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Real Investment Evidence in Residential Energy Retrofit: Lessons from a Large-Scale Italian Case Study

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Abstract

The decarbonization of the building stock by 2050, as set by the European Green Deal, calls for an unprecedented wave of energy renovations. Yet, reliable evidence on the real costs and performance of retrofit interventions remains scarce. This paper presents the results of a large-scale technical and economic analysis conducted on 34 residential buildings, all renovated under a national Italian programme supporting energy efficiency improvements. For each building, pre- and post-renovation energy performances were assessed using standardised procedures, while detailed investment cost data were collected for all implemented measures, including envelope insulation, HVAC system upgrades, and renewable integrations. By combining these datasets, the study evaluates the actual cost-effectiveness of different retrofit strategies, revealing the true financial effort required to achieve substantial energy improvements. The results highlight both the opportunities and limitations of current approaches, showing a significant gap between theoretical models and real outcomes. The findings contribute to the European debate on the economic sustainability of deep renovation policies.

Keywords: EPBD recast; building energy retrofit; building renovation policies; cost-effectiveness assessment; residential buildings; Green Deal; building renovation costs

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1. Introduction

Building energy efficiency has a key role in international policies for guiding the evolution toward a sustainable built environment [1]. As a matter of fact, buildings are responsible for 40% of energy consumption and 36% of the EU's CO_2 emissions [2], largely driven by space heating and domestic hot water demand, which together represent about 80% of household energy use [3]. Indeed, the EU building stock is aged and frequently inefficient, with 85% of buildings built before 2000, of which 75% have a poor energy performance [4]. Similarly, the Italian building stock is markedly old and inefficient; more than 60% of the buildings were constructed over 45 years ago, before the first national energy efficiency laws [5]. Therefore, reaching an energy-efficient building stock requires high and effective renovation rates, which in most cases is feasible only through credit transfer and invoice discount mechanisms to offset the related high costs, making energy refurbishment interventions more accessible to building owners [6]. In recent years, incentive policies for the energy renovation of buildings were used in many European countries such as Denmark, Germany, France, Belgium, Greece, and the Netherlands [7]. In Italy, the "Superbonus" scheme constituted an unprecedented attempt to trigger large-scale renovation

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through a highly generous fiscal mechanism. Introduced by Law Decree No. 34/2020 [8], it allowed beneficiaries to recover up to the full eligible investment, and it was widely implemented via credit transfer and invoice discount mechanisms. The eligibility required achieving at least a two-class energy performance improvement, documented through pre- and post-retrofit Energy Performance Certificates (EPCs), realising at least one of the two "leading" measures (at least 25% of opaque envelope insulation or central heating system replacement), to which one or more "additional" measures can be added, such as window replacement, individual HVAC upgrade, renewable energy systems integration, etc. Furthermore, the compliance with technical requirements and spending caps was mandatory. The EPCs in Italy provide the standard metric of building energy performance by assigning an energy efficiency label on a scale from G (least efficient) to A4 (most efficient) based on the building's overall primary non-renewable energy consumption indicator.

In 2024, according to the decarbonization target provided for by the European Green Deal [9], where the EU is committed to reducing 1990 greenhouse gas emissions by at least 55% by 2030 and reaching a carbon-neutral building stock by 2050, transforming the existing buildings into zero-emission buildings [10], the last recast Energy Performance of Buildings Directive (EU) 2024/1275 [11] called for doubling the current annual renovation rate. To this aim, Member States should incentivise deep renovations with higher financial, fiscal, administrative, and technical support. If achieving zero-emission buildings through renovation is not technically or economically feasible, at least a 60% reduction in primary energy use could be considered. Moreover, sizeable programmes should prioritise the renovation of the worst-performing buildings, ensuring an overall reduction of at least 30% in primary energy use. Against these directions, several studies have attempted to quantify the scale of investments needed to meet the EPBD 2030 objectives. At the European level, U. Keliauskaite et al. [12] have estimated an amount of €150 billion per year, using a synthetic price index developed by averaging two Eurostat price indices for the period 2015–2023, covering costs of new residential building construction, maintenance, and repair. At the regional level, L. Forni et al. [13] have quantified the total expenditure of €118.9 billion for Lombardy's and Piedmont's residential stock, using unitary prices that reflect the costs of materials, labour, and installation.

However, these findings lie as scenario-based estimates of aggregate investment needs rather than as evidence of cost-optimal renovation pathways. In this respect, several studies in the literature have assessed the cost-effectiveness of renovation strategies at the building or stock level. A. Ferreira et al. [14] have assessed different wall and roof insulation solutions, showing that solutions with a lower U-value than the ones reported in the Portuguese Standards can be cost-effective up to a building life of 50 years. Similarly, E. Touloupaki et al. [15] have demonstrated the inadequacy of the Greek regulation's current building envelope insulation limits, considering an economic lifecycle of 30 years. L. C. Felius et al. [16], instead, pointed out how building automation control strategies are more cost-effective in compact buildings, where the potential of reducing heat losses through the envelope is limited. A. Akgüç and A. Zerrin Yılmaz [17], instead, have compared the cost-effectiveness of different HVAC solutions for high-rise residential buildings in Turkey, highlighting the potential of photovoltaic and heat recovery systems, which can reduce the annual energy consumption and global cost by 50% and 23%, respectively, if integrated in conventional HVAC upgrade interventions. Other studies have developed decision support tools and simulation/optimisation procedures for building and building stock scale to identify cost-effective renovation packages by jointly assessing energy performance and life cycle costs [18–21].

Nevertheless, a recurring limitation of the above-mentioned studies is that cost-effectiveness scenario analyses rely on reference nominal costs rather than actual costs

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observed in realised refurbishment intervention. In addition, auxiliary costs related to temporary works and safety measures, as well as design and professional services, are often omitted, implying substantial uncertainty in the actual renovation cost ranges.

Against this background, this paper provides empirical evidence on the true cost-efforts required to achieve substantial energy improvements for 34 residential buildings located in the average Italian climate implemented under the Italian "Superbonus" programme, highlighting the actual cost-effectiveness of different retrofit strategies. The novelty lies in the availability of auxiliary costs, referred to as ancillary works and safety measures, as well as design and professional services, besides the disaggregated cost data for each intervention, i.e., direct construction items (materials and labour). By integrating this cost dataset with pre- and post-retrofit EPC information for the renovated residential buildings, the study (i) quantifies the real-world dispersion of unit prices across the envelope, heating system, and renewable measures; (ii) benchmarks how auxiliary costs amplify total expenditures and uncertainty compared with direct costs alone; and (iii) evaluates the cost-effectiveness of different retrofit packages in terms of non-renewable primary energy reduction, explicitly accounting for the implementation share of each measure. The findings can be useful in the European debate on the economic sustainability of deep renovation policies, providing insight into the aspects to be considered for implementing EPBD-aligned incentive trajectories.

2. Materials and Methods

The analysis is based on an empirical dataset of Superbonus-funded renovation projects involving 34 multi-family residential buildings refurbished between 2021 and 2024. The buildings were constructed between the 1960s and the 1990s, a period to which 66% of Italy's residential building stock belongs, according to the most recent national building census [22]. The sample is located in the Italian climate zone D, representative of average heating season severity at the national scale and characterised by official heating degree days between 1401 and 2100 (base temperature of 20 °C), according to the Italian Decree n. 412 [23]. The location of the buildings is shown in Figure 1, where the names and the edges of the interested provinces are reported. Data consistency is supported by the fact that all renovation projects were managed under a single General Contractor, who coordinated the procurement and contractual arrangements referring to different construction companies and design studios. Having a General Contractor is not mandatory, but it is a common approach in deep renovations, ensuring a smooth building renovation process with a sales commission of around 10% of the overall cost.

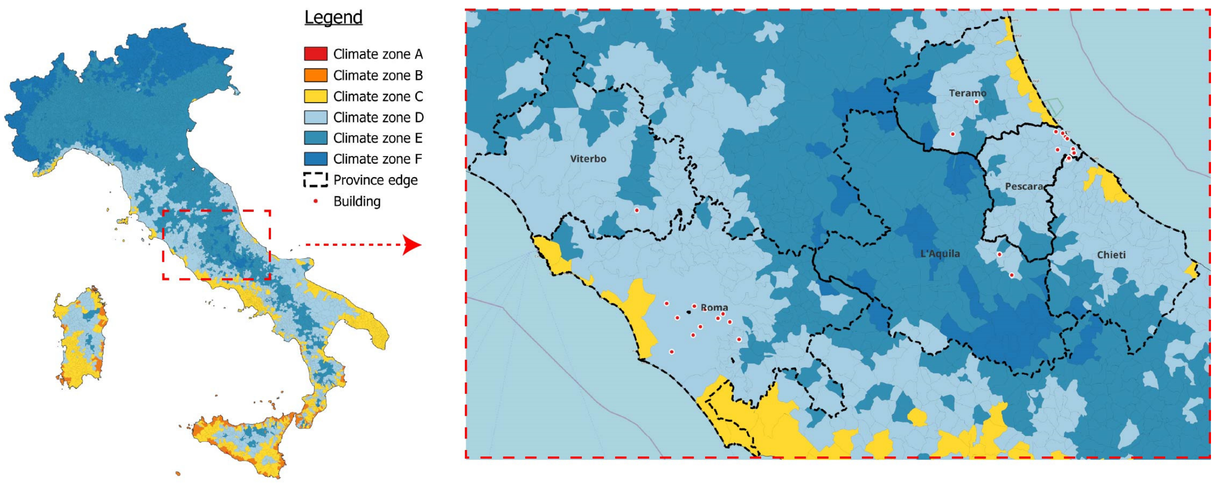

Figure 1. The locations of the buildings. The QGIS elaboration [24].

2.1. Dataset Construction and Data Preprocessing

The data were collected and elaborated from the official technical and administrative documents generated throughout the incentive process by the companies.

The building renovations implied different packages of measures, starting from the basic (EN) building envelope adopted in all the 34 cases to the following composite ones: (EN + SY) building envelope and heating system; (EN + SY + PV) building envelope, heating system, and photovoltaic integration; and (EN + SY + ST) building envelope, heating system, and solar thermal integration.

For each building, the defined database, besides the main dimensional information, combines: (i) building energy performance indicators, referred to the pre- and post-retrofit energy performance certificates; (ii) overall building renovation costs, including VAT, distinguishing between the direct measures cost, i.e., materials and labours, and the auxiliary cost, i.e., ancillary works and safety measures, as well as design and professional services; (iii) the direct cost (excluding VAT) of each single measure that composes the refurbishment package; and (iv) the auxiliary cost for each single measure, derived from the available overall auxiliary building renovation costs by adopting the same proportion of the direct cost of the considered renovation measure with respect to the direct cost of the overall measures of the package. In Table 1, a summary of the main features of the renovated buildings is reported.

Table 1. The main features of the renovated buildings.

Building Id	Heated Floor Area [m^2]	Intervention Package	Overall Cost [€]	Pre-$EP_{gl, nren}$ [kWh/m^2]	Post-$EP_{gl, nren}$ [kWh/m^2]
1	1058.7	EN	557,220	133.78	84.07
2	2425.0		1,757,026	144.54	91.31
3	3122.0		2,169,023	98.37	54.78
4	6761.3		4,990,361	96.81	59.64
5	8065.8		7,624,700	117.71	74.16
6	2722.3		2,219,969	156.55	96.43
7	1762.5		1,333,982	137.94	83.12
8	1004.3	EN + SY	495,835	149.42	70.17
9	610.4		334,715	126.72	74.86
10	1767.6		1,428,358	89.59	51.18
11	852.4		819,170	122.77	93.39
12	1215.3		651,569	141.20	79.40
13	3450.8		2,032,228	81.23	58.61
14	588.7		613,102	152.83	87.17
15	560.7		624,375	274.94	120.60
16	6671.0		3,091,652	126.22	40.09

Table 1. *Cont.*

Building Id	Heated Floor Area [m^2]	Intervention Package	Overall Cost [€]	Pre-EP$_{gl, nren}$ [kWh/m^2]	Post-EP$_{gl, nren}$ [kWh/m^2]
17	1064.4	EN + SY + PV	1,123,756	107.51	51.94
18	2050.4		2,353,171	122.33	36.77
19	2273.2		1,937,800	121.72	36.61
20	2754.8		1,346,289	195.60	99.61
21	2842.7		1,454,448	189.44	110.66
22	2871.9		1,411,899	182.67	106.24
23	2780.0		1,315,229	212.03	115.80
24	1927.6		1,109,446	127.93	43.67
25	1154.5		1,250,718	132.08	42.97
26	5312.7		2,915,816	129.80	42.26
27	2276.4		2,357,324	130.22	79.47
28	4311.9		3,801,640	123.54	81.34
29	4311.9		3,821,313	127.19	85.88
30	435.6	EN + SY + ST	351,264	244.63	133.16
31	1125.2		815,953	101.12	56.69
32	556.9		419,740	282.37	89.44
33	239.1		223,094	150.79	73.23
34	1534.9		1,557,331	65.83	18.71

In particular, the renovation measures were classified as follows:

- Building envelope (EN) refurbishment:
  - ○ Thermal insulation of the opaque envelope (OP).
  - ○ Window replacement (TR).
- Building heating system (SY) upgrade: the replacement of conventional gas-based boilers used for space heating (H), in some cases coupled with domestic hot water production (H + DHW), with:
  - ○ Condensing boilers (CB).
  - ○ Condensing boilers and thermostatic valves for the radiators (CBTV).
  - ○ Hybrid systems (air-to-water heat pumps with CB back-up) (HY).
  - ○ Hybrid systems (air-to-water heat pumps with CB back-up) and thermostatic valves for the radiators (HYTV).
- Solar thermal system integration (ST).
- Photovoltaic system integration (PV).

2.2. Cost Analyses

The cost-effectiveness of the renovation packages was assessed by considering the annual cost, defined as the sum of the annual cost of building management and maintenance, the annual discounted instalment of initial costs, and the product of the cost of the initial investment and the annual discount factor. A calculation period of 30 years and an interest rate of 3% were considered, in line with the EU recommendations [25], and according to the methodology, adopted within the Annex 75 (Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables) project of the International Energy Agency (IEA) [26,27]. The calculation does not include incentives, tax deductions, etc., and the electricity and natural gas costs were set to 0.18 €/kWh and 0.71 €/Sm^3, respectively, according to the latest available Italian energy prices provided by the Italian energy services management company [28].

Hence, the cost-effectiveness of each building energy renovation was analysed by comparing the primary energy reduction, as the percentage variation between pre- and post-retrofit conditions, against the related annual cost per heated floor surface (€/m^2).

3. Results and Discussion

3.1. Cost Characterisation

This section characterises the observed unit prices of the renovation measures, highlighting the contribution of the auxiliary costs to the overall cost. Figure 2 compares the specific cost per heated floor area for each intervention package, distinguishing between (i) direct construction costs and (ii) the overall costs (including the auxiliary costs). The related statistical descriptors are reported in Table 2.

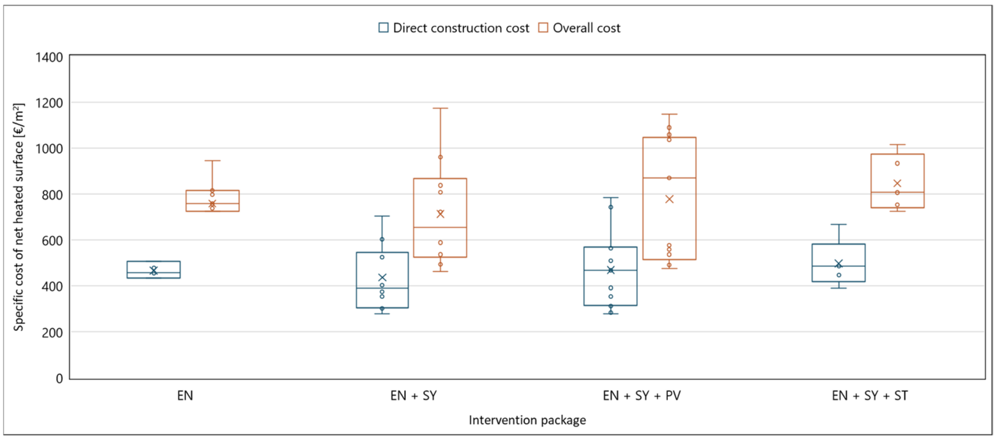

Figure 2. The box plot of the direct construction cost and overall cost based on the intervention package.

Table 2. The statistical descriptors of the specific cost of the intervention packages.

Cost	Intervention Package	Median	IQR	Min	Max	SD	CV
Direct construction	EN	457.0	72.3	277.4	652.5	110.5	24%
	EN + SY	389.0	240.1	277.1	702.3	143.7	33%
	EN + SY + PV	467.0	255.6	278.2	785.1	167.6	36%
	EN + SY + ST	485.1	163.7	389.7	667.8	104.0	21%
Overall	EN	756.8	90.9	526.2	945.4	126.0	17%
	EN + SY	654.5	342.4	463.4	1173.2	231.4	32%
	EN + SY + PV	870.3	531.2	476.3	1147.6	259.8	33%
	EN + SY + ST	806.3	234.6	725.4	1015.4	123.4	15%

The observed values provide two key insights. First, the overall costs are significantly higher than the direct construction costs across all packages, confirming that a substantial share of the economic effort is not captured when the analyses focus exclusively on material and labour items. On average, direct construction costs are 60% of the overall cost. Second, adding the auxiliary cost, besides providing a reduction on the coefficient of variation, i.e., relative dispersion, leads to consistently larger IQRs, indicating a wider absolute dispersion. As a matter of fact, while direct construction prices are constrained by different commercial products only, auxiliary costs strongly depend on the built context (building height and façade complexity, construction site areas, interference with occupants, site access constraints, etc.). Moreover, different sizes of the construction companies involved across the construction sites could reveal different labour costs.

Despite the fact that Table 2 highlights substantial differences between direct cost and overall cost among each renovation package, their absolute dispersions are close to or higher than the absolute differences between the packages. As a matter of fact, statistical testing of differences between intervention packages, assessed using the Kruskal–Wallis H-test, revealed an H-value of 0.74 (p = 0.86) and 1.41 (p = 0.70) for direct construction cost and overall cost, respectively. Therefore, no statistically significant differences were detected ($p > 0.05$), indicating a substantial overlap between packages' specific costs.

Hence, further investigation has been done with reference to the renovation measures to identify the main cost drivers beyond the intervention packages.

Figure 3 reports the distribution of unit prices of each renovation measure related to all collected data, grouped in boxplots to highlight both the median and the spread of the distribution. The prices are the overall ones, including the direct construction cost (materials and labour) and the related auxiliary costs.

Overall, Figure 3a–e show that unit prices are characterised by systematic dispersion, as detailed in Table 3, where the related statistic descriptors are reported to allow a quantitative interpretation of variability.

Two complementary mechanisms can explain this heterogeneity: (i) technical, e.g., different commercial products and associated labour costs, implying different direct costs, and (ii) contextual, such as building site accessibility, building morphology, etc., implying different auxiliary costs.

Further analysis of the composition of direct costs was carried out using multivariate regression, considering variables related to the technical mechanism. The same analysis was not carried out for the auxiliary cost because no detailed data on the contextual mechanism were available.

The regression equations were constructed following a consistent analytical framework across all renovation measures. In each model, two common predictors were systematically included: (i) a proxy for the quantity of intervention to test the presence of potential economies of scale and (ii) a categorical variable representing the construction company ($\gamma_{company}$) to account for the impact of the different related labour costs. Beyond these common predictors, each equation incorporates other predictors specifically related to the renovation measure under analysis. Equation (1) is related to EN (OP) and considers: the opaque envelope insulated area (A_{ins}) expressed in m^2; the percentage of opaque envelope insulated ($A_{ins,\%}$); the building surface-to-volume ratio ($\frac{S}{V}$); the adopted insulation technology (δ_{ins}), distinguishing between EPS, EPS + thermal plaster, and EPS + cavity wall insulation. Equation (2) is related to EN (TR) and considers: the area of replaced windows (A_w); the average window size ($A_{avg,w}$); the thermal transmittance of the windows (U_w); and the installation typology ($\delta_{w,sys}$) that distinguishes normal frame, monoblock window frame, and the replacement of the shutters. Equation (3) is related to the SY and considers: the number of apartments served (N_{ap}); the type of the system, distinguishing between decentralised and centralised; the service covered, distinguishing between H and H + DHW; and the type of heating system upgrading (CB, CBTV, HY, and HYTV). Equation (4) is related to PV and considers: the total power installed (P_{pv}) expressed in kWp and the energy storage system ratio, expressed as the ratio between the energy storage capacity (ESS) and the total power installed. Finally, Equation (5) is related to ST and considers: the area of the ST panel installed (A_{st}) and the thermal storage volume capacity (Vol).

$$\frac{€}{\text{m}^2\ of\ opaque\ envelope} = \beta_0 + \beta_1 \ln(A_{ins}) + \beta_2 A_{ins,\%} + \beta_3 \frac{S}{V} + \delta_{ins} + \gamma_{company} \quad (1)$$

$$\frac{€}{\mathrm{m}^2\ of\ transparet\ envelope} = \beta_0 + \beta_1 \ln(A_w) + \beta_2 A_{avg,w} + \beta_3 U_w + \delta_{w,sys} + \gamma_{company} \quad (2)$$

$$\frac{€}{apartment\ served} = \beta_0 + \beta_1 N_{ap} + \beta_2 T_{sys} + \beta_3 T_{ser} + \delta_{sys} + \gamma_{company} \quad (3)$$

$$\frac{€}{kW_p} = \beta_0 + \beta_1 \ln(P_{pv}) + \beta_2 \frac{ESS}{P_{pv}} + \gamma_{company} \quad (4)$$

$$\frac{€}{\mathrm{m}^2\ of\ pannel} = \beta_0 + \beta_1 A_{st} + \beta_2 Vol + \gamma_{company} \quad (5)$$

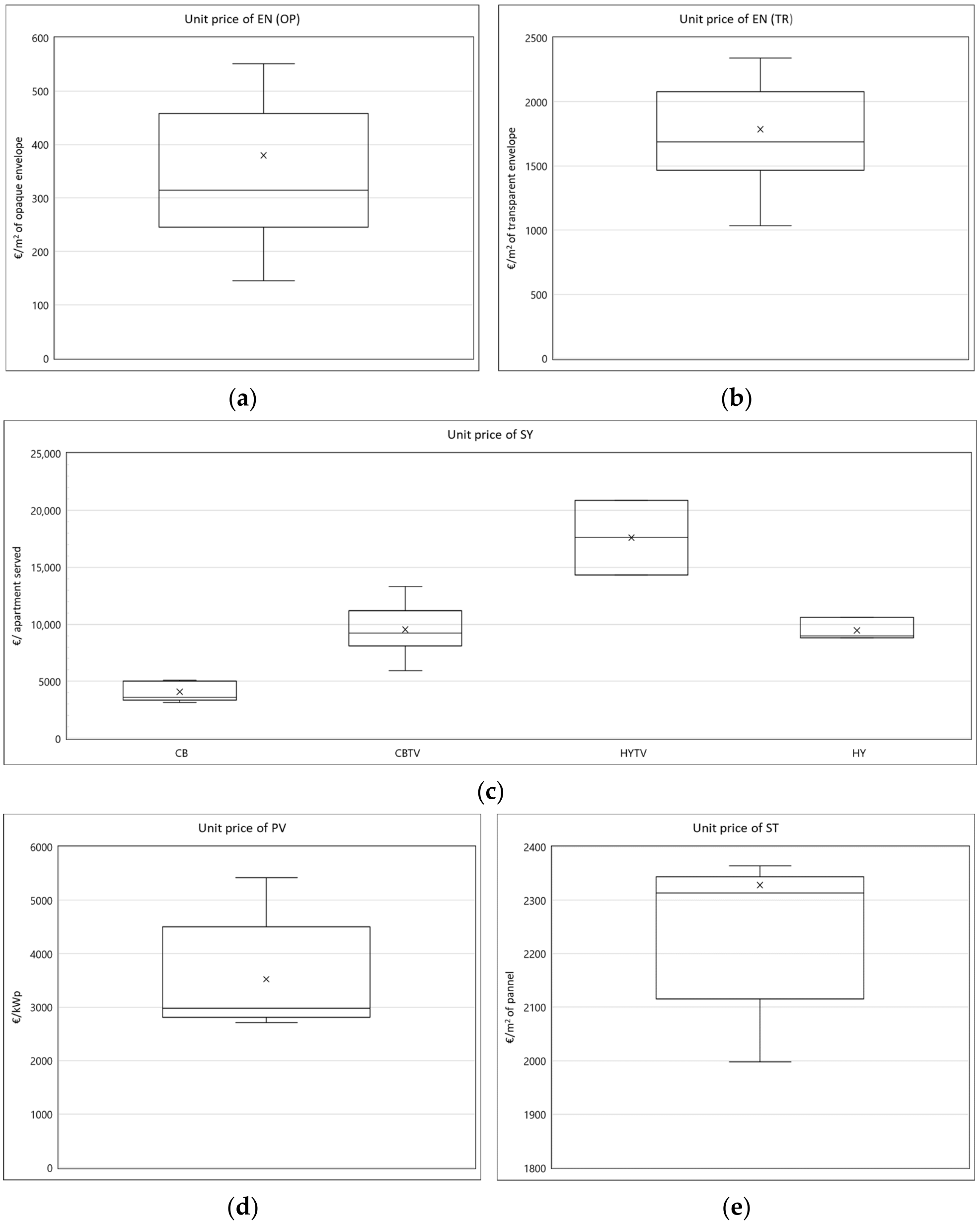

Figure 3. Unit prices for: (**a**) opaque envelope upgrade, (**b**) transparent envelope upgrade, (**c**) H and DHW system upgrade, (**d**) solar photovoltaic integration, and (**e**) solar thermal integration.

Figure 4 reports the linear regressions between the observed and predicted unit costs for each renovation measure. Overall, the models demonstrate satisfactory predictive performance, with R^2 values ranging from 0.71 to 0.97. Higher explanatory capacity is observed for EN (OP), SY, PV, and ST, with values over 0.80, whereas EN (TR) exhibits relative lower values of 0.71. This computed lower value means that, while the main structural predictors defined capture a significant share of variability, additional unobserved factors, such as site-specific installation complexity or architectural constraints, may contribute to residual variance.

Table 3. The statistic descriptors of the unit prices (direct and auxiliary) of the renovation measures.

Renovation Measure	Median	IQR	Min	Max	SD	CV
EN (OP)	308.6	184.6	145.4	947.1	195.2	52%
EN (TR)	1688.2	612.7	1035.1	3681.7	546.7	31%
SY (CB)	3599.4	1679.3	3144.2	5121.3	894.7	22%
SY (CBTV)	9218.1	3079.2	5936.6	13,309.3	1955.1	20%
SY (HY)	8972.9	1763.2	8825.9	10,589.1	978.3	10%
SY (HYTV)	17,600.0	/	14,331.3	20,868.7	4622.6	26%
PV	3214.6	330.1	2568.9	4580.1	571.6	17%
ST	2978.1	1693.1	2714.0	5420.3	1110.9	32%

To assess which predictors mostly drive the unit costs, the related variance impact was assessed through semi-partial R^2 defined as $\Delta R_j^2 = R^2 - R_j^2$, where R^2 is the coefficient of determination of the full model, while R_j^2 is the one related to the reduced model obtained after removing the predictor, j. The values are reported in Table 4.

The comparison of the ΔR^2 among each renovation measure shows that the proxy for intervention quantity exhibits negligible values (typically $\Delta R^2 \leq 0.04$) for EN(OP), EN(TR), and SY, indicating that scale effects have a limited unique contribution to explaining unit cost dispersion. Conversely, for PV and ST, this proxy is the main driver. The company proxy generally provides a marginal contribution with values up to 0.042, suggesting that the variability of the labour costs related to the different companies is not significant. The main exception is the EN (OP), where $\gamma_{company}$ becomes a primary driver (ΔR^2 = 0.181) together with the surface-to-volume ratio. However, this is consistent with the empirical structure of the dataset, where certain insulation technology, i.e., EPS + cavity wall insulation, was implemented by a specific company, absorbing the related variability. As a matter of fact, excluding $\gamma_{company}$ in the EN (OP) regression model, the ΔR^2 of the predictor, δ_{ins}, increases. Therefore, for EN (OP), the dominant drivers are the isolation packages, (δ_{ins}) and $\frac{S}{V}$, which technically represents the building geometric complexity and execution conditions. The unit cost of EN (TR) is mainly governed by the thermal performance (U_w), followed by the installation typology ($\delta_{w,sys}$). For SY, δ_{sys} overwhelmingly dominates the unit cost (ΔR^2 = 0.703).

To summarise, the findings obtained and described in this section show that ranking renovation costs based solely on renovation package type are statistically weak; with reference to the renovation measures, the predictors defined in the multivariate regression applied to the direct costs revealed enough accuracy in assessing the unit costs, highlighting the main drivers. These aspects are very important, as they show the complexity of defining "representative" unit prices towards stock-level policy scenarios [13].

Table 4. Variance impact of each variable expressed as semi-partial R^2.

EN (OP)		EN (TR)		SY		PV		ST	
Variable	**ΔR^2**	**Variable**	**ΔR^2**	**Variable**	**ΔR^2**	**Variable**	**ΔR^2**	**Variable**	**ΔR^2**
$\ln(A_{ins})$	0.002	$\ln(A_w)$	0.042	N_{ap}	0.003	$\ln(P_{pv})$	0.271	$\ln(A_{st})$	0.468
$A_{ins,\%}$	0.042	$A_{avg,w}$	0.020	T_{sys}	0.002	$\frac{ESS}{P_{pv}}$	0.021	Vol	0.310
$\frac{S}{V}$	0.181	U_w	0.548	T_{ser}	0.004	$\gamma_{company}$	0.042	$\gamma_{company}$	0.238

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Table 4. *Cont.*

δ_{ins}	0.045	$\delta_{w,sys}$	0.081	δ_{sys}	0.703
$\Upsilon_{company}$	0.181	$\Upsilon_{company}$	0.002	$\Upsilon_{company}$	0.000

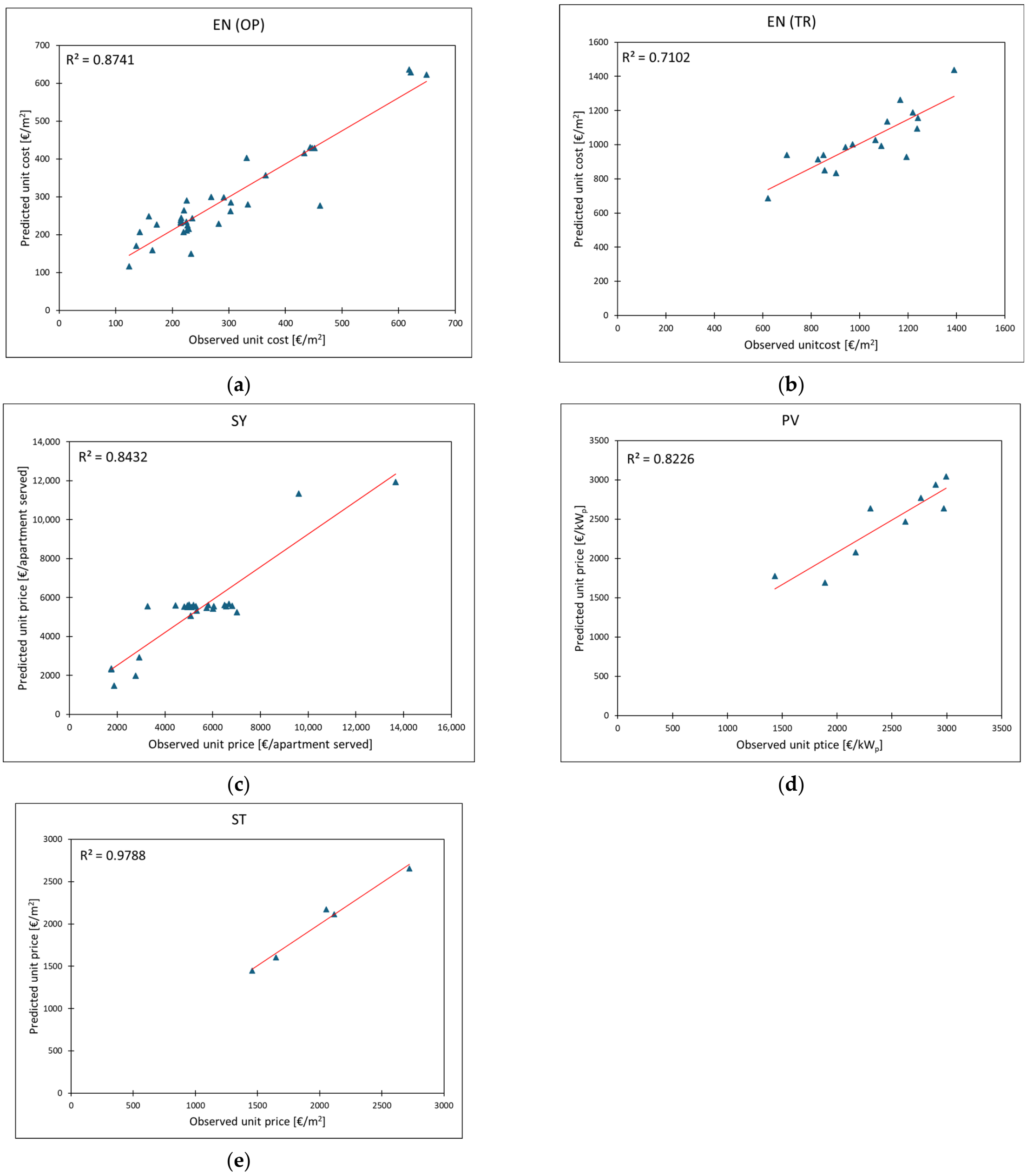
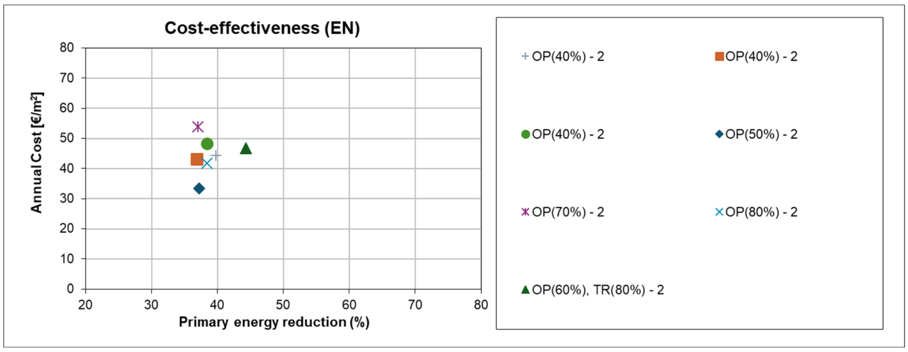


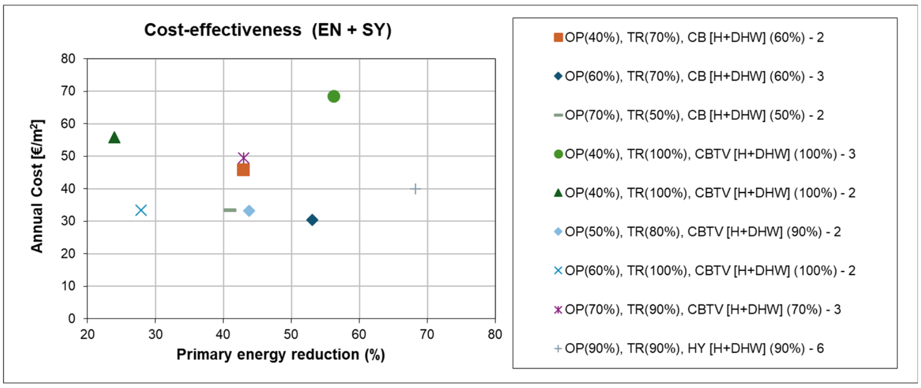
Figure 4. Linear regression between observed and predicted unit costs: (**a**) EN (OP), (**b**) EN (TR), (**c**) SY, (**d**) PV, and (**e**) ST.

3.2. Cost-Effectiveness Assessment

Figure 5 compares the cost-effectiveness of the retrofit packages by plotting the annual cost per heated floor surface (€/m^2) against the primary energy reduction. The energy reduction is reported as a percentage variation between pre- and post-retrofit conditions of the non-renewable primary energy indicator, extracted from the EPCs. To support the interpretation of the results, the legend reports, for each building, the implementation share of each measure relative to the total building. In detail, for opaque and transparent envelope measures (OP and TR), the reported percentages correspond to the fraction of the total heat-loss area retrofitted; for heating system upgrades, the percentage indicates the share of upgraded heating systems among all the apartments. For PV and ST, the percentage represents the share of equivalent dwellings served. Finally, the legend also reports the number of energy class jumps.



(**a**)



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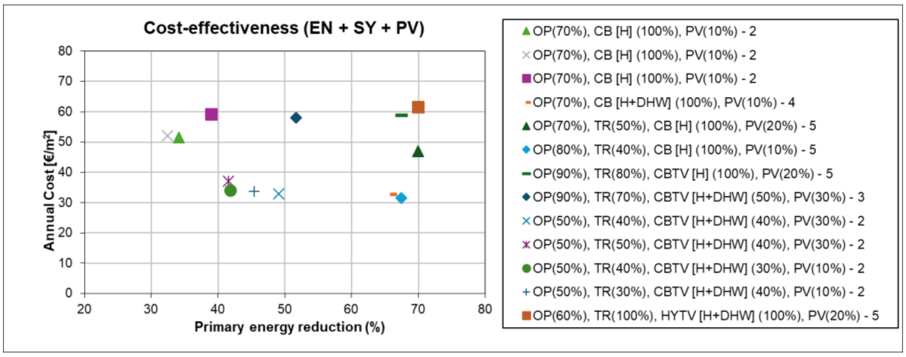

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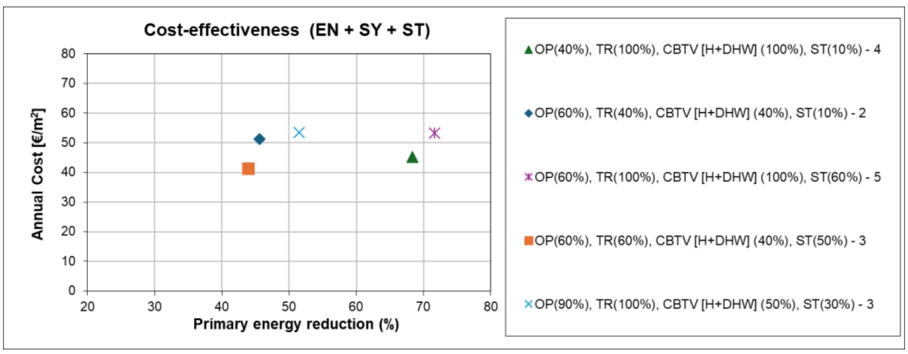

(**d**)

Figure 5. The cost-effectiveness of the retrofit packages: (**a**) EN, (**b**) EN + SY, (**c**) EN + SY + PV, and (**d**) EN + SY + ST.

Across the packages of measures, the annual cost spans comparable ranges but remains markedly dispersed. The EN package ranges from approximately 30 to 55 €/m^2, while EN + SY extends from 30 up to about 70 €/m^2. When on-site renewables are added, EN + SY + PV typically lies between 30 and 60 €/m^2, whereas EN + SY + ST clusters are around 40–55 €/m^2. This variability cannot be attributed solely to the package composition, as it reflects the strong dispersion of the observed unit prices and the non-negligible weight of auxiliary costs, which substantially affect the annual cost even for comparable renovation measures, as discussed in detail in the previous section.

In terms of energy outcomes, the EN package exhibits a narrower band of reductions. The primary energy savings fall between 35% and 40% when measures are limited to the opaque envelope, whereas the case including a high share of transparent components (TR) achieves reductions up to approximately 45%. By contrast, the composite packages show substantially wider spreads: EN + SY ranges from roughly 25% to about 70%, EN + SY + PV from 35% to 70%, and EN + SY + ST from about 45% to above 70%. Overall, adding system upgrades and renewables generally enables larger reductions than envelope measures alone; however, the wider dispersion observed for composite packages indicates that higher savings are not systematically achieved. These savings, in fact, depend on both specific building features (such as the building compactness, where high values lead to more effective energy reduction giving the same renovation measure [29]) and on the extent to which the implemented measures are applied (i.e., the portion of the envelope treated, the fraction of generators replaced, including whether DHW is addressed, and the share of renewable energy systems). As a matter of fact, a subset of composite package cases yields reductions comparable to, or even lower than, those obtained with the EN package. Furthermore, considering the goal of at least 60% reduction in primary energy consumption as a threshold for deep renovation, as outlined in the last EPBD [11], only a limited number of cases meet this requirement. For the considered buildings, the target is reached when composite package cases reveal an energy improvement implying a jump of at least four classes, suggesting that deep renovation requires both the building envelope and heating system upgrades with proper intervention shares. In particular, to reach this requirement, intervention shares should reach at least:

- For EN + SY intervention packages: 90% for both building envelope and heating systems using HY.
- For EN + SY + PV intervention packages: (i) from 70% to 80% of opaque envelope, (ii) from 40% to 50% of transparent envelope, (iii) 100% of heating systems (H) using CB, and (iv) from 10% to 20% of PV.
- For EN + SY + ST intervention packages: 40% of opaque envelope, 100% of transparent envelope, 100% of heating systems (H and DHW) using CB, and 10% of ST.

It has to be noted that all the assessed packages include envelope measures, which imply pay-back times (PBT) much longer than the calculation period of 30 years, as already known in the literature [30,31]. In fact, the net present values (NPV) calculated for the buildings within the EN package in the present study reveal PBT exceeding 100 years, regardless of the assumption of reasonable discount factors, interest rates, and energy price variation.

4. Conclusions

Translating the last EPBD policy principles into an effective incentive design requires robust evidence on the real economic effort and the possible variability of outcomes. This study contributes to the debate by reporting the results of a technical and economic analysis conducted on 34 residential buildings renovated under a recent Italian incentive programme aimed at enhancing the performance by at least two energy classes. For each building, energy performance was compared before and after renovation, and detailed cost records were compiled for all implemented measures, including building envelope improvements, heating system upgrades, and renewable integrations. Comparing direct construction costs with overall costs highlighted, systematic cost variability on the one hand, and the significant impact of auxiliary costs, which, on average, accounted for 40% of the total economic effort, on the other hand. Moreover, the type of intervention packages is a statistically weak driver for ranking renovation costs. Further cost composition analysis enabled the explanation of cost variability. The observed unit prices for the same building renovation measures revealed systematic dispersion, largely due to the different building features, as demonstrated by the extended variable incidence of auxiliary costs, i.e., the ones for temporary works, safety measures, and professional services, as well as due to the direct costs of the materials and labour, of which the main drivers have been identified—specifically, the surface-to-volume ratio and the insulation technology for EN (OP), the thermal performance for EN (TR), the type of heating system upgrading for SY, the installed power for PV, and area of installed panel for ST.

As a consequence of the observed cost variability, the assessed annual cost across the same intervention package adopted by the considered buildings remains markedly dispersed, even when comparable measures within the package are considered. On the energy performance side, the considered case study buildings revealed that envelope-only interventions cannot reach 60% of primary energy reductions. The EPBD deep renovation target can be satisfied only by adding heating generator replacement coupled with a near-complete opaque and transparent envelope refurbishment or with a partial envelope refurbishment but integrating renewable energy. These retrofit combinations are associated with an energy class improvement of at least four classes, which could be considered as a possible policy constraint for defining deep retrofit incentive schemes. However, this finding should be interpreted with caution, as the four-class jump emerges from buildings located in the specific Italian climate zone of this study and may not be directly transferable to the wider national context.

Under the point of view of the future policies, it should be highlighted that the design of very generous incentives can generate significant benefits for homeowners even in case of non-economic sustainable renovation, considering the weak PBTs of the envelope measures mentioned for the sample. Moreover, it has to be noted that the Superbonus implied a market price distortion, from which there is no subsequent reversion, as also attested by other national incentives from the past. In particular, it contributed in increasing the Italian construction costs up to the 13%, while, within the same period, the increment of the prices of the materials, energy, etc., was attested at about 7% [32]. Therefore, future EPBD-aligned incentive policies should introduce schemes that prioritise renovation measures accounting for real cost investment efforts and cost drivers, controlling possible market speculations.

Possible further studies could focus on applying the same analysis to other available case studies considering other climates and renovation measures.

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Abbreviations

The following abbreviations are used in this manuscript:

EPC	Energy Performance Certificate
$EP_{gl,\,nren}$	Global Non-Renewable Primary Energy Performance Index
EPBD	Energy Performance Building Directive
EN	envelope
OP	opaque (envelope)
TR	transparent (envelope)
SY	heating system
H	space-heating service
DWH	domestic hot water service
CB	condensing boiler
CBTV	condensing boiler and thermostatic valves
HY	hybrid system
HYTV	hybrid system and thermostatic valves
ST	solar thermal
PV	photovoltaic
PBT	pay-back time
NPV	net present value

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