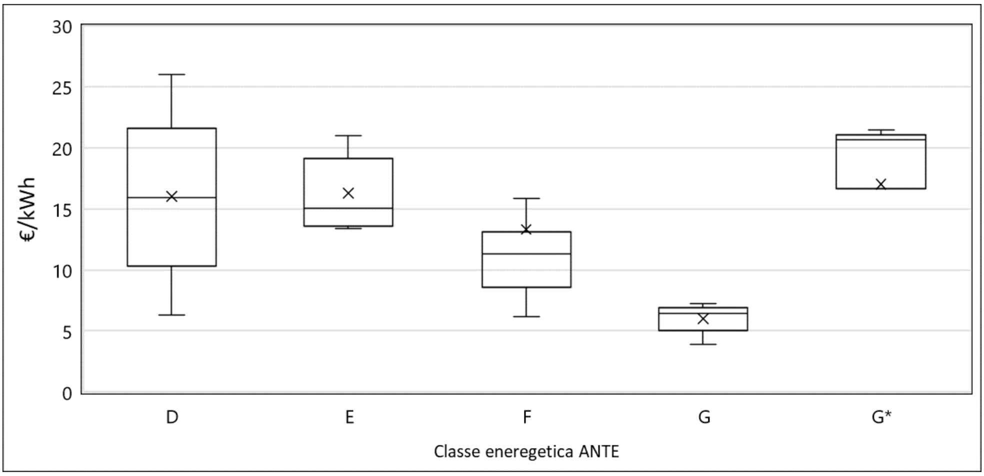

Fig. 6. Box plot of primary energy abatement cost according to the pre-retrofit energy class.

4 Conclusions

This paper provides building-level empirical evidence from the Italian “Superbonus” experience to inform EPBD-aligned incentive trajectories, combining EPC-based pre/post performance indicators with real, disaggregated investment costs. Two upfront cost-to-benefit metrics were used to benchmark outcomes dispersions across retrofit packages and baseline conditions: cost per unit of primary energy reduced (€/kWh) and cost per unit of CO_2 avoided (€/kgCO_2). The cost characterisation analyses highlight a systematic dispersion among the unit prices provided by both technical factors and contextual factors, together with the non-negligible costs related to the ancillary works and safety measures, which should always be considered in cost-effectiveness scenario analyses to obtain the actual costs. Results from the abatement cost analyses support the EPBD-oriented emphasis on deep renovation and prioritisation of the worst-performing buildings, through observed orders of magnitude and distributional behaviour. The abatement costs, together with the dispersions, systematically decrease when targeting worse pre-retrofit energy classes, with median values moving from about 16 to 7 €/kWh and from 61 to 35 €/kgCO_2 when comparing higher-performing to worst-performing classes. Envelope-only retrofits exhibit the highest primary-energy abatement distribution (median 13.7 €/kWh) and carbon abatement distribution (median around 80 €/kg CO_2), consistent with the limited decarbonization leverage when standard boilers are not upgraded. When heating/DHW systems are upgraded, primary-energy abatement improves in central tendency (median 9.61 €/kWh) but with a wider spread, indicating that deep retrofit can generate both very favourable and unfavourable outcomes. Packages integrating PV show the lowest typical primary-energy abatement (median 6.4 €/kWh) with comparatively limited dispersion, whereas solar-thermal packages display higher typical values and larger variability. Hybrid-system cases are consistently less favourable for primary-energy abatement (median 20.3 €/kWh) and show poor CO_2 abatement profiles in this dataset. This result should be interpreted with caution, as a key limitation is that the proposed abatement metrics do not consider different lifespans across measures. Therefore, the study outcomes must be read as screening-level evidence. Nevertheless, the findings indicate that expenditure caps and energy-class jump compliance are weak policy proxies for decarbonisation: they do not control the large dispersion of €/kWh and especially €/kgCO_2 that emerges under real-world renovations. EPBD-aligned schemes should therefore adopt outcome-based corridors, by modulating incentive intensity through empirically calibrated sliding thresholds and minimum energy reduction requirements, complemented by design/technology safeguards to reduce the risk of high-cost/low-impact projects. Future work should strengthen robustness through a full life-cycle cost framework, also considering dynamic energy-price effects to claim alignment with cost-optimal approaches stated in the last EPBD.

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