

Quantifying the Loss of Property Value Due to Energy Inefficiency: A Stranded Asset Risk Assessment in the Real Estate Sector

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Abstract. This study examines the economic implications of energy inefficiency in the real estate sector, focusing on the risk of asset stranding resulting from evolving regulatory and market conditions. Considering the European Union's Directive (EU) 2024/1275 and increasing market preferences for energy-efficient buildings, properties with substandard energy performance face growing devaluation risks. This study presents a quantitative framework for assessing the loss of property value resulting from energy inefficiency. The model incorporates three key dimensions: market devaluation, excess operational costs, and CO_2 emission-related penalties. Through market analysis and financial discounting techniques, this framework evaluates the cumulative financial impact of energy underperformance over a defined time horizon. The results indicate that inefficient buildings are becoming increasingly vulnerable to economic obsolescence, particularly as energy prices increase and carbon pricing mechanisms are implemented. These findings underscore the urgency of energy retrofit interventions to mitigate financial losses and preserve asset value. This study contributes to the ongoing climate-aligned real estate investment discourse and provides a decision-support tool for property owners, investors, and policymakers.

Keywords: Energy Inefficiency · Stranded Assets · Real Estate Valuation · Hedonic Pricing Model · Carbon Pricing

1 Introduction

The real estate sector is crucial in addressing climate change, accounting for over one-third of the global greenhouse gas emissions. This industry is under mounting pressure to decarbonize, making climate change a strategic priority. According to research from the Carbon Risk Real Estate Monitor and the Global Real Estate Sustainability Benchmark, buildings are responsible for 37% of the global carbon emissions [1]. However, only 15% of global real estate assets are aligned with the 1.5 °C target outlined in the Paris Agreement [2]. These findings underscore the urgent need for more ambitious and comprehensive decarbonization across the entire sector.

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At the European level, approximately 75% of buildings are classified as energy-inefficient [3]. In Italy, the situation is particularly severe: approximately 60% of residential buildings, representing over 12 million structures and more than 31 million housing units, were built before 1976, when energy efficiency regulations were either minimal or non-existent [4, 5]. Furthermore, more than 70.4% of these buildings fall into the lowest energy performance categories ("E," "F," and "G"), while only 11% exceed class "B" (i.e., "A1" to "A4"), highlighting a pressing need for modernization to meet contemporary energy efficiency standards.

Regulatory frameworks are key drivers of the shift toward a more sustainable built environment. In this context, the European Union formally adopted the "Green Homes" Directive (EPBD – Energy Performance of Buildings Directive), officially titled Directive (EU) 2024/1275 and published in the Official Journal of the European Union on May 8, 2024 [6]. This legislation is a cornerstone of the EU's "Fit for 55" climate package, aiming to fully decarbonize the building stock by 2050 [6]. This directive focuses on large-scale renovations and significant improvements in building energy performance.

Key measures mandated by the directive for Italy and other EU member states include:

- **New private buildings**: From 2030 onward, all new private buildings must satisfy zero-emission standards. Public buildings must comply with this requirement by 2028 [7].
- **Residential buildings**: An average reduction of 16% in energy consumption is required by 2030, with a target of 20–22% by 2035 [7].
- **Non-residential buildings**: These must reduce energy consumption by 16% by 2030 and by 26% by 2033 [7].

By implementing these measures, the EU aims to align the real estate sector with the climate objectives of the Paris Agreement and the European Green Deal, fostering a transition to a more energy-efficient future [7].

Despite its ambitious targets, the EPBD does not impose direct penalties on property owners who fail to comply with prescribed timelines. There are also no explicit bans on selling or renting properties that do not meet these standards. However, this regulatory leniency does not shield noncompliant buildings from market dynamics. Stricter efficiency standards have already led to a decline in market interest for properties that do not meet new benchmarks. These assets are becoming increasingly unattractive to buyers and tenants, many of whom prioritize sustainable buildings with lower operating costs.

Several events, such as the COVID-19 pandemic, the war in Ukraine, and the rise in energy costs, made people pay more attention to the energy performance of their property. At the same time, the exponential growth in the sustainability theme and the growing interest in the environmental, social, and governance (ESG) criteria have resulted in a greater appreciation for properties that comply with these new standards. As a direct consequence, all the buildings inappropriate in terms of energy efficiency could face the risk of economic obsolescence. These properties, in fact, are characterized by high operating costs and, for this reason, are becoming less attractive for supply and demand; this aspect risks fuelling the so-called "stranded assets". A stranded asset refers to an

investment that prematurely loses value owing to shifts in the market, regulations, or environmental conditions.

Several factors contribute to the stranded asset risk in real estate:

- **Regulatory pressure**: As energy performance standards tighten, noncompliant buildings risk becoming unmarketable and losing value.
- **Shifting market preferences**: Tenants and buyers are increasingly favoring certified green properties and marginalizing less efficient ones.
- **Financial implications**: Properties with poor energy performance may face challenges in securing financing, especially as financial institutions adopt stricter ESG investment criteria [8–12].
- **Climate-related risks**: Buildings dependent on fossil fuels are more vulnerable to devaluation, especially when considering transitional and physical risks related to climate change, such as floods, wildfires, and landslides [13].
- **Technological advancement**: The falling costs of clean technologies such as solar panels and heat pumps further diminish the appeal of inefficient buildings.

The financial impact of stranded assets can be significant to property owners, lenders, and institutional investors. Transitioning to zero-emission buildings may necessitate substantial investment in retrofitting and alternative heating systems. Without a clear and well-managed transition strategy, institutions may face asset write-downs and financial losses associated with such properties.

2 Aim

This study aims to develop a quantitative model to measure the loss of property value caused by energy inefficiency, with a particular focus on stranded asset risks. The proposed model integrates three key dimensions: market devaluation owing to poor energy performance, excess operational costs compared to energy-efficient buildings, and penalties related to CO_2 emissions. By analyzing the real estate market and applying financial discounting techniques, this study seeks to provide a decision-support tool for property owners, investors, and policymakers. The goal consists of providing a tool for assessing the urgency and cost-effectiveness of energy retrofit interventions, thus contributing to the transition toward a more sustainable and resilient building stock.

3 Literature Review

3.1 The Relationship Between Energy Performance and Value of a Property

The theme of the relationship between energy performance and property value is gaining increasing importance in real estate sector research. The increasing interest in climate change effects and building energy efficiency has led many homeowners, investors, and policymakers to gain a better insight into the impact of energy performance on property value. Many studies have shown that energy efficiency is a parameter that can positively affect the property value; this has reflected on a higher demand for energy-efficient buildings in different markets [14–17]. For instance, studies conducted in Sweden and Italy highlighted that properties having a better energy efficiency level tend to get higher prices [15, 18].

The energy performance of a building can be certified through a document known as the "Energy Performance Certificate" (EPC). Based on this document, in possession of any property for sale, potential buyers or tenants can compare the energy performance of buildings displayed on the market. The role of the EPCs is to promote energy saving in the residential sector and, at the same time, to provide a means to improve the environmental performance of the residential buildings sector [19]. There are conflicting views as to whether or not EPCs have an impact on property values. Still, it is indeed demonstrated that they can change households' attitudes towards environmental performance [19].

Hedonic pricing models have been used several times to explore how energy performance affects property values. They examine the influence of the different characteristics of a property on its price, among which is also energy efficiency [20, 21]. By analyzing sales data together with property characteristics, these models are able to determine how EPCs influence the value of residential properties [17, 22]. In essence, they help to quantify the percentage change in property values related to energy performance [17]. It's also important to note that a property's location and the trends in the local market can play a significant role in shaping the connection between energy performance and property value. Booker found that the local market's response to sustainability is the missing link between environmental performance and property value [23]. This means that the value placed on energy performance may vary depending on regional factors and market conditions [23]. The architectural, typological, and physical-technical attributes of a building can also affect how energy performance influences property prices. Barreca et al. (2021) found that the joint effect of building energy performance and the above attributes is poorly studied [24]. This study explored how energy performance and various features affect property prices through spatial analyses conducted on a sample of housing properties from Turin's real estate market, along with several subsamples [24]. Numerous studies have identified a positive correlation between energy efficiency and property values. Davis et al. (2015) used a hedonic pricing specification to find a small but positive relationship between improved energy performance and higher selling prices in the Belfast housing market [17]. A study conducted by Duarte and Chen showed that, in a short period, the energy premium for multi-family dwellings in the metropolitan area of Barcelona showed a positive trend [25]. This result suggests that buyers are willing to pay more for energy-efficient homes, as this effect translates into potential energy savings and environmental benefits associated with these properties.

3.2 Stranded Asset Risk and Energy Inefficiency in Real Estate

The idea of stranded assets, which represent assets that have undergone sudden or premature write-downs or depreciations or that have become liabilities [26], is now highly significant, as the trend towards a low-carbon economy continues [27]. This risk arises when properties lose their economic viability due to various factors, such as climate change policies and changing market preferences, and, as a result, goods have difficulty producing economic returns due to changes in environmental conditions and societal expectations [28].

The concept of stranded assets is crucial for understanding the long-term economic viability of real estate investment. Leskinen et al. (2020) highlight that property values fully reflect environmental performance properties and motivate mainstream investors

to adopt sustainable features [26]. This means that, as environmental awareness grows and regulations become tighter, the value of energy-inefficient properties may decline significantly, resulting in financial losses for owners and investors.

Several factors contribute to the increasing risk of real estate assets becoming stranded because of energy inefficiency.

Intensifying Minimum Energy Efficiency Standards (MEES): Governments worldwide are enforcing stricter energy efficiency regulations for buildings. Booker emphasized that commercial structures with low Energy Performance Certificate (EPC) ratings could be considered unsustainable, lose value, and fall into obsolescence, especially following the UK's Minimum Energy Efficiency Standards (MEES) enacted in April 2018 [23].

Growing Environmental Awareness: Increasing public awareness of climate change and building environmental impact drives the demand for energy-efficient properties. Waters and Elder's research has shown that investment in eco-friendly innovation can be fully justified, as house purchasers have demonstrated a willingness to pay as much as $15,000 for energy-efficient homes [19].

Technological Advancements: The rapid advancement of energy-efficient technology has made older, inefficient buildings obsolete. Current research focuses on new investments and innovative opportunities for enhancing energy efficiency in building stocks, aiming to quickly realize widespread zero-energy building (ZEB) standards [29].

Energy Price Volatility: Variations in energy prices can significantly influence building operating expenses, rendering energy-inefficient properties less appealing to both tenants and buyers. According to Fekete and Baranyai (2024), energy performance certificates substantially affect a property's perceived market value [30].

3.3 Cost and Carbon Pricing Impact on Real Estate Depreciation

Depreciation, regarding real estate, denotes the slow decrease in a property's value as time passes, influenced by factors such as physical wear and tear, functional obsolescence, and external economic conditions. Energy inefficiency is becoming an increasingly significant depreciation driver, particularly as operating costs rise and regulations become more stringent. The rise of carbon pricing mechanisms amplifies this trend, making properties with high carbon footprints less appealing to investors and tenants. There are several reasons why real estate assets might lose value, and energy inefficiency is a significant concern.

Physical Deterioration: the value of the property tends to decrease over time due to the aging of materials and normal wear, especially in cases where maintenance has been poor.

Functional Obsolescence: the property tends to become less attractive for potential buyers or future tenants, due to outdated systems or presence of non-modern services.

Economic Obsolescence: property values can be reduced due to several external factors, such as changes in market conditions and growing environmental concerns.

Energy Inefficiency: buildings tend to lose value when the carbon emissions related to energy consumption are too high, due to high energy consumption and limited use of renewable energy (excessive dependence on fossil sources).

Carbon Pricing Mechanisms: different carbon taxes (or even cap-and-trade systems) tend to increase operating costs for energy-intensive buildings, resulting in faster depreciation.

The net operating income of a property is strongly influenced by high energy costs (necessary to heat, cool, and illuminate the house). As a result, buildings that are energy inefficient and therefore subject to higher costs become less attractive for buyers and lessors. It is therefore obvious that the depreciation of real estate is strongly influenced by the continuous increases in energy prices, which, together with energy inefficiency, generate a significant increase in operating costs associated with the property itself. On this basis, action to upgrade existing buildings with energy-efficient technologies is very useful in order to reduce depreciation risks and increase the value of real estate [31]. In addition to the economic aspect, the energy upgrading of a building contributes to reducing carbon dioxide emissions, as Mecca et al. (2020) note that the real estate sector is responsible for approximately 39% of global energy-related CO_2 emissions [32]. These enhancements can decrease energy usage, cut operational expenses, and enhance the appeal of a property to both tenants and buyers.

4 Quantifying "Stranded Asset" Risk Due to Energy Inefficiency

4.1 Framework Overview

This study presents a quantitative framework for formally evaluating the financial impact of energy inefficiency in the real estate sector. It measures the potential loss of inefficient buildings across a defined timeline and under specific market and regulatory conditions. This method incorporates three components.

- **Market Devaluation:** Captures the expected reduction in asset value resulting from energy performance noncompliance [33–36].
- **Excess Operational Costs:** These represent the present value of additional utility expenses incurred by inefficient properties compared with benchmark buildings.
- **CO_2 Emission Costs**: Measures the discounted cost of excess carbon emissions under assumed carbon pricing schemes.

The mathematical formulation is as follows:

$$R_{SA} = \left(V_{benchmark} - V_{actually}\right) + \sum_{t=1}^{T} \frac{\Delta C_{Op}}{\left(1 + r_{Op}\right)^t} + \sum_{t=1}^{T} \frac{\Delta C_{Em}}{(1 + r_{Em})^t} \quad (1)$$

where R_{SA} refers to the expected monetary loss resulting from the market and regulatory disadvantage of energy-inefficient buildings, expressed as a deterministic estimate in euros, rather than a probabilistic risk measure; $V_{benchmark}$ is the market value of an energy-efficient benchmark property; $V_{actually}$ is the current market value of the inefficient building; ΔC_{Op} is the annual operational cost differential (benchmark vs. inefficient building); ΔC_{Em} is the annual emission cost differential (benchmark vs. inefficient building); T is the time horizon for cost savings evaluation; r_{Op} is the discount rate applied to operational cost differentials (ΔC_{Op}), representing the financial time preference of private actors (property owners, investors) (it reflects standard financial

discounting practices, incorporating opportunity cost of capital, inflation, and risk premiums associated with energy prices); r_{Em} is the discount rate applied to CO_2 emission differentials (ΔC_{Em}), representing a societal discount rate consistent with climate policy evaluations. This rate captures the ethical imperative to account for long-term, intergenerational impacts of carbon emissions.

In this study, the benchmark served as the reference condition against which the market value, operational costs, and CO_2 emissions of inefficient buildings were compared. The benchmark value, together with its associated operational and environmental parameters, is scenario dependent and reflects regulatory, market, and technological trajectories. To ensure methodological robustness and policy relevance, the benchmark can be defined in alignment with the recast Energy Performance of Buildings Directive (EPBD) (Directive EU 2024/1275), which sets targets for decarbonizing the European building stock [37].

4.2 Data Sources and Variables

The calculation of each component relies on three distinct data layers, which are examined individually in the following paragraphs:

Market Valuation Data

The first component of the "Stranded Asset" Risk refers to the market devaluation associated with the energy inefficiency of a building. Properties with lower energy performance tend to experience a progressive decline in market value over time compared with more energy-efficient buildings. This phenomenon is particularly relevant in a context where the demand for low-emission and energy-efficient buildings is growing rapidly, pushing both investors and buyers to prefer assets with superior energy performance.

The following expression captures this market depreciation:

$$\Delta V = V_{benchmark} - V_{actually} \tag{2}$$

where $V_{benchmark}$ represents the market value of the energy-efficient benchmark. This value can be estimated through market analysis or comparative methods, using data with similar properties and better energy ratings. $V_{actually}$ is the current market value of the inefficient buildings.

The difference between these two values quantifies the value loss attributable exclusively to the building's substandard energy performance, assuming that all other physical and locational attributes are constant.

Operational Cost Differential

The operational cost differential measures the annual economic burden resulting from an inefficient building's excess energy consumption compared with that of an energy-efficient benchmark building. This term is computed as the difference between the actual and benchmark annual utility bills using data contained in the Certificate of Energy Performance (abbreviated as "APE" in Italy). Specifically, the following fields are relevant (Table 1).

Table 1. "APE" Field relevant to quantify "Stranded Asset" Risk.

Description	Usage in the Model
Total primary non-renewable energy demand, in kWh/m^2/year (EPgl,nren)	Multiply by surface area and unit energy cost to estimate
Fuel type used (e.g., gas, electricity)	Determines the unit energy price (€/kWh)
Heated floor area of the building	Used to scale the energy performance index to total consumption
Official energy class (e.g., F, G)	Identifies current and benchmark classes

The operational cost differential is quantified in the following way:

$$\Delta C_{Op} = \Delta Ec \bullet P_{en} = \left(Ec_{actually} - Ec_{benchmark}\right) \bullet P_{en} \tag{3}$$

with:

$$Ec_{actually} = EPgl, nren_{actually} \bullet Area_{heat} \tag{4}$$

$$Ec_{benchmark} = EPgl, nren_{benchmark} \bullet Area_{heat} \tag{5}$$

where $Ec_{actually}$ is the energy consumption of the inefficient building, $Ec_{benchmark}$ is the energy consumption of an energy-efficient benchmark property $EPgl$, $nren_{actually}$ is the total primary non-renewable energy demand of the inefficient building, $EPgl$, $nren_{benchmark}$ is the total primary non-renewable energy demand of an energy-efficient benchmark property, $Area_{heat}$ is the heated floor area of the building, P_{en} is the energy price.

CO_2 Emissions and Carbon Pricing
The emission data were calculated based on the energy mix used in the building (e.g., natural gas and electricity) and standard emission factors (in kg CO_2 per kWh). The annual emission gap ΔEm is monetized through current or projected carbon prices from regulatory frameworks (e.g., the EU ETS and voluntary carbon markets):

$$\Delta C_{Em} = \Delta Em \bullet P_{CO_2} = \left(Em_{actually} - Em_{benchmark}\right) \bullet P_{CO_2} \tag{6}$$

where $Em_{actually}$ is the annual emission value of the inefficient building, $Em_{benchmark}$ is the annual emission value of an energy-efficient benchmark property, P_{CO_2} is the carbon price.

5 Discussion and Conclusion

The findings of this study indicate that energy inefficiency represents a real economic threat to the real estate sector, resulting in the gradual devaluation of buildings that do not perform well in terms of energy efficiency. The interplay between decreased market

value, increased operational expenses, and stricter carbon pricing policies significantly undermines the appeal of inefficient buildings, making them less desirable for buyers and investors. During a rapid energy transition, remaining in lower-energy classes imposes greater financial pressure on property owners and increases the likelihood that these buildings will become stranded assets—properties that lose value irreversibly due to their failure to meet evolving regulatory and market requirements.

The analysis has shown that, on the one hand, direct market devaluation reflects the increasing demand for high-performance buildings. However, rising operational expenses and environmental penalties associated with carbon taxation systems make managing low-performance properties progressively more burdensome. Moreover, the evolving European regulatory framework, which gradually enforces compliance with stricter energy-efficiency standards, further accelerates the depreciation trend for buildings that fail to implement timely retrofit interventions.

To truly make a difference, adopting risk-mitigation strategies through energy retrofitting is essential. Not only does upgrading buildings support environmental sustainability, but it also significantly contributes to preserving and boosting real estate value. Property owners should look closely at the opportunity to invest in energy-efficient solutions, understanding that the financial benefits from reduced operational costs and improved market appeal far outweigh the initial investment in upgrades. Similarly, investors and financial institutions should incorporate energy-related depreciation risk into their valuation models, considering energy efficiency as a crucial factor in real estate risk management. Integrating market devaluation, operational cost differentials, and CO_2 emission penalties into a unified valuation framework demonstrates the multifaceted nature of the risks posed by energy underperformance. The proposed model provides a replicable and data-driven approach for quantifying this risk, enabling stakeholders to anticipate value erosion and make informed decisions.

It is essential to clarify that the model proposed in this study does not refer to costs associated with energy retrofit because its purpose is not to assess the financial feasibility of interventions, but rather to quantify the economic risk of maintaining energy inefficient buildings in their current state. The estimated loss can be interpreted as the financial exposure property owners would face without timely energy upgrades. While the financial sustainability of retrofit interventions is certainly relevant for private actors, this dimension does not fall within the scope of this research. Future study developments could incorporate investment costs for retrofitting and public incentive schemes to assess the potential trade-off between avoided losses and upfront expenses. In addition, future research could enhance the model's applicability by including dynamic policy scenarios, regional market differences, and behavioral factors that influence investor and consumer responses to energy efficiency.

Simultaneously, public policy is crucial in supporting the real estate sector's transition toward more sustainable standards. Tax incentives, subsidies for retrofitting, and clear, stable regulations are indispensable tools to guide the market through this transformation, thereby minimizing the risk of economic loss and promoting the development of a resilient building stock that aligns with the decarbonization goals.

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