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A probabilistic framework for stranding risk assessment and EPBD IV scenario analysis for the Italian building stock

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ABSTRACT

The building sector is a major contributor to global GHG emissions, constituting an essential player in national and global decarbonization strategies. In this framework, governments have started requiring higher building energy performances to reduce emissions, with the new European Energy Performance of Buildings Directive (EPBD) representing a further step in this direction. Such requirements could be enforced at a large scale with specific penalties for the property owners, such as the stranding of non-compliant assets, making them not rentable or marketable until requirements are met. A few countries have already applied these measures but with a limited extent and effective implications compared to the decarbonization goals. Thus, while the consequent impact is potentially considerable given that a significant share of existing buildings would be stranded, a high uncertainty characterizes its assessment, calling for a probabilistic approach. However, no probabilistic methods have been formulated for stranding risk. This paper critically reviews the state-of-the-art approaches for stranding assessment of buildings. A probabilistic framework based on methodologies derived from natcat risk assessment is also presented. A scenario-based analysis is carried out on the Italian building stock and compared to the impact of natural hazards. Results reveal that stranding risk can be relatively significant in terms of expected monetary losses. The categorization of this risk as sustainability-induced "creative destruction" is also discussed. The findings provide insights into which policies would be required to implement decarbonization pathways for the building stock while underlining how energy retrofit design can adapt to mitigate stranding risk.

1. Introduction

The building sector was responsible for roughly one-third of global energy consumption in 2019 [1]. A significant contributor is the energy consumption for heating and cooling purposes [2]. To reduce the dependency on fossil fuels, lower the carbon footprint of buildings, and improve their overall energy need, various building regulations have been introduced over the past three decades [3,4]. This has brought interest to the study of the impact of these new regulations on the existing building stock and the construction industry overall, with specific reference to the so-called stranding risk [5–7]. A stranded asset is an asset that has lost value in an unanticipated way or usability sooner than expected. The stranding effect induced by climate change (CC) and its mitigation measures can affect the building industry in several different ways.

Starting from the materials level, certain classes of widely used compounds have been banned in the past, as is the case of chlorofluorocarbons (CFCs) previously adopted as foaming agents and refrigerants [8,9]. Indeed, due to their capacity to deplete the ozone layer, they were gradually phased out between 1995 and 2010 under the Montreal Protocol of 1989 [10,11]. Since

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Nomenclature	Definition
Abbreviation	
BEP	Environmental break-even period
CPB	Embodied carbon performance of the building
CRREM	Carbon Risk Real estate Monitor
EPB	Energy performance of the building
EPC	Energy performance certificate
NET	Net energy consumption target
PBE	Performance-based Engineering
$P(Sr(t_i))$	Probability of stranding at a given year t_i
RT1, RT2	Retrofit Design 1 and 2
SL	Service Life
TEC	Total energy consumption
t_p	Year of stranding risk assessment
YEI	Yearly Emission intensity
YEP	Yearly Emission pathway
Notations and Units	
EAL	Expected Annual Loss [% y^{-1}]
Bp	Building performance
Crt	Retrofit cost per area [€/m^2]
Ksr	Retrofit cost [€]
Lrt	Retrofit loss variables
Mp	Mandatory performance
Nd	Number of fatalities per year [y^{-1}]
Nrt	Fatalities-construction cost ratio [$€^{-1}$]
UC	Unit cost of construction [€/m^2]
Vsr	Stranding Risk Variables

the protocol's enforcement, the ozone layer has reportedly started healing [12]. Such compounds have been replaced by HFCs, which have a considerable GWP. The magnitude of the emissions from these HFC banks was estimated to contribute 0.3–0.5°C to global warming by 2100 [13,14]. To mitigate such effects, the Kigali Amendment [15,16] was added to the Montreal Protocol to introduce a gradual phase-out of high-GWP HFCs in the coming decades. Similarly, more and more attention is being paid to other high embodied carbon materials, ranging from predominantly structural applications, such as steel and concrete [17], to insulation materials [18].

A different type of stranding linked to the effects of CC can be induced by natural hazards [19,20]. Indeed, CC has been linked to an increased possibility of weather-related disasters such as floods [21], hurricanes [22] and wildfires [23]. This higher likelihood can indeed cause a possible stranding via the combination of perceived risk and under-insurance [24]. Moreover, these disasters can directly damage the existing building stock, permanently or temporarily unusable [25].

The energy transition process itself can lead to a significant loss of value or complete stranding of the building stock situated in those areas that were developed due to the presence of natural resources or manufacturing processes with high environmental impact [5]. This scenario could affect, for example, a coal mining city or a logging district [6]. An allegedly more direct stranding mechanism can be prompted by enforcing stricter building regulations requiring mandatory certificates, higher energy, or environmental performances. An example of that has been the introduction of standardized energy performance certificates (EPC) in the EU with the 2002 Energy Performance of Buildings Directive (EPBD) [26]. The directive required mandatory EPCs for buildings on sale or rent, and the 2010 version [27,28] required it to be clearly stated in any advertisement. While non-compliance with this obligation would have implied an effective stranding, the impact on the EPC outcomes on the market values of properties has also been investigated. The outcomes of these studies range from a clear positive correlation between value and energy performances [29,30] and weak or no correlation at all [31]. The existence of a positive correlation is, however, confirmed when the impact of other non-mandatory certifications, such as LEED or Energy Star, are considered [32–34]. Nonetheless, this stranding mechanism has had no significant effects given that: (i) the cost of an energy audit for a mandatory EPC is a small fraction of the value of a property, (ii) any effect on market value is complex and influenced by many factors, (iii) more advanced certifications are usually not mandatory. The slow rate of energy retrofits of the existing building stock somehow confirms this. Taking the EU as an example, 80% of the buildings were constructed before 1990, and a third of them were built before 1960 [35]. In 2014, the annual rate of new building construction was 0.19% in Spain and Italy, and 0.56% in Germany [36]. In comparison, the EU needs to increase the annual building renovation rate from the current 0.2% to 3% to meet its environmental goal for 2050 [37].

As a result, the EU Commission has proposed revisions to the 2015 EPBD [38–41] to introduce minimum energy performance requirements for existing residential and commercial buildings. While, to this day, the enforcement mechanism of such a requirement is not yet defined, this could realistically be similar to the one linked with the EPC introduction. Thus, a non-compliant building would eventually be prohibited from selling or renting, resulting in an effective stranding. This would be in line with both the 2023 draft [40,41] final version [41] of the new EPBD, also called "EPBD IV". Furthermore, this approach has already been enforced since 2023 by the UK for commercial and residential buildings [42], even if with wide exemption possibilities. Besides, France will enforce renting restrictions based on EPC from 2025 [43]. A similar regulatory approach has also been considered by the Italian Central Bank [44]. Along the same line, [45] underlines the importance of uniform EPCs for the EPBD IV implementation. Moreover, the new EPBD underlines that any energy performance requirement should be increased following a pathway leading to a net zero-emission target [46] by 2050 per the 2015 Paris Agreement [47]. The adherence to a decarbonization path is the basis of a state-of-the-art method for assessing stranding risk, i.e. the Carbon Risk Real Estate Monitor, CRREM, framework [7,48,49].

This method, however, treats the risk in a deterministic way, assuming a scenario in which the hazard source, i.e. the stranding, is already known in most of its characteristics. On the other hand, legislation introduced in Germany [50] and under discussion in the United Kingdom [51] has shown that the enforcement of any mandatory requirement for decarbonization of buildings' energy is not straightforward to forecast. Moreover, CRREM is not meant to assess the impact side, i.e. the costs linked to stranding itself, which are, by its nature, mostly coupled to retrofit activities. Meanwhile, the risks linked to natural hazards are usually assessed with the performance-based engineering (PBE) methods [52] which, based on the total probability theorem, allows for an independent evaluation of hazard, fragility, damage, and loss. PBE has been adapted and applied to different natural hazards, such as tsunamis [53], hurricanes [54], wind [55], floods [56], coastal hazards in general [57] and fires [58,59]. Thus, given the strength of sustainability trends and the significance of the possible impacts on the building stock, methods for stranding risk analysis could benefit from a probabilistic approach to risk assessment. Moreover, an estimate of the total costs of an EPBD enforcement scenario and extensive retrofit campaign, as in [60], could provide valuable insights into how to manage this emerging risk of the energy transition. To improve the capabilities of current stranding risk assessment practices and to understand the importance of this emerging risk, this paper has the following research goals, also corresponding to the phases of this study:

(1) Carry out a critical review of the current methods for stranding risk assessment of the building stock to highlight some of the existing limitations (Section 2);
(2) Provide a viable probabilistic framework for stranding risk assessment, able to overcome some of the current limitations (Section 3);
(3) Perform a simplified scenario-based analysis of the EPBD-induced stranding risk for the Italian building stock (Section 4.1);
(4) Compare this impact with others from natural hazards in order to assess the significance of stranding risk (Section 4.2).

To the best of authors' knowledge there are no other studies in the scientific literature with the above-mentioned goals. The results are then discussed in Section 5, while the main conclusions of the study are drawn in Section 6 along with some comments on future developments.

2. Critical review of current methods

As underlined in a 2019 review [5], up to that moment, there was no analytical tool to assess the stranding risk of buildings. Still, analytical tools had already been available to evaluate the "Environmental, social and governance", or ESG, score of real estate, such as the Global Real Estate Sustainability Benchmark (GRESB) [61], and agreement with country-level energy performance target for buildings [62]. To fill this gap, the CRREM framework was developed as a result of an EU Horizon 2020 research program [49,63]. As a result, also the aforementioned GRESB has integrated the CRREM framework within its benchmark system. Adopting a certain degree of simplification, we can summarize the CRREM procedure in the following steps [7]:

(a) downscaling, to country level and building sector, of the residual budget of CO_2 emissions according to 1.5 and 2°C global warming scenarios [47];
(b) a yearly emission pathway (YEP) for each building type, such as residential, commercial, etc., is evaluated and defined in terms of a series of yearly emission intensities (YEIs) expressed in $\mathrm{kgCO_2\ m^{-2}\ y^{-1}}$;
(c) quantify a net energy consumption target (NET) depending on the building type and climate and based on the forecasted renewable energy budget according to the net-zero scenario in 2050 [64];
(d) the examined building is compared to the pathway. If, at a given year, its YEI is higher than YEP or total energy consumption (TEC) is higher than NET, the building is considered "stranded";
(e) costs estimation as a function of energy consumption, retrofit costs, and an assumed carbon tax

Notably, both YEP and NET are not available for all countries. While CRREM appears to be the only tool to link stranding risk to quantitative decarbonization pathways, it presents some limitations and operational shortcomings.

2.1. CRREM framework limitations

Starting from steps (a) and (b), the YEP does not consider the emissions relevant to the embodied carbon of the constructions and retrofit activities. On one side, this is aligned with classifying emissions in three different sections, namely Scope 1,2 and 3. This derives from the reporting protocol, which is mandatory for some private companies around the globe [65]. In particular, Scope 1 derives from emissions directly linked to the activities of a company, while Scope 2 is mainly relevant to indirect emissions due to energy use and generation. Scope 3 accounts for, among other things, the use of materials that may have generated GHG emissions not directly linked by the entity purchasing and using those materials. Also, the CRREM emphasizes the adherence to the principle of "energy efficiency first", which aims at reducing operational consumption and emissions [66]. On the other hand, as also underlined in the CRREM documentation [67], downscaling emission budget to economic sectors can be robust only with a holistic approach to buildings. Moreover, while Scope 3 emissions are linked to other actors, a designer can significantly influence the level of the embodied carbon of any retrofit or new construction [68,69].

The issue of embodied carbon may be significant given that recent studies have emphasized that buildings may exhibit poorer environmental performance despite their high efficiency due to the significant amount of embodied carbon required during construction or retrofitting [70]. The existing trade-off has been found to be significant in terms of whole-life emissions [71].

The optimization of these factors is markedly influenced by the carbon density of the energy grid, both in the present and in prospective scenarios. This area has only recently garnered significant research attention [72–75]. For example, the German building code allows for a reduction in thermal insulation requirements if low-carbon heating technologies are utilized [76].

Some studies have also integrated considerations of future climate projections [69,72,77] and risks of damage [69] into this optimization process.

The neglect of embodied carbon aligns with the fact that most building codes have not systematically addressed the issue of the high embodied energy and carbon footprint of construction materials. However, the French RE2020 [78], enforced in early 2022, and the Danish BR2018 [79], enforced in 2023, introduced specific thresholds for both energy consumption performance and, for the first time, the embodied carbon of new buildings. For instance, single-family houses are now required to have an environmental impact over their reference life lower than 160 kg CO_2m^{-2} due to energy consumption and 410 kg CO_2m^{-2} due to embodied carbon. Consequently, embodied carbon is expected to outweigh energy consumption in the envisioned high-efficiency and low-carbon energy grid scenario. This dual-performance approach may also be adopted in other countries [80] at the broader EU level in the near future, as the Energy Performance of Buildings Directive (EPBD) is currently undergoing revision to incorporate life-cycle emissions from building materials [38,39]. This incorporation will be based on integrating environmental product declarations (EPD) for the materials used in the building [78,79]. A compliant EPD is becoming an increasingly important requirement in the EU and is regulated by ISO 14025:2006, 21930:2017, and the associated EN 15804 [81]. Similar programs for Type III declarations are now being implemented worldwide [82,83].

Along this line, the relationship between regulation enforcement and actual stranding constitutes a limitation in the assumptions underlining step (3) of CRREM procedure. Indeed, this assumption can be expressed as follows:

$$P(Sr(t_i)) = \begin{cases} 1, & \text{if } YEI(t_i) > YEP(t_i) \vee TEC(t_i) > NET \quad \forall t_i \in [t_p, 2050], \\ 0, & \text{if } YEI(t_i) < YEP(t_i) \wedge TEC(t_i) < NET \quad \forall t_i \in [t_p, 2050], \end{cases} \tag{1}$$

where $P(Sr(t_i))$ is the probability of stranding at a given year t_i and t_p is the year of the assessment. Eq. (1) implies that a stranding automatically occurs when the building performance is lower than those required by the pathways. Notably, the procedure is meant for new buildings and existing ones. However, no enforced regulation worldwide implements a stranding process in this way for either private residential buildings or real estate. Indeed, the aforementioned example of the mandatory EPC introduced by the 2002 EPBD [26] did not require a minimum performance but merely the presence of an EPC. Also, several building codes prescribe minimum post-retrofit performances as reviewed in [69], but none prescribe a mandatory retrofit. Moreover, the already enforced UK regulation [42] and the new EPBD revision [41], which could introduce mandatory retrofits coupled with a stranding mechanism, does not consider a YEI performance while focusing on the EPB. Indeed, no building codes directly prescribe minimum retrofit performances in terms of YEI. It is true, however, that emission intensity reduction is indirectly obtained with other prescriptions.

2.2. CRREM operational limitations

As a result of the framework characteristics described in Section 2.1, the practical implementation of CRREM can present three main shortcomings.

The first one is linked to the service life, SL, of new construction or retrofitted buildings. SL has long been a fundamental variable in design conception, being it critical to determine structural and non-structural performances [84]. More recently, however, SL has become an essential variable of the environmental impact of energy retrofits as it defines the amortization period of the embodied carbon [69,72]. The SL of residential building components varies from 50 years for structural and non-structural components, with the former including both infills and thermal insulation, [69,72,84], to 20–30 years for windows, heating and other energy generation or storage systems [73]. Hence, it could be argued that a compliant retrofit design should guarantee a non-stranding of at least 20 years to avoid reducing the SL of any major component. According to this assumption, we can write:

$$P(Sr(t_i)) = 0, \text{ if } P(Sr(t_p)) = 0 \;\; \forall t_i \in [t_p, t_p + min(\mathbf{SL})] \tag{2}$$

where **SL** is a vector of the SLs of each building component. Nonetheless, the YEP appears more demanding than what would currently comply with several building codes. For reference, building codes in the UK [85], Germany [76], France [86] and Italy [87] still allow installing a natural gas boiler for thermal energy in energy retrofits. As a result, a compliant insulation retrofit in a temperate climatic zone can deliver a final thermal energy consumption of 35 $\mathrm{kWh\ m^{-2}\ y^{-1}}$ [88]. In the case of a modern natural gas boiler system, this would be characterized by a carbon density of 0.213 $\mathrm{kgCO_{2eq}\ kWh^{-1}}$ [89], thus leading to a total of $35 \cdot 0.213 = 7.45\ \mathrm{kgCO_{2eq}\ m^{-2}\ y^{-1}}$. This emission intensity, according to the 1.5 °C pathway evaluated for residential buildings in Italy in the 2022 CRREM version v2.03, would be higher than $YEP_{IT}(2033) = 6.5\ \mathrm{kgCO_{2eq}\ m^{-2}\ y^{-1}}$. The relevant pathway is

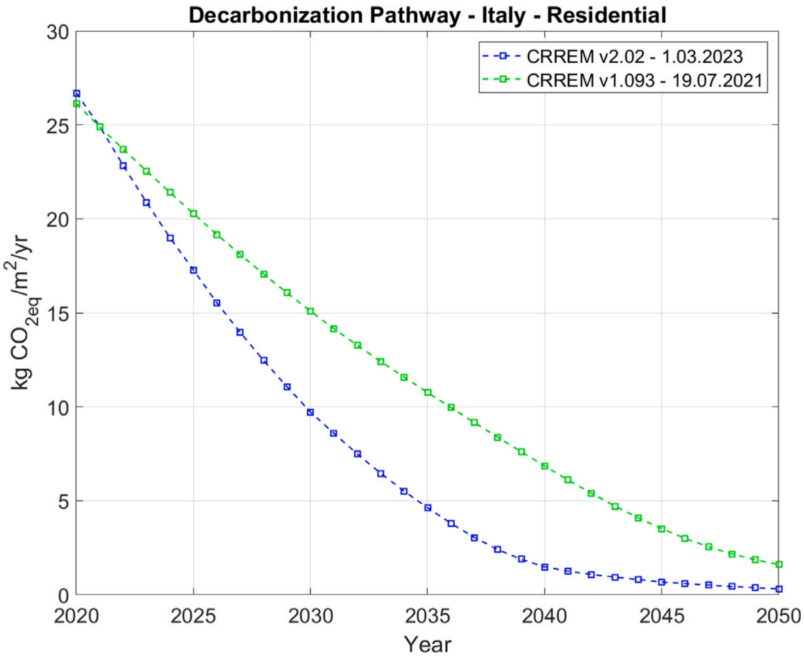

Fig. 1. Decarbonization pathways for Italian residential buildings.

Table 1
Decarbonization pathways for Italian residential buildings from CRREM.

Year	CRREM v2.02 ($kgCO_{2eq}$ m^{-2} y^{-1})	CRREM v1.93 ($kgCO_{2eq}$ m^{-2} y^{-1})
2020	26.69	26.13
2021	24.91	24.89
2022	22.84	23.71
2023	20.87	22.54
2024	18.99	21.40
2025	17.28	20.28
2026	15.53	19.17
2027	13.95	18.10
2028	12.46	17.06
2029	11.06	16.06
2030	9.72	15.09
2031	8.59	14.16
2032	7.49	13.27
2033	6.46	12.41
2034	5.51	11.58
2035	4.63	10.76
2036	3.80	9.96
2037	3.05	9.16
2038	2.40	8.38
2039	1.89	7.61
2040	1.48	6.85
2041	1.26	6.11
2042	1.08	5.40
2043	0.94	4.72
2044	0.81	4.09
2045	0.68	3.52
2046	0.60	3
2047	0.52	2.55
2048	0.44	2.17
2049	0.38	1.86
2050	0.31	1.61

depicted in Fig. 1. Therefore, under CRREM framework assumptions, adherence to enforced building codes could imply an actual use for some components shorter than their available SL.

The second practical shortcoming is linked to the efficiency of a YEP-compliant retrofit's economic and carbon investment. On the economic side, the overall benefits of building retrofits are delivered by lower operational costs. Still, these benefits can vary significantly on design characteristics and other economic variables [90]. It is known that high-energy performance buildings can result in worse environmental performance if embodied carbon emissions are considered [70]. This effect is more evident when future energy scenarios are taken into account [69,72,73]. Along this line, a 2023 report [68] quantifies the expected embodied emissions linked to deep building retrofit in 88 $\mathrm{kgCO_{2eq}\ m^{-2}\ y^{-1}}$. For reference, this is 58 and 293 times more than $YEP_{IT}(2040)$ and $YEP_{IT}(2050)$, see Table 1. Moreover, combining economic costs and operational emissions, [88] concludes that high-performance retrofits are not the most convenient solution regarding the marginal cost of CO_2 abatement. This is also confirmed by [91] which also considers embodied emissions. Hence, taken as the only design target, adherence to the expected YEP poses the risk of sub-optimal efficiency in terms of economic and environmental return.

The last limitation of the CRREM framework here identified derives from the connections between YEP and the energy grid carbon intensity. Indeed, the parameter YEP is the result of the combination of TEC and the relevant emission factor EF, which would be the indicator of the energy carbon density. EF is relevant to the installed energy system, with a fixed value for independent systems and a variable one for those based on electricity from the grid. Neglecting the case of a multi-component TEC and assuming the case of an electricity-based energy system, the relationship can be written as follows:

$$YEP(t_i) = TEC \cdot EF(t_i) \tag{3}$$

where $EF(t_i)$ is the expected pathway of the carbon density of the electricity grid. This pathway is, however, not fixed and can be updated based on the trend of the decarbonization process and the consequent impact on the residual budget of CO_2. For instance, this has already happened in the transition between the CRREM versions v1 and v2, where $YEP(t_i)$ became generally steeper in several countries to account for lower-than-planned decarbonization results. See for reference Fig. 1 and Table 1. This implies that any requirement for a building regarding emissions and energy can change according to the present state of the residual budget. Hence, we can rewrite Eq. (1) as follows:

$$P(Sr(t_i)) = \begin{cases} 1, & \text{if } YEI(t_i) > YEP(t_i, t_p) \vee TEC(t_i, t_p) > NET \quad \forall t_i \in [t_p, 2050], \\ 0, & \text{if } YEI(t_i) < YEP(t_i, t_p) \wedge TEC(t_i, t_p) < NET \quad \forall t_i \in [t_p, 2050] \end{cases} \tag{4}$$

where t_p is now influencing also YEP and TEC. From a practical viewpoint, this means that a stranding risk assessment of a building retrofit is not conclusive and can change based on the time of the assessment.

3. A probabilistic approach to stranding risk assessment for existing buildings

In this section, we will present a probabilistic framework for the stranding risk assessment of existing buildings. The framework assumes stranding risk as the combination of a hazard source and the vulnerability to it. This is derived from standard risk practices [92] from which we will neglect the exposure concept for practical reasons. Moreover, vulnerability will be considered as the result of the building response and the associated costs. We define the vector **Vsr** as the expected risk variables due to stranding, which can be formulated as follows:

$$\mathbf{Vsr} = P(Mp, t_i) \cdot P(Bp < Mp) \cdot \mathbf{Lrt}(\Delta p) \tag{5}$$

where $P(Mp)$ is the probability that a mandatory minimum performance Mp for existing buildings would be introduced at the given time t_i; $P(Bp < Mp)$ is the probability that the building performance Bp would be below the mandatory threshold; **Lrt** is the impact of a retrofit which depends on the difference $\Delta p = Mp - Bp$. The main assumptions of Eq. (5) are the following:

(I) The introduction of a Mp effectively results in the stranding of the building whereas $Bp < Mp$. The stranding is assumed to replicate the enforcement mechanism of the 2002 EPBD [26] and the 2015 UK regulation [42], thus forbidding selling or renting the building.
(II) Mp, Bp are assumed to be statistically independent.
(III) The possibility of multiple stranding events over a given period is neglected. As a result, the effects of different retrofits on both the parameter Bp and the cumulative costs are not considered.

The expected loss derives from the impact of a retrofit that bridges the difference between Bp and Mp and reverses the stranding. This impact could be defined in simple terms of retrofit costs or other indirect metrics, such as the decline in property value or downtime. The proposed methodologies to tackle each part of the framework are presented in Sections 3.1–3.3 while a general scheme is depicted in Fig. 3.

3.1. Hazard model

The hazard term, as in Eq. (5), is characterized by three components, i.e. Mp, t_i, and the relevant probability $P(Mp, t_i)$. In detail, Mp could potentially have several forms. One of these forms can be the EPB, intended as a given energy class of European EPCs, which is already adopted in the relevant UK regulation [42] and indicated as a viable option in the EU EPBD revision [41]. The

Table 2
Stranding Hazard model, characteristics and methods.

Type of Mp	Hazard model	Definition method
• Energy: EPB, TEC, • Emission: YEI, • Mixed, prescriptive approach	• $P(Mp, t_i)$, • $P(Mp)$, • Scenario-based	• Inference from empirical data • Expert elicitation

already present integration in current legislation would support the possibility of this Mp form. Another way to consider energy consumption as Mp could be in the more direct form of TEC, which is the ultimate goal of the EU EPBD [41]. Furthermore, a given YEI could become a Mp, which aligns with CRREM assumptions. Besides, these performance measures could be coupled and added to a set of prescriptive measures already present in most building codes [3,69].

The probability function $P(Mp, t_i)$ underlines that the likelihood of a Mp enforcement can vary upon the time t_i. This can reflect several different possibilities. For instance, $P(Mp)$ could increase and Mp be more demanding over time due to a delay in the decarbonization efforts or to CC-related adverse effects. On the other hand, the opposite trend could result from decreasing political willingness and/or external economic factors. Two more simplified versions of $P(Mp, t_i)$ could: (i) neglect the influence of t_i leading to the definition of a time-invariant $P(Mp)$, (ii) assume a deterministic scenario-based analysis with a given Mp.

The possible methodologies to define the hazard model fall within two different categories. The first one is the inference from empirical data which is the approach used for other hazards, both natural [93,94] and man-made [59]. However, there is available data on large-scale stranding of existing buildings as intended in this work, while limited data exists about the occurrence of conceptually similar stranding. In this respect, risk assessment practice can resort to expert elicitation when dealing with highly uncertain or scarcely-recorded hazards. This method systematically gathers and synthesizes judgments from specialists in relevant fields to assess and define potential hazards. Experts provide insights based on their knowledge, experience, and interpretation of available information, contributing to a more comprehensive understanding of the hazards understudy [95–97]. A summary of the characterization of the stranding hazard model is reported in Table 2.

3.2. Response model

To define a response model, it is necessary to evaluate Bp that will need to be equivalent to the type of Mp as listed in Table 2. In general, a common component, even if not sufficient alone, of Bp is the EPB, which is based on the energy demand of the building. A basic method for calculating the building energy demand relies on the concept of annual heating and cooling degree days (HDD and CDD) [98–100]. This approach offers a direct and less complex process, yielding results less influenced by the unique characteristics of each building. However, more sophisticated dynamic and simulation-based models can provide more accurate predictions [101–103]. Overall, these methods can provide a direct measure of the energy demand, allowing a deterministic evaluation with $P(Bp < Mp)$ possibly being either 0 or 1. On the other hand, in the case of a top-down assessment, the energy demand can be inferred from a limited number of the building characteristics' [104], relevant statistical data [105] or probabilistic models [106]. These approaches can describe Bp in a probabilistic manner with a variable degree of uncertainty. As already discussed, whereas Mp is in terms of YEI, the energy demand must be coupled with the relevant EF. Again, the definition of proper EFs can be done in a deterministic way in the case of fossil-fuel energy systems or electricity-based with predetermined energy sources. However, in the case of electricity deriving from the grid, EF can be uncertain, and thus also the relevant YEP as in Eq. (3). A scenario-based approach is often used to take into account future energy uncertainties [69,72,73,107]. The difference between a deterministic and a probabilistic or top-down assessment is also present in terms of compliance with a prescription-based Mp. Indeed, some specific performances of technical elements, such as envelope components, or energy systems efficiency, could not be directly available. In this case, the statistical distribution of these characteristics can be retrieved by dedicated databases, such as TABULA [108].

3.3. Loss model

The expected loss from stranding can be defined in different ways. The most direct is the economic cost of the retrofit able to revert the stranding. The topic of the costs of an energy retrofit is a well-investigated topic, with analyses ranging from scenario-based deterministic [109] to probabilistic approaches [110], see Fig. 2 for reference.

Moreover, additional costs can derive from downtime during retrofit activities. This topic has not been investigated in connection with energy retrofit, probably due to low significance and high uncertainty. Still, probabilistic methods have been applied to assess downtime impact following damage from natural hazards [111,112]. Another typical loss component of conventional risk assessment for the building stock is injuries and fatalities following damage [113]. On the other hand, retrofit activities and relevant building sites reportedly lead to injuries and fatalities among workers, as quantitatively investigated by [114,115].

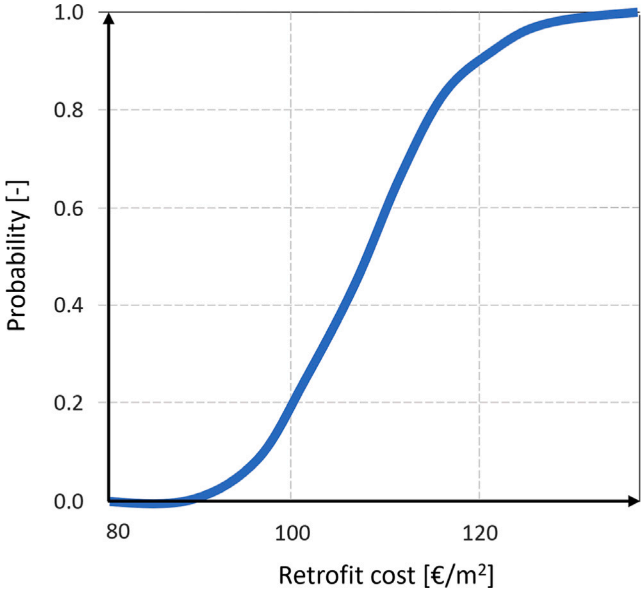

Fig. 2. Cumulative distribution function of retrofit costs after [110].

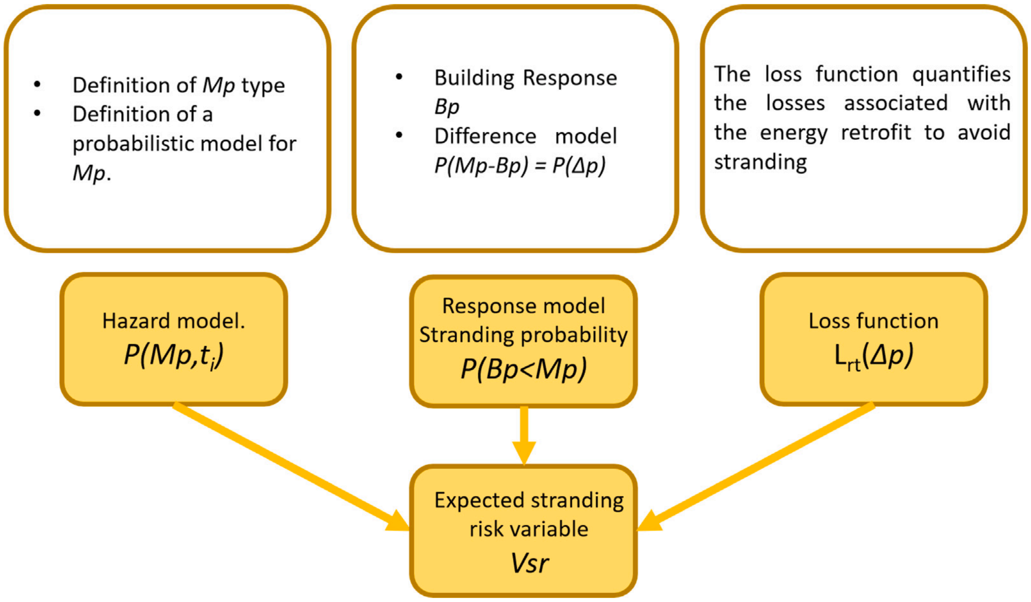

Fig. 3. Scheme of the procedure for stranding risk assessment.

4. A case study application

This section will present a simplified application of the procedure presented in Section 3 for stranding risk assessment. Moreover, stranding risk will be compared to natural hazards. The comparison among risks for a given building stock can provide useful insight into planning and prioritizing risk mitigation measures and policies [57]. For instance, a comparison between expected economic loss from different natural hazards hitting the same building stock can be carried out as made in [25]. Besides, different hazards can be compared to provide a reference for the acceptable rate of fatalities due to buildings' risks [116,117]. In detail, we will assume the Italian building stock as a case study and compare a scenario-based stranding risk to the impacts of two natural hazards. To perform a meaningful comparison, we will select comparable measures for the expected losses. In particular, concerning the economic part, the loss will be considered as the cost for the necessary energy retrofit to reverse the stranding and for repair and

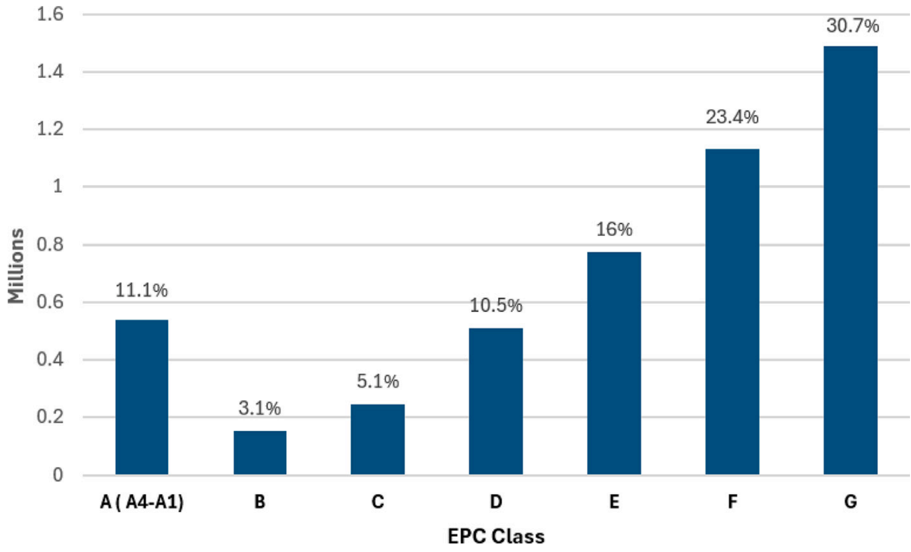

Fig. 4. EPC class prevalence of the Italian building stock after [118].

reconstruction in the case of natural hazard damages. Thus, in both cases, the costs would restore the assets to the condition before the negative impact.

4.1. Scenario-based stranding risk assessment of the Italian building stock

4.1.1. Scenario-based hazard and response models

Starting from the hazard model, we will assume a scenario inspired by the proposed 2023 draft of the EPBD [39,40]. The EU Parliament approved the draft in a plenary session on 14 March 2023. After that, an institutional negotiation process started discussing amendments to the draft and its implementation. The 2023 version approved by the EU Parliament introduced a mandatory minimum EPC level of Class D from 2030 for non-residential and public buildings and 2033 for residential ones. However, an updated final version has been approved in another plenary session on 12 March 2024 [41]. In this version, the planned goals are expressed in terms of reduction of primary energy consumption for residential buildings and minimum energy performance for non-residential ones. For example, the primary energy consumption of the residential building stock should decrease by 16% by 2030 and 22% by 2033 compared to the 2020 level. The difference between the 2023 and 2024 versions would allow for a more gradual retrofit pace and more flexibility in mandatory requirements. Notably, additional higher requirements would be periodically introduced until 2050 "*in line with the transformation of the residential building stock into a zero-emission building stock*" [41]. Finally, the 2024 EPBD does not establish how these targets should be achieved, which is left to each EU country, but lists the enforcement of minimum EPC thresholds as a possible way. On these premises, we will assume the enforcement of a mixed Mp_s composed of two main parts. The first part is the minimum EPC level of Class D, inspired by the 2023 EPBD draft and the UK regulation with gradual enforcement over the whole building stock in line with the 2024 EPBD. This MP_s is assumed to lead to stranding for buildings of lower EPC classes. The second segment encompasses the prescriptive measures to retrofit buildings and access fiscal incentives currently enforced in Italy [87,109].

Concerning the response model, Bp_s can be derived from the SIAPE database of the Italian National Agency for Energy [118]. SIAPE provides a publicly accessible online tool to consult the database of EPCs. In 2024 the database collects almost 5 million residential EPCs representing a sizeable statistical sample. Also, according to Italian law, EPCs have to be prepared by a certified professional which guarantees a minimum level of accuracy. Besides, despite any limitation of the absolute reliability of EPCs in defining the energy class, a compliant certificate exhaustively defines the comparison between Mp_s and Bp_s. In particular, 30.7% of the EPCs report a Class G, 23.4% Class F and 16% Class E, see Fig. 4 for reference. Assuming this distribution to be valid for the whole building stock we can write:

$$P(Bp_s < Mp_s) = R_s = (30.7 + 23.4 + 16)\% = 70.1\% \tag{6}$$

where R_s is the expected share of stranded buildings in the scenario under study.

4.1.2. Scenario-based loss model

As per the framework presented in Section 3, the impact of stranding is linked to the retrofit that the building has to undergo to reach Mp_s. As in traditional natcat risk assessment [113], in this scenario analysis we will assume $\mathbf{Lrt}_s$ as a vector composed of the relevant costs and fatalities defined as follows:

$$\mathbf{Lrt}_s = [Crt, Nrt] \tag{7}$$

Table 3
Breakdown of retrofit measures costs.

Archetype	Retrofit measure			
	INS (€/m^2)	NG (€/m^2)	HP (€/m^2)	SC (€/m^2)
A	263.7	14.5	36.3	11.4
B	232	8.6	21.5	17.7
C	177.7	9.3	23.3	15.1

Table 4
Retrofit costs for RT1 and RT2.

Archetype	Retrofit Design	
	RT1 (€/m^2)	RT2 (€/m^2)
A	289.6	311.4
B	258.3	271.2
C	202.1	216.1

where Crt and Nrt are the costs and the number of fatalities, respectively. Among the assumed retrofit designs, we will consider the ones which entail the following measures:

- Insulation of the building envelope, including the replacement of windows - INS;
- Installation of a modern natural gas boiler and a heat pump - NG;
- Installation of a hybrid heating system with a natural gas boiler and a heat pump - HP;
- Installation of solar collectors - SC.

On these bases, two retrofit designs are considered: (i) RT1, which entails INS, NG and SC; (ii) RT2, which entails INS, HP and SC. As underlined by [109], RT1 does not always guarantee to reach Class D, which is, however, the case for RT2. Moreover, as shown by Eq. (3), a net zero-emission building stock, which is the 2050 goal of the 2024 EPBD [41], would hardly be compatible with any energy system based on fossil fuel.

In detail, [109] also presents the costs of different retrofits in agreement with the minimum requirements [87] included in Mp_s of three building archetypes. These archetypes are defined by [109] with different technical features retrieved from the TABULA database [108]. As the most distinctive feature, building archetypes A, B and C have a total building area of 230, 1318 and 6080 m^2, respectively. These archetypes were selected by [109] to be representative of the Italian residential building stock according to two main criteria. First, the building area covers a significantly wide range of residential buildings, from single-family houses with archetype A to large residential blocks with archetypes C. Second, the time of building construction covers four decades thus encompassing multiple pre-retrofit characteristics: 1960s for archetype C, 1980s for B and 1990s for A. The work estimates the retrofit costs for the four archetypes, including different interventions equivalent to the design RT1. As a reference, for archetype A, these costs are in the range of €64700–68500, depending on the climate zone. We will consider the average value of this narrow interval and the ratio between the cost and the building area, i.e. about 290 €/m^2. The data from [109] are used to estimate the costs of the HP. In detail, from relevant experience and industrial sources, we gather that HP has a cost roughly 2.5 times higher than NG. A breakdown of each retrofit measure cost is reported in Table 3 while a summary of RT1 and RT2 costs is shown in Table 4.

From Table 4, it is possible to appreciate that costs are usually lower for larger buildings and that the difference between RT2 and RT1 is around 10%. Notably, these costs do not include professional design fees and financing costs in agreement with risk assessment for natural hazards [25]. Overall, these values align with other works relevant to different countries. Indeed, for Germany, [88] analyzes a wide range of possible retrofits with costs ranging from 318 to 524 €/m^2 depending on the type of buildings and their final energy performances. Similarly, for Switzerland, [119] reports a retrofit cost range from 250 to 600 CHF/m^2. For simplicity, we will also assume single RT1 and RT2 costs equal to the average of the range of the three archetypes, i.e. 250 and 266.2 €/m^2. While such values can be considered the cost component Crt_s of Lrt_s, this approximation neglects the actual prevalence of the archetypes within the building stock. Hence, we assume $Crt_{s,RT1}$ = 250 €/m^2 and $Crt_{s,RT1}$ = 266.2 €/m^2. Thus, to approximately extend these costs to the entire Italian residential building stock we retrieve from [113] a total surface of 2.5 billion m^2 based on a 2001 national census. For reference, EU database provides a value of 2.53B m^2 [120] while other industry sources provide a similar estimation at 2.8 B m^2 [121] or a significantly higher one at 4.1 B m^2 [122]. Hence, we define $Ksr_{s,RT1}$ and $Ksr_{s,RT2}$ as the expected cost to revert the stranding of the building stock with RT1 and RT2 retrofits, respectively. Hence, Eq. (5) can be rewritten and $Csr_{s,RT1}$ and $Csr_{s,RT2}$ computed as follows:

$$Ksr_{s,RT1} = (0.701 \cdot 250 \cdot 2.5)B\ € = 438B\ € \tag{8}$$

$$Ksr_{s,RT2} = (0.701 \cdot 266.2 \cdot 2.5)B\ € = 466.3B\ € \tag{9}$$

A similar calculation has been performed for the Portuguese building stock by [60]. In detail, the work reports a total expenditure of 76B€to retrofit 71% of the residential building stock according to the relevant building code standards. Given that the retrofitted

Table 5
Fatalities and investments in the Italian construction sector.

Year	Fatalities	Investments (B €)
2018	193	126.7
2019	202	130
2020	205	122.8
2021	208	153.1
2022	171	176.6

building surface would have been close to $0.71 \cdot 436 = 309$ Mm^2 [120], this leads to an average retrofit cost of roughly 246 €/m^2. The similarity between this value and $Crt_{s,RT1}$ supports the results of Eqs. (8) and (9). In order to perform a comparison with other risks and scenarios, the costs listed $Ksr_{s,RT1}$ and $Ksr_{s,RT1}$ can be transformed into an Expected Annual Loss, EAL. The EAL is the expected yearly loss, usually normalized by a unit cost, UC, which should equal the cost of the complete building construction. From [113] and [123] we retrieve that, for Italy, $UC = 1350$ €/m^2. Also, to simulate gradual enforcement and to annualize the expected costs, we assume a constant retrofit rate set to cover the whole building stock in 2050. This implies, starting from 2024, a period of $T_s = 26$ years, which allows us to calculate $EAL_{s,RT1}$ and $EAL_{s,RT1}$ as follows:

$$EAL_{s,RT1} = (0.701 \cdot 250)/(UC \cdot T_s) = 0.49\%\ \mathrm{y}^{-1} \tag{10}$$

$$EAL_{s,RT2} = (0.701 \cdot 266.2)/(UC \cdot T_s) = 0.52\%\ \mathrm{y}^{-1} \tag{11}$$

$EAL_{s,RT1}$ and $EAL_{s,RT1}$ derive from the share of stranded buildings but are relevant to the entire residential building stock. It has to be underlined that these values pertain to a given time interval, which makes them *fixed-term* risk metrics. This approach is used to study hazards that are not ergodic [124,125], such as epidemics or seismicity during an earthquake swarm [117]. The second component of $\mathbf{Lrt}_s$ pertains to the fatalities caused by retrofit activities, i.e. Nrt_d. It is assumed that: (i) fatalities would be among the construction workers realizing the retrofit; (ii) other casualties such as injuries are neglected. As underlined by research works on empirical data, casualties in the construction sector can be correlated to overall construction costs [115,126] or specific activities such as scaffolding [114]. Opting for the cost-based approach, we retrieve from [126] that, in South Korea from 2013 to 2019, 829 fatalities occurred in residential construction works worth 347B$. Using micromorts as units of measure, mM as in [127,128], this leads to a cost-adjusted fatality rate of $Nrt_{d,K} = 2.38 \cdot 10^{-3}$ mM (\$ y)$^{-1}$. To derive a similar value for Italy, we first rely on the database of the National Institute for Insurance against Accidents at Work (INAIL) [129] to gather the fatalities number in the construction sector from 2018 to 2022. The monetary value of construction works in the same years can be retrieved from [130]. The relevant data are reported in Table 5.

Making an average of the five years listed in Table 5, we obtain $Nrt_s = 1.38 \cdot 10^{-3}$ mM (\$ y)$^{-1}$. While the data here used for Italy are not segmented for types of construction works as in [126], the magnitude similarity between $Nrt_{d,K}$ and Nrt_s supports the validity of the approach. Moreover, a possible explanation for the higher value of $Nrt_{d,K}$ could be that the South Korean construction industry has a relatively higher risk level than other countries [131]. We define N_d as the expected number of fatalities per year and calculate $N_{d,s,RT1}$ and $N_{d,s,RT2}$ as follows:

$$Nd_{s,RT1} = Nrt_s \cdot Ksr_{s,RT1}/T_s = 23.3\ \mathrm{y}^{-1} \tag{12}$$

$$Nd_{s,RT2} = Nrt_s \cdot Ksr_{s,RT2}/T_s = 24.8\ \mathrm{y}^{-1} \tag{13}$$

$Nd_{s,RT1}$ and $Nd_{s,RT2}$ are, similarly to $EAL_{s,RT1}$ and $EAL_{s,RT1}$, *fixed-term* risk metrics relevant to the scenario understudy. Both EALs and Nds are reported in Table 6.

4.2. Natural hazards

We have selected seismic and flood hazards given their historical significance for the Italian building stock and the availability of risk analyses.

4.2.1. Seismic risk

The quantification of seismic risk for the existing building stock is based on the analysis performed by [113]. In detail, the analysis combines seismic hazard models [132], exposure data and empirical fragility curves for costs [133,134] and casualties [135]. The hazard model consisted of a map of peak ground acceleration, assuming uniform stiff soil, with a specific return period. Concerning exposure data, the analysis employed a detailed mapping of key structural characteristics of the building stock, such as: (i) age of construction; (ii) number of floors and (iii) type of construction, if reinforced concrete or masonry. Besides, empirical fragility curves provided the probabilistic model for damage states resulting from the combination of peak ground acceleration and structural characteristics. These damage states are then linked to specific repair and reconstruction costs expressed as a fraction of UC. It is worth noting that these costs are assessed with a top-down approach rather than starting from a relevant set of materials and activities needed for the repair and reconstruction. However, as assessed in [136], the results are still reliable. Besides, the

Table 6
Comparison of risk metrics for the Italian building stock.

Risk metrics	Type of risk			
	Stranding		Seismic	Flood
	RT1	RT2		
EAL (y^{-1})	0.49%	0.52%	0.063%	0.09%
Nd (y^{-1})	23.3	24.8	505	15.8

satisfactory large-scale comparison with real historical data made by [113] also supports this assumption. The results in terms of EAL are relevant to the entire building stock and computed considering the same UC and used in Eqs. (10) and (11). Hence, we gather that $EAL_{eart} = 0.063\%$ y^{-1} and $Nd_{eart} = 505$ y^{-1}. These values are reported in Table 6. For reference, [113] underlines that, while EAL_{eart} is rather in line with the last 50 years of earthquake consequences in Italy, Nd_{eart} is five times higher. On the other hand, as explained by [113,137] earthquakes are associated with high uncertainties, and the relevant consequences can easily be much above some decades average. Finally, risk metrics can vary significantly depending on the hazard level of a given area and the built environment vulnerability. As a result, EALs can exhibit up to 2 orders of magnitude difference [113,138]. For reference, in the case of an RC building with more than 4 floors, EAL can vary between 0.001 and 0.13% y^{-1} according to the geographical location and age of construction [138], whereas for older unreinforced masonry building this value can be several times higher [139].

4.2.2. Flooding risk

The quantification of flooding risk for the Italian building stock is based on a 2023 report from the Italian Central Bank [140]. This report combines data from flood hazard models [141,142], exposure levels of the building stock based on the national census, as in [143], and damage curves [144]. The analysis presents two main approaches based on the use of two different hazard models developed by ISPRA [141] and JRC [142] respectively. The latter provides the for every area analyzed the flood depth for each return period considered. ISPRA model however provides data on the entire national territory and accounts in some areas for the presence of flood defences. Flood water depth from the JRC model allows however to use empirical damage curves [144] that, by adopting the same UC, would permit a direct comparison with the risk assessed in Sections 4.1 and 4.2.1. Thus we selected the approach based on the JRC model which considered the actual height of the building compared to the expected flood depth. The results provide an expected loss of "*building wealth*" equal to 4B€ or 0.09% per year. It has to be noted that this percentage is assessed in comparison with the market value of the building stock. Consequently, the absolute value of the loss is also a result of such an assumption. This could appear to be not consistent with the methodology used for $EAL_{s,RT1}$, $EAL_{s,RT1}$ and $EAL_{s,eart}$. On the other hand, the damage curves [144] used by [140] have been developed to calculate the buildings' damage as a function of the weather depth of the flood. Still, the damage cost is expressed as a fraction of the construction cost and not the market value of the single building. This is also confirmed by [123] that uses the same damage curves to evaluate the EALs due to earthquakes and floods as a fraction of the construction cost, which we have defined as UC. Thus, given the annual loss in percentage value from [140] is, de facto, comparable with $EAL_{s,RT1}$, $EAL_{s,RT1}$ and EAL_{eart} even if the absolute monetary value is not. Therefore, we can write $EAL_{flood} = 0.09\%$y^{-1}. The expected number of fatalities can be evaluated using statistical data from 50 years between 1964 and 2014 [145]. In this period, floods have caused 784 deaths in Italy, which leads to $Nd_{flood} = 15.8$y^{-1}. These results are listed in Table 6. Overall, these risk metrics should be considered in perspective given the high uncertainty and current trends. Indeed, according to [123], EAL can reach 0.57% in certain locations of the Veneto region in the north of Italy. Moreover, given that Nd_{flood} has been retrieved from historical data, it should be noted that, on average, the mortality due to floods and other natural hazards has been declining in the last few decades [146,147].

5. Discussion and limitations

5.1. Discussion

This study carried out a simplified stranding risk assessment of the Italian building stock based on a scenario derived from the 2024 EPBD. The comparison reported in Table 6 shows that the EAL from Stranding risk in the considered scenario is roughly three times the combined EALs from seismic and flood risks.

This highlights the importance of investigating stranding risk and its relationships with retrofit design, environmental goals and relevant policies. In this respect, the approach presented in Section 3 could represent a more robust method to assess such risk. While it requires additional data and analytical efforts, especially when full-probabilistic analyses are involved, it is aligned with other risk assessment practices. This would allow portfolio managers and insurance stakeholders to consider the relevant impacts.

Besides, the sheer size of the retrofit costs of the analyzed scenario raises the question of whether it could be categorized as sustainability-induced "creative destruction" [148]. The concept of "creative destruction" was popularized by Schumpeter at the beginning of the 20th century [149] as a derivation from Marxist theory [150]. The concept was used to describe the obsolescence of old productive methods by newer, more profitable or efficient ones with consequent loss of value. The more recent [148,151], and others hereafter, presented the impact of sustainability in terms of "creative destruction" for various industry sectors. In this case, the sustainability trend would have prompted the replacement, i.e. "destruction", of less environmentally friendly productive forces. Concerning the construction sector, few studies have referred, in a qualitative way, to the same phenomenon [152,153].

Along the same line, the Buildings Performance Institute Europe (BPIE) concluded that the level of investment required by EPBD goals would be similar to that of the WWII postwar reconstruction [39]. Besides, a publication from the Italian National Agency for New Technologies, ENEA, advocated for a "Marshall plan" to support the renovation of EU buildings [154]. The reference is to the extensive damage received by the European building stock during WWII, which, however, exhibited different magnitudes even among the most affected European countries as, for example, between Germany [155,156] and Italy [157]. Conversely, the comparison with destructive natural hazards in Table 6 appears to be a quantitative hint of the applicability of the sustainability-induced "creative destruction" definition.

It is worth noticing that a similar order of magnitude has already been found by [60] for the retrofit of the Portuguese building stock. Besides, it has been highlighted that, given the massive resources required, the implementation of decarbonization pathways should adhere to the principle of fairness [158].

Moreover, the scale of the phenomenon could trigger the rise of several cascading risks [159,160]. In this respect, few studies have highlighted how the transition to electricity-based thermal energy, as in the HP retrofit measure, could not be met by the existing or short-term planned energy grid [161,162]. Another example of cascading risks is related to the increased fire risk due to retrofits involving combustible thermal insulation [59,163] or heat pumps with flammable refrigerants [164,165] whose diffusion is supported by the phasing out of high-gwp halocarbons [15]. Besides, the absence of countermeasures to embodied carbon in retrofit prescriptions [69] may hinder the decarbonization efforts [68] in a mechanism similar to the energy-emission trap [166].

Finally, these results may inform the development or revisions of policies about: (i) the practical implementation of decarbonization pathways for the building environment, (ii) the technical requirements or minimum performances of energy retrofits, (iii) the enforcement of stranding measures for building assets. Concerning (i), this study highlight that net-zero targets by 2050 pose significant challenges that cannot be faced by the building environment alone but require massive results for the energy sector too. About (ii), it appears that current technical requirements for building energy retrofits are not compatible with net-zero targets and may result in additional costs. Regarding point (iii), it is critical to consider the economic impact of stranding measures so that they will not result in an unfair burden or an ineffective stimulus to retrofit.

5.2. Limitations

Several limitations affect the methodology and the application presented in Sections 3 and 4. First, enforcing any Mp could follow different paths for buildings depending on their destination use. This differentiation can be made based on (i) investment or personal use property, (ii) commercial or residential use. Thus, the combinations of these factors and additional sub-categorizations could influence stranding risk assessment.

Both the methodology presented in Section 3 and the assessment of the EALs in Section 4 assume that a retrofit would, immediately or in the short-term, occur right after both the stranding and any damage from natural hazards. While this is a common hypothesis in assessing physical risks, stranding risk may exhibit a different nature.

For Mp enforced on large building stock, Mp and the average Bp may not be statistically independent. Indeed, policymakers may calibrate the level of Mp considering the average Bp level and the consequent impact. Similarly, the evolution in time of Mp and Bp may be correlated, since multiple stranding events could have a significant impact. Moreover, Mp could also be dependent on the loss function $\mathbf{Lrt}_s$ as in the UK regulation [42], where the retrofit costs for owners are capped for residential buildings and linked to a financial return for commercial ones.

The definition of the loss function $\mathbf{Lrt}_s$ is also affected by high uncertainty. For reference, a standard indicator of the economic efficiency of a building energy retrofit is the ratio between the yearly energy saving and the initial costs, IES parameter from now on. In this respect, a 2022 report of the Bank of Italy [167] estimated that a cost of 13.95B€ in retrofits of the building stock would have led to yearly energy saving of 191 ktoe equal to 2.21MWh. Thus, the resulting IES equals 0.16kWh/€. In comparison, the same study used as a basis for Table 4, estimated the IES in the range from 0.34kWh/€ in the warmest climate zone to 0.63kWh/€ in the coldest one [109]. Thus, there is almost a 300% difference between the IES from [167] and the middle of the range from [109]. We have however not considered the report [167] because: (i) the report has, most probably, considered the cumulative costs of both energy and seismic retrofit, as was presented in the reported source [168], which could have reduced the relevant IES; (ii) the same source [168] does not provide enough details to verify the relevant calculations; (iii) IES has been estimated to be 0.35kWh/€ for Portugal [60] and in the range 0.40–0.65kWh/€ for Germany, not considering extreme retrofits, [88], which are more in line with [109]. Still, the aforementioned differences highlight the variability in the cost estimation, which also significantly depends on professional design costs, financing fees and several economic trends [169]. Besides, the fatality rate for stranding risk has been estimated assuming a constant proportionality between fatality and costs of construction work. Nonetheless, it has to be considered that such a relationship is more likely variable over time [170]. Along this line, factors such as carbon tax rates or others that may contribute to loss assessment have not been considered in the scenario analysis. This simplification has allowed an approach comparable with conventional risk assessment methods for other natural hazards. Finally, the analytical framework formalized by Eq. (5) could result in a non-linear system if the probabilistic models for "hazard", "response" and loss entail several parameters. Thus, theoretically, a sensitivity analysis would be useful to quantify the parameters' influence on results' variance. However, in the specific case of the scenario analysis provided in Section 4.1, Eq. (8), (9), (12) and (13) are linear combinations where the three segments are proportionally correlated in the same way to the result. However, within the same equations, a single scenario parameter can influence multiple factors. For instance, shifting the EPC threshold, i.e. Mp_s, from class D to class E and F would have lowered R_s from Eq. (6) by 16% and 23.4% respectively. This difference would also increase in the final risk assessment given the expected lower retrofit costs to deliver a lower Δp.

6. Conclusions and future developments

This work has investigated the stranding risk of the building stock given the envisaged energy transition. First, a critical review of the state-of-the-art procedures has been presented. Second, this work proposes a probabilistic framework for stranding risk assessment. Third, we performed a scenario-based assessment of stranding risk for the Italian building stock. Fourth, the relevant results have been compared to the effects of seismic and flood hazards.

The main conclusions, in relation to the goals presented in Section 1, are outlined below:

(1) Current methodologies, such as CRREM, are affected by some limitations mainly due to: (i) inconsistency between envisaged decarbonization pathways and enforced minimum performance prescriptions, (ii) the evolving nature of such pathways given the relationship with the remaining emission budget, (iii) the incompatibility between the pathways and currently adopted technological solutions for building energy retrofits. These limitations can result in practical issues on the design level and relevant stranding assessment.
(2) Some limitations can be solved with a more robust and probabilistic approach. From a practical viewpoint, such an approach requires data and analysis that are not yet available, given the recent nature of stranding risk. However, existing methods derived from other risk assessment practices can deliver such results.
(3) A scenario based on the enforcement of the 2024 EPBD has been used to evaluate the costs associated with the stranding risk for the Italian building stock. The estimated total costs are over 400B euros.
(4) The expected annual loss from stranding, seismic and flood risk of the Italian building stock has been compared. In the considered scenario, stranding risk is worth three times seismic and flood risks combined.

As regards further developments, the definition and application of the proposed design method could be improved by future research along the following lines: (i) techniques such as expert elicitation can be adopted to achieve a full probabilistic definition of the stranding hazard, (ii) the scenario analysis of stranding risks can be modified and expanded to account for any evolution in public policies, (iii) loss functions for stranding risk can be updated and increased in detail to account for different building archetypes and technology or materials adopted for energy retrofits, (iv) a more comprehensive approach to risk quantification for the building stock including other man-made and natural hazards and their possible interactions, (v) extend the approach to other geographies with different climates and hazard sources, (vi) the possible cascading risks and the environmental impact of large-scale stranding should be investigated also considering planned decarbonization pathways.

CRediT authorship contribution statement

Rocco di Filippo: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gianluca Maracchini:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Funding acquisition, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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