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A quantitative comparison on the use of thermal insulation materials in three European countries through the TEnSE approach: Challenges and opportunities

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ABSTRACT

Europe has about 75 % of energy inefficient buildings and 8 % of population in energy poverty with difficulties of affording energy bills for keeping adequate levels of warmth, cooling, lighting, and energy use for household appliances in building stock. The implementation of thermal insulation in existing buildings would allow to address both energy efficiency and energy poverty and to align with the Net Zero Emission Scenario. This research proposes an inverse decision-making approach to investigate on the reasons behind the use of some thermal insulation materials in three countries within the European Economic Area (Italy, Norway, and Portugal), differing in terms of Energy Poverty as well as environmental and legislative contexts. For this reason, four macro-domains objectives, framed in Technical (T), Environmental (En), Safety (S) and Economic (E) topics, named as TEnSE, were considered. Ten thermal insulation materials commonly used in these countries were compared to understand which of four perspectives affects their choices in current times among several stakeholders. As none of the selected materials has obtained the highest score among stakeholders and their use is presumably due to buildability, challenges and opportunities in their future implementation are discussed considering different climate 'what-if' scenarios.

1. Introduction

The International Energy Agency (IEA) has reported that in 2021 buildings sector is, directly and indirectly, responsible for around one-third of total final energy- and process-related CO_2 emissions subdivided as follows: 8 % from the use of fossil fuels in buildings, 19 % from the generation of electricity and heat used in buildings, and 6 % related to the manufacture of cement, steel and aluminium used for buildings construction. At European level, the European Union (EU) Commission through the Building Stock Observatory (BSO) reported that the building sector is responsible for more than 40 % of the energy consumption and 36 % of greenhouse gas emissions, which mainly stem from construction, usage, renovation, and demolition. To align with the Net Zero Emission Scenario, the EU building sector, which currently has a large percentage of energy inefficient buildings (roughly 75 %), needs to reduce its carbon emissions by more than half by 2030 and close to zero by 2050 through decarbonization efforts.

This evidence has led to define strategies aimed at decreasing the energy demand of existing buildings and improving the energy performance of new ones [1–3]. Sandberg et al. [4] estimate that more than 90 % of existing dwellings will still exist in 2050, which is the year defined by the EU Directive 2018/844 [1] for the achievement of climate-neutrality of building stock. The new policies connected to population densification and decarbonization encourage the adaptive reuse of existing buildings, their maintenance, refurbishment, and retrofit, even though such activities may be more complex and less

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efficient than the construction of new high-performance buildings. The "restructuring" behaviour aims to protect the cultural aspects of the existing buildings, as well as to make better use of buildings and resources [5]. Together with this aspect, it is worth noticing that people, living in buildings with poor energy efficiency and/or being unable to afford expensive energy retrofit due to low incomes, can be exposed to extreme apparent temperatures (i.e., temperatures equivalent perceived by humans due to the combined effects of air temperature, air humidity and ventilation), as reported by the World Health Organization (WHO). As an example, 30 % of the winter mortality and morbidity in Europe is caused by cold housing [6]. Together with the energy demand, an EU-wide survey revealed that 8 % of the European population, predominantly in southern and eastern EU countries [6,7], had difficulty or inability to maintain adequate thermal comfort inside their houses [8] due to Energy Poverty (EP), i.e., the condition to have difficulties of affording energy bills for keeping adequate levels of warmth, cooling, lighting, and energy to power appliances in building stock [9]. However, EP can be mitigated by means of two measures that make buildings more resilient and sustainable [10]: (i) long-term measures, i.e., to decrease energy-related expenditures through the improvement of the energy efficiency of dwellings; (ii) short-term measures, i.e., to increase household income and protect against utility disconnections through price regulation, and direct financial support.

For all the above reasons, all EU countries should establish long-term measures to support the renovation of their national building stock into a highly energy efficient and decarbonised building stock by 2050. The requirement for EU countries to adopt long-term measures is set out in the Energy Performance of Buildings Directive (2010/31/EU), revised in 2018 (2018/844/EU), that are part of EU countries integrated national energy and climate plans (NECPS). In this respect, it is worth noticing that the demand for thermal insulation materials in building applications has been estimated to increase at a Compounded Average Growth Rate (CAGR) of 3.5 % in the period 2015–2027 in line with the global demand. Thus, our research is focused on long-term measures, specifically the energy renovation of the existing building envelope through the thermal insulation of exterior walls, roofs, lofts, and floors, which are effective passive solutions to: (a) reduce energy needs, heat losses in buildings [11] and building's environmental impacts, and (b) improve indoor thermal comfort, indoor air quality and its effect on the well-being of the users. Indeed, this study is part of the wider EEA Granted EFFICACY project (Energy eFFiciency building and CirculAr eConomY for thermal insulating solutions), whose overall objective is a comprehensive database contributing to the New European Bauhaus. Indeed, through the Agreement on the European Economi,c Area (EEA), Iceland, Liechtenstein and Norway are partners in the internal market with the Member States of the European Union. To promote a continuous and balanced strengthening of economic relations and trade, the parties to the EEA Agreement have established a Financial Mechanism year, known as EEA Grants. EEA Grants aim to reduce social and economic disparities in Europe and strengthen bilateral relations between these countries and beneficiary countries.

The selection of thermal insulation materials has been recognised as one of the most challenging and complex steps of a building project due to the wide range of available products and the fulfilment of several criteria which may be conflicting in some cases. Multi-Criteria Decision Making (MCDM) methods can be effectively used to solve this kind of decision-making problems, as they allow to identify the best possible alternative or set of alternatives based on the decision-makers' preferences and priorities. Siksnelyte-Butkiene et al. [12] discussed a systematic review of MCDM methods commonly implemented for the selection of thermal insulation materials in buildings, providing a comparative evaluation among the methods. They have grouped the reviewed articles in three categories related to: (i) sustainability assessment, (ii) suitability assessment and (iii) methods selection. For the sustainability assessment, TOPSIS method is commonly used both at single material and whole partition level, demonstrating that organic-based materials (e.g., hemp fibres, cellulose, sheep wool) and green roofs are solutions highly sustainable-oriented. Both for the suitability assessment and the methods selection, several MCDM methods (e.g., TOPSIS, VIKOR, AHP, MOORA) are implemented, however the number of studies does not allow to identify the most recurrent MCDM method as it depends on the aim of the study. Although the good performance of MCDM methods in a wide range of applications [13–18], one of their limitations is the identification of criteria and their importance that vary case-by-case based on the attitude of single experts [19]. However, it was possible to categorise these criteria into four domains (economic, social, technological, and environmental) representing the pillar of sustainability and to identify the most popular criterion within each domain [12]. Another limitation of MCDM methods is related to the validation of outputs that can be proven mainly through practice [20].

This research aims at objectively identifying an approach whether specific stakeholders have influenced the choice of the most used thermal insulation materials in three countries within the European Economic Area, differing in terms of Energy Poverty as well as of environmental and legislative contexts. To this purpose, we have proposed a straightforward approach, called TEnSE not biased by stakeholders either nudgers, to calculating the performance score of the selected thermal insulation materials for building retrofit. This is based on indicators reflecting four objective domains – Technical (T), Environmental (En), Safety (S) and Economic (E) – whose values are gathered from the Environmental Product Declaration (EPD) of each thermal insulation material. Outcomes were also discussed considering future climate projections and their impact at regional scale.

2. Material and methods

When it comes to the choice of the most suitable thermal insulation material for building retrofitting, an ensemble of requirements is becoming fundamental to consider rather than only the thermal performance of the material itself [21]. To this purpose, an inverse decision-making approach was proposed based on four domains, hereafter namely called TEnSE – Technical (T), Environmental (En), Safety (S) and Economic (E) – to critically compare the performance of thermal insulation materials commonly used in three countries belonging to the European Economic Area: Italy, Norway, and Portugal. These domains were considered after having demonstrated they are the most effective criteria to consider in the selection of thermal insulation materials for building retrofit [12,22–25].

2.1. Data and metadata collection per country

Data from national and European statistics – i.e., EUROSTAT through the *European Union Statistics on Income and Living Conditions* (EU-SILC) for the monitoring of the development of poverty and social inclusion in the EU – were extracted and clustered based on the TenSE domains to show similarities/differences among the three countries:

- **T**: urgency and attitude towards the necessity of building retrofit (e.g., building stock density and publication of regulations with specific requirements on thermal insulation, the overall energy consumption and supply).
- **En**: attention to environmental contexts based on the specific climate conditions of the area under study (e.g., ASHRAE [26] and Köppen-Geiger climate zone [27] and heating/cooling degree-days (hereafter HDD/CDD)).
- **S**: capability of population to live in satisfactory and safety conditions inside their dwelling (e.g., keeping home adequately warm/cool or living in a dwelling with deficits such as leaking roof, damp walls, floors or foundation, or rot in window wooden frames or floor).

- **E**: capability of population to face building-related expenses (real Gross Domestic Product - GDP - pro capita as a measure of economic welfare excluding negative effects of economic activity) and of country to produce primary energy (i.e., energy productivity).

2.2. Data collection on thermal insulation materials

Reports provided by private and public companies involved in the building sector at national level were consulted to identify the most used thermal insulation materials in the three countries. In Norway, a recent market research on the thermal insulation materials [28] and other architecture and design marketplaces (i.e., Archiexpo, Europage, Archiproducts, Materials Market, and Barbour Product Research) provided the following products: wood fibre (WF), mineral wool (MW), polyurethane foam (PUR), polyisocyanurate (PIR), phenolic foam (PF), expanded and extruded polystyrenes (EPS and XPS). For the Italian and Portuguese building sectors, we also considered what reported in the Erasmus Plus project OERCO2 (Open Educational Resource), whose goal was to calculate CO_2 emissions in the life cycle of construction materials. In Italy, the most common insulating materials are cellulose fibre (CF), WF, MW including glass wool (GW) and rock wool (RW), PUR, EPS, XPS and expanded cork agglomerate (ICB). In Portugal, the most used thermal insulation materials according to the manufacturers were EPS and XPS, ICB, MW, PUR, PIR, and thermal mortars (TM).

In this study, one parameter (p) per domain was selected according to the most popular criterion used in each domain as highlighted by Siksnelyte-Butkiene et al. [12]. Environmental Product Declarations (EPD) in accordance with EN 15804 [29] and ISO 14025 [30] were used to extract data to associate with TEnS domains. Price lists provided by national database or private companies operating in the building sector were accessed for E domain.

- **T**: thermal conductivity (λ in $W \bullet m^{-1} \bullet K^{-1}$).
- **En**: quantity of the equivalent carbon dioxide ($CO_{2,eq}$) emissions in terms of Global Warming Potential (GWP) per 1 m^2 of products taking as reference the production stage of materials according to a cradle-to-gate approach, modules A1-A3 (i.e., from raw material extraction to manufacturing), of the Life Cycle Assessment (LCA). In this way, $CO_{2,eq}$ emissions due to transport to the construction site (A4) and installation into the building (A5) can be excluded as varying from place to place.
- **S**: fire reaction according to EN 13501-1 [31] so to pay attention to the safeguard of the intervention and use (e.g., smoke release).
- **E**: minimum and maximum price of the thermal insulation material per square meter (€ m^{-2}) per the whole thickness range. In the case of Italy, unit costs were gathered from a specific database for public works that allows estimating the value of the cost of material and any building operation. References for Norway and Portugal were reported in detail as footnotes in Table 1.

Then, all parameters (p) were linearly normalised between 0 and 1 (p'), where 0 corresponds to the worst case and 1 to the best case among the alternatives. Indeed, normalisation allows to perform the analysis with dimensionless criteria, as they may have different units of measurement, making it challenging to compare and evaluate alternatives using a single metric [20]. The normalisation is pivotal to fix the ideal optimal solution among alternatives and ensure there is no change in the values of the input matrix [32]. For the sake of clarity, the lowest values for λ, amount of GWP and unit cost as well as the fire reaction class "A" corresponded to 1, the opposite to 0. In the case of unit cost, the approved price lists provided a range of values corresponding to the minimum and maximum allowable thickness per each material. Thus, p' was computed taking into account both the average unit cost and the difference between maximum and minimum unit cost per each material: p' = 1 when both average and difference are the lowest among the alternatives, whereas p' = 0 in the opposite case. Table 1 reports p and p' values associated with TEnSE domains and used to build a database of the most used thermal insulation materials in the three countries.

In addition, for T and E domains, it was evaluated the potential heating and cooling energy savings in the three countries when each thermal insulation material was applied to the external walls of existing buildings. We used an initial thermal transmittance (U-value) of 2.5 $W \bullet m^{-2} K^{-1}$ for buildings built before 1945 (commonly defined as historical buildings) and a U-value = 1.6 $W \bullet m^{-2} K^{-1}$ for buildings built in 1970-89 as references according to Ref. [33]. To compute the final U-value after the application of the thermal insulation material, a reference thickness of 100 mm was considered [34]. Thus, equations (1a) and (1b) were used to provide the heating and cooling energy demands (ED_{heat} and ED_{cool} respectively) in $kWh \bullet m^{-2} \cdot year^{-1}$, whereas equations (2a) and (2b) were used to provide the heating and cooling energy costs in $€ \bullet m^{-2} \cdot year^{-1}$ (EC_{heat} and EC_{cool} respectively) before and after the implementation of each thermal insulation material [35,36]:

$$ED_{heat} = k \cdot HDD \cdot U_{value} \quad \text{eq. 1a}$$

$$ED_{cool} = k \cdot CDD \cdot U_{value} \quad \text{eq. 1b}$$

$$EC_{heat} = ED_{heat} \cdot \frac{C_{gas}}{\eta} \quad \text{eq. 2a}$$

$$EC_{cool} = ED_{cool} \cdot \frac{C_{elect}}{\varepsilon} \quad \text{eq. 2b}$$

Where k is a conversion coefficient equal to 0.024 (h); HDD and CDD are heating and cooling degree days, computed as the summation of the difference between daily outdoor temperature and base indoor temperature (°C, T_{base} = 15.5 °C for heating and T_{base} = 22.0 °C for cooling [37]); C_{gas} is the price of the natural gas in $€ \cdot kWh^{-1}$; C_{elect} is the price of electricity in $€ \cdot kWh^{-1}$; η is the thermal performance of the heating system; and ε is the thermal efficiency ratio of the cooling system. In this research, C_{gas} and C_{elec} of 2020 were gathered from EUROSTAT database: C_{gas} = 0.057 $€ \cdot kWh^{-1}$, 0.1322 $€ \cdot kWh^{-1}$ and 0.056 $€ \cdot kWh^{-1}$ and C_{elec} = 0.133 $€ \cdot kWh^{-1}$, 0.092 $€ \cdot kWh^{-1}$ and 0.114 $€ \cdot kWh^{-1}$ for Italy, Norway and Portugal, respectively. η and ε were set equal to 0.85 and 2, respectively [35,36].

2.3. Stakeholders-oriented selection of thermal insulation materials

An inverse decision-making approach [38] was proposed to objectively compare data and metadata feeding databases and to identify the underlying aspects on the selection of thermal insulation materials in the three countries according to the TEnSE domains. As emerged from the literature, criteria and weights are mainly defined via surveys or questionnaire filled in by specific experts [12]. In order to avoid a biased evaluation on the reason behind the choice of thermal insulation materials depending on the expertise of the stakeholders involved, twenty-four scenarios were identified as the permutations that can be obtained by associating a weight (w) – from 1 (low importance) to 4 (high importance) – to each domain for every thermal insulation material, i.e., a set of six permutations for each TEnSE (Table 2). This approach makes it possible to compare the products' score regardless of the influence of specific experts and nudgers or the use of *ad-hoc* interviews/questionnaires, which might be time-consuming and misleading without a validation. To obtain the final Stakeholders' Score (StS) ranging between 0 and 10 (eq. (3)), weights (w) were multiplied by the normalised values of the parameters (p') attributed to each material:

$$StS = \sum_{k=1}^{4} p_k^{'} w_k \quad \text{eq. 3}$$

StS can be globally visualised via stoplight charts: green indicates the relatively high-performance solution (StS >5) and red the relatively low-performance solution (StS <5).

Table 1

Information on the most used thermal insulation materials in three European countries (Italy, Norway, and Portugal) clustered by type (organic plant, inorganic mineral derived, organic fossil fuel derived, structure (fibrous, cellular, porous), and building application location. A relevant parameter (p) and its normalisation (p') is collected according to TEnSE domains: Technical, Environmental, Safety and Economic. For each parameter, it is reported the normalised parameter (p') according to the description in Section 2.2. C = cellular, F = fibrous, P = porous.

Thermal insulation material based on EPDs	Type	Internal microstructure	Building main applications	Parameter (p and p')	Technical		Environmental		Safety		Economic					
					Thermal conductivity		GWP total [A1-A3]		Reaction to fire		Unit cost [min-max]					
											Italy		Norway		Portugal	
				Unit	$W\bullet m^{-1}\bullet K^{-1}$	–	$kgCO_{2eq}\bullet m^{-2}$	–	A1/F	–	$€\bullet m^{-2}$	–	$€\bullet m^{-2}$	–	$€\bullet m^{-2}$	–
Cellulose fibre (CF) [a]	Organic plant	F	Roofs, floors, walls		0.039	0.24	−9.33	0.05	B-S2, d0	0.8	8.4–25.92	0.85	n.a	n.a	16	0.62
Expanded cork agglomerate (ICB) [b]		C	Roofs, floors, walls		0.043	0.08	−612.00	1.00	E	0.2	16.13–23.79	0.71	52.2–235.5	0.00	9.75–26.20	0.35
Wood fibre (WF) [c]		F	Roofs, floors, walls		0.037	0.32	−47.62	0.11	E	0.2	3.46–31.22	0.89	5.0–28.6	0.90	9.70–19.40	0.61
Mineral wool (MW) [d]	Inorganic mineral derived binder	F	Roofs, walls		0.032	0.52	3.6	0.03	A1	1.0	10.47–57.60	0.44	2.7–34.3	0.90	10.91–25.01	0.37
Thermal mortars (TM) [e k]		P	Walls		0.045	0.00	21.89	0.00	A1	1.0	20.66	0.65	1.4–4.7	1.00	12.75–34.00	0.00
Expanded polystyrene (EPS) [f]	Organic fossil fuel derived	C	Roofs, floors, walls		0.038	0.28	21.96	0.00	E	0.2	10.07–60.42	0.41	2.1–16.6	0.96	4.52–11.45	1.00
Phenolic foam (PF) [g]		C	Roof, floors, walls		0.021	0.96	15.57	0.01	C-s2, d0	0.6	12.08–92.44	0.00	n.a	n.a	n.a	n.a
Polyisocyanurate (PIR) [h l]		C	Roofs, walls		0.023	0.88	0.33	0.03	B-S2, d0	0.8	13.7–68.48	0.24	31.5	0.77	9.80–15.07	0.77
Polyurethane foam (PUR) [i]		C	Roof, vertical cavities		0.020	1.00	13.8	0.01	E	0.2	9.94	1.00	32.4–50.8	0.70	6.90–29.00	0.29
Extruded polystyrene (XPS) [j]		C	Roofs, floors, walls		0.034	0.44	7.56	0.02	E	0.2	8.88–53.29	0.52	13.1–13.1	0.92	6.79–13.58	0.88

Unit Cost Italy: https://prezziario.regione.veneto.it/, https://www.regione.lazio.it/cittadini/lavori-pubblici-infrastrutture/tariffa-prezzi-lavori-pubblici.
Unit Cost Norway: https://www.xl-bygg.no/, https://www.obsbygg.no/, https://www.byggmakker.no/, https://www.kork24.no/shop/11-lyd-og-varme-kork-isolasjonsplater/, https://isotech.no/isokit/.
Unit Cost Portugal: http://www.geradordeprecos.info/.

[a] CAPEM.
[b] Amorim Cork Insulation.
[c] IBU – Institut Bauen und Umwelt e.V.
[d] KnaufInsulation.
[e] DIASEN srl.
[f] Finja.
[g] Kingspan.
[h] Europerfil.
[i] Polyurethan dammt besser.
[j] DANOSA.
[k] Thermo-plaster ecological thermal and breathable, formulated with cork, natural hydraulic lime, clay and diatomaceous powders.
[l] Fire reaction of PIR varies according to additives (from B,s2-d0 to F). In this study, B,s2-d0 was considered as it was the most occurred. It is worth noticing that in this paper the criterion is related to safety of households, although it could be considered as a technical parameter.

Table 2
Permutations of weights (w) to compute Stakeholders' Score (StS) according to TEnSE approach from 1 (low importance) to 4 (high importance).

Domain (parameter)	Weights (w) for Stakeholders																							
	Technical expertise						Environmental expertise						Safety expertise						Economical expertise					
	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x
Technical (Thermal conductivity)	4	4	4	4	4	4	1	1	2	2	3	3	1	1	2	2	3	3	1	1	2	2	3	3
Environmental (GWP total [A1-A3])	1	1	2	2	3	3	4	4	4	4	4	4	2	3	1	3	1	2	2	3	1	3	1	2
Safety (social issues) (Reaction to fire)	2	3	1	3	1	2	2	3	1	3	1	2	4	4	4	4	4	4	3	2	3	1	2	1
Economic (Unit cost)	3	2	3	1	2	1	3	2	3	1	2	1	3	2	3	1	2	1	4	4	4	4	4	4
Total	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**

2.4. Climate and population 'what-if' scenarios

Although this can be a 'what-if' exercise, i.e., a hypothetical condition, climate projections and their impact on energy demand and population may help the policymakers to understand future country dynamics and to define proper mitigation and adaptation decision-making strategies. Both projections on energy and population can be considered valid if thermal properties of the existing building and demographic flows are assumed invariant over the whole projection period.

Heating and cooling degree-days (HDD/CDD) are weather-based technical indices designed to describe the need for the heating and cooling energy requirements of buildings. Here, HDD/CDD projections were extracted from the Copernicus Climate Data Store (CDS) taking into account two representative concentration pathways (RCP), namely RCP4.5 (i.e., moderate scenario corresponding to a radiative forcing at 4.5 W•m^{-2} with a temperature (T) increase of approximately 1.8–2.0 °C by 2100) and RCP8.5 (i.e., more extreme scenario corresponding to a radiative forcing at 8.5 W•m^{-2} with a T increase close to 4 °C by 2100) [39]. HDD and CDD data used in this study were the output of the Global Circulation Model (GCM) – IPSL-CM5A-LR – and the Regional Circulation Model (RCM) – WRF331F – in the framework of the EURO-CORDEX simulations [37], in two 30-years periods, i.e., near future (NF, 2021–2050) and far future (FF, 2071-2100). Both total annual HDD/CDD and annual daily average HDD/CDD projections were used to calculate future $ED_{heat/cool}$ and to show geographical areas most affected by future T increase at country level, respectively.

Finally, the estimation of the number of persons having their usual residence in the three countries in 2050 and 2100 was extracted from EUROSTAT to understand if climatological scenarios may exacerbate migration flows and depopulation/population of some EU regions, becoming responsible for the intensification of Energy Poverty and social disparities.

3. Results

3.1. Countries characterisation

Italy is characterised by the highest building stock density (45 km^{-2}), before and after the first national thermal regulation, together with the highest annual primary energy consumption (132.32 $Mt_{oil,eq}$ -Mt of oil equivalent-) and the highest total gross available energy (1.82•10^5 GWh) if compared with Norway (11 km^{-2}, 25.01 $Mt_{oil,eq}$ and 0.35•10^5 GWh) and Portugal (39 km^{-2}, 19.50 $Mt_{oil,eq}$ and 0.26•10^5 GWh). Both southern countries are called to elaborate strategies and implement solutions in a short time to be compliant with the EU Directive 2018/844 [1].

For the sake of completeness, values of the maximum thermal transmittance (U-value in W•m^{-2}•K^{-1}) of buildings suggested by the national decrees of each country on thermal regulations of building sector are provided in Table 3.

Both Italy and Norway have a diverse range of climate zones, as objectively classified by both Köppen-Geiger and ASHRAE. This can be attributed to the presence of a variety of landscapes across a broader latitude range compared to Portugal. Climate zones identified by national regulations reflect the variability issued by Köppen-Geiger and ASHRAE classification, except for Norway, where climate zones were discarded since 1980 to homogenise the legislation at national level. Italian climate zones according to Köppen-Geiger classification are mainly temperate (Csa, Csb, Cfa, Cfb), partially continental close to Alpine arch and in some Apennine sites (Dfb, Dfc) and arid in southern region (Bsk), and, finally, polar in the alpine region (ET). Specifically, Csa and Csb zones correspond mainly to ASHRAE 3A and classes C and D of the Italian D.M. 26 June 2021, whereas Cfa and Cfb to ASHRAE 4A and class D of the Italian D.M. 26 June 2021. Norwegian climate zones are mainly continental (Dfb and Dfc), moderately polar in the central

Table 3
Maximum thermal transmittance (U-value in W•m^{-2}•K^{-1}) recommended in the latest version of national regulations in Italy, Norway, and Portugal. For the sake of brevity, we report the definition of climate zones considering the heating degree-days (HDD) in Italy and Portugal. Italy: A (HDD ≤600 °C), B (601 °C ≤ HDD ≤900 °C), C (901 °C ≤ HDD ≤1400 °C), D (1401 °C ≤ HDD ≤2100 °C), E (2101 °C ≤ HDD ≤3000 °C), F (HDD ≥3001 °C). Portugal: I1 (HDD ≤1300 °C), I2 (1300 °C < HDD ≤1800 °C), I3 (HDD >1800 °C). Norway has a unique climate zone within the whole country.

ITALY	Ministerial Decree - D.M. 26 June 2021	NORWAY	Building code from 2015 (TEK 17):	PORTUGAL	Decree 101-D, 2020
	Maximum U-value		Maximum U-value requirements for heated buildings		Maximum U-values
CLIMATE ZONE	Vertical opaque structures subject to redevelopment	CLIMATE ZONE	External walls	CLIMATE ZONE	Vertical exterior elements
A	0.40	1	0.18	I1	0.50
B	0.40				
C	0.36			I2	0.40
D	0.32				
E	0.28			I3	0.40
F	0.26				
CLIMATE ZONE	Opaque horizontal or inclined roof structures subject to redevelopment	CLIMATE ZONE	External roofs	CLIMATE ZONE	Horizontal exterior elements
A	0.32	–	0.13	I1	0.40
B	0.32				
C	0.32			I2	0.40
D	0.26				
E	0.24			I3	0.30
F	0.22				
CLIMATE ZONE	Horizontal opaque floor structures subject to redevelopment	CLIMATE ZONE	Floors towards outdoor air and floors on the ground	CLIMATE ZONE	Horizontal interior elements
A	0.42	1	0.10	I1	0.40
B	0.42				
C	0.38			I2	0.40
D	0.32				
E	0.29			I3	0.30
F	0.28				

(ET) and poorly temperate in southern coasts (Cfb and Cfc). Portuguese climate zones are mainly temperate (Csa and Csb, mainly corresponding to ASHRAE 3A) and partially arid in southern region (Bsk). It is worth noticing that if compared with classes of the Portuguese regulation, class I1 corresponds mainly to Csa, class I2 to Csa and Csb and class I3 to Csb. Finally, Norway has the highest and the lowest value of heating degree-days (HDD = 5098.68 °C) and cooling degree-days (CDD = 0.11 °C), respectively, whereas Portugal has the highest value of CDD = 266.79 °C (Table 4).

Italy has a relatively high population density overall. However, it is worth noting that the northern regions of Italy tend to be more densely populated, as well as the coastal areas. As for Norway, while it is not densely populated as a whole, there are concentrated population centres primarily located in the southern regions, particularly in coastal areas. Cities such as Oslo (Cfb), Bergen (Cfb), and Stavanger (Cfb) are among these population centres. Portugal exhibits a significant asymmetry in terms of population distribution, with most of the population residing in specific regions. The northern coastal region, particularly the Porto district (Csb), along with the central region, specifically the Lisbon district (Csb) and southern Algarve region (Csa), have higher population concentrations.

When comparing social and economic factors, it is evident that Norwegians can take advantage from high GDP pro capita (68850 €), good equivalised disposable income (25.3) and a high energy productivity (12.775 € $kg_{o,eq}^{-1}$, in terms of economic output per unit of energy use). As a result, they can adequately heat their homes (with only 0.8 % of the population reporting unfavourable thermal conditions) and live in high-quality dwellings (with only 6.3 % of the population residing in homes with leaking roofs, damp walls/floors/foundations, or rotting window frames/floors), data according to EUROSTAT data in 2020.

3.2. Comparison of thermal insulation materials performance at single-oriented parameter

Looking at Fig. 1a, both organic (CF, EPS, PUR and XPS) and inorganic (MW) thermal insulation materials are employed by the three countries. Italy would favour organic materials (both plant and fossil fuel derived), Norway mainly organic fossil fuel derived (adding PF and PIR), finally, Portugal all of them. Italy and Norway have in common the use of WF, whereas Italy and Portugal have in common the use of ICB, due to the availability of cork (*Quercus suber* L., bark of the tree), that widely grow in both countries. The Portuguese *Montado* agro-forestry-pastoral system produces approximately half of the cork harvested annually worldwide, even though no incentives or support programs are available for the application of cork or insulation cork boards as a sustainable material. On the other hand, Italy has a similar agroforestry system, named *Meriagos*, and it is the fifth worldwide producer with around 3 % from cultivation areas in Sicily, Sardinia, and Tuscany. The PF choice by Norway could be due to their low thermal conductivity, that makes it possible to well perform once applied to roof and walls. In addition, PF is not hardly flammable performing better than other organic fossil fuel products and, like PUR, can be expanded as foam and hence easily applicable under-tile and for vertical surfaces and cavities. It is worth noticing that PIR, usually employed in Norway and Portugal, requires only half of the thickness of mineral-based insulation products (e.g., MW), which is especially relevant in countries with harsh winters (ET climate zone according to Köppen-Geiger classification) and, being usually cut into boards, can be used in insulated metal panels, wall cavities and as insulated plasterboards.

Looking at Fig. 1b, no specific attention is paid to the material microstructure, although it is worth mentioning that the exposure to MW fibres with a diameter of about 1 μm could be dangerous as, if handled without (or with inappropriate) individual protection, may be inhaled, potentially damaging the respiratory system or eyes, and skin [40].

Fig. 2 shows the heating energy demand (ED_{heat}) for heating after the implementation of thermal insulation materials to external walls with an initial U_{value} of 2.5 W•m^{-2} K^{-1} (built before 1945) and 1.6 W•m^{-2} K^{-1} (built in the period 1970–1989) in Italy, Norway, and Portugal. All thermal insulation materials applied with a thickness of 100 mm allow to meet the requirement of both Italian (Ministerial Decree - D.M. 26 June 2021, specifically for climate zones A, B and C with HDD

Table 4

Brief report on parameters in the framework of TEnSE macro-area available for Italy, Norway and Portugal in 2020. Köppen-Geiger classification: BSk (Cold semi-arid climate), Cfa (Humid subtropical climate), Cfb (Temperate oceanic climate or subtropical highland climate), Csa (Hot-summer Mediterranean climate), Csb (Warm-summer Mediterranean climate), Dfb (Warm-summer humid continental climate), Dfc (Subarctic climate), ET (Tundra climate). ASHRAE classification: 2A (hot humid), 2B (hot dry), 3A (warm humid), 3B (warm dry), 3C (warm marine), 4A (mixed humid), 4C (mixed marine), 5A (cool humid), 5C (cool marine), 6A (cold humid), 7 (very cold), 8 (subarctic).

Domain	Parameters	Unit	Italy	Norway	Portugal
Technical	Area	km^2	302 073	385 207	92 226
	Building stock density	km^{-2}	45	11	39
	Residential building stock density	km^{-2}	40	4	38
	First thermal regulation	year	1967	1928[a]	1990
	Building stock density before thermal regulation	km^{-2}	26	8	23
	Primary energy consumption	$Mt_{oil,eq}$	132.32	25.01	19.50
	Total gross available energy	GWh	$1.82\bullet10^5$	$0.35\bullet10^5$	$0.26\bullet10^5$
Environmental	Climate zone by national regulations (based on HDD)	–	A, B, C, D, E, F	I, II, III, IV[b]	I1, I2, I3 (winter) V1, V2, V3 (summer)
	Climate zone (Köppen-Geiger [27])	–	BSk, Csa, Csb, Cfa, Cfb, Dfb, ET	Cfb, Cfc, Dfb, Dfc, ET	BSk, Csa, Csb
	Climate zone (ASHRAE [26])	–	2B, 3A, 3B, 4A, 4C, 5C, 6A, 7, 8	5A, 5C, 6A, 7, 8	2A, 3A, 3B, 3C, 4C, 5C
	Cooling degree days (CDD)	°C	241.55	0.11	266.79
	Heating degree days (HDD)	°C	1750.40	5098.68	1007.58
Social/Safety	Number of persons having their usual residence in a country	–	59 641 488	5 367 580	10 295 909
	Average number of persons per household	–	2.3	2.1	2.5
	Population unable to keep home adequately warm by poverty status	%	8.3	0.8	17.5
	Population living in a dwelling with a leaking roof, damp walls, floors or foundation or rot in window frames of floor by poverty status	%	19.6	6.3	25.2

Table 4 (*continued*)

Domain	Parameters	Unit	Italy	Norway	Portugal
Economic	Gini coefficient of equivalised disposable income (–)	–	32.5	25.3	31.2
	Real GDP pro capita	€	24 910	68 850	18 060
	Energy productivity	€ $kg_{o,eq}^{-1}$	10.278	12.775	7.973
	Price of the natural gas	€ kWh^{-1}	0.057	0.1322	0.0561
	Price of electricity	€ kWh^{-1}	0.1331	0.0927	0.1138

Data from EUROSTAT 2020 (last update 24/03/2023).

[a] Note that for Norway the first thermal regulation is from 1928, but statistics provide the building stock from 1997, which is the year of the Norwegian Building Code "Technical Regulations under the Norwegian Planning and Building Act (PBA)", which have been performance-based since 1997.

[b] before 1980, then no climate zone.

<1400 °C) and Portuguese (Decree 101-D, 2020, for all climate zones) national decrees, whose suggest $U_{value,max} = 0.40$ W•m^{-2} K^{-1}. In this case, $ED_{heat} < 20$ kWh•m^{-2}•year^{-1} when applied to building before 1945 (with an energy saving of 89–97 kWh •m^{-2}•year^{-1} in Italy and 51-55 kWh•m^{-2}•year^{-1} in Portugal) and $ED_{heat} < 15$ kWh•m^{-2}•year^{-1} when applied to building between 1970 and 1989 (with an energy saving of 7–15 kWh•m^{-2}•year^{-1} in Italy and 30-34 kWh m^{-2}•year^{-1} in Portugal). The choice of Norway towards PUR makes it possible to well perform accordingly to the TEK 17 ($U_{value,max} < 0.18$ W•m^{-2} K^{-1}) with $ED_{heat} < 25$ kWh•m^{-2}•year^{-1} (allowing to save 259-283 kWh•m^{-2}•year^{-1} for building before 1945 and 153-174 kWh•m^{-2}•year^{-1} for building built in 1970-89); whereas the choice of Italy towards organic fossil fuel derived materials, WF and CF makes it possible to well perform climate zones with HDD ≥1401 °C ($U_{value,max} <$ 0.32 W•m^{-2} K^{-1} for vertical opaque structures) with $ED_{heat} < 15$ kWh•m^{-2}•year^{-1} (allowing to save 259-283 kWh•m^{-2}•year^{-1} and 153-174 kWh•m^{-2}•year^{-1}, respectively). It is worth noticing that, in cold climates, thermal insulation materials could be installed with a thickness up to 300 mm [34], if possible.

In Italy and Portugal, the implementation of such thermal insulating solutions would require a maximum heating energy cost (EC_{heat}) less than 1.00 €•m^{-2}•year^{-1}, whereas in Norway $EC_{heat} < 8$ €•m^{-2}•year^{-1} for building before 1945 and $EC_{heat} < 7$ €•m^{-2}•year^{-1} for building between 1970 and 1989.

The cooling energy demand (ED_{cool}) after the application of thermal insulation materials is close to zero in Norway (due to the very low CDD ~ 0.11 °C) with an energy saving up to 44 kWh•m^{-2}•year^{-1} and <2.5 kWh m^{-2} year^{-1} in Italy and Portugal with $EC_{cool} < 0.15$ €•m^{-2}•year^{-1}.

Fig. 3 shows the distribution of thermal insulation products considering only parameters related to TEnS domains (economic macro-area is excluded) as, based on EPDs European documents, they do not vary at country level. The selection of thermal insulation products by country might not be driven by a specific parameter, except for PF and PIR that, commonly used in Norway, are characterised by a low thermal conductivity ($\lambda < 0.025$ W m^{-1} K^{-1}) and a good reaction to fire (C-s2, d0 and B-S2, d0, respectively). Both features would allow meeting wooden Norwegian vernacular architecture requirements of high thermal resistance (even with low thickness) and high safety against fire. Specifically, the total GWP during the manufacturing process (modules A1-A3) does not largely vary between inorganic mineral derived and organic fossil fuel derived products that can emit up to 21.96 $kgCO_{2,eq}$•m^{-2}.

A significant total GWP reduction occurs with organic plant products ranging between −612.00 $kgCO_{2,eq}$•m^{-2} of ICB and −9.33 $kgCO_{2,eq}$•m^{-2} of CF. Although CF is often made by hammer milling waste newspaper, the relatively higher GWP with respect to WF (−47.62

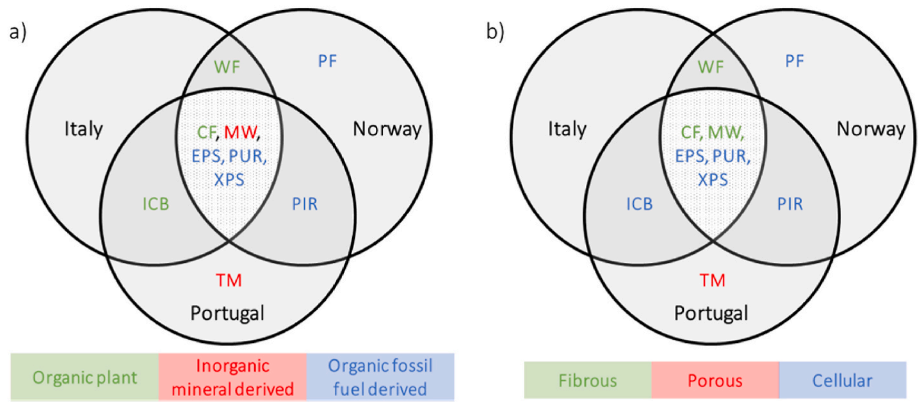

Fig. 1. Venn diagram of the most used thermal insulation materials divided by (a) type (green: organic plant, red: inorganic mineral derived, and blue: organic fossil fuel derived) and (b) fibrous (green), porous (red), cellular (blue) structure in three European countries: Italy, Norway, and Portugal. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

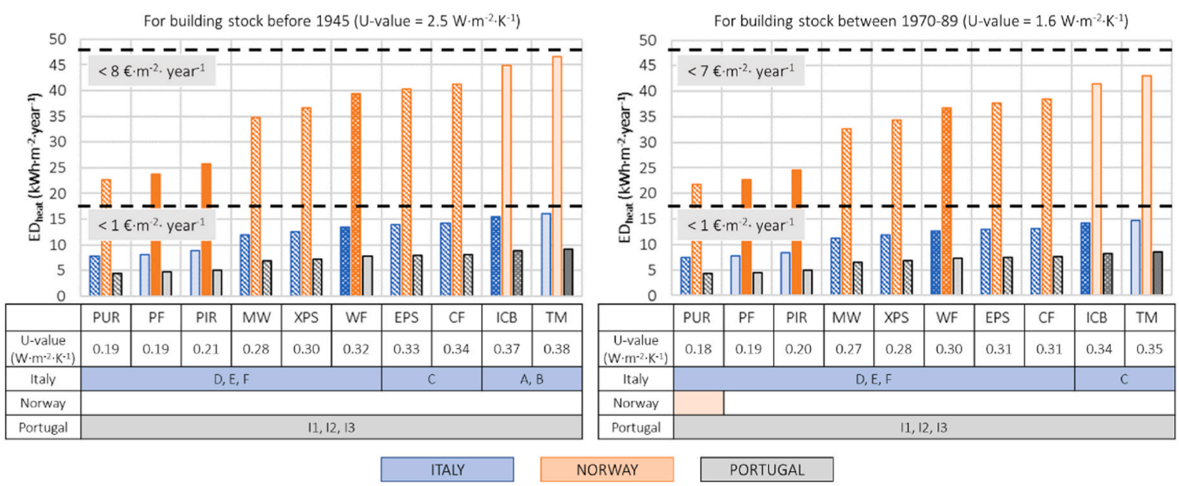

Fig. 2. Energy demand for heating when a 100 mm thickness of each thermal insulation material is applied to external walls in Italy, Norway, and Portugal [34]: a) initial U-value of 2.5 W•m^{-2} K^{-1} corresponding to the highest U-value for buildings before 1945 [35]; b) initial U-value of 1.6 W•m^{-2} K^{-1} corresponding to the highest U-value for buildings between 1970 and 1989 [35].

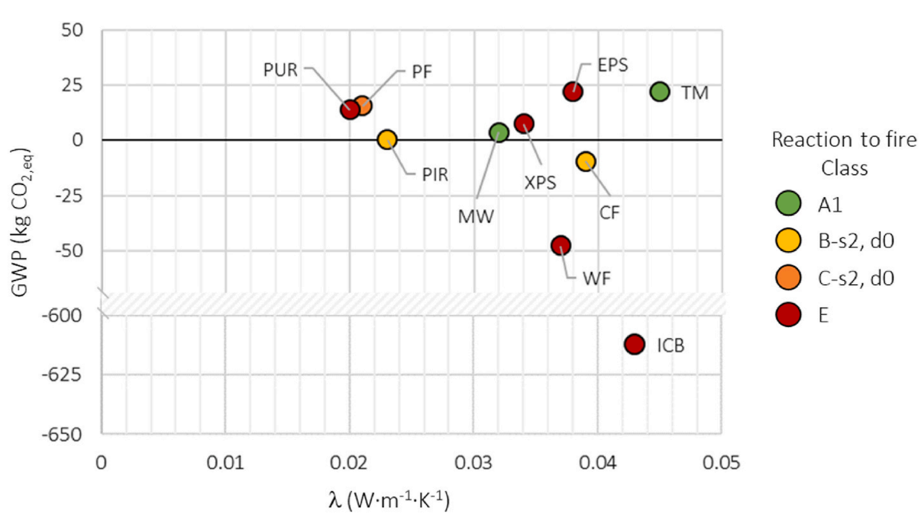

Fig. 3. Total Global Warming Potential (GWP) versus thermal conductivity (λ), dots are coloured based on the reaction to fire class.

$kgCO_{2,eq}$•m^{-2}) can be mainly due to chemical treatments (e.g., boric acid for retarding the spread of fire). We can conclude that it is fundamental the balance between different criteria to help in the decision of a thermal insulation material.

As the global market is moderately competitive due to many suppliers in the building insulation market, prices do not significantly differ, especially in the case of organic fossil fuel derived in each country (Fig. 4). Most thermal insulation products have a unit cost less than 10.00 €•m^{-2} (green cells). The Italian price list applies the lowest unit cost to WF (range between 3.46 and 31.22 €•m^{-2}) followed by CF, XPS and PUR, while the highest unit cost (minimum unit cost of 15.00 €•m^{-2}) to ICB and TM (thickness >0.01 m). The Norwegian market applies the lowest unit cost to WF (unit cost comparable with Italian market), MW, TM and EPS (price comparable with Portuguese market) and the highest unit cost to ICB, PIR and PUR. The low unit cost of WF in Italian and Norwegian markets might be due to the availability of the raw material and its large implementation in northern Italy and Norway vernacular architecture, typically characterised by wooden building stocks. The high unit cost of ICB in Norway is mainly due to import expenses. The Portuguese market applies the lowest prices to EPS, PUR and XPS, while the highest to CF and TM.

3.3. Stakeholders-oriented selection towards thermal insulation materials

The selection of thermal insulation materials by the three countries is analysed according to attitudes/concerns of several stakeholders not specifically identified (Fig. 5). The purpose is to recognise which TEnSE parameters might influence the stakeholders' choice. Fig. 5 provides the average values calculated from the six permutations per each TEnSE domain. No thermal insulation material reaches the minimum and maximum StS with the parameters selected within TEnSE, but it ranges between 2 and 7 meaning that products' performance varies in a narrow interval.

In Italy, the lowest average StS is associated with EPS (StS = 2) and XPS (StS = 3) mainly due to their higher unit cost with respect to other products, their flammability and the high GWP in manufacturing process (21.96 and 7.56 $kgCO_{2eq}$). StS of other products never exceeds 6. PIR and PUR could be preferred in terms of technical perspectives by professionals due to their low λ (<0.025 W•m^{-1} K^{-1}) together with a good reaction to fire (PIR) and a low unit cost (PUR). However, PUR is more commonly used in the three countries than PIR, likely due to its lower unit cost.

CF and MW could be chosen due to safety concerns by professionals because of their good reaction to fire (B-S2, d0 and A1 classes, respectively) and comparable unit cost. ICB would be selected for its low environmental impact in the manufacturing process together with its relatively low unit cost. WF, TM and PF have a similar average StS (∼4) and would be chosen for their good performance related to unit cost, low reaction to fire and low λ, respectively. However, even a good StS, PF and PIR would be excluded from the most used thermal insulation materials by Italian stakeholders due to their unit cost, whereas TM for its low λ and high GWP.

In Norway, the lowest average StS is associated with ICB that would be excluded by all stakeholders due to its low performance in TSE parameters - making it unsuitable for its implementation in harsh cold climate and in wooden building structures. WF, EPS, PUR and XPS would be selected due to their competitive unit cost, revealing the high importance of economic perspective. Even though CF and PF are listed among the most common thermal insulation materials, StS was not calculated due to missing unit cost. However, TEnS parameters would suggest that they would be chosen due to their good reaction to fire (B-S2, d0 and C-S2, d0 classes, respectively) and very low λ of PF (λ = 0.021 W•m^{-1} K^{-1}, making it suitable for its implementation according to TEK 17 where U-value$_{max}$ = 0.18 W•m^{-2} K^{-1}). The highest StS is associated with MW and PIR due to the high reaction to fire and the low λ, respectively, becoming the first choices among Norwegian stakeholders oriented to safety and technical issues.

In Portugal, the TEnSE approach would suggest that PIR is chosen due to the high performance of all parameters (especially unit cost), meeting the requirements of most stakeholders. On the contrary, all stakeholders would exclude the use of TM for the tested criteria. However, this solution is listed among the most commonly implemented thermal insulation materials due to its geometrical and material compatibility with existing buildings that have architectural restraints and adhere to vernacular styles, focusing the importance of constructive details (application concerns) when selecting thermal insulation materials.

WF would be also excluded due to its relatively high cost with respect to the Portuguese market of other products and, to some extent, its high reaction to fire (E class). CF, ICB, PUR and XPS have a similar average StS ranging between 3.8 and 4.3, suggesting that their use is not driven by a specific stakeholder perspective, but rather by market conditions.

4. Discussion

4.1. TEnSE versus MCDM methods

The TEnSE is an inverse decision-making approach that was here developed to understand the rationale behind the choice of specific thermal insulation materials in three EEA countries, differing for Energy Poverty as well as for environmental conditions and legislative contexts. The TEnSE includes quantitative parameters that can be directly extracted from Environmental Product Declarations and approved national price lists. The rationale behind TEnSE lays its foundation on the most common used multi-criteria decision-making (MCDM) methods – VIKOR and TOPSIS [12] – that aim at identifying alternative the closest to the ideal solution based on an ensemble of criteria and weights derived by a balance between total and individual satisfaction [41]. However, the TEnSE does not pursue the aim to identify the best overall solutions, neither provide a ranking index with respect to the ideal alternative. Finally, the TEnSE considers an ensemble of criteria commonly implemented in other MCDM methods but with a set of weights permutations that does not exclude *a-priori* the perspectives of several experts' or nudgers within the same domain, as it could happen through the use of interviews/questionnaires to specific experts.

4.2. From TEnSE score to the application of thermal insulation materials

The TEnSE approach allowed to pinpoint an empirical rule in the choice of thermal insulation materials in the case of Norway, where the choice of PIR could be due to the low λ (being suitable to reach thermal transmittance suggested by TEK 17) and reaction to fire (minimising the

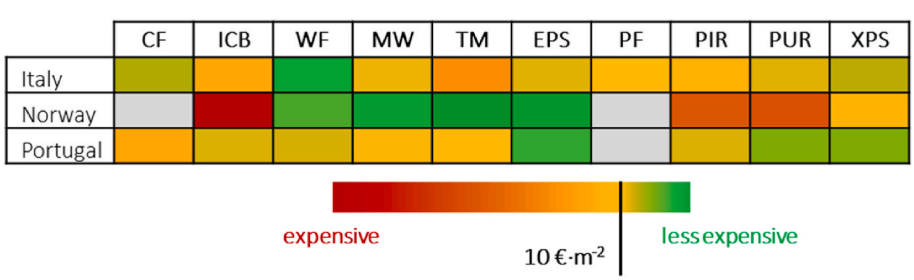

Fig. 4. Heat map of normalised unit cost in Italy, Norway, and Portugal. Data in grey boxes were not representative and were not available.

	Italy				Norway				Portugal			
	T	En	S	E	T	En	S	E	T	En	S	E
CF	4	4	5	6	--	--	--	--	4	4	5	5
ICB	4	6	4	5	3	5	3	3	3	5	4	4
WF	4	3	3	5	4	3	3	5	3	3	3	4
MW	5	4	6	5	6	5	7	7	5	4	6	5
TM	3	3	5	5	4	4	6	6	2	2	4	2
EPS	2	2	2	3	3	3	3	5	4	3	3	5
PF	5	3	4	3	--	--	--	--	--	--	--	--
PIR	6	4	6	4	7	5	7	7	7	5	7	7
PUR	6	4	5	6	6	4	4	5	5	3	3	4
XPS	3	2	3	3	4	3	4	5	4	3	3	5

Fig. 5. Stoplight charts of Stakeholders' Score (StS) where each thermal insulation material is rated as poor (red), good (white) or excellent (green) according to the performance with respect to the TEnSE approach. The last column provides module C3 of LCA according to EPD. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

fire risk in wooden structures) and the relatively low unit cost with respect to other products such as MW. In the case of Italy and Portugal, the selection of λ, GWP, reaction to fire and unit cost as representative parameters of the TEnSE would be not exhaustive to identify the reason behind the selection of some thermal insulation materials, suggesting that other parameters should be considered in relation to the specific features in each country. Although it can be assumed that stakeholders in areas characterised by a high building stock density prior of the implementation of national thermal regulations (>35 buildings per km^2) - corresponding to a high number of inefficient buildings, along with a low GDP pro capita - could favour the choice of products with low unit cost, notwithstanding this preference does not stand out due to the low market competitiveness.

In addition, stakeholders in regions characterised by prevalently humid climate could favour the choice of products based on their moisture performance (e.g., resistance to water vapour permeability), but such information are often missing in technical data sheet, making difficult the comparison among several products.

Here, we provide useful information on the implementation of these products that could open interesting discussion in the light of Figs. 1 and 5.

Although CF has a lower score than ICB and WF in terms of GWP, it has the main advantage to be implemented in vertical or horizontal applications through dry laying without requiring to be mixed with water or to be wet (application/constructive concerns). The common implementation of ICB in Italy and Portugal – besides the high raw materials availability that cut costs in opposite to Norway (Section 3.3) – would be also due to the applicability through boards that are easily and directly handled and cut on site. In addition, a previous study conducted at the Instituto Superior Técnico (IST) of Lisbon University, has verified that ETICS with ICB boards are environmentally advantageous in terms of carbon emission and consumption of non-renewable primary energy being less polluting than ETICS with EPS boards [42]. The use of WF may be mainly due to the compatibility with vernacular architecture in northern Italy and Norway.

Although TM has lower thermal performance in Italy and Portugal compared to other thermal insulation board materials (EPS, XPS, MW, ICB), its main use lies in its possibility to level uneven surfaces manually and be applied on ancient walls because has a higher drying capacity, being more porous material. This characteristic allows for negligible on-site energy consumption, Additionally, TM can be directly applied over the substrate by adding water to the dry mix making it suitable for retrofitting external walls of historic buildings and vernacular architecture with porous substrates [43].

The common use of organic fossil fuel-derived products is mainly due to their availability in both rigid boards and spray foam, making versatile their applicability.

4.3. *Climate 'what-if' scenarios towards the future selection of thermal insulation materials*

Table 5 reports HDD/CDD projections under the intermediate RCP4.5 and worst-case RCP8.5 scenarios in two 30-years periods – near future (NF, 2021–2050) and far future (FF, 2071-2100) – together with the estimation of the number of persons having their usual residence in the three countries in 2050 and 2100.

In all projections, the temperature increase will be likely responsible for a decrease in HDD and an increase of CDD with a different extent in the three countries (Table 5), causing a shift of climate zones [44], affecting migration flows and heating/cooling energy demands [37]. Accounting for ED_{heat} and ED_{cool}, it should be expected that there would be a decrease in heating demand together with an increase in cooling demand. It is possible to provide the following information keeping invariant the thermal transmittance of current existing buildings:

- Italy: ED_{heat} will tend to decrease from 2 % (RCP4.5 in NF) to 35 % (RCP8.5 in FF), especially in the Alpine and Apennine regions where the annual daily HDD will be up to −2 °C per day (Fig. 6); whereas ED_{cool} will tend to slightly increase in NF in both RCPs and will be much higher in FF up to +57 %, especially along coastlines, major islands and Po Valley (Fig. 6).
- Norway: ED_{heat} will tend to homogeneously decrease from 10 % (RCP4.5 in NF) to 20 % (RCP8.5 in FF), with an annual daily HDD of −2 °C per day over the country except for the southern coastline (Fig. 6); whereas ED_{cool} will tend to more than double in all circumstances ($ED_{cool} = 1$ kWh•m^{-2}•$year^{-1}$), although CDD seem to be unaffected with respect to the current conditions.
- Portugal: ED_{heat} will tend to decrease from 8 % (RCP4.5 in NF) to 43 % (RCP8.5 in FF), especially in the northern regions where the annual daily HDD will be up to −1 °C per day (Fig. 6); whereas ED_{cool} will tend to increase from 18 % (RCP4.5 in NF) to 61 % (RCP8.5 in

Table 5
Brief report on parameters in the framework of EnS domains for Italy, Norway, and Portugal. NF = near future (2021–2050), FF = far future (2071-2100).

Domain	Parameters [unit]	Projection	Italy		Norway		Portugal	
Environmental	Heating degree days (HDD) [°C]		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
		NF	1713	1680	4574	4528	929	925
		FF	1475	1143	4072	3510	778	577
	Cooling degree days (CDD) [°C]		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
		NF	245	253	5	5	324	347
		FF	340	558	11	24	442	693
Social	Number of persons having their usual residence in a country [−]	2050	53 332 659		6 215 295		9 650 059	
		2100	50 194 524		6 731 629		8 981 056	

Data from EUROSTAT (last update 24/03/2023).

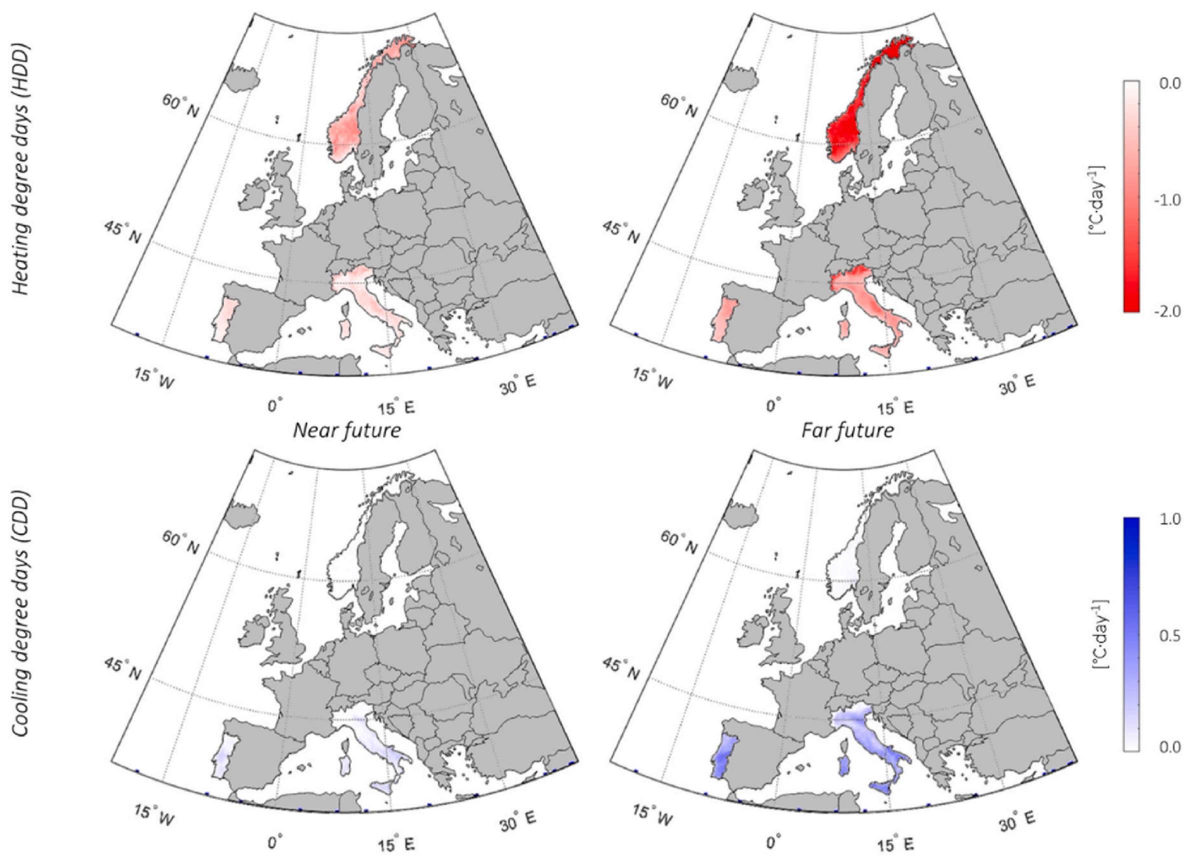

Fig. 6. Difference in annual daily average heating degree days (HDD, top panels) and cooling degree days (CDD, bottom panels) under RCP4.5 between 2020 and the climatological scenarios in near future (NF, 2021–2050), and far future (FF, 2071-2100) in Italy, Norway, and Portugal. Grey areas are not subject of this article.

FF), especially in the inner southern area close to the broader with Spain (Fig. 6).

Starting from these 'what-if' scenarios, the decrease in ED_{heat} might be not sufficient to balance the increase of ED_{cool}, especially considering the unpredictable evolution of electricity costs, that remain more expensive in the Mediterranean countries as more affected by the global warming (i.e., Italy and Portugal). Therefore, the increase of ED_{cool} might contribute to the increase of Energy Poverty risk in countries with a low GDP and the risk of social disparities [45]. It is worth noticing that, in Norway, the milder climate due to global warming and the increased domestic investment in energy efficiency have masked the increased electricity consumption and cost [46].

Here, we provide the consequences of such scenarios on population flows likely due to the increase of indoor thermal discomfort and the lack of implementation of long-term measures to struggle energy poverty. Indeed, this aspect is crucial to understand future social dynamics related to energy issues and thermal comfort. First, migration flows might intensify the estimation provided by EUROSTAT, leading to the depopulation of southern countries (e.g., Italy and Portugal) and a higher demography increase in northern countries (e.g., Norway, where in the period 1990–2015 a significant increase of population was already observed), thus opening new social challenges. Thus, local governments of depopulated areas shall further face the issue of neglected/abandoned buildings and the potential environmental impact of their demolition together with the impact of the spontaneous degradation of materials on landscape. In addition, people living in buildings with low thermal efficiency and in Energy Poverty might be exposed in summertime to prolonged thermal stresses due to CDD increase. Unfortunately, building thermal insulation might not be sufficient to improve indoor thermal comfort in summer, rather it might be responsible of indoor overheating if applied with high thickness. That can become an issue for Nordic countries, as the building stock is not prepared to withstand increasing heat waves, such as the one experienced in June 2020 [47]. Thus, people more susceptible to the adverse effects of extreme weather conditions (about 22–24 % of the total population in

Italy and Portugal) could exacerbate pathologies leading to an increase in the number of hospital admissions and fatalities, especially among elderly individuals [48]. As a matter of fact, during the 2003 European heatwave, there were an estimated 2,399 excess deaths in continental Portugal, with a particularly higher impact observed in the inner districts (Csa regions) [49]. In Italy, there were 3,134 excess deaths with a particularly higher impact observed in the north-western cities and in two southern cities at 700 and 800 m above mean sea level (Cfb and Csb regions) with the highest occurrence among people aged 75 years and elder [50]. The European Environment Agency (https://www.eea.europa.eu/data-and-maps/figures/number-of-fatalities-due-to) has reported that in the period 1990–2016 heatwaves caused between 1000 and 5000 fatalities in Portugal and more than 10000 fatalities in Italy (Norway data were not available). At the opposite, fatalities due to cold spells were not recorded in Portugal, were between 50 and 100 in Italy, and were not available in Norway. Nevertheless, nowadays, the economically disadvantaged districts in Oslo, which often have a higher concentration of immigrant populations, are grappling with social inequalities [51].

To sum up, the energy efficiency of existing buildings through thermal insulation materials opens to outbreaking challenges and opportunities in this period of changing climate. Although most organic fossil fuels-derived materials are being replaced by organic plant or mineral-based ones, some considerations should be outlined to understand if their implementation could be potentially beneficial or disadvantageous in mitigating and adapting to climate change scenarios. Organic plant materials (CF, ICB and WF) are characterised by a negative GWP at manufacturing process, contributing at the reduction of greenhouse gas emissions (GHGs), although the waste process can be responsible for up to 64 $kg_{CO2,eq}$ (WF according to EPD). On opposite, inorganic-based materials (MW and TM) are characterised by a null GWP in the waste process and high reaction to fire (like CF, but the manufacturing process might increase GWP for the use of fire-retardant additives), contributing to limiting the risks connected to the impact of wildfire on dwellings close to wide green area. Indeed, risks of wildfire, especially at low latitudes (e.g., Italy and Portugal), are boosting due to an increased drought and the prolongation of fire season from the mid spring to the end of summer [52,53]. The long-lasting use of organic fossil fuel-derived products could diminish the impact of water infiltration and percolation thanks to their capability of repelling water and acting as a moisture barrier. Indeed, heavy rainfall might intensify such risk due to a higher occurrence of events, especially in sites locate in northern and eastern Eurasia [54] (e.g., Norway), and might largely contribute to cities flooding, if the water cannot drain quickly into the ground and the drainage system cannot cope with the peak flow.

For a deep understanding of the relationship between the material choice and sustainable building design in future scenarios, it will be necessary to include other building life cycles phases [55] in the TEnSE, such as bio-susceptibility, buildability, maintainability, and other constructive details. However, such parameters are hardly provided in Environmental Product Declarations (EPD) or equivalent documentation as they are hardly quantifiable. Bio-susceptibility would allow to investigate whether the thermal insulation material can be predisposed to, or sensitive to, developing biodeteriogens, i.e., fostering microbial growth [56], and hence sick building syndrome (SBS) due to the capability of holding vapour and/or liquid water by percolation, infiltration, or capillary rise, specifically in regions possibly suffering from intense precipitation. Buildability would allow to consider all the aspects related to health/safety of workers and material handling, but they can widely vary from case to case [57]. In this way, the choice of the material might be driven by the exposure of workers to uncomfortable temperatures, both indoor and outdoor. Finally, maintainability would allow to explore the ability of the thermal insulation material to be retained in or restored to a state in which it can perform its required functions [58], providing useful information on the environmental impact and service life costs.

5. Conclusions

This research proposes a new inverse decision-making approach, called TEnSE, that allows to compare the properties of thermal insulation materials based on four domains (technical, environmental, safety and economic). Cellulose fibres, wool minerals and organic fossil fuel-derived products are the most used materials for building thermal insulation due to their low unit cost and easy applicability (both as board and foam or blankets) and workability (as foam). They are widely applied in Italy, Norway, and Portugal, although with differences in terms of climate zones and welfare of people. Other products, such as expanded cork agglomerate (Italy and Portugal) and wooden fibres (Italy and Norway), are chosen and applied as the raw materials are widely available in the related countries and the production stage requires a low environmental impact, keeping a good thermal insulation performance in accordance with the national decrees on thermal regulations. However, the research put in evidence that the economic domain has the greatest importance in all countries although the relatively low market competitiveness. In addition, constructive restraints can also be important, since some products can be applied only in boards.

Thermal insulation materials could highly impact the overall energy efficiency and sustainability of buildings as they contribute to improve the thermal performance of the building envelope, appliances, or other equipment. However, there is no one material (or technology) that can solve alone the energy issue in new buildings (near-zero-energy buildings) as well as in retrofitting/refurbishment (renovation) projects of existing buildings. Indeed, the improvement in energy efficiency through passive thermal insulations may contribute to reducing both energy bills (hence, Energy Poverty) and the greenhouse gases emissions from fuel combustion. The differences among Italian, Norwegian, and Portuguese approach to thermal insulation of external walls show the complexity of the future problems associated with preparing uniform European thermal legislation. A new procedure should be proposed for comparing the thermal performance differences between diverse types of wall systems built in different EU countries and in the standardisation of the procedures. Nowadays, it is important to understand the properties of materials for each specific application, prioritising the use of Eco materials (low environmental impact), giving attention to technical problems related to high thickness (overheating in summertime) and hygrothermal pathology due to low water vapour permeability or high moisture content that might favour biological proliferation. At last, workers might play a key role in having contributed and contributing to the choice and use of thermal insulation materials, as they usually follow the design provided in technical data sheet.

Further research will be the implementation of the TEnSE approach including other parameters, such as durability, bio-susceptibility, maintainability, buildability, and other constructive details. Such parameters are hardly provided in EPD or equivalent documentation. The aim is to consider the perspectives from a wider range of stakeholders (e.g., workers) to effectively understand the sensitivity towards future climate projections and the Energy Poverty risk.

CRediT authorship contribution statement

F. Frasca: Writing – original draft, Formal analysis, Data curation, Conceptualization. **B. Bartolucci:** Data curation. **J.L. Parracha:** Data curation. **O. Ogut:** Data curation. **M.P. Mendes:** Writing – review & editing. **A.M. Siani:** Writing – review & editing, Formal analysis. **J.N. Tzortzi:** Writing – review & editing. **C. Bertolin:** Writing – review & editing, Supervision, Funding acquisition. **I. Flores-Colen:** Writing – review & editing, Supervision, Funding acquisition, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal

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Data availability

Data will be made available on request.

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