Marginal Costs of Building Energy Retrofit

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Abstract. The aim of decarbonizing the economy implies taking action in several areas, one of which is the building industry. Users are likely to benefit from the transition to green buildings in multiple ways, such as lower energy bills as well as higher healthiness and perceived comfort. Nonetheless, those benefits come at a cost. Indeed, property owners must incur substantial capital expenditures to build new high-efficiency constructions or to refurbish outdated ones. While the economic benefits of green buildings have been deeply addressed in the literature over the last two decades, much less attention has been paid to the related costs. This study aims to widen the knowledge about the marginal costs of improving energy efficiency in residential properties. Three detached houses and four to five energy efficiency measures are analyzed. Once the costs are computed through bills of quantities, the energy performance indices and the energy rating bands are identified. We find a substantial gap between the marginal cost curve drawn based on the latest figures and the same curve drawn according to a survey conducted in the late 2000s. The changes in technical standards for calculating building energy performance in the mid-2010s explain almost half the gap. The latest technical standard introduced the novelty of the so-called reference building, a fictitious building sharing the same overall shape but meeting minimum mandatory requirements. That approach has attracted criticism due to supposed flaws and side effects. Here, we show that it also makes building energy efficiency targets much less affordable.

Keywords: Building Industry · Energy Efficiency Measures · Marginal Costs

1 Introduction and Background Literature

Seeking energy efficiency in buildings brings with it several economic issues. Among these, two prominent concerns can be summarized as follows [1]. First, do high-performing buildings command a price premium, resulting in higher market values compared to traditional ones? Second, do high-performing buildings incur a cost premium, leading to greater capital expenses than ordinary ones? The answers to these questions are essential for identifying the cost-benefit balance and, therefore, the profitability of investing in energy efficiency measures for homes and workplaces.

While the first issue has been intensely investigated over the last two decades, the second issue still lacks extensive research and consistent empirical evidence. On the

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one hand, plenty of reliable market-based data has been published on the price and rent premiums for energy-efficient dwellings and offices. Accordingly, the first question has been chiefly answered since dozens of studies have investigated the real estate markets, finding consistent evidence over the last two decades that energy efficiency in buildings is rewarded with higher prices and rents. On the other hand, cost data for efficient residential and commercial buildings is uncertain, sparse, and scattered in the literature. Hence, the second question has yet to be fully answered because only a few works deal with it - namely, looking at potential economic shifts on the building industry's side - and their findings are contrasting at best.

1.1 A Brief Overview of the First Issue: The Price Premium for Energy-Efficient Buildings

Due to the wide availability of real estate market data, dozens of studies pointing to substantial price premiums for energy-efficient buildings have been published so far [2, 3]. Most of them deal with urban real estate markets in cities belonging to the European Union's (EU) member countries [4, 5], thanks to the Energy Performance Certificate system put forward by Directive 2010/31/EU [6–8], which enables to investigate the relationship between energy rating bands and property prices or rents when building units are sold or rented. Even so, other significant studies can be found concerning the United States [9, 10] and Eastern Asia [11, 12].

Comprehensive literature reviews on the topic can be found here [13] and here, too [14].

1.2 The Issue Still to Be Resolved: The Cost Premium for Energy-Efficient Buildings

Based on the empirical findings presented in several recent studies, high-efficiency buildings should be expected to cost more. A common way to improve efficiency, especially as far as consumption is concerned, is to substitute operating energy with embodied energy, as the two are known to be characterized by an inverse relationship (see Fig. 1, left panel) [13]. In turn, embodied energy has been shown to bear a positive - and likely nonlinear - relationship with construction cost (see Fig. 1, right panel) [15, 16]. Accordingly, the higher the energy performance, the higher the construction cost should be.

A literature review article analyzes seventeen early documents on the topic at hand [17], mainly trade publications and reports based on United States (US) data issued between 2000 and 2009, and a minority of papers in peer-reviewed journals, again with a predominance of US data, published between 2009 and 2014. The authors point out that the results are far from convergent. Two documents suggest there is no cost premium for LEED-certified buildings in the US, while a third paper [18] finds clues of higher construction costs for Green Star buildings compared to conventional ones in New Zealand, but the difference lacks statistical significance. A few documents find the cost premium for buildings that include green features and solutions to be low to moderate, that is to say, between 2 and 8%. Other sources set the bar of incremental costs for energy-efficient buildings higher: 11% for a residential project in the US [19],

17 to 18% for other residential buildings, up to 21% for the Platinum LEED certification of an office building, and a record high of 46% for school buildings [20].

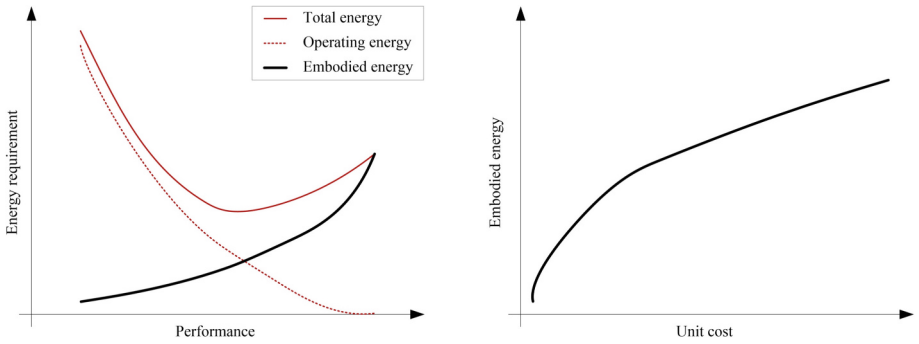


Fig. 1. Embodied energy and construction cost (sources: left panel – authors' study based on [13]; right panel – authors' study based on [15, 16]).

Just a few other studies dealing with the issue of additional upfront costs for green buildings have been published over the last fifteen years. One of them analyzes a sample of 160 LEED-certified buildings across the US, finding that the cost premium is about 4% on average and in the range of 2 to 9% [21]. Quite similarly, a study identifies a 7% additional cost for a Gold LEED-certified building and a 9% above-normal cost for a Platinum LEED-certified one [22]. Another work surveys 121 green building projects in Singapore and concludes that the cost premium lies between 5 and 10% [23]. A relatively recent study claims the cost premium is lower than the likely market premium as documented in the literature, the former being up to no more than 6.5% [24]. Finally, an investigation into the 6-Homestar certification documents shows that it attracts a 3-to-5% additional capital cost for ten detached and terraced houses in New Zealand [25].

1.3 Aim and Structure of This Study

The above literature review makes it clear that empirical findings on the cost side of green buildings are scarce and scattered. More importantly, their diverging results - from no to substantial cost premiums when comparing high-performing buildings to conventional ones - are at odds with the compelling need to understand how the economics of green buildings work on the cost side; they also cast a shadow on the ability to evaluate the economic viability and profitability of investing in the field. Under such a framework, this work aims to improve the knowledge about cost-side aspects of energy efficiency in buildings, as well as to investigate some possible reasons why large swings in the results characterize the few studies conducted so far. The analysis is meant to provide new and updated data concerning the marginal costs of energy efficiency measures usually adopted in dwelling retrofit and to compare them with previous data from European Union (EU) funded projects.

The remainder of this paper is organized as follows. Section 2 describes the method, starting with the cost theory in microeconomics and then identifying the marginal cost for energy efficiency in buildings. Section 3 presents the case studies, the analyzed energy retrofit measures, and the data sources. Section 4 discusses the results: first, a reliable marginal cost curve is traced, and then it is shown that marginal cost estimation largely depends on the method used to assess building energy performance, which changed over time, making it challenging to identify univocal marginal cost thresholds corresponding to increasing building performance. Finally, Sect. 5 draws conclusions and paves the way for further developments.

2 Method

The microeconomic theory of production identifies seven categories of short-run costs that characterize firms' activities. Six of these categories are as follows: variable costs (also known as direct costs in accounting), fixed costs (specifically, overhead expenses in accounting), their sum as total costs, and then average fixed, average variable, and average total costs (meaning the costs per unit of output). Out of all those categories, the most important one - as far as the identification of the optimal output level is concerned - is represented by the seventh: marginal costs, which are defined as the change in total cost resulting from the production of an additional unit of output [26, 27]:

$$MC = \Delta TC / \Delta Q \tag{1}$$

Marginal costs are of utmost importance in firms' decisions about the optimal output. In plain terms, production is worth expanding as long as the cost of each additional output unit (the marginal cost, as a matter of fact) is lower than the benefit of the same unit (the marginal benefit, indeed) so that each additional unit of output contributes to increasing and maximizing profit.

The above reasoning can be easily transferred to pursuing energy efficiency in buildings [28]. Let us assume that EPI_0 is the actual energy performance index of a building unit, EPI_1 represents the improved energy performance index of that same unit once an energy efficiency measure is implemented, and EPI_2 stands for the further improved energy performance index resulting from the adoption of an additional energy efficiency measure. Knowing the costs to be incurred for those measures (TC_1 and TC_2, respectively), the marginal costs can be calculated as follows (note the reversal of terms in the denominator since the energy performance index is bound to decrease as performance increases):

$$MC_1 = TC_1 / (EPI_0 - EPI_1) \tag{2}$$

$$MC_2 = TC_2 / (EPI_1 - EPI_2) \tag{3}$$

When it comes to constructing a new home or renovating an old one, how far is it worth pushing energy performance? Similarly to firms' decision-making process, energy efficiency is worth pursuing until the capital expenditure incurred to gain an improvement of one kWh/m^2 y in energy performance - namely, an additional energy

saving unit - is lower than the corresponding benefit. Therefore, knowledge of marginal costs is a precondition for making viable and profitable decisions regarding the adoption of energy retrofit measures.

3 Case Studies and Data Sources

3.1 Case Studies for Updated Marginal Cost Data

Three detached houses are used as case studies. They are located on the outskirts of small-sized towns in Northeastern Italy, which means they fall within the E climate zone (from 2,101 to 3,000 degree days). One of the case studies was built in the early sixties, and two others in the early seventies; thus, they are characterized by the use of the same construction materials: hollow clay bricks for the walls, wood for slabs and roofs, and single-glazed windows. The gross floor area varies from 80 to 226 m^2, with heating volumes in the 274 to 901 m^3 range (see Figs. 2 and 3).

For each case study, four to five retrofit measures - to be implemented sequentially - are investigated. The first measure - adopted in the second and third case studies only - features replacing the heating system, limited to the boiler, with a new, state-of-the-art condensation one. The second focuses on the thermal insulation of the walls by installing a polyurethane foam coating layer, of which the thickness (10 to 14 cm) and placement (indoor or outdoor) depend on specific constraints. The third measure is to complete the thermal insulation of the building envelope by replacing the wooden roof and complementing it with a coating layer (14 cm thick). The fourth action is the installation of aluminum thermal break frames provided with triple-glazing windows. The fifth and last measure foresees the installation of solar photovoltaic panels on the roof combined with a heat pump.

Considering the building as-is, all three case studies are rated G, with energy requirements of about 358, 283, and 238 kWh/m^2 y, respectively. The costs of implementing each retrofit measure are calculated through bills of quantities (see Table 1), which include the cost of construction materials and systems, manpower, the cost of other goods and services required to run the building site, and overhead expenses of the construction company. The corresponding energy performance and the resulting energy saving are calculated according to the methodology adopted with the Inter-ministerial Decree 26.06.2015, which implements Directive 2010/31/EU.

3.2 Early Cost Data for Comparison Purposes

Early figures of marginal costs related to the refurbishment of residential properties are taken from Factor 4, an EU-funded project that dates back to the late 2000s (in full: “Program of actions towards Factor 4 in existing social housings in Europe”). Based on the information included in the deliverables of that project, three multi-family buildings located in Northern Italy (E climate zone) are selected as case studies. The properties were built in the mid-eighties, early fifties, and early nineties, respectively. The analyzed energy retrofit measures are as follows: insulation of the building envelope, separately for the walls and the roof; replacement of windows and frames; reduction of thermal bridges;

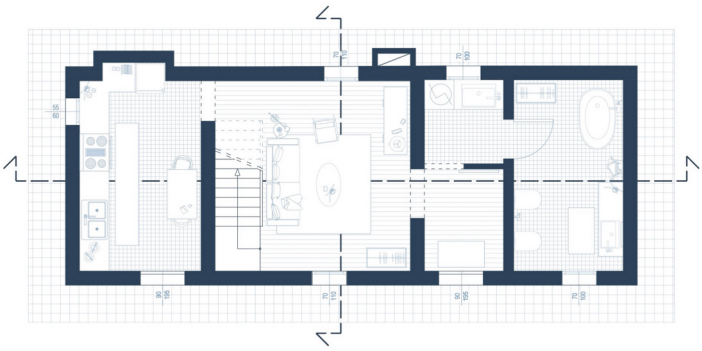
installation of a mechanical extract ventilation system. Building on energy audits, the marginal costs have been reconstructed and presented in a later conference paper [29] and further used for comparison with marginal benefits in a research article [14].



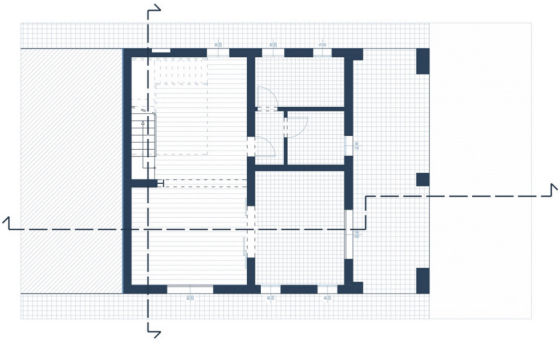
Fig. 2. Selected views of the case studies.

The construction cost indices provided by Istat, the Italian National Institute of Statistics, are used to update historical marginal cost data chronologically. Those indices are specific to the building industry, as they account for changes - on a monthly and yearly basis - in the costs of construction materials, manpower, and overhead expenses to run building sites [30].

Case study 1



Case study 2



Case study 3

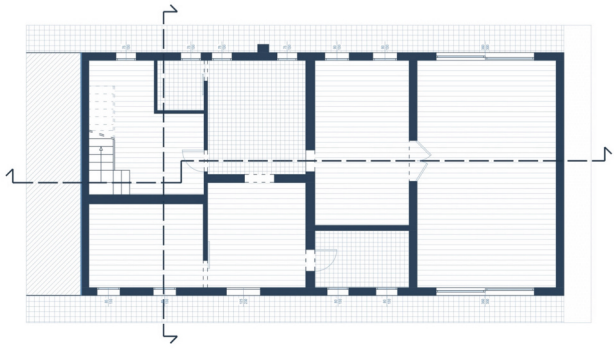


Fig. 3. Ground floor plans of the case studies.

Table 1. Excerpt from the bill of quantities for the third measure: coating layer of the roof.

Description of work	Unit (UoM)	Quantity	Rate (€/UoM)	Total (€)
Case study 1				
Removal of roof tiles	m^2	68.90	17.87	1,231
Replacement of wooden planks	m^2	68.90	19.14	1,319
Providing and laying in position insulation panels	m^2	68.90	67.28	4,635
Providing and laying in position new roof tiles	m^2	68.90	31.78	2,190
Scaffolding rental and erection/dismantling	m^2	169.83	17.92	3,043
Auxiliary construction worker	hrs	120.00	26.39	3,167
Skilled construction worker	hrs	40.00	33.42	1,337
General construction worker	hrs	–	–	–
Total				16,922
Case study 2				
Removal of roof tiles	m^2	145.44	17.87	2,599
Replacement of wooden planks	m^2	145.44	19.14	2,784
Providing and laying in position insulation panels	m^2	145.44	67.28	9,785
Providing and laying in position new roof tiles	m^2	145.44	31.78	4,622
Scaffolding rental and erection/dismantling	m^2	200.07	17.92	3,585
Auxiliary construction worker	hrs	168.00	26.39	4,434
Skilled construction worker	hrs	56.00	33.42	1,872
General construction worker	hrs	–	–	–
Total				29,680
Case study 3				
Removal of roof tiles	m^2	126.15	17.87	2,254
Replacement of wooden planks	m^2	126.15	19.14	2,415
Providing and laying in position insulation panels	m^2	126.15	67.28	8,487
Providing and laying in position new roof tiles	m^2	126.15	31.78	4,009
Scaffolding rental and erection/dismantling	m^2	201.52	17.92	3,611
Auxiliary construction worker	hrs	224.00	26.39	5,911
Skilled construction worker	hrs	56.00	33.42	1,872
General construction worker	hrs	112.00	31.67	3,547
Total				32,106

4 Results and Discussion

As expected, marginal costs are low for the first implemented retrofit measures, namely, the ones that provide a slight increase in energy performance (see Table 2).

Table 2. Energy performance, retrofit cost, and marginal cost calculation.

Energy efficiency measure	Additional investment cost	Energy performance index	Performance gain	Energy rating band	Marginal cost
	(€)	(kWh/m^2 y)	(kWh/m^2 y)		(€/kWh y)
Case study 1					
building as is	–	358.07	–	G	–
Boiler replacement	–	–	–		–
Wall insulation	12,810	222.44	135.63	F	1.19
Roof insulation	16,922	155.25	67.19	E	3.17
Windows replacement	6,249	142.86	12.39	E	6.34
Photovoltaic system	11,727	118.83	24.03	D	6.13
Case study 2					
building as is	–	282.56	–	G	–
Boiler replacement	2,505	235.28	47.28	G	0.37
Wall insulation	19,480	192.79	42.49	F	3.21
Roof insulation	29,680	142.11	50.68	E	4.11
Windows replacement	12,736	115.88	26.23	D	3.40
Photovoltaic system	13,063	111.32	4.56	C	20.08
Case study 3					
building as is	–	237.69	–	G	–
Boiler replacement	2,787	199.98	37.71	G	0.33

(*continued*)

Table 2. (*continued*)

Energy efficiency measure	Additional investment cost	Energy performance index	Performance gain	Energy rating band	Marginal cost
	(€)	(kWh/m^2 y)	(kWh/m^2 y)		(€/kWh y)
Wall insulation	28,867	165.96	34.02	F	3.76
Roof insulation	32,106	123.48	42.48	E	3.35
Windows replacement	20,719	103.24	20.24	D	4.54
Photovoltaic system	15,012	100.12	3.12	D	21.33

They are as low as 0.33–0.37 Euros/kWh for the replacement of the boiler and in the range of 1.19 to 3.76 Euros/kWh for the insulation of the walls, which let the case study buildings shift from the G to the F rating band. By contrast, marginal costs considerably grow when cumulating several retrofit measures and trying to push energy performance beyond given thresholds. They are likely to increase two to fivefold, with record highs of 6.34 Euros/kWh for the fourth measure and 21.33 Euros/kWh for the fifth, enabling them to reach the D and C rating bands.

Merging all the cost figures in the same diagram and searching for a reliable fitting function led to tracing an exponential curve (see Fig. 4, left curve). The fitting function - which has an R^2 index of 0.4815 - is as follows:

$$MC = 96.444e^{-0.022EPI} \tag{4}$$

The implication is that the marginal costs of energy retrofit measures stay within five Euros/kWh when trying to reach an energy performance between 200 and 100 kWh/m^2 y. Still, approaching the threshold of 100 kWh/m^2 y, the marginal costs will likely increase sizably. The above results are less favorable than those found in early studies, where the bar for a steep increase in marginal costs is set at about 50 kWh/m^2 y [14, 31].

4.1 Changes in Costs Over Time

When tracing the marginal cost, early data derived from the source mentioned in Subsect. 3.2, an exponential fitting curve - whose R^2 index is 0.8412 - can be found again (see Fig. 4, right panel):

$$MC = 99.254e^{-0.060EPI} \tag{5}$$

Based on early data, a surge in marginal costs is expected when aiming for a performance of about 50 kWh/m^2 y or less.

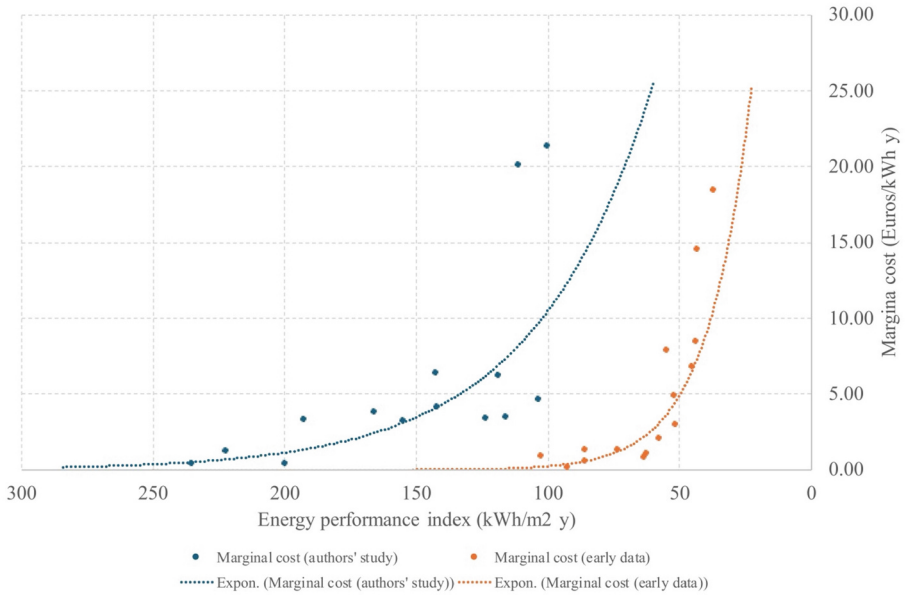


Fig. 4. Energy performance and marginal costs.

One could argue that the difference between Eqs. (4) and (5) is easily explained by the upward shift in construction costs over the last two decades, but that is not the case. All in all, the actual increase in costs the building industry experienced explains only a negligible fraction of that difference (see Fig. 5, the orange and green dotted lines).

4.2 Changes in Methods Over Time

The case studies are similar in terms of building typology and climate zone. Therefore, converging results would have been expected, provided the computational rules of building energy performance have remained the same. Actually, a significant change occurred in the method. In the second half of the 2000s, the building code (Legislative Decree 192/2005, implementing Directive 2002/91/CE) based the calculation of energy performance on two variables: degree days and heat transfer surface-to-volume ratio. Nowadays, the latest technical standard (Inter-ministerial Decree 26.06.2015, implementing Directive 2010/31/EU) features the novelty of the so-called reference building, namely, a fictitious building sharing the same overall shape but meeting minimum mandatory requirements.

By recalculating the latest figures of marginal costs using the building code previously in place, it can be easily noticed that the gap with older data narrows considerably (see Fig. 5, the blue dotted lines). The revised fitting function is as follows:

$$MC = 236.36\mathrm{e}^{-0.053\mathrm{EPI}} \tag{6}$$

meaning the expected steep increase in marginal costs is likely to occur when approaching an energy performance between 80 and 50 kWh/m^2 y.

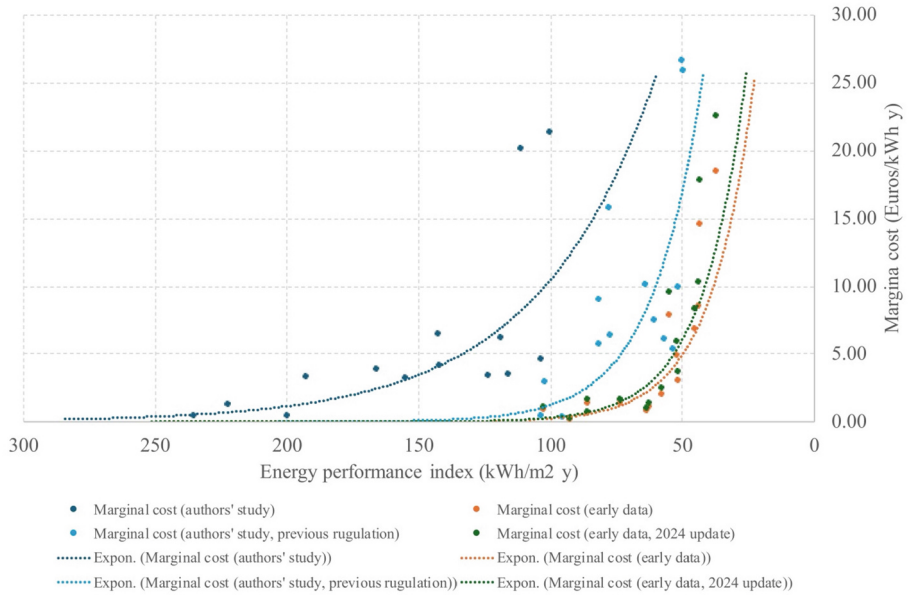


Fig. 5. Explaining the gap in marginal cost data.

5 Conclusions

Knowledge of the marginal costs of building energy efficiency measures is crucial to identifying their profitability by comparing them with their related marginal benefits, so that both policymakers and investors can identify energy retrofit projects that are economically viable. Yet, while marginal benefit estimation has attracted considerable interest and attention over the last two decades, the literature has neglected to analyze marginal costs.

This study provides updated figures concerning the marginal costs of energy retrofit measures in residential buildings. Even on a level playing field - meaning the same building typology and climate zone - those figures point to higher costs for achieving any given energy performance than previously known.

Data on the marginal costs of energy efficiency measures calculated before the mid-2010s are likely no longer helpful due to changes in the computational methodology for building energy performance. As far as the method changes are concerned, a few authors have come to criticize the so-called reference building approach for estimating energy performance [32], claiming that it might be prone to foster energy modeling and design that are characterized as poor, at best, if not even inefficient [33]. Here, we show that it is also likely to make building energy efficiency targets much less affordable as it shifts backward the performance threshold for which a steep increase in marginal costs has to be expected.

Future extensions of this research can help overcome its current limitations. In particular, the results presented here are based on a survey limited to three single-family buildings, all belonging to the same building typology and located in a uniform climate

zone. It would be beneficial to extend the analysis by including additional buildings, not only detached houses, in a wider geographical area.

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