

A novel prescriptive approach for buildings' insulation design considering embodied carbon

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ABSTRACT

The reduction of energy consumption and environmental impact of buildings is critically important. Thermal insulation is highly effective in reducing energy needs. Therefore, national policies have regulated and encouraged insulation retrofits. Their environmental convenience depends on the carbon footprint of the materials used and the carbon density of the energy consumed. However, this is not usually reflected in prescriptions, and no studies have tried to formulate practical solutions for this integration. This work proposes a prescriptive approach based on Type-III declarations of materials and the carbon footprint of thermal energy to improve the environmental convenience and feasibility of retrofits. The life cycle environmental balance of thermal insulation retrofits is first investigated with a simplified analytical model. Then, the analytical model is applied to a parametric case study. The effect of natural hazards on maintenance-related emissions is also considered, an aspect quite unexplored in the literature. The results demonstrated that the impact of the embodied carbon is significant, especially considering future realistic low-carbon energy scenarios and the impact of a natural hazard on the needed maintenance. The proposed approach, conceived to be applicable in current practices, allows for a reduction of the minimum thermal resistance of the opaque envelope by up to 33% in the case of low embodied carbon materials and low carbon density heating technologies. The novel approach can still deliver energy savings of more than 60% and reduce the life cycle emissions and materials required, opening new perspectives for more sustainable and holistic regulations in the building sector.

1. Introduction

The building sector was responsible for roughly one-third of global energy consumption in 2019 [1]. A major 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, thermal insulation of the building envelope has been identified as a highly effective solution [3,4]. To address this, various building regulations have been introduced over the past three decades, implementing stricter thermal insulation requirements for both renovations of existing buildings and new constructions [5]. This translates into lower U-values for the various parts of the building envelope [6]. For example, in the UK, the thermal insulation requirements for roofs and walls are 0.16 W/m²K and 0.2 W/m²K, respectively [7]. In Italy, the requirements vary based on the climate zone and range from 0.27–0.19 W/m²K for roofs and 0.38–0.22 W/m²K for walls [8].

Plastic-based polymeric materials are widely used as thermal insulation solutions in the building industry [9,10]. Indeed, PU, XPS, and EPS have good thermal properties and a relatively low price compared to

inorganic fibrous insulation materials like mineral or glass wool [11]. These two characteristics have made this class of materials relatively successful in the market until now and in the near term [10,12,13]. Concerning the lower costs, this is of notable importance. Fiscal policies are indeed more and more inclined to support energy retrofits, but the efficiency of public expenditure in terms of environmental benefits has been questioned [14]. Moreover, high-efficiency performances for deep energy retrofits and new buildings have been linked with a low cost/benefits ratio regarding emissions abatement [15]. Also, policy and economic scenarios are critical parameters to assess the viability of buildings' energy retrofits [16–18]. In addition to the envisaged cost benefits, the superior thermal performances of plastic-based materials translate into a smaller thickness of the insulation layer, which designers envisage for both practical and economic reasons [19]. Besides, several studies have applied Life Cycle Assessment (LCA) to methods to assess and optimize the environmental impact of specific insulation materials. For instance, plastic-based materials tend to be characterized by higher embodied energy and carbon values, due to their high environmental impacts in both production and end-of-life stages [20]. As a

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Nomenclature	
Abbreviations	
CPB	Embodied carbon performance of the building
EPB	Energy performance of the building
HYP1, HYP2	Hypotheses 1 and 2
RG1, RG2, RG3, RG4	Research goals 1, 2, 3, 4
LCA	Life Cycle Assessment
Notations and Units	
A_{ff}, A_r, A_w	First floor area and insulated area of roofs and windows [m ²]
A_n	Area of a given opaque envelope component n [m ²]
A_{tot}	Total insulated area [m ²]
BEP	Environmental Break-even period [y]
δ_H	difference of ΔR_n between configurations S_{H1} and S_{H2} [%]
δ_L	difference of ΔR_n between configurations S_{H1} and S_L [%]
δHE	difference between HE_s and HE_{rf}
$\Delta GW P_{rf}$	GWP impact of the whole energy retrofit [kgCO _{2eq} /(m ² · y)]
$\Delta GW P_{TI}$	GWP impact of the thermal insulation [kgCO _{2eq} /(m ² · y)]
ΔR_n	Additional thermal resistance from a new insulation layer for a given opaque envelope component n [(K m ²)/W]
ΔR_r	Additional thermal resistance from standard design [(K m ²)/W]
ΔR_d	γ -adjusted additional thermal resistance [(K m ²)/W]
EC_{FU}	Embodied carbon of the functional unit [kgCO _{2eq} /(R · m ²)]
EE_{FU}	Embodied energy of the functional unit [kWh/(R m ²)]
EE_{TI}	Embodied energy of thermal insulation per floor area [kWh/m ²]
EHR	Embodied energy investment ratio
$GW P_E$	Global Warming Potential of the heating energy [kgCO _{2eq} /kWh]
$GW P_{Es}, GW P_{Er,f}$	Starting and post-retrofit $GW P_E$ [kgCO _{2eq} /kWh]
$GW P_{T_{ec}}$	Total embodied carbon of insulation material [kgCO _{2eq}]
$GW P_{ec}$	Embodied carbon of insulation material per year of service life [kgCO _{2eq} /y]
η	Efficiency of the heating technology [–]
η_s, η_{rf}	Starting and post-retrofit η [–]
HDD	Heating Degree Days
HE	Dissipated heat for thermal conduction of opaque envelope [kWh]
HE_s, HE_{rf}	Starting and post-retrofit HE [kWh]
ρ	Density [Kg/m ³]
λ	Thermal conductivity [W/(m K)]
Lf	Service life of the thermal insulation [y]
Lr	Annual loss rate [%/y]
R_s, R_{pr}	Starting and post-retrofit thermal resistance [(K m ²)/W]
S_{H1}, S_{H2} and S_L	GWP-invariant configurations

result, it is not trivial for these quantities to be offset by lower energy consumption during the life cycle of the retrofit [21]. Several studies have consequently highlighted the existence of an energy and environmental optimization problem concerning building insulation [22–24]. Recent research has also underlined that high-efficiency buildings may overall have worse environmental performances due to the significant amount of embodied carbon required at the moment of construction or retrofit [25].

This optimization can be significantly influenced by the carbon density of the energy grid, both current and future, which is an object of relatively recent research [20,26,27]. [28] underlines how neglecting future energy scenarios, especially in the context of net-zero goals [29], may lead to higher use of materials and relevant embodied carbon. Still, no methods for revising retrofit building codes accordingly are being proposed. In this respect, the German building code [30] allows a reduction of minimum thermal resistance requirements if low-carbon heating technologies are used. Other studies have also included, in such optimization, future climate prospects [20,31] and cost-effectiveness [32–34]. Another non-negligible issue linked to plastic-based materials is the resulting waste management [35]. Notably, in 2015, the building sector was responsible for 19% of the total primary nonfiber plastics production and 5% of the relevant waste, equal to 5 megatonnes [36].

Both embodied carbon and the waste issue can be worsened by any damage and repair to the building during its operational life. Regarding this last point, probabilistic methods have been applied to quantify, in terms of environmental metrics, the risks posed by natural hazards such as earthquakes [37–39], winds [40], and tsunamis [41]. A recent FEMA guideline [42] provides procedures and tools for integrating seismic hazard effects with LCA to calculate the climate change potential, expressed in terms of CO₂ equivalent, related to repair, reconstruction, or maintenance activities following seismic-related damages. These methodologies are primarily based on the Economic Input-Output method (EIO-LCA) and the bill of materials (BOM) approach. The EIO-LCA method [43] calculates the environmental impact of activities by transforming costs into CO₂ equivalent using dedicated sector-level data matrices. The BOM approach, conversely, leverages statistical databases [44,45] to quantify the embodied energy and/or carbon associated with a certain amount of material. Besides, it has been found that plastic-based materials, given their combustible nature [46], can worsen the consequences of fires [47–49]. Indeed, it has been shown that the consequences of a fire may be relevant not only when primary structural elements are considered [50,51], but also when devices or non-structural elements are subjected to thermal attack [49,52].

New-generation prescriptions have begun to cope with these issues with different degrees of effectiveness. As a reference, the fire risk aspects have been mitigated with regulations about the flammability of combustible thermal insulation [53]. Still, no studies have considered the risk aspects in the environmental balance of prescriptive approach for energy retrofit. Otherwise, building codes have not yet faced the problem of the high embodied energy and carbon of construction materials, except for the French RE2020 [54] and the Danish BR18 [55]. In particular, the RE2020 enforced at the beginning of 2022, set specific thresholds for both the energy consumption performance and, for the first time, the embodied carbon of new buildings. New Single-Family Houses (SFH) will be required to have an environmental impact, over their reference life, lower than 160 kgCO₂/m² due to energy consumption and 410 kgCO₂/m² due to embodied carbon. Thus, embodied carbon is posed to be much more significant than energy consumption in the envisaged high-efficiency and low-carbon energy grid scenario. The same double-performance principle may also be implemented at the broader EU level in the near future. The Energy Performance of Buildings Directive, EPBD, is indeed being revised, considering the life-cycle emissions of building materials [56,57]. In detail, the Energy Performance of Buildings, EPB, is usually regulated through procedures

based on national and international codes, such as ISO 52000 [58]. Similarly, the embodied Carbon Performance of Buildings, CPB, will be based on combining the environmental product declarations, or EPD, of the materials used in the building [54]. The presence of a compliant EPD is more and more a prerequisite in the EU and is regulated by ISO 14025:2006, 21930:2017, and the linked EN 15804 [59]. While the EU has pioneered the application of the EPD framework, similar programs for Type III declarations are being implemented globally [60–62].

Nonetheless, the double-performance frameworks proposed and enforced until now are limited to new constructions. This is expected since the computation of the CPB requires extensive knowledge of the whole set of materials involved, which is difficult to obtain for existing structures [63]. While a CPB accounting solely for retrofit materials would be feasible to assess, this is not considered in dedicated codes. Otherwise, the EPB can be more easily calculated, so the retrofit prescriptions are based on such parameters and closely linked ones [5]. For reference, 80% of the building stock in the EU is older than 1990, with a third being older than 1960 [64]. The yearly rate of new building construction in 2014 was 0.19% in Spain and Italy, and 0.56% in Germany [65]. In comparison, the EU will need to increment the yearly building renovation rate from the current 0.2% to 3% to meet its environmental goal set for 2050 [66]. According to [66], at this rate, the activity volume would be comparable to the 20th-century European post-war reconstruction. As a result, the relative importance of energy retrofits of existing buildings is expected to be critically significant [67]. However, such a massive challenge may also deliver a significant negative effect deriving from the embodied energy and emissions of building materials [68]. Conversely, while modern insulation materials capabilities, costs, and availability present non-negligible differences that can influence designers' decisions [11,32], current retrofit prescriptions do not assign any design role to their embodied carbon levels. However, while viable and effective regulatory tools are necessary to implement CPB considerations into current energy retrofit prescriptions for buildings, no studies in the literature try to formulate amendments to the available prescriptive regulations or propose completely new ones. Moreover, no studies try to estimate the impact of natural hazards on embodied carbon estimation. Building on these gaps, the main aim of this paper is to propose an alternative prescriptive approach for energy retrofit regulations with tailored prescriptions considering embodied carbon emissions and carbon intensity of thermal energy. This aim is based on the following two research Hypotheses (HYP), i.e:

- the existence of an optimization gap for environmental benefits of energy retrofits that can be filled with available materials and technologies (we can do better with available materials, HYP1);
- a revision of the common prescriptive approaches for energy retrofits is feasible to include CPB and obtain higher environmental performance while keeping a straightforward application (we can ask more from our interventions without increasing complexity, HYP2).

At this aim, this paper is divided into the following four phases, corresponding to the considered Research Goals (RG):

- (1) Reviewing the most advanced building codes and the relevant thermal insulation prescriptions for new buildings and energy retrofits to confirm the existence of a CPB gap for energy retrofits (RG1, Section 2);
- (2) Assessing the impact of materials' embodied carbon and energy on the life cycle greenhouse gases (GHG) emissions of energy retrofits, considering both present and future energy scenarios, through a simplified analytical model (RG2, Sections 3, 4.1 and 4.2);
- (3) Evaluating the influence of other factors, such as natural hazards, and increasing temperatures due to global warming on life cycle GHG emissions (RG3, Section 4.3);

- (4) Proposing a possible optimization of the current standard prescription framework for thermal insulation within buildings' energy retrofits, able to integrate CPB with EPB, thus addressing the lack of CPB prescriptions for energy retrofits of existing buildings (RG4, Section 5).

The main novelty of this work thus lies in the formalization of a viable prescriptive approach for building retrofits to design thermal insulation, considering material embodied carbon and heating energy systems. This approach will allow better environmental performances and material savings while still delivering a significant reduction in energy consumption. The outcomes and limitations are then discussed in Section 6. The study's main conclusions are drawn in Section 7 together with some comments on future developments.

2. Review of current building codes for thermal insulation and energy retrofits requirements

This section presents a brief review of a few relevant existing building codes regulating energy performance and thermal insulation to confirm the existence of a CPB gap. The reviewed building codes have been categorized based on the application to new and/or existing buildings and the following criteria:

- (I) Presence of a prescribed minimum EPB;
- (II) Presence of prescribed minimum R-values, R_{pr} , for buildings' envelope/components and if these values can vary upon carbon density of energy or materials;
- (III) Presence of a prescribed minimum CPB.

Starting from the Italian case, there are two sets of requirements for new buildings [69] and existing ones [8,69], with this last code being mandatory for fiscal incentives. Both codes prescribe minimum EPB, allowing for fossil-fuel and electricity-based heating systems. Still, minimum levels of renewable energy are prescribed for use within the new buildings even if there are no explicit threshold for operational carbon emissions. Depending on the climatic zone, different minimum R-values are prescribed for residential buildings in both codes. For the largest climatic zone, "E", the minimum R-values, depending on the opaque envelope component, are 3.84–4.54 m²K/W and 4–5 m²K/W for new and existing buildings, respectively. These thresholds do not vary based on the carbon density of energy or materials. The codes do not prescribe a minimum CPB.

In the UK, a unified building code [7] provides energy efficiency prescriptions for new and existing dwellings. A minimum EPB is prescribed, which also entails a target greenhouse gases, GHG, emission performance related to energy consumption. Both fossil-fuel and electricity-based heating systems are allowed. Minimum R-values are set depending on the opaque envelope component. Their threshold ranges are 3.84–6.66 m²K/W and 5.55–6.66 m²K/W for new and existing buildings, respectively. These thresholds do not vary based on the carbon density of energy or materials. The code does not prescribe a minimum CPB.

The German GEG code [30] regulates the energy efficiency of new and existing buildings. A minimum EPB is prescribed, and fossil fuel and electricity-based heating systems are allowed. Still, minimum levels of renewable energy are prescribed for use within the new buildings even if there are no explicit threshold for operational carbon emissions. Minimum R-values are variable values depending on the opaque envelope component and the type of heating energy. Their threshold ranges are 4–6.66 m²K/W and 3.33–4.16 m²K/W for new and existing buildings, respectively. Notably, this code allows a reduction of 15% of thermal insulation requirements in case heating energy would be from renewable sources. The GEG code does not prescribe a minimum CPB.

As discussed in Section 1, the French RE2020 [54] sets a minimum EPB and CPB for new buildings. Moreover, the EPB is set in terms of both energy consumption and relevant operational carbon emissions.

Some exceptions are provided, but it virtually excludes fossil fuel-based heating systems. Besides, RE2020 does not prescribe any minimum thermal insulation values. Unlikewise, prescriptions for retrofits of existing buildings are more conventional [70]. A minimum EPB is prescribed, and fossil fuel and electricity-based heating systems are allowed. Minimum R-values are set depending on the climatic zone and opaque envelope component. Their threshold ranges are 3–5.2 m²K/W for the climatic zone H1, which covers the most significant share of the country and exhibits the coldest climates. These thresholds do not vary based on the carbon density of energy or materials. The code does not prescribe a minimum CPB. As a result, while a CPB is present in the RE2020 [54] for new buildings, it is not included in the prescriptions for retrofit of existing buildings [70].

The Danish BR18 [55] applies to both new and existing buildings and also includes a mandatory indirect threshold for embodied carbon. However, it has to be considered that: (i) it only applies to new buildings with a surface of more than 1000 m², (ii) differently from French code the emission limit is set to the sum of operational and embodied carbon, specifically to 12 kg CO_{2eq} per year of reference life, (iii) a minimum EPB and minimum thermal resistance are still present. Overall, the BR18 seems to give the designer more freedom with a cumulative embodied and operational threshold, potentially allowing for a flexible approach. However, it also entails energy prescriptions which practically limits this flexibility.

The 2022 California code [71] regulates the energy efficiency of new and existing buildings. A minimum EPB is prescribed, and fossil fuel and electricity-based heating systems are allowed. The peculiarity of the code is that it offers two approaches: “performance” and “prescriptive”. The “performance” approach is based on a more refined software-based calculation of energy consumption and allows non-conventional solutions for, among other things, insulation. Nonetheless, mandatory minimum R-values exist for both “performance” and “prescriptive” approaches. These are generally comparable with those of their European counterparts, in the order of 3–5 m²K/W. Overall, the “performance” approach entails lower minimum insulation requirements. The code does not prescribe a minimum CPB and an operational carbon emissions threshold.

A summary of the criterion analysis is reported in Table 1. For reference, [72] reviews the energy building codes of Norway, Sweden, Finland and Russia. All these countries would have the same categorization of Italy and the UK as presented in Table 1 except for the Finnish code that prescribes a maximum heat transfer and not a minimum level of thermal insulation. Overall, the prescription of a minimum level of thermal insulation is a rather common approach [73]. Notably, there are some other EU countries in the process of implementing mandatory CPB for new buildings [74]. Therefore, all the codes for retrofits do not consider the issue of embodied carbon. Notably, Germany and California allow a reduction of thermal insulation requirements based on energy consumption size and carbon density.

3. Methodology

This work will rely on numerical simulations as the basis for the revising proposal of the current standard prescription framework for thermal insulation within building energy retrofits. This section presents a simplified analytical model to assess the impact of the insulation material embodied carbon on the life cycle GWP of energy retrofits. In particular, the life-cycle GWP of an energy-retrofit intervention based on the addition of an external thermal insulation layer, i.e. $\Delta GW_{P_{TI}}$ from now on, is influenced by:

- The total embodied carbon level of the new insulation material, including the production and the end-of-life stages, expressed as $GW_{P_{T_{ec}}}$;
- The expected service life of the thermal insulation, expressed as L_f ;

Table 1

Building energy standards - relevant national codes for new and existing buildings and comparison based on Criterion I, II and III defined in Section 2.

Country	Application	Criterion		
		I	II	III
Italy	New Buildings [69]	Yes	Yes	No
	Retrofits [8]	Yes	Yes	No
UK	New Buildings [7]	Yes	Yes	No
	Retrofits [7]	Yes	Yes	No
Germany	New Buildings [30]	Yes	Yes - Variable Based on energy source	No
	Retrofits [30]	Yes	Yes - Variable Based on energy source	No
France	New Buildings [54]	Yes	No	Yes
	Retrofits [70]	Yes	Yes	No
Denmark	New Buildings [55]	Yes	Yes	Yes
	Retrofits [55]	Yes	Yes	No
California (US)	New Buildings [71]	Yes	Yes - Variable on energy assessment method	No
	Retrofits [71]	Yes	Yes - Variable on energy assessment method	No

- The thermal resistance to be added, expressed as ΔR_n ;
- The heating energy demand related to the heat conduction from the opaque components, expressed as HE ;
- The carbon density of the energy, expressed as GW_{P_E} .

The list above preliminary neglects other parameters that can influence $\Delta GW_{P_{TI}}$ such as, among others, the starting thermal resistance of the building envelope, which affects the HE value, the building shape and the consequent relative weights of the different envelope components. Thus, given the existing relationships among the different parameters, we can write:

$$\Delta GW_{P_{TI}} = f(GW_{P_{T_{ec}}}, L_f, \Delta R_n, HE, GW_{P_E}) \quad (1)$$

where the nature of f depends on the methods and the assumptions adopted. In the following subsections, the modeling choices adopted for the calculation of the embodied carbon of the insulating material (Section 3.1) and the GWP of building energy consumption due to space heating (Sections 3.2 and 3.3) are presented. Then, the formulation adopted to compute the GWP saving achievable through a retrofit intervention is shown in Section 3.4. A visual scheme of Eq. (1) is depicted in Fig. 1.

3.1. Embodied carbon of thermal insulation material

The impact of the embodied carbon of the insulating material is dependent on the length of its service life L_f [23]. From an analytical viewpoint, the yearly amortization of $GW_{P_{T_{ec}}}$, written as:

$$GW_{P_{ec}} = \frac{GW_{P_{T_{ec}}}}{L_f} \quad (2)$$

Most of the insulation materials have guaranteed durability of 50 years [22,26], which also defines the value of the parameter L_f assumed in this study. It should be noted that this work exclusively consider the insulation material given its predominant contribution compared to other components of the insulation installation, such as mortar and connections.

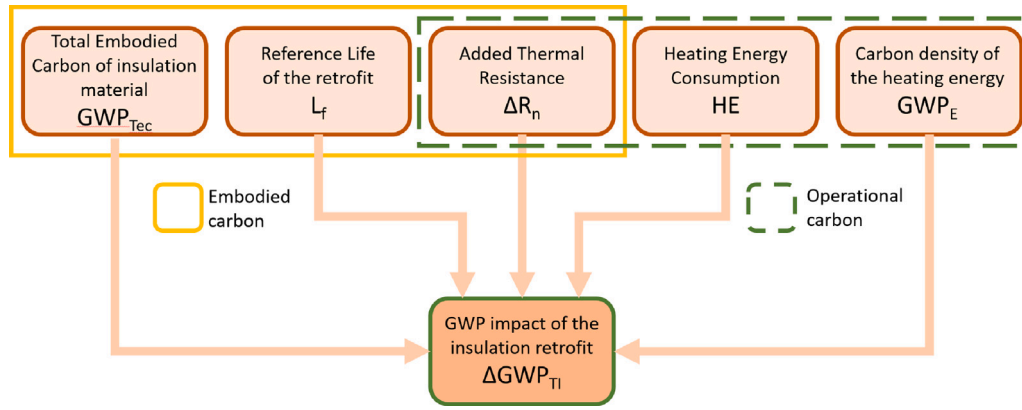


Fig. 1. Visual scheme of the main parameters influencing the environmental impact of thermal insulation retrofit - ΔGWP_{TI} .

Several studies have already provided estimations for embodied carbon, with the most common measure being the carbon density expressed in kgCO_{2eq} per kg [11,24,32] or m^3 of the material [20]. However, to have a better comparison between different materials, a “Functional Unit” (FU) needs to be defined, i.e. the quantity (in kg) providing the same additional thermal resistance [22,75]. Accordingly, the analytical formulation of the FU can be written as:

$$FU = R \cdot \rho \cdot \lambda \cdot A \quad (3)$$

where ρ is the density of the material, λ is the relevant thermal conductivity, A is the area to be insulated and R is the thermal resistance to be considered. As found in [22], the parameter ρ can highly influence the results and easily become the most significant factor. Notably, [75] states that the density of widespread insulation materials such as glass wool (GW), stone wool (SW), and polyurethane (PU) can vary in a range where the higher bound is three times the lower one. It is also true that ρ and λ are correlated in a linear or non-linear way [76,77]. As a result, even when the FU is considered, a generalization based on the material class can lead to high uncertainty in the embodied carbon assessment [22,78]. For this reason, in this work a product-based approach enabled by Type-III declaration EPD data is adopted (and proposed in the prescriptive approach described in Section 5). EPD data entail the quantification of the GWP linked to the life cycle of the insulation material, expressed in kgCO_{2eq} per FU. The selected FU is also defined in such declarations, expressed as a quantity of R per m^2 of covered surface [21,31,78]. Most of the time, the FU is evaluated with R equal to 1 Km/W , which will be the standard measure in this study. It is worth noting that EPDs data cover life stages from A to D, thus including end-of-life and recycling scenarios. Most of the current EPDs for heterogeneous insulation materials, i.e. sandwich panels or similar, provide GWP for all the components involved in the FU, see for Ref. [79]. If not, the relevant measure should equal the sum of the component contributions normalized for the FU, also paying attention to the possible end-of-life scenarios, e.g. considering the recycling of the different materials only if materials are separable.

For reference, according to an EPD review presented in [21,22], plastic-based materials present an embodied carbon density in the range between 2 and 5 $\text{kgCO}_{2eq}/\text{FU}$, without accounting for EoL stage. In comparison, wools and natural or non-conventional ones are below 2 $\text{kgCO}_{2eq}/\text{FU}$. This difference directly relates to higher energy consumption in manufacturing and raw materials extraction [11,21]. Notably, some non-conventional materials, such as cellulose or wood-based ones, can exhibit a negative embodied carbon contribution in their production stages due to the biogenic content of sequestered atmospheric carbon dioxide [21,26].

3.2. Energy demand model

A simplified approach to evaluate the building energy demand HE is adopted in this study. This method relies on the notion of yearly heating and cooling degree days (HDD and CDD) [4,78,80] and allows a straightforward and results that are not overly dependent on specific features of individual buildings. Moreover, despite any case-specific approximations, the HDD approach enables the computation of the energy solely related to heat loss per year from the building's opaque envelope conduction [16,78]. This aligns with the primary goal of this study, as it enables a direct comparison among different insulation retrofit solutions [49]. Nonetheless, more advanced dynamic and simulation-based models can deliver more precise outcomes [3,81,82].

The energy demand model presented in this work does not include cooling energy. This is because: (i) AC applications are not so widespread in residential buildings and several codes do not prescribe minimum cooling performances, (ii) cooling energy consumption is still a fraction of the heating consumption [83], (iii) overall, the cooling energy consumption shows a weaker correlation with thermal insulation of opaque components of the building envelope [3,26,84,85]. This last point is confirmed by the fact that lowering the heat gains from windows during hot months can impact the cooling energy more than walls and roof insulation [84]. Besides, according to [86,87], if windows are not adequately shielded from sun radiations, walls' insulation can lead to detrimental overheating in hot climates. Based on a commonly used formulation [80,88], HE can be analytically defined as

$$HE = \frac{24h \cdot HDD \cdot \sum_n (R_n^{-1} \cdot A_n)}{A_h} \quad (4)$$

where n indicates a specific building envelope component and A_h is the heated floor surface. R_n and A_n are the relevant thermal resistance and area of the opaque components. HDD is the value of the heating degree days, computed by considering an internal temperature of 20 °C, commonly taken as a Refs. [16,78,89]. In the framework of an energy retrofit, R_n would depend on the starting thermal transmittance value, R_{ns} and the parameter ΔR_n , as expressed below:

$$R_n = R_{ns} + \Delta R_n \quad (5)$$

The influence of R_{ns} on Eq. (5) and, consequently, (1) can be not negligible, as also discussed in [20,27].

3.3. Energy scenarios and GWP of heating energy consumption

To transform the heating energy demand evaluated with Eq. (4) in the GWP impact of energy consumption, GWP_{HE} , the following equation will be adopted:

$$GWP_{HE} = \frac{HE \cdot GWP_E}{\eta} \quad (6)$$

Table 2
Energy scenarios with relevant heating technologies and carbon density $GW P_E$.

Energy Scenario	$GW P_E$ (kgCO _{2eq} /kWh)	Heating Technology	η
NG	0.213	Natural Gas Boiler	1
E19	0.334	ASHP	3
E30	0.143	ASHP	3
EPv	0.050	ASHP	3

where η represents the efficiency of the heating technology.

This study considers four scenarios focusing on the carbon density of the heating energy.

The first scenario, *NG*, entails a natural gas boiler technology as the heating generator. This is currently the most common heating source, with a prevalence of 61% in North America, 46% in Eurasia, and 46% in Europe [90]. Notably, many countries and international institutions are trying to reduce this prevalence in favor of electricity-based heating sources [91]. From [92], it is retrieved that in the case of a natural gas boiler, $GW P_E(NG) = 0.213$ kgCO_{2eq}/kWh. In this study, η is set equal to 0.99 according to the performances of a modern natural gas condensing boiler [93].

The second, third, and fourth scenarios involve an electricity-based heating source, such as an air source heat pump (ASHP). The difference will be in the carbon intensity of the electricity production [94]. The second scenario, *E19*, will be selected according to [94] as the 2019 average EU electricity carbon intensity with $GW P_E(E19) = 0.334$ kgCO_{2eq}/kWh. Reportedly, this carbon density is assessed with a well-to-wheel approach, which already includes grid efficiency and can simplify the calculations. This value is thus 30% higher than the carbon density relevant to the production phase only and equal to 0.255 kgCO_{2eq}/kWh for 2019 according to Eurostat data [95]. The third scenario, *E30*, is chosen to simulate the expected reduction of the EU electricity carbon density by 2030 in agreement with the current decarbonization plans [95–97]. While the expected value is 0.110 kgCO_{2eq}/kWh at the production stage, in this study the value is increased by 30% to match a well-to-wheel estimation and set therefore $GW P_E(E30) = 0.143$ kgCO_{2eq}/kWh. These values are comparable with carbon densities from other countries and, considering the future reduction in $GW P_E$, they are not new [26,98,99]. A 2016 report from the UK parliament stated that the planned reduction in carbon density should reduce the electricity footprint from 0.37 in 2015 to 0.1 kgCO_{2eq}/kWh in 2030 [100]. In 2017, the US states of New York and California reported electricity carbon density levels below 0.2 kgCO_{2eq}/kWh [101]. The California state is also projected to reach a value of 0.097 kgCO_{2eq}/kWh in 2030, down from 0.175 in 2020 [102]. The last scenario, *EPv*, will consider the case of a Solar Photovoltaic energy source with $GW P_E(EPv) = 0.050$ kgCO_{2eq}/kWh [94]. Notably, the *EPv* scenario also agrees with some countries' goals for long-term decarbonization. Thus, while this research neglects the dynamic nature of $GW P_E$ [20,98,99], the considered scenarios represent a fully comprehensive range of possible variations.

For the ASHP technology, relevant to *E19*, *E30* and *EPv* scenarios, the system efficiency is set with $\eta = 3$. The efficiency of ASHP for heating generation, usually defined with the parameters COP or SCOP, can exhibit significant variations when actual field tests are considered [103]. Nonetheless, this analysis relies on the lowest bound value from a recent test campaign made in a cold-climate country [104], which provided a COP range of 3–3.5. Similar results were registered by a large field test in the UK [105]. The characteristics of the four scenarios are reported in Table 2.

3.4. Analytical formulation for GWP balance

The state-of-the-art of LCA analyses for thermal insulation often present highly specific applications with advanced dynamic models [81, 82]. However, when rather general conclusions have to be drawn,

simplified analytical models can be used to perform streamlined numerical multi-variate analyses [20,26]. Also, it is important to note that prescriptive regulations on minimum post-retrofit thermal insulation, as reviewed in Section 2, do not differentiate, in most cases, on factors that would be considered in dynamic models or, in any case, proper of specific building archetypes. Besides, a high number of analyses would be required to assess the contribution of a single component with respect to a multivariate input. Thus, this Subsection presents the formulation of a simplified analytical model to assess the environmental convenience of an energy retrofit intervention.

The goal of an energy retrofit is, most of the time, to realize energy savings, deliver smaller operational costs, and lower the environmental impact of an existing building. In this work, we will focus only on two retrofit components, i.e. the heating technology and the thermal insulation of the opaque building's envelope. Thus, it is possible to write:

$$\Delta GW P_{rf} = GW P_{HE_s} - GW P_{HE_{rf}} - GW P_{ec} \quad (7)$$

where $GW P_{HE_s}$ and $GW P_{HE_{rf}}$ represent the starting and post-retrofit GWP impacts of the heating energy due to opaque envelope thermal dispersion. $GW P_{ec}$ is the embodied carbon linked to the thermal insulation retrofit including production and considered End-of-Life stages. Noteworthy, the interventions relevant to $GW P_{HE_{rf}}$ would also include the emissions related to the installation of an ASHP for scenarios *E19*, *E30*, *EPv* whose linked embodied carbon is not included in Eq. (7) since this is not the focus of this work. In [26] an ASHP system results in 368.8 kgCO_{2eq} per Kw of capacity, that, divided for a heated floor surface in the order of 10^2 m², would make this contribution not so significant. Scenario *EPv* also includes installing a photovoltaic system whose embodied carbon would already be included in $GW P_E(EPv)$. We can use Eqs. (4)–(6), to define $GW P_{HE_s}$ and $GW P_{HE_{rf}}$ as follows:

$$GW P_{HE_s} = \frac{HE_s \cdot GW P_{Es}}{\eta_s} = \frac{24h \cdot HDD \cdot \sum_n (R_{sn}^{-1} \cdot A_n) \cdot GW P_{Es}}{\eta_s} \quad (8)$$

$$GW P_{HE_{rf}} = \frac{HE_{rf} \cdot GW P_{Erf}}{\eta_{rf}} = \frac{24h \cdot HDD \cdot \sum_n ((R_{sn} + \Delta R_n)^{-1} \cdot A_n) \cdot GW P_{Erf}}{\eta_{rf}} \quad (9)$$

Eq. (7) can consequently be rewritten as:

$$\Delta GW P_{rf} = 24h \cdot HDD \cdot \sum_n (A_n \cdot (\frac{R_{sn}^{-1} \cdot GW P_{Es}}{\eta_s} - \frac{(R_{sn} + \Delta R_n)^{-1} \cdot GW P_{Erf}}{\eta_{rf}})) - GW P_{ec} \quad (10)$$

From Eq. (10), it can be seen that two addends contribute to $\Delta GW P_{rf}$. The first one is relevant to the shift from the starting parameters $GW P_{Es}$ and η_s to $GW P_{Erf}$ and η_{rf} . This shift is relevant to the modifications to the heating technology and the different energy scenario. To isolate the contribution of the thermal insulation to $\Delta GW P_{rf}$ Eq. (1) can be rewritten as follows:

$$\Delta GW P_{TI} = 24h \cdot HDD \cdot \sum_n (\frac{A_n \cdot GW P_{Erf}}{\eta_{rf}} \cdot (R_{sn}^{-1} - (R_{sn} + \Delta R_n)^{-1})) - GW P_{ec} \quad (11)$$

where $GW P_{ec}$ can be expressed by rewriting Eq. (2) as follows:

$$GW P_{ec} = \frac{GW P_{Tec}}{Lf} = \frac{\sum_n (\Delta R_n^{-1} \cdot A_n) \cdot EC_{FU}}{Lf} \quad (12)$$

where EC_{FU} is the embodied GWP value retrieved from a Type-III environmental declaration including production and EoL stages and expressed in terms of kgCO_{2eq}/(R · m²).

The Break-Even Period parameter BEP measures the GWP impact of the additional thermal insulation compared to the embodied carbon of the material. BEP , in detail, represents the number of years required to nullify the embodied carbon of the insulation material due to the reduced impact of energy consumption, i.e. an environmental payback period. The concept of the environmental “break-even” has been studied by [25] as a way to optimize the “investment” of immediate and generally consistent GHG emissions or a positive return over the life cycle of a building. The analytical formulation is defined below:

$$BEP = \frac{GW P_{T_{ec}}}{\Delta GW P_{T_I} + GW P_{ec}} \quad (13)$$

It should be noted that the contribution of end-of-life and beyond-system boundaries scenarios (stages C and D in the EPD) physically happens after the BEP itself. Thus, BEP is measured in equivalent years but does not represent the chronological distance between the retrofit's realization and the environmental break-even since a part of the “investment” (e.g. stage C) is still to happen at BEP year.

4. Numerical applications and results

This section aims to provide a practical application of the analytical model presented in Section 3 with a simplified case study to achieve the RG22 and 3 described in Section 1. The case study, boundary conditions and results are reported in Section 4.1. Then, Section 4.2 analyses the impact of embodied energy (RG2). Finally, Section 4.3 presents the effects of physical risks and climate change (RG3).

4.1. Boundary conditions and simulation results

The trend of $\Delta GW P_{T_I}$ and other key parameters defined in Section 3.4 is simulated with respect to ΔR_n , EC_{FU} and the energy scenario listed in Table 2.

The case study will be a benchmark three-storeys residential RC building with a 14 m by 14 m square floor plan and a floor height of 3.5 m. The case study has been conceived to be realistic, common enough and requiring simple calculations. The overall dimensions are adapted from [49] also assuming a 15% of the walls' envelope to be windowed. Only the second and the third floors are considered to be insulated, representing a total heated area of $A_h = 392 \text{ m}^2$. Thus, it is possible to calculate the surface of the opaque building envelope as follows:

$$A_{tot} = \sum_n A_n = A_{ff} + A_r + A_w$$

$$= (196 + 196 + 333.2) \text{ m}^2 = 725.2 \text{ m}^2 \quad (14)$$

where A_{ff} , A_r and A_w are the areas of the dispersing opaque surfaces of the first floor, the roof and the walls. This leads to a ratio $S/V = 0.6$ that falls within the range of common building archetypes selected by [106] for an analysis on energy retrofits of the Italian building stock.

Section 2 shows that the prescribed maximum R-values differ for each opaque building envelope component. Top roofs tend to have higher prescribed R-values compared to walls. This is supported by the fact that these components are responsible for the most significant part of heat dissipation [84]. The differences among the envelope's R-values requirements are not constant or proportional. In this research Eqs. (7)–(12) will adopt the same value for each n component for R_n , R_{sn} , ΔR_n in order to simplify the visualization of the results. The analysis assumes a uniform $R_s = 0.80 \text{ m}^2\text{K/W}$, representative of conventional designs from old uninsulated RC buildings, while ΔR_n will vary in the range from 1 to $5 \text{ m}^2\text{K/W}$. Thus, this range should bring the final R-value to a maximum of $5.80 \text{ m}^2\text{K/W}$, compatible with the prescription presented in Section 2. Based on the review from [21], EC_{FU} is set to vary in the range from 0 to $5 \text{ kgCO}_{2eq}/(\text{R} \cdot \text{m}^2)$ with $R = 1 \text{ m}^2\text{K/W}$. HDD is set equal to 2550, i.e. the half value of the range for the Italian climate zone E. The relevant parameters are reported in Table 3.

Table 3

Simulation main parameters and relevant specific values or boundary conditions.

Parameters	Value
Starting R-value R_{sn}	$0.80 \text{ m}^2\text{K/W}$
Insulation R-value ΔR_n	$1 < \Delta R_n < 5 \text{ m}^2\text{K/W}$
Material embodied carbon EC_{FU}	$0 < EC_{FU} < 5 \text{ kgCO}_{2eq}/(\text{R} \cdot \text{m}^2)$
Heated floor area A_h	392 m^2
Area to be insulated A_{tot}	725.2 m^2
HDD	2550 K

Table 4

“GWP-invariant” configurations and relevant EC_{FU} , $GW P_{HE_{rf}}$ and $GW P_{ec}$ in the different energy scenarios.

Conf.	EC_{FU} ($\text{kgCO}_{2eq}/(\text{R} \cdot \text{m}^2)$)	$GW P_{HE_{rf}} - GW P_{ec}$ ($\text{kgCO}_{2eq}/(\text{m}^2 \cdot \text{y})$)			
		NG	E19	E30	EPv
S_{H1}	3.5	4.92 - 0.56	2.54 - 0.56	1.09 - 0.56	0.38 - 0.56
S_{H2}	3.5	4.92 - 0.56	2.54 - 0.56	1.14 - 0.48	0.43 - 0.34
S_L	1	5.34 - 0.14	2.85 - 0.13	1.68 - 0.1	0.84 - 0.05

The parameters of Table 3 are selected to depict a significant set of boundary conditions that, however, do not cover the whole spectrum of possible scenarios and building shapes. The parameter A_{tot} indeed depends on the building's geometry. It is important to underline, nonetheless, that, according to the analytical model of Section 3.4, A_{tot} is an equal factor of both the terms of the sum in Eq. (10). $\Delta GW P_{T_I}$ could consequently be normalized per unit of area to be insulated. The simulation results for the four scenarios listed in Table 2 are depicted in Fig. 2, 3, 4 and 5 respectively.

As expected, for Scenario NG, EC_{FU} exhibits a low influence on $\Delta GW P_{T_I}$ (see Fig. 2) due to the high impact of the life cycle energy consumption on the total emissions. Conversely, in Fig. 3, 4 and 5 a stronger correlation between $\Delta GW P_{T_I}$ and EC_{FU} can be observed.

The results are better analyzed by referring to three different “GWP-invariant” configurations, i.e. characterized by the same $\Delta GW P_{T_I}$, reported as data snips in the figures. These configurations, namely S_L , S_{H1} and S_{H2} , are representative, given a certain degree of approximation, of natural inorganic (S_L) and plastic-based insulation materials (S_{H1} and S_{H2}) [20,21,31] in terms of EC_{FU} . On this premise, the three configurations have different ΔR_n selected to obtain an equal $\Delta GW P_{T_I}$. In particular, S_L is characterized by the low EC_{FU} , set at $1 \text{ kgCO}_{2eq}/(\text{R} \cdot \text{m}^2)$, and a lower ΔR_n . This is, as expected, the opposite of S_{H1} , which presents a higher EC_{FU} equal to $3.5 \text{ kgCO}_{2eq}/(\text{R} \cdot \text{m}^2)$. The third configuration, S_{H2} , shares the same EC_{FU} of S_{H1} but with a lower ΔR_n . The EC_{FU} values of the “GWP-invariant” configurations and the resulting operational and embodied carbons, i.e. $GW P_{HE_{rf}}$ and $GW P_{ec}$, for the energy scenarios are listed in Table 4.

Figs. 2 and 3 only reports the data snips for S_{H1} and S_L given the negligible difference in terms of ΔR_n between S_{H1} and S_{H2} . The parameters δ_L and δ_H are defined as the percentage differences, in terms of ΔR_n , necessary to reach the same $\Delta GW P_{T_I}$. The two parameters are calculated as follows:

$$\delta_L = \frac{\Delta R(S_L) - \Delta R(S_{H1})}{\Delta R(S_{H1})} \quad (15)$$

$$\delta_H = \frac{\Delta R(S_{H2}) - \Delta R(S_{H1})}{\Delta R(S_{H1})} \quad (16)$$

Besides, the parameter δHE is introduced as a measure of the impact of the thermal insulation on the heating energy consumption, evaluated as follows:

$$\delta HE = \frac{HE_{rf} - HE_s}{HE_s} \quad (17)$$

where $HE_s = 141 \text{ kWh}/(\text{m}^2 \cdot \text{y})$. The values of BEP , δ_L and δHE for the four scenarios listed in Table 2 and considering the configurations S_L and S_{H2} , are reported in Table 5.

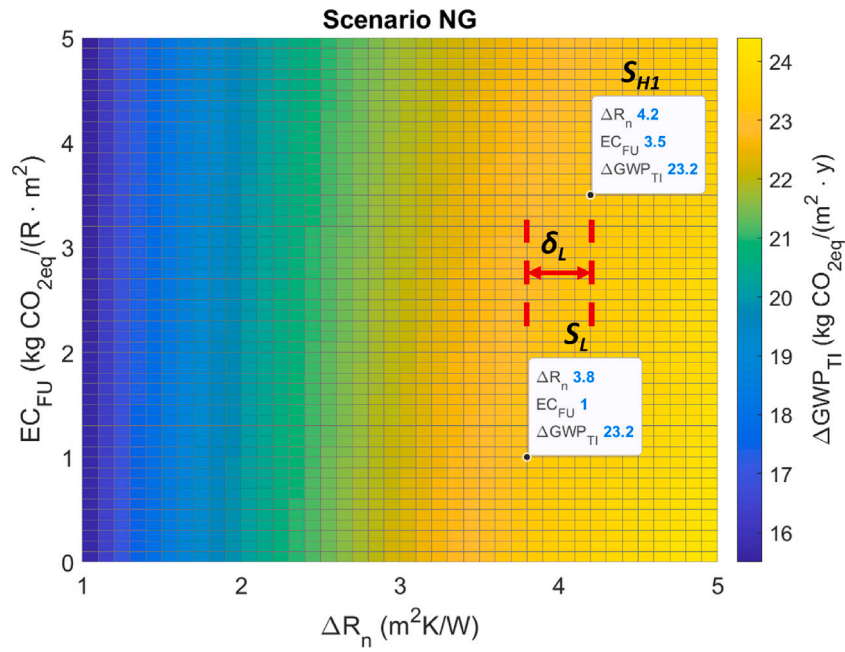


Fig. 2. ΔGWP_{T1} trend, on the color scale on the right, with respect to EC_{FU} , on the y-axis, and ΔR_n , on the x-axis, in the Scenario NG. The data nips report the values of ΔGWP_{T1} , EC_{FU} , and ΔR_n in the configuration S_{H1} , and S_L . δ_L is the normalized difference in terms of ΔR_n between S_{H1} and S_L .

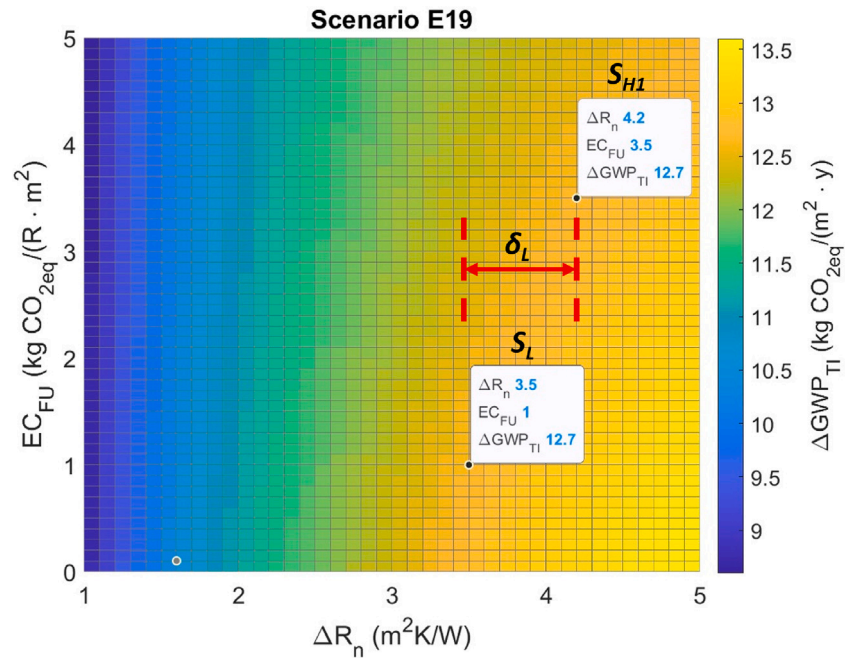


Fig. 3. ΔGWP_{T1} trend, on the color scale on the right, with respect to EC_{FU} , on the y-axis, and ΔR_n , on the x-axis, in the Scenario E19. The data nips report the values of ΔGWP_{T1} , EC_{FU} , and ΔR_n in the configuration S_{H1} , and S_L . δ_L is the normalized difference in terms of ΔR_n between S_{H1} and S_L .

Table 5

Values of BEP , δ_L and δHE in each energy scenario and according to the configurations S_{H1} , S_{H2} and S_L .

Scenario	BEP (years)			δ_L (%)	δ_H (%)	δHE (%)		
	S_{H1}	S_{H2}	S_L			S_{H1}	S_{H2}	S_L
NG	1.14	1.14	0.24	-9.5	≈ 0	-83.6	-83.6	-82.2
E19	2.05	2.05	0.5	-17	≈ 0	-83.6	-83.6	-80.9
E30	4.81	4.22	0.99	-33	-14	-83.6	-81.3	-74.6
EPv	13.73	9.06	1.73	-66	-40	-83.6	-72.5	-63.5

The results from Table 5 show that the reductions in ΔR_n generally lead to a negligible or small variation of energy consumption (δHE) in all the scenarios, while effectively abating BEP . For instance, in the NG scenario, the δ_L equal to -9.5% corresponds to a δHE of the S_L solution just 1.4% lower than that obtained for the S_{H1} configuration. In the E30 scenario, the S_{H2} configuration exhibits similar results. In the EPv scenario, $\delta_L = -66\%$ and $\delta_H = -40\%$ lead to 20.1% and 11.3% lower δHE compared to S_{H1} configuration. As expected, energy consumption and thermal insulation thickness are non-linearly correlated and adding more insulation material delivers a diminishing marginal return. Conversely, the negative contribution of embodied

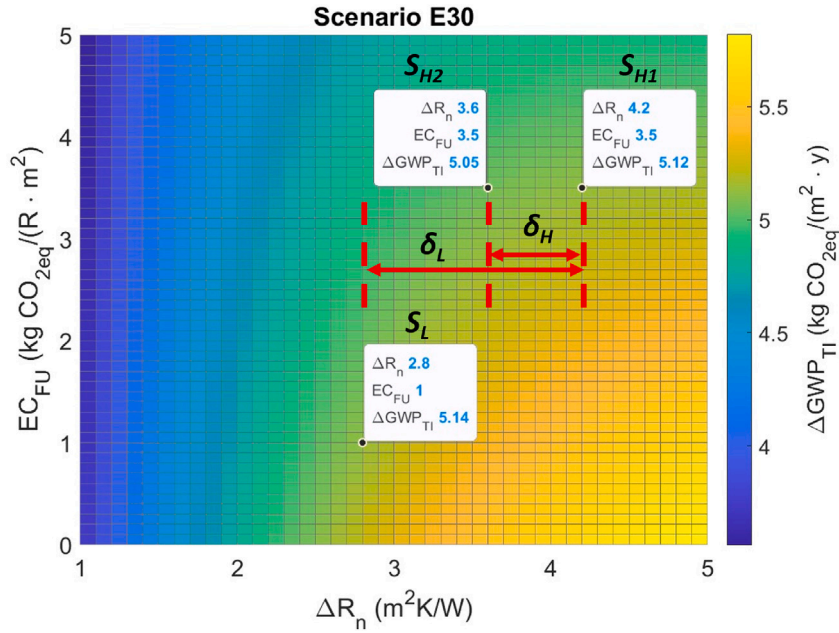


Fig. 4. ΔGWP_{Tl} trend, on the color scale on the right, with respect to EC_{FU} , on the y-axis, and ΔR_n , on the x-axis, in the Scenario E30. The data nips report the values of ΔGWP_{Tl} , EC_{FU} , and ΔR_n in the configuration S_{H1} , S_L and S_{H2} . δ_L and δ_H are the normalized difference in terms of ΔR_n between S_{H1} and S_L and between S_{H1} and S_{H2} respectively.

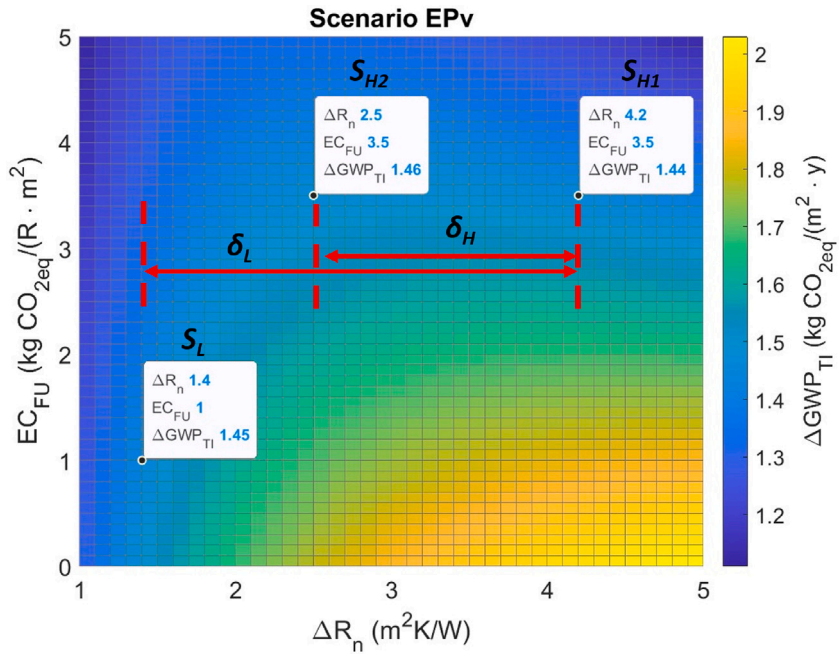


Fig. 5. ΔGWP_{Tl} trend, on the color scale on the right, with respect to EC_{FU} , on the y-axis, and ΔR_n , on the x-axis, in the Scenario EPv. The data nips report the values of ΔGWP_{Tl} , EC_{FU} , and ΔR_n in the configuration S_{H1} , S_L and S_{H2} . δ_L and δ_H are the normalized difference in terms of ΔR_n between S_{H1} and S_L and between S_{H1} and S_{H2} respectively.

carbon to the environmental balance grows linearly with the quantity of insulation material employed. In particular, the reduction of ΔR_n (e.g. δ_L and δ_H) across the GWP-invariant configurations grows according to (i) the reduction of the carbon density of the heating energy and technology (i.e. passing from a high-carbon energy scenario to another lower one, e.g. from NG to E19, or from E19 to E30) and (ii) the reduction of the embodied carbon of the insulation material (e.g. passing from δ_H to δ_L). However, the influence of (i) appears

to be the most significant. This is mainly due to the lower share of energy-related emissions on the total life cycle emission in low-carbon scenarios. Such an outcome agrees with other studies involving future energy scenarios [20,26]. These results fulfill the research goal RG2, as presented in Section 1, and validate the first hypothesis HYP1 given that different configurations can deliver shorter environmental break-even (BEP) with a still significant energy saving (δ_H). Moreover, S_{H2} and S_L configurations are compatible with widely used materials.

Table 6

Values of EHR in each energy scenario and according to the configurations S_{H1} , S_{H2} and S_L .

Scenario	EHR (%)		
	S_{H1}	S_{H2}	S_L
NG	1.9	1.9	0.66
E19	5.8	5.8	1.86
E30	5.8	5	1.49
EPv	5.8	3.5	0.75

4.2. Impact of embodied energy of insulation material

The configurations S_{H1} , S_{H2} and S_L exhibit different energy consumption while being “GWP-invariant” due to the different thermal resistance. However, Eqs. (15) and (16) are limited to the energy consumption of the building, while not considering the embodied energy of the retrofit materials. Materials with higher embodied carbon also have higher levels of embodied energy [20,21]. In particular, [21] analyzes an EPD database and defines a linear relationship between embodied carbon and embodied energy. It is possible to calculate the embodied energy per FU, EE_{FU} , of each configuration by rewriting this function as follows:

$$EE_{FU} = (8.42 + EC_{FU} \cdot 15.77) \cdot 0.28 \quad (18)$$

where EE_{FU} is expressed in kWh/(R · m²). To provide the relative weight of the embodied energy, the parameter EE_{TI} is defined as:

$$EE_{TI} = \frac{EE_{FU} \cdot A_{tot} \cdot \Delta R}{A_h \cdot Lf} \quad (19)$$

where EE_{TI} measures the impact of the embodied energy expressed per m² of floor area per year. To assess the impact of EE_{TI} within the different configurations and energy scenarios, the parameter EHR is computed as follows:

$$EHR = \frac{EE_{TI} \cdot \eta}{HE_s} \quad (20)$$

Thus, EHR can be considered the “investment” (or “initial cost”) in embodied energy to obtain the energy saving δHE listed in Table 5. The values of EHR for the configurations S_{H1} , Hr_{TI} , S_L are listed in Table 6.

From Table 6, it can be noted that the efficiency of the energy investment is much higher in the S_L configuration compared to S_{H1} . Notably, when EHR is accounted for, the difference in the energy consumption among the GWP-invariant configurations becomes smaller. With reference to the configurations S_{H1} and S_L in the scenario E30 this difference can be computed as follows:

$$\frac{\delta HE(S_{H1})}{\delta HE(S_L)} = \frac{0.836}{0.746} = 1.12 \quad (21)$$

$$\frac{\delta HE(S_{H1}) - EHR(S_{H1})}{\delta HE(S_L) - EHR(S_L)} = \frac{0.836 - 0.058}{0.746 - 0.0149} = \frac{0.778}{0.731} = 1.06 \quad (22)$$

It can be noted that the difference in terms of energy saving goes from 12% in Eq. (21) to 6% in Eq. (22). Hence, when EHR is considered, the increment between the actual energy consumption between S_{H1} and S_L is reduced by 50%. Given this effect's significance, embodied energy's impact should not be neglected.

4.3. Impact of climate change and other risks

This subsection will discuss the relative weight of two external factors not included in the simulations presented in Section 4.1.

The first factor is the possible influence of climate change on the parameter HDD. For reference, [107] predicted a reduction of 30%–40% of HDD in the UK in 2050, with [20] assuming a 2050 reduction of 35%. Similarly, [31] considered an HDD reduction of 25% for Norway

Table 7

Values of BEP , δ_L and δHE in each energy scenario and according to the S_{H1} , S_{H2} and S_L configurations including seismic risk and climate change.

Scenario	BEP (years)			δ_L (%)	δ_H (%)	δHE (%)		
	S_{H1}	S_{H2}	S_L			S_{H1}	S_{H2}	S_L
NG	1.34	//	0.35	−12	//	−83.6	//	−81.6
E19	2.37	//	0.45	−21	//	−83.6	//	−80
E30	5.6	4.71	1.02	−43	−19	−83.6	−80.5	−74.2
EPv	16.02	8.65	1.83	−71	−44	−83.6	−69.3	−60

in 2070. A 2017 report from the Italian governmental agency ISPRA [108] predicted a reduction of HDD for Climate Zone E in 2050 of 18% and 13% according to future scenarios RCP8.5 and RCP4.5 [109], respectively. According to scenario RCP4.5 for the Italian climatic zone E [108], it is possible to infer −5% in HDD in 2025. Assuming 2025 as the starting point for a linear decrease in HDDs, the average reduction in the first 25 years is −9%. For the last 25 years of L_f , HDDs are assumed constant at −13% from the base level. Thus, for the whole L_f , according to the proposed analytical approach, the HDD reduction can be set at a uniform −11%.

The second factor involves the impact of risks that may damage the retrofitted building. Any repair activities would result in additional materials and relevant emissions, as already discussed in Section 1. Still, such impact has never been considered in studies dedicated to assessing and revising thermal insulation prescriptions for energy retrofits. For reference, [39] estimated an annual loss of 0.13% of the construction cost for RC buildings with 1970s seismic design in earthquake-prone Italian regions. According to [110] the annual loss due to seismic hazard can reach 1% in the case of old buildings in the most earthquake-prone regions. Besides, at the country level, an annual loss of 0.068%, equivalent to 3.4% over a service life of 50 years, is calculated in [110]. Overall, this also confirms the relative importance of structural retrofit among the possible strategies to lower the environmental impact of buildings [111]. A similar annual loss rate has been calculated for wooden buildings due to wind risk [40].

All these risks would result in higher absolute values of δ_L , δ_H and BEP due to a higher $GW P_{ec}$. This increment can be analytically expressed by rewriting Eq. (12) as follows:

$$GW P_{ec} = GW P_{T_{ec}} \cdot \left(\frac{1}{L_f} + L_r \right) \quad (23)$$

where L_r is the annual loss rate due to risk-induced damage. Eq. (23) implies that the L_r effect does not overlap with the assumed lifetime exhaustion. To provide the impact of the combination of risks and climate change, the same simulations as in Section 4.1 are run with a uniform HDD reduction of 11% and $L_r = 0.1\%$. The GWP-invariant configurations with the same assumptions and the relevant results are reported in Table 7.

Table 7 shows a not negligible increase of δ_L and δ_H and a higher difference between BEP s in each configuration. These results fulfill the RG3 and further reinforce the research hypothesis HYP1 defined in Section 1.

5. Proposal for prescriptions' revision: a GWP-invariant approach

The results listed in Tables 5 and 7 show the quantification of the optimization gap. This constitutes the basis for formulating a novel approach to thermal insulation design. The proposed approach aims to cover Goal (4) presented in Section 1. It shifts the prescription from a fixed minimum thermal resistance to a variable threshold. This threshold will vary upon four factors: (i) the starting R-value, R_s , (ii) the prescribed post-retrofit minimum R-value, R_{pr} , (iii) the carbon density of the post-retrofit heating technology, (iv) the embodied carbon level per functional unit, with $R = 1$ Km/W, from the EPD, EC_{FU} . Whereas the EPD would present end-of-life alternative scenarios, the one implying lower emissions should be considered to favor material

Table 8

Coefficient γ values to be selected according to the carbon density of the heating energy system, $GW P_E$, and of the insulation material, EC_{FU} .

	$GW P_E$ -H	$GW P_E$ -M	$GW P_E$ -L
EC_{FU} -H	1	0.9	0.85
EC_{FU} -M	0.95	0.8	0.75
EC_{FU} -L	0.9	0.75	0.66

with recycling options. In brief, according to this approach, the thermal insulation to be added depends on a reduction coefficient that varies based on the embodied carbon of the insulation material and the type of heating technology. The procedure is compared to the standard design method in Fig. 6. The first step of the procedure is to evaluate the R -value to be added. This can be done by rewriting Eq. (5) as follows:

$$\Delta R_r = R_{pr} - R_s \quad (24)$$

The second step is to decide the strategy for the energy retrofit, which is intended to fall within three categories:

- “ $GW P_E$ -H”: in the case of a natural gas boiler (high-carbon scenario);
- “ $GW P_E$ -M”: in the case of an ASHP (medium);
- “ $GW P_E$ -L”: in the case of either an ASHP or a PV generation system (low).

The third step pertains to the categorization of EC_{FU} according to the following ranges:

- “ EC_{FU} -H”: if $EC_{FU} \geq 3 \text{ kgCO}_{2eq}/(\text{R} \cdot \text{m}^2)$
- “ EC_{FU} -M”: if $1 \text{ kgCO}_{2eq}/(\text{R} \cdot \text{m}^2) < EC_{FU} < 3 \text{ kgCO}_{2eq}/(\text{R} \cdot \text{m}^2)$
- “ EC_{FU} -L”: if $EC_{FU} \leq 1 \text{ kgCO}_{2eq}/(\text{R} \cdot \text{m}^2)$

These thresholds are not set to encompass specific categories of insulation materials but to define ranges of EC_{FU} wide enough to impact the environmental balance and allow for a ΔR_r optimization. According to [21,22], plastic-based materials tend to fall within EC_{FU} -H, stone wool within EC_{FU} -M while glass wool and non-conventional materials pertain to EC_{FU} -L. However, these categorizations are affected by significant uncertainties and do not play a role in the proposed approach, which is product-specific and based on standardized Type-III declarations. Moreover, given the evolution of manufacturing technologies and the growing adoption of recycled polymers or innovative compounds, it is reasonable to update these thresholds every five years.

The final step is to select the design coefficient γ from Table 8.

The coefficient γ can then be used to evaluate the actual minimum additional thermal insulation as follows:

$$\Delta R_d = \gamma \cdot \Delta R_r \quad (25)$$

If a Type-III declaration is not available for the chosen material, γ is set according to the $GW P_E$ -H row from Table 8. This specific case replicates the aim of the German and Californian codes [30,71], which reduce thermal insulation based on the carbon density of heating energy. As a result, the scheme of the procedure is depicted in Fig. 6.

The values of γ from Table 8 are set to shift the design toward the GWP-invariant configurations S_L and S_{H2} listed in Tables 5 and 7. Still, the reduction associated with γ is lower than the various δ_L and δ_H of the E30 and EPv scenarios from the same tables. For instance, the minimum γ is 0.66, which entails a -33% while for the E30 scenario δ_L is equal to -43% . This keeps the absolute value of δ_{HE} well above 70%. Thus, γ would lower BEP and allow for a reduction of materials and costs while still guaranteeing significant energy consumption reductions. Thus, a novel and more optimized framework for thermal insulation prescriptions is feasible, and the solution proposed fulfills the RG4 presented in Section 1. The straightforward approach, with no additional data and calculation required, validates the second hypothesis HYP2 of this work.

6. Discussion

Overall, the simulation results from Section 4 have highlighted the significance of embodied carbon in the environmental impact of energy retrofits. This is increased by expected future energy scenarios, confirming similar results from [20,26], and the impact of risks. Indeed, it is demonstrated that materials with lower EC_{FU} can enable GWP-invariant configurations with a less insulated building envelope. As a result, both HYP1 and HYP2 are confirmed. Moreover, the proposed design approach presented in Section 5 represents a novel solution to the lack of CPB considerations in the building codes reviewed in Section 2.

6.1. Practical implications

Concerning the γ design approach described in Section 5, its main goal is to facilitate the use of insulation materials with a lower EC_{FU} and the installation of low-GWP heating and energy generation systems. This is obtained by coupling this combination with less demanding minimum requirements. This translates into a better CPB of energy retrofits and a lower BEP which help to mitigate the embodied carbon issue [25] as envisaged by recent building codes [54,57]. Notably, a critical necessity of CPB-based building codes is the availability of Type-III declarations, which this approach also encourages. Besides, given the effect of γ , insulation materials with lower EC_{FU} and, usually, lower λ [11] will not necessarily need higher thicknesses [13,49]. This facilitates the general feasibility, especially when close buildings or public and private roads are present, and implies lowering costs related to (i) losing floor space when insulation is on the inner side of the envelope [19] and (ii) the actual cost of the material [32]. For reference, [32] reports that EPS has a volumetric cost between 0 and 50% lower than glass and stone wool. The respective ρ and λ also increase the weight of such a difference on the final costs.

A downside of lower thermal resistance is a higher operational heating energy consumption. This would effectively make the transition to low-carbon energy grids more difficult. At the building level, however, with $\delta_L = -33\%$, which corresponds to $\gamma = 0.66$, δ_{HE} is still -74.6% as reported in Table 5. Furthermore, lower costs and higher material availability would increase the buildings' renovation rate, which is also significantly critical. Besides, this effect is mitigated by the higher embodied energy associated with higher EC_{FU} , as shown by Eqs. (21) and (22).

Moreover, adopting the γ design does not require additional calculation or data from the current practice, except for the Type-III declaration. In the absence of such a declaration, the design can nonetheless be applied. Also, being ISO-regulated [59], EPDs will constantly be updated to state-of-the-art methods. Indeed, it is expected that these regulations would adapt to the anticipated decarbonization of the grid and the evolution of disposal or recycling protocols. Incineration may be suboptimal compared to waste disposal [112] in a scenario of abundant low-carbon energy and more efficient waste management technologies. Notably, stages C and D are neglected when considerations about the residual CO2 budget are taken into account [113]. Besides, the feasibility of recycling thermal insulation materials is not straightforward [114]. As a result, it can be argued that EPDs may not be accurate in predicting stages C and D GWP and energy impacts a few decades from now. It is worth noticing that the characteristics of the insulation material, such as λ , are, however, already required to compute the necessary thickness to guarantee ΔR_r from Eq. (24). Besides, $GW P_E$ only requires a qualitative definition depending on the type of heating technology, in an apparent contradiction with the quantitative approach used for simulation in Section 4. However, it is true that (i) the E30 scenario seems well within the current trends in many countries, (ii) the codes generally prescribe minimum η evaluated according to national and international standards [115]. [20] reports that the operational deterioration of η over the service life of

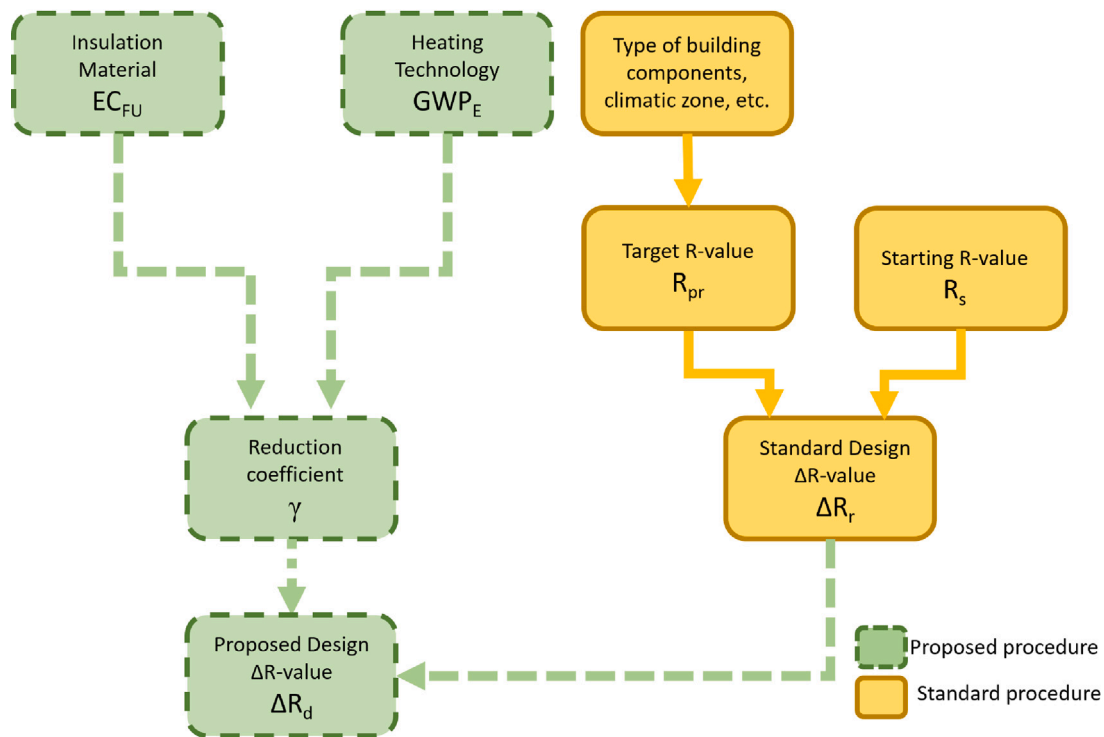


Fig. 6. Scheme of the proposed procedure.

the heating system can increase the insulation benefits. Still, periodic maintenance, similarly prescribed for natural gas boilers, can mitigate this effect. Noteworthy, the relative easiness of adopting such a design approach alongside the above-mentioned implications should be considered by policymakers within new regulations to mitigate embodied carbon in the building sector.

6.2. Limitations

Limitations about the specific values of γ mainly concern the initial assumptions of the simulations presented in Section 4.1. As reported in Table 3, we set $R_n = 5 \text{ m}^2\text{K/W}$ and a starting $R_{ns} = 0.8 \text{ m}^2\text{K/W}$. Given the similarities between Eqs. (5) and (24), it is clear that these two values can influence δ_L , δ_H and, consequently, γ . A higher R_n , equivalent to a more demanding R_{pr} , would increase γ with the opposite effect for R_s . This is consistent with the fact that more stringent minimum requirements would make the impact of embodied carbon even more significant. The HDD value and, thus, the type of climate also affect the weight of γ coefficients. On one side, a higher HDD would reduce the impact of EC_{FU} and the optimization effect of the γ design. Conversely, in cold climates, R_{pr} also tends to be higher. Overall, while these effects are related to heating energy consumption, an application in cooling-dominated regions would require further analyses. However, it is reasonable to think that the general flow of the proposed design would still be effective. Indeed, thermal insulation could be not so effective in reducing cooling energy consumption or even detrimental in some cases [84,87]. The building geometry may also affect the balance between embodied carbon and operational energy [116], together with the use destination of the building itself. The service life of the energy retrofits L_f is a parameter which, due to the possible differences between design and actual use, could affect the environmental performance [23]. L_f should, nonetheless, be kept coherent with the working life prescribed by other codes relevant to structural design [117]. Notably, the weight of climate change and physical risks, as calculated in Section 4.3, could play a significant role in the optimization effort. However, the assessment of their contributions is

affected by high uncertainty. It must also be considered that, in real applications, heating systems are designed to satisfy a minimum power output, which depends on the technology and the thermal insulation of the space to be heated. Analytically, this introduces a dependency between R_n and η , also influenced by the scale of the heating system and other installation characteristics. Finally, the ratio EHR depends on the linear relationship expressed in Eq. (19), which can be revised based on updated empirical data. In this respect, Type-III declarations include the quantification of primary energy resources.

In sum, the coefficients listed in Table 8 should be considered tentative values within certain boundaries. However, the analytical framework can be adapted to cope with different boundary conditions and their uncertainties.

Other approaches could be adopted to lower the impact of the embodied carbon of an energy retrofit involving thermal insulation. For the sake of discussing, one could set a maximum threshold on the EC_{FU} forcing the designers and producers to adapt. Also, a lower R_{pr} could be set, thus reducing the embodied carbon while increasing the operational energy consumption. At the same time, prescriptions could include a maximum R-value to avoid the use of excessive material. Finally, different technologies such as dynamic thermal insulation [118] and thermal energy storage [119] could become more widespread and deliver better performances.

7. Conclusions and future developments

This work aims to bridge a gap between the present prescriptions on thermal insulation for building retrofits and the issue of embodied carbon in the construction industry. The existence of an optimization gap in thermal insulation design is proven, along with the feasibility of a novel framework for prescriptive thermal insulation design. The proposed approach indirectly integrates embodied carbon and energy performance, addressing the lack of embodied carbon prescriptions for energy retrofits of existing buildings. This is obtained by shifting from a fixed R-value target to a variable one, dependent on the insulating material's embodied carbon and the heating energy's carbon density. This

favors low-carbon materials and heating technologies by lowering the insulation requirements while keeping the same GWP impact. Planned future energy scenarios are also considered, delivering a strategically coherent and harmonized design method. A simplified application to a residential building is also shown. The main conclusions, in relation to the goals presented in Section 1, are outlined below:

- 1 Few countries have started taking into account embodied carbon effects in their building codes, but these are limited, until now, to new constructions. Conversely, embodied carbon is not considered in any building code for energy retrofits despite the need to retrofit a significant number of existing buildings;
- 2 There is room for optimization of retrofits' environmental impact and materials use within common prescriptions range for minimum thermal resistance. Indeed, depending on the energy scenarios, insulation materials with low embodied carbon can deliver an equal or better GWP impact with less added thermal resistance. Conversely, the reduction in operational energy is still high and also benefits from less embodied energy;
- 3 EPDs and other metrics, already available in the current design practices, can enable the practical implementation of a thermal insulation design based on variable minimum thermal resistances. This approach can deliver a more optimized design.

As regards further developments, the definition and application of the proposed design method could be improved by future research along the following lines: (i) a more comprehensive set of simulations accounting for different climates and buildings' shape and use; (ii) the inclusion of cooling energy consumption together with the adoption of dynamic modeling; (iii) a statistical analysis of available EPDs with a focus on embodied carbon and energy to include the impact of uncertainties in the general framework; (iv) build a predictive model of how EPDs metrics could vary in different future energy scenarios; (v) the extension of the approach to other components such as windows.

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CRediT authorship contribution statement

Rocco di Filippo: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Writing – Original Draft, Visualisation, Funding acquisition. **Gianluca Maracchini:** Formal Analysis, Investigation, Writing – Original Draft, Writing – review & editing, Project administration, Funding acquisition. **Rossano Albatici:** Validation, Writing – review & editing, Supervision. **Rosa Di Maggio:** Validation, Writing – review & editing, Supervision. **Oreste S. Bursi:** Writing – review & editing, Supervision, Funding acquisition.

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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