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Environmental impacts of waterproof membranes with respect to their radon resistance

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ABSTRACT

Gas radon is the main source of ionising radiation for humans and the second most common cause of lung cancer after tobacco smoke. Radon is present in the ground, and its concentration differs between different soils according to parameters such as permeability and mineral composition. As radon mainly penetrates buildings through cracks and fractures at the foundation level, this area requires research focus. This study aims to assess the contribution of environmental embodied impacts of ten macro-categories of membranes that are installed to protect buildings against radon. This study aims to evaluate membranes because they are one of the cheapest and easiest radon level-reducing solutions for both new and existing buildings. The data used in the comparison were obtained from environmental product declarations (EPDs) downloaded from open-access databases. The environmental embodied impacts were calculated for the A1–A3 Life Cycle Assessment (LCA) stages and compared with each other in relation to one square meter and radon resistance, which are the parameters that highlight the performance of a membrane in terms of effectiveness for protection against radon. Finally, a comparison of the performance of the radon-proofing solutions with their environmental embodied impacts was conducted using the CML2001 methodology. The results of this investigation enable, for the first time, the selection of the most efficient and environmentally friendly radon-proof membrane at the design stage. Through this analysis (combining performance and environmental impacts), we found that polymeric membranes, such as HDPE and LDPE membranes, were the best options for achieving radon resistance in the range of 100–150 Ms/m in terms of environmental impacts, whereas the PVC membrane displayed the highest values of embodied impacts.

1. Introduction

Radon in buildings is considered to be the most common indoor air pollutant leading to harmful effects on the health of the general population, and it has been recognised as the second most frequent cause of lung cancer after smoking [1,2], with a vulnerability that accounts for 10–15% [2,3]. Moreover, it is the primary source of exposure to ionising radiations [4,5]. The danger to radon lies in the fact that it cannot be perceived by the human senses because it is invisible, tasteless, and odourless [6,7]. This radioactive noble gas in the soil (and in construction materials and water in a lower percentage [8]) can easily enter buildings through cracks, pipes, and fractures at the foundation level [9]. The radon supply rate from the soil to the indoor environment is proportional to the soil permeability [10]. Once the radon is inside the building, it accumulates in spaces directly in contact with the ground (ground floors, underground floors, and cellars) [11,12]. Thus, as it tends to enter from the soil, it is advisable to place radon-level-reducing components at the foundation level.

The European Union's Directive 2013/59/Euratom [13] recommends that if the average radon concentration in a dwelling exceeds 300 Bq/m^3 (the action level), measures should be taken to decrease this amount, indifferently for new and existing buildings or residential areas and workplaces.

Another challenge for the European Union is to address the drastic decrease in the demand for energy in the building sector, which now amounts to 40% of the total European consumption, associated with 36% of CO_2 emissions [14]. The EU/2010/31 directive [15] indicates that the minimum requirements for service and technical solutions should be accomplished through an optimised balance between investments and energy savings obtained during the building's life cycle. However, the energy spent and greenhouse gases emitted during the material production stages (e.g. material extraction and manufacturing)

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cannot be omitted.

Currently, the literature does not include studies on the environmental impacts derived from the production of materials used to design radon control technologies. A literature review was conducted using research engines and databases (specifically, Web of Science, Scopus, and Google Scholar) to identify studies on countermeasures for radon in buildings and their impacts on the environment. The keywords 'radon in buildings', 'radon and environmental impacts', 'radon protection and sustainability', and 'radon measures embodied impacts' were used for this review. The results highlight a gap in the literature on this topic; thus, this paper focuses on the above knowledge gap to narrow it down.

However, studying different measures from the perspective of sustainability is not new [16,17]; measures against radon use certain components, such as waterproofing materials, that are already used in roofs. Thus, to some extent, the effects of such roof materials on the environment have been studied with slightly different intentions [18].

Still, the originality of this work is that the embodied impacts are presented for different types of waterproof membranes with respect to their radon resistance (R_{Rn}, Ms/m), which expresses the ability of a waterproofing product to form a barrier against radon penetration [19]. R_{Rn} depends on the product thickness and the radon diffusion coefficient (D, m^2/s) of the product. Materials with higher R_{Rn} form a better barrier against radon penetration – more details are available in Section 2.2. Waterproof membranes were chosen because they are one of the easiest to install and are the cheapest solutions for reducing radon risk [5,20]. This work aims to highlight the embodied impacts of renewable and non-renewable primary energy (MJ), freshwater consumption (m^3), acidification potential (AP; kg - SO_2 eq.), ozone depletion potential (ODP; kg CFC-11 eq.), global warming potential (GWP; kg - CO_2 eq.), eutrophication potential (kg - $PO4^{3-}$ eq.), photochemical ozone creation potential (kg - C_2H_4 eq.), abiotic depletion potential elements (kg - Sb eq.), and abiotic fossil fuel depletion (MJ) for ten macro-categories of waterproof membranes and compare them in terms of one square meter and R_{Rn}. The manuscript aims to identify the most environmentally friendly type of membrane in terms of its ability to provide sufficient protection against radon by its thickness and R_{Rn}. Moreover, CML2001 [21,22], a characterisation method often used for environmental assessment in the building industry, is used to normalise and weigh the environmental parameters through a single-score indicator that highlights a membrane's environmental friendliness. Nevertheless, this assessment does not cover all environmental impacts of radon-proof membranes throughout the life cycle of the entire building. However, it investigates the 'cradle-to-gate' boundary, which is strictly connected to the material production stream (from the supply of raw material to the delivery to the gate).

1.1. Motivations and objectives

A key priority of Directive 2013/59/Euratom [13] is to reduce exposure to radon in buildings. Moreover, this directive has increased the awareness of radon risk indoors by implementing rules in every European country since 2018, with consequent monitoring and risk-mitigating actions [4].

New buildings should be designed and built using preventive measures to ensure that radon concentrations are as low as possible [23]. Many European countries have undertaken resource development programs to achieve such aims [24]. The problem of high indoor radon concentrations is present in Europe and other countries (e.g. Canada [7] and the United States [25]), where indoor heating is important because of a high-temperature difference between outdoor and indoor environments in winter [26,27]. Moreover, building thermal retrofitting may improve the envelope airtightness and, consequently, reduce the air exchange rate if the ventilation is not precisely and simultaneously controlled [8,11,28]. This phenomenon, accompanied by a possible reduction in the air exchange rate, leads to higher indoor radon concentrations in thermally retrofitted residences [29,30].

This paper was created as a part of the EU RadoNorm project [31] under the umbrella of the Horizon 2020 framework program (H2020). The project's scope aims for effective radiation protection based on improved scientific evidence and social considerations. The authors' task is related to the investigation of the embodied impacts of various types of radon control technologies on the environment. This study is part of a broader study that compares other similar solutions (e.g. passive or active soil ventilation or air gap ventilation [32]).

2. Materials and methods

2.1. Selection of waterproof membranes

This study selected the following ten types of waterproof membranes among the five different macro-categories based on their chemical composition (Table 1). Membranes are the subjects of analysis because they can be representative of other building elements, and the methodology can easily be replicated.

Table 1 presents the different thicknesses of these membranes; for example, bituminous membranes can reach thicknesses of up to 5 mm, whereas polymeric membranes can reach a maximum thickness of 2 mm but are usually thinner (from 0.2 mm). Thus, this aspect has been considered for further calculations because not every membrane can have a whole range of thicknesses, as it would be unrealistic.

2.2. Radon resistance calculation for each membrane

The radon resistance values were determined for ten widely-used waterproofing materials sorted into five groups according to their chemical composition. These values were then compared to evaluate the best membrane performance in terms of radon risk protection. Eq. (1) is used to calculate R_{Rn} for each waterproofing material [33].

$$R_{Rn} = \frac{sinh\frac{d}{l}}{\lambda.l} \tag{1}$$

where R_{Rn} is the radon resistance (s/m), λ is the radon decay constant (s^{-1}), d is the thickness of the material (m), l is the radon diffusion length in the material calculated as $l = (D/\lambda)^{1/2}$ (m), and D is the radon diffusion coefficient of the waterproof material (m^2/s).

For each membrane type, the average radon diffusion coefficients (D

Table 1
List of waterproof membranes selected for this work.

Acronym	Composition	Macro-category	Range of typical thicknesses
MAP	Membrane made of SBS (styrene-butadiene-styrene) modified bitumen	Bituminous membrane	3/5 mm
OAP	Membrane made of oxidised asphalt	Bituminous membrane	3/4 mm
SMA	Coating made of SBS modified bitumen	Bituminous coating	2/4 mm
SPC	Polymer-cement coating	Other coatings	1/3 mm
PVC	Plasticised polyvinylchloride	Polymeric membrane	0.6/2 mm
LDPE	Low-density polyethylene membrane	Polymeric membrane	0.2/2 mm
HDPE	High-density polyethylene membrane	Polymeric membrane	0.2/2 mm
EPDM	Rubber membrane	Polymeric membrane	1/2 mm
TPO	Thermoplastic polyolefin	Polymeric membrane	1/2 mm
MA-PE	Polyethylene foil coated with SBS modified bitumen	Composite membrane	1/2 mm

Membrane - a prefabricated waterproofing product in the form of a strip or a foil manufactured in a factory. Coating – a wet waterproofing product applied in-situ by spraying or trowelling.

values) were obtained from the database of the Faculty of Civil Engineering of the Czech Technical University in Prague [19], which collects D values measured according to the method developed in cooperation with the National Radiation Protection Institute in Prague. This method has been in use since 1995. In 1999, the method was accredited, and in 2017 it became a part of the ISO/TS 11665–13 standard (method C) [34]. Table 2 presents the above calculations. To simplify the process, only values for the 2 mm-thickness of each membrane are shown. Nevertheless, the methodology is representative of the calculations conducted for other thicknesses.

The same calculations were conducted for other thicknesses (0.2, 0.5, 0.6, 1, 3, 4, and 5 mm) to better understand how the R_{Rn} changes with the thickness. The thicknesses of the individual types of membranes were chosen to be suitable for the protection of the building substructure. For example, as presented in Table 1, the thickness range of PVC membranes is 0.6/2 mm, whereas that of MAP membranes is 2/5 mm.

2.3. *Environmental impact categories*

After selecting the ten different types of membranes, we collected the environmental product declarations (EPDs) for the environmental data for the LCA production stage (modules A1-A3) [35], i.e. module A1 corresponds to the raw material supply, A2 corresponds to the transportation of the material to the manufacturer, and A3 corresponds to the manufacturing process – in the EPDs, only Modules A1 to A3 are mandatory, which corresponds to a cradle-to-gate analysis (Fig. 1). These declarations considered the embodied impacts from the extraction and transportation of the raw materials to the manufacturing stages. Currently, EPDs are the most complete and credible environmental certifications available.

The datasets were consulted in online and open-source databases, such as the EPD International [36], Ökobaudat [37], EPD Online Tool [38], and EPD Ireland [39]. The use of the presented method may be limited by the fact that open-source databases provide a number of construction options. In fact, if other databases had been considered, other options might have emerged. Environmental impact categories were chosen according to the scope and aim of each LCA. Table 3 lists the categories usually chosen for the construction sector [40].

The impact assessment methodology considered for generic datasets was CML2001, which is a characterisation method often used for environmental assessment in the building industry, and EN 15804:2012 [40] or ISO 14025:2006 [41] was employed for the data available in EPDs.

The embodied impact calculation was not conducted in any specific LCA software but directly in MS Office Excel. The required data were imported from the EPDs collected from the LCA open-source databases. Every membrane was converted to the same thickness to properly compare the results; thus, the aforementioned embodied impacts were calculated for the selected ranges (0.2, 0.5, 0.6, 1, 2, 3, 4, and 5 mm). As every membrane is not available at every thickness (owing to an unrealistic possibility of manufacturing membranes with such thicknesses), some results have been considered for exercise purposes. However, these are not displayed in the graphs shown in the Results Section to avoid confusion.

2.4. *Embodied impacts*

The datasets used to collect data from EPDs have been listed in MS Excel because more than one membrane has been itemised for the same category. Notably, this process provided more examples of membranes with the same chemical compositions but different embodied impacts for the A1-A3 production stages because they were produced by other manufacturers. Thus, the average of embodied impacts for the environmental impact categories has been listed to describe a membrane covering more than one EPD. For example, Table 4 lists the data collected for the PVC membranes and the resulting average data for this category. The data represent membranes with a thickness of 1.5 m, and a simple multiplication will transform their thicknesses into potential values for other thicknesses (e.g. 2 mm, 3 mm, etc.).

Table 2
Calculation of radon resistance values for 2 mm-thick membranes (d).

Typology	avg. D [m^2/s]	λ [s^{-1}]	avg. l [m]	avg. R_{Rn} [Ms/m]
MAP	1.71×10^{-11}	2.1×10^{-6}	2.85×10^{-3}	127
OAP	1.25×10^{-11}	2.1×10^{-6}	2.44×10^{-3}	179
SMA	2.67×10^{-11}	2.1×10^{-6}	3.57×10^{-3}	79
SPC	1.96×10^{-10}	2.1×10^{-6}	9.65×10^{-3}	10
PVC	1.72×10^{-11}	2.1×10^{-6}	2.86×10^{-3}	126
LDPE	1.65×10^{-11}	2.1×10^{-6}	2.80×10^{-3}	132
HDPE	6.10×10^{-12}	2.1×10^{-6}	1.70×10^{-3}	408
EPDM	1.87×10^{-10}	2.1×10^{-6}	9.44×10^{-3}	51
TPO	3.27×10^{-10}	2.1×10^{-6}	1.25×10^{-2}	1
MA-PE	1.54×10^{-11}	2.1×10^{-6}	2.71×10^{-3}	142

This type of calculation was conducted for all types of membranes listed in Section 2.1. Consequently, for homogeneity of the results, the data were calculated for the entire thickness range, but only a few results per membrane representing realistic scenarios were properly considered for discussion.

2.5. *Single-score indicators for environmental parameters*

Ten types of membranes were assessed using the Centre of Environmental Science (CML) method, better known as CML2001. CML2001 is an impact assessment method that restricts quantitative modelling to the early stages in the cause-effect chain to limit uncertainties. The results are grouped into midpoint categories according to common mechanisms (e.g. climate change) or commonly accepted groupings (e.g. ecotoxicity) [42]. Normalisation factors for CML2001 were calculated using the total substance emissions and characterisation factors per substance. This method aims to provide best practices for midpoint indicators, thereby operationalising the ISO14040 series of standards [43]. The characterisation factors of this method were also used for the environmental assessment of construction products according to EN 15804 + A1 [40].

In this study, CML2001 was used to obtain results for January 2016. For example, the CML2001 midpoint indicators were used to assess construction products according to EN 15804 + A1. Subsequently, we compared the single-score indicators of the membranes calculated using CML2001 after normalisation and weighing to identify the best membrane in terms of embodied environmental impacts.

3. Results

In this study, ten kinds of radon-proof membranes were assessed in terms of their embodied environmental impacts and R_{Rn} performance. This kind of study is unique because embodied impacts for radon-proof membranes have been neglected thus far, and the approach to compare them to radon resistance has still not been investigated.

3.1 Radon resistance calculation for each membrane and its possible thickness.

The R_{Rn} for each membrane and each selected thickness was calculated using the method reported in the Methodology Section, thereby considering the average values of D [m^2/s] and l [m]. The results are shown in Fig. 2.

As Fig. 2 shows, in some thickness ranges, the values of R_{Rn} can never

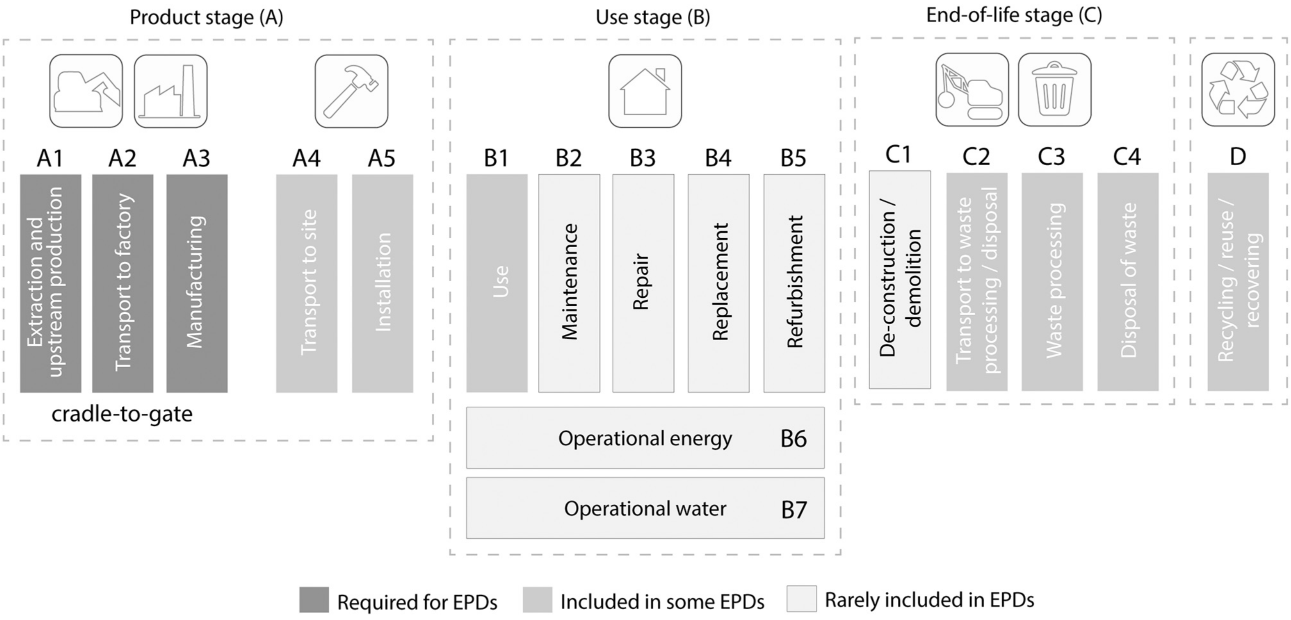

Fig. 1. Life cycle stages included in EPDs. Visualisation made by the authors.

Table 3
Impact categories and their units of measurement.

	Impact categories	Acronym	Unit measure
Life cycle parameters (use of resources)	Renewable primary energy	PERT	[MJ]
	Non-renewable primary energy	PERNT	[MJ]
	Freshwater consumption	FW	[m^3]
Environmental parameters	Acidification potential	AP	[kg - SO_2 eq.]
	Ozone depletion potential	ODP	[kg - CFC-11 eq.]
	Global warming potential	GWP	[kg - CO_2 eq.]
	Eutrophication potential	EP	[kg - $(PO_4)^{3-}$ eq.]
	Photochemical ozone creation potentials	POCP	[kg - C_2H_4 eq.]
	Abiotic depletion potential elements	ADPe	[kg - Sb eq.]
	Abiotic fossil fuel depletion	ADPf	[MJ]

be achieved because of the unavailability of the membrane at that specific thickness, as it would not be effective in its scope; for example, it is not possible to produce a membrane with a thickness of 1 mm for the MAP and EPDM. A thickness of 2 mm is the most common among the selected membranes; notably, considering a thickness of 2 mm, the HDPE membrane presents the highest R_{Rn} value (408 Ms/m), whereas the SPC membrane has the lowest value (10 Ms/m), followed by the TPO (6 Ms/m). In theory, an OAP membrane with a thickness of 5 mm would obtain a high R_{Rn} value (>600 Ms/m); however, in the building sector, R_{Rn} values higher than 600 Ms/m are not generally required; thus, it has been considered at this maximum level. On the contrary, R_{Rn} values lower than 5 Ms/m have not been evaluated because they are not effective in reducing the radon risk; thus, even if a membrane could be produced in one of the selected thicknesses but had a R_{Rn} value lower than the lower limit (5 Ms/m), it was not considered in the study because of its inferior performance in terms of radon control. However, such membranes could be used for other applications, such as waterproofing. For example, even if the TPO membrane can be produced with a thickness of 1 mm, it is not displayed in the graph because its R_{Rn} is lower than the minimum possible value (specifically, 3 Ms/m).

3.1. *Investigation of the most suitable membrane in terms of environmental impacts and efficiency in radon protection*

The embodied environmental impacts of the ten membranes were compared to understand which among them affects the environment more or less than the others for a specific parameter while also considering their effectiveness in reducing the radon risk.

The results of the embodied primary energy, both renewable (PERT) and non-renewable (PERNT) are shown in Fig. 3 and are compared with the R_{Rn} of each membrane. The following figure shows different membranes and their thicknesses.

According to the results shown in Fig. 3, on the one hand, the membrane with the highest embodied energy consumption from

Table 4
Example of the calculation of the average embodied environmental impacts for three datasets collected from different EPDs. These data refer to membranes with a thickness of 1.5 mm.

MEMBRANE	PERT	PERNT	FW	AP	ODP	GWP	EU	POPC	ADPe	ADPf
PVC – EPD 1	12.70	135.00	0.03	1.45×10^{-2}	2.50×10^{-8}	4.93	2.06×10^{-3}	2.05×10^{-3}	1.88×10^{-5}	129.00
PVC – EPD 2	7.16	134.26	0.01	1.38×10^{-2}	6.08×10^{-8}	5.39	1.57×10^{-3}	2.72×10^{-3}	8.69×10^{-4}	123.15
PVC – EPD 3	15.90	154.00	0.05	3.08×10^{-2}	2.58×10^{-10}	7.03	2.42×10^{-3}	3.02×10^{-3}	1.09×10^{-2}	147.00
AVERAGE	**11.90**	**141.00**	**0.03**	$\mathbf{1.97 \times 10^{-2}}$	$\mathbf{2.87 \times 10^{-8}}$	**5.78**	$\mathbf{2.02 \times 10^{-3}}$	$\mathbf{2.60 \times 10^{-3}}$	$\mathbf{3.93 \times 10^{-3}}$	**133.00**

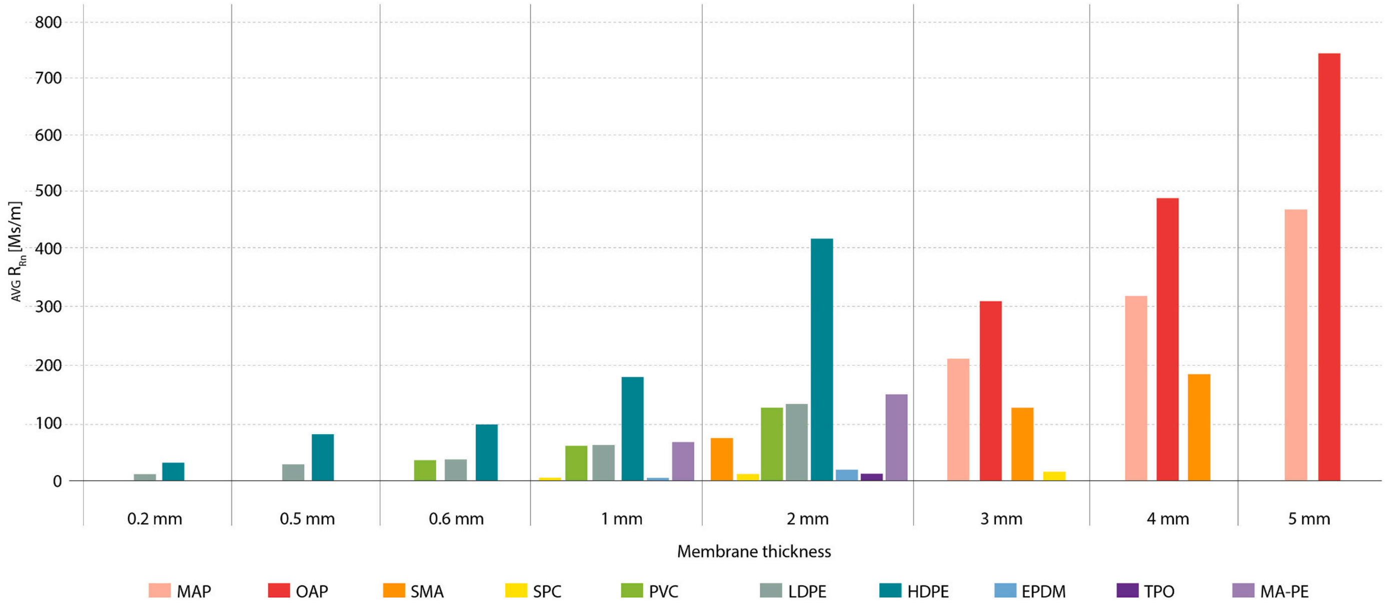

Fig. 2. Overview of the average radon resistance for different membrane thicknesses. A few values of radon resistance could not be achieved as some specific thicknesses were unrealistic for certain types of radon proof membranes.

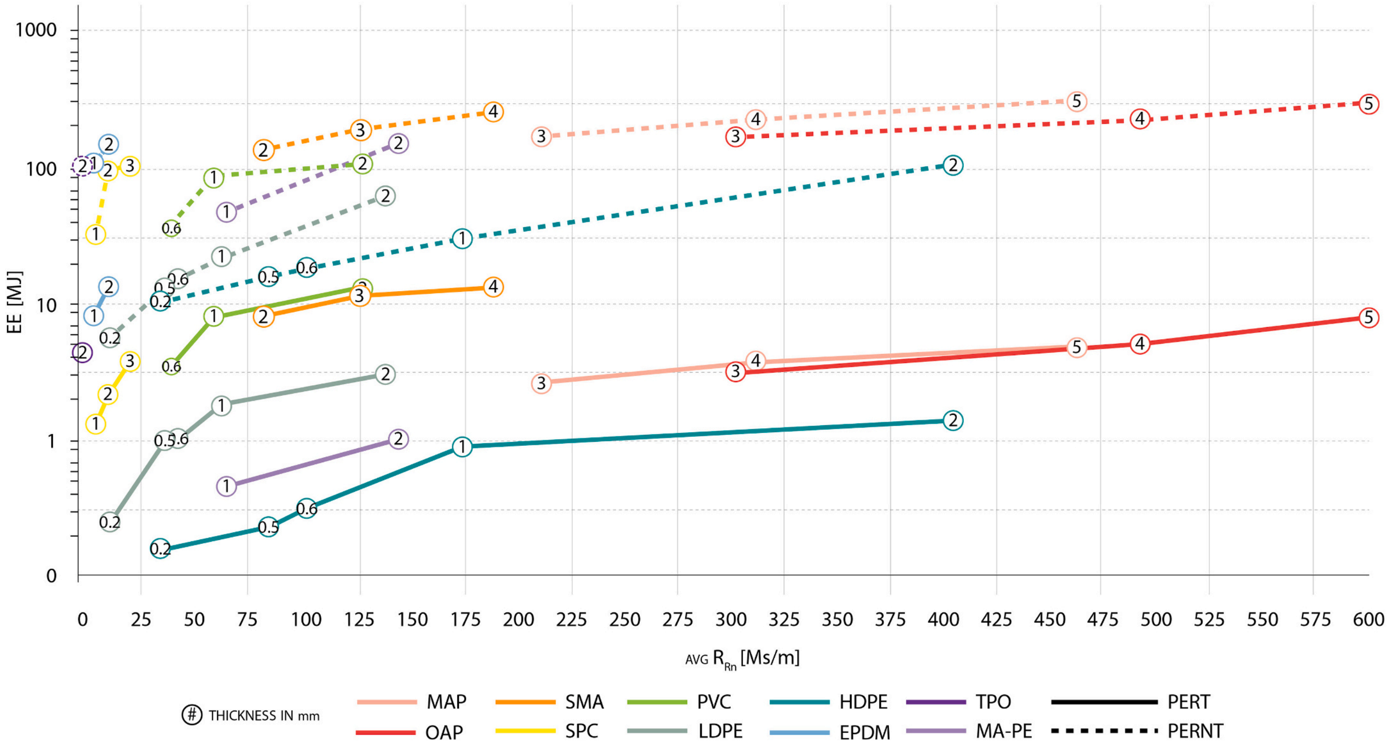

Fig. 3. Comparison of membranes in terms of embodied energy (EE) – total renewable (PERT) and total non-renewable (PERNT) (MJ), and radon resistance (Ms/m).

renewable sources is EPDM, while those with the lowest values are the HDPE and LDPE membranes. Considering non-renewable sources, the OAP and LDPE membranes present the highest and lowest impacts, respectively. Conversely, considering the R_{Rn} (hypothetically between 75 and 125 Ms/m), HDPE membranes with thicknesses of 0.5/0.6 mm were the most environmentally friendly and effective for radon protection, considering both renewable and non-renewable energy sources.

The same process can be conducted for other parameters, such as the GWP. Fig. 4 shows that the SMA membrane had a higher carbon emission. In contrast, the HDPE membrane had the lowest carbon emissions in terms of the GWP. However, considering the R_{Rn} (a hypothetical

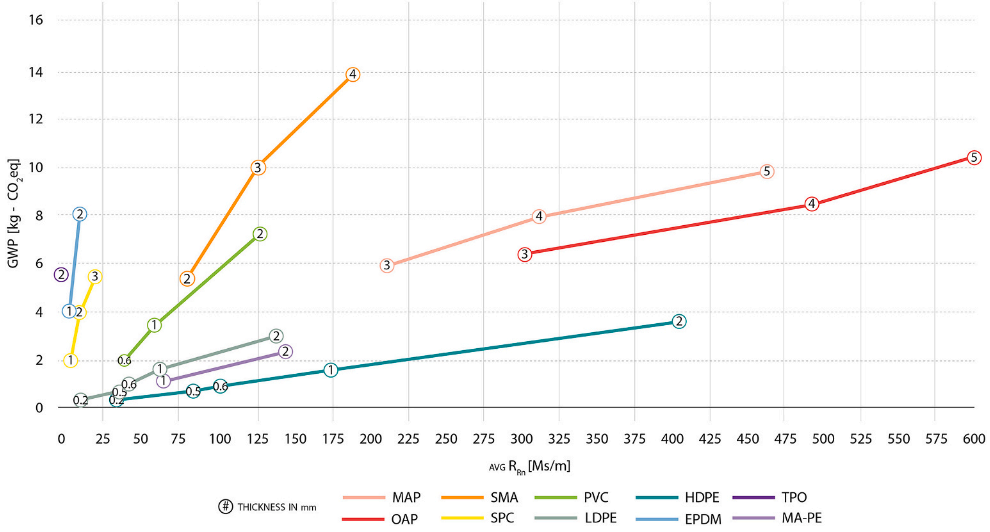

Fig. 4. Comparison of membranes in terms of embodied emissions – GWP [kg - CO_2 eq.] and radon resistance [Ms/m].

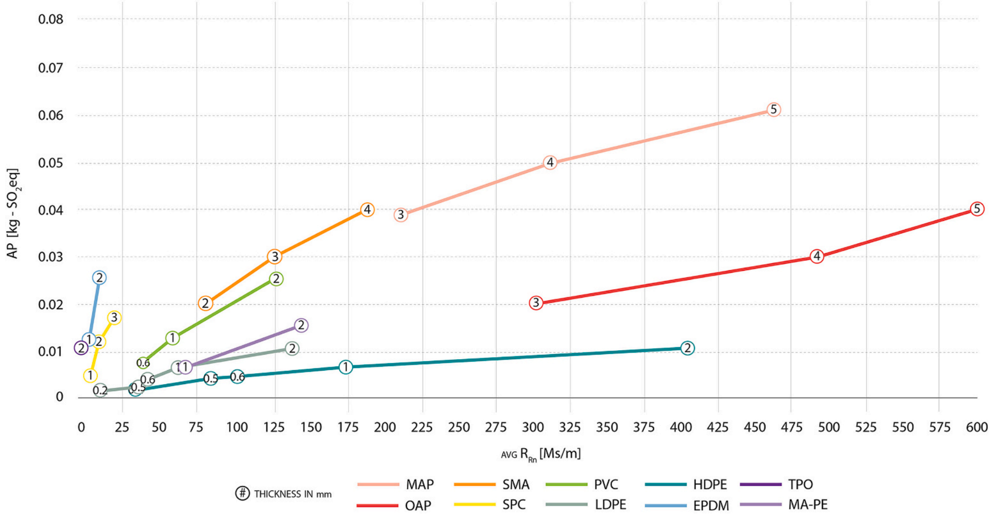

Fig. 5. Comparison of membranes in terms of the acidification potential – AP [kg - SO_2 eq.] and R_{Rn} [Ms/m].

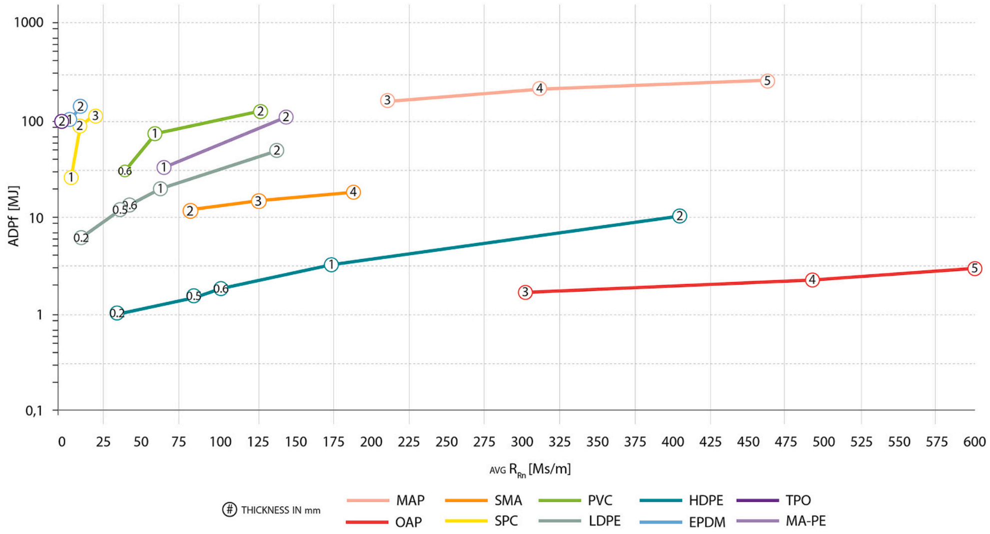

Fig. 6. Comparison of membranes in terms of abiotic fossil fuel depletion – ADPf [MJ] and radon resistance [Ms/m].

range between 75 and 125 Ms/m), the HDPE membrane was always the best with regard to both parameters (thickness of 0.5/0.6 mm).

Considering AP (Fig. 5), for example, the membrane with the highest impact was the MAP membrane. In contrast, the LDPE membrane had the lowest AP impact. However, considering the R_{Rn} (a hypothetical range between 150 and 225 Ms/m), the HDPE membrane with a thickness of 1 mm was the best membrane with regard to both parameters.

Finally, considering another environmental parameter, specifically ADPf (Fig. 6), the membrane with the highest impact was MAP, followed by EPDM. In contrast, the HDPE and OAP membranes showed the lowest values. Still, even considering the R_{Rn} (hypothetically a range between 75 and 125 Ms/m), the best membrane for both parameters is the HDPE membrane with a 0.5/0.6 mm thickness.

3.2. *Assessment of the most environmentally friendly membrane according to a single-score indicator*

One of the aims of this study is to highlight the membrane that is most environmentally friendly and simultaneously effective in protecting against radon. To meet this goal, the average dataset of the environmental parameters (excluding the life cycle parameters) of the ten types of radon-proof membranes was normalised and weighted using the CML2001 method to calculate a single-score indicator.

Once the calculations were made, the ten single-scores were combined with the R_{Rn} values of each membrane (Fig. 7) to investigate which one was the most environmentally friendly in terms of environmental parameters and also simultaneously showed great radon resistance. This is the main result of this study as it shows that all the environmental parameters have been considered simultaneously owing to the calculated single-score indicator, as described in Section 3.2. Consequently, it is easy to identify the best membrane for each thickness range.

Figure 8 shows the same results as in Fig. 7, but the membranes are sorted by the R_{Rn} range and not by thickness. Thus, when choosing a membrane exhibiting R_{Rn} in the range of 100–150 Ms/m, it is easy to select the most efficient and environmentally friendly membrane. In this case, the most suitable membrane was an HDPE membrane with a thickness of 0.6 mm, which showed the lowest single-score indicator value.

Furthermore, Fig. 9 shows the comparison of MAP and PVC membranes in terms of the single-score indicators and R_{Rn}, considering both the average values and the minimum and maximum values.

Moreover, we also considered the maximum and minimum values of R_{Rn} that were calculated by considering the maximum and minimum values of D (m^2/s), as presented in Table 5. Once D is considered in the other two scenarios, the maximum and minimum values of R_{Rn} can be obtained for each realistic thickness. Only two out of ten membranes have been investigated because they are illustrative of the applied method.

Thus, through the comparison of MAP and PVC membranes in Fig. 8, it is possible to highlight that it would be more appropriate to use MAP insulation in most cases, even when considering the minimum and maximum values of R_{Rn}. With the exception of the need for R_{Rn} of up to approximately 50 Ms/m, MAP is considered to be the best option, both in terms of radon protection and environmental friendliness, because the single-score indicator of MAP is lower than that of the PVC membrane.

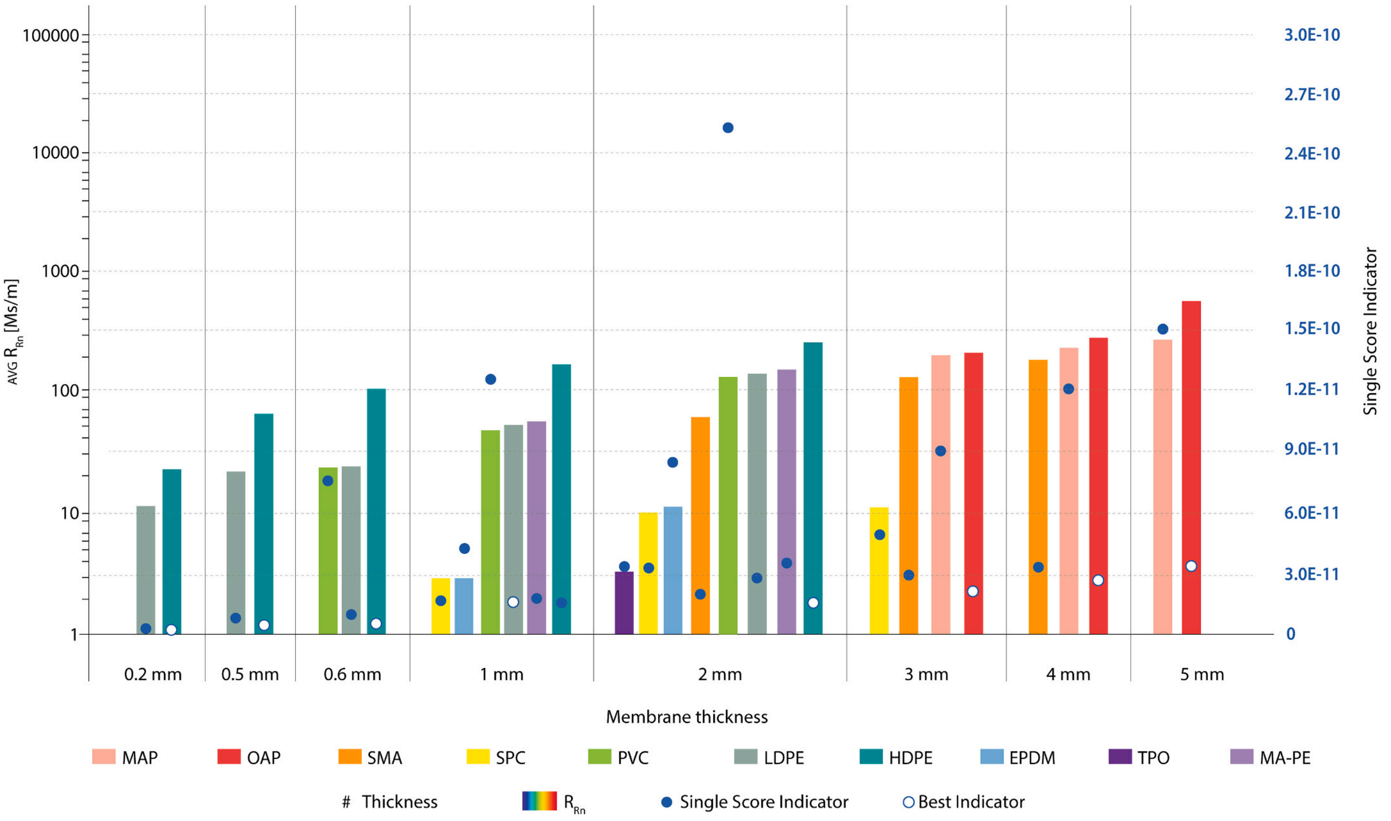

Fig. 7. Radon resistance performance and single-score indicators (blue and white dots) of the selected membrane sorted by thickness values.

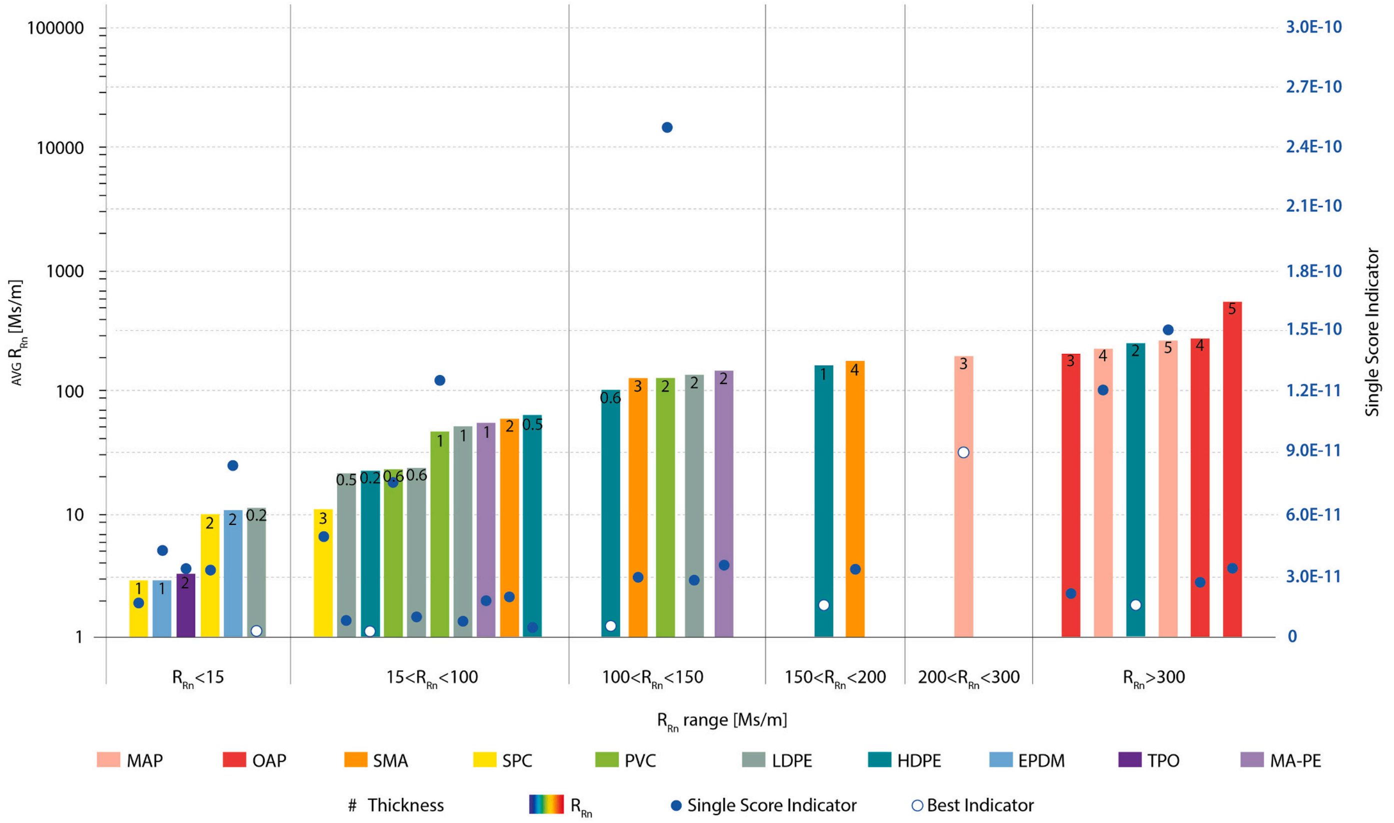

Fig. 8. Overview of membranes sorted by thickness ranges along with the radon resistance and single-score indicators (blue and white dots).

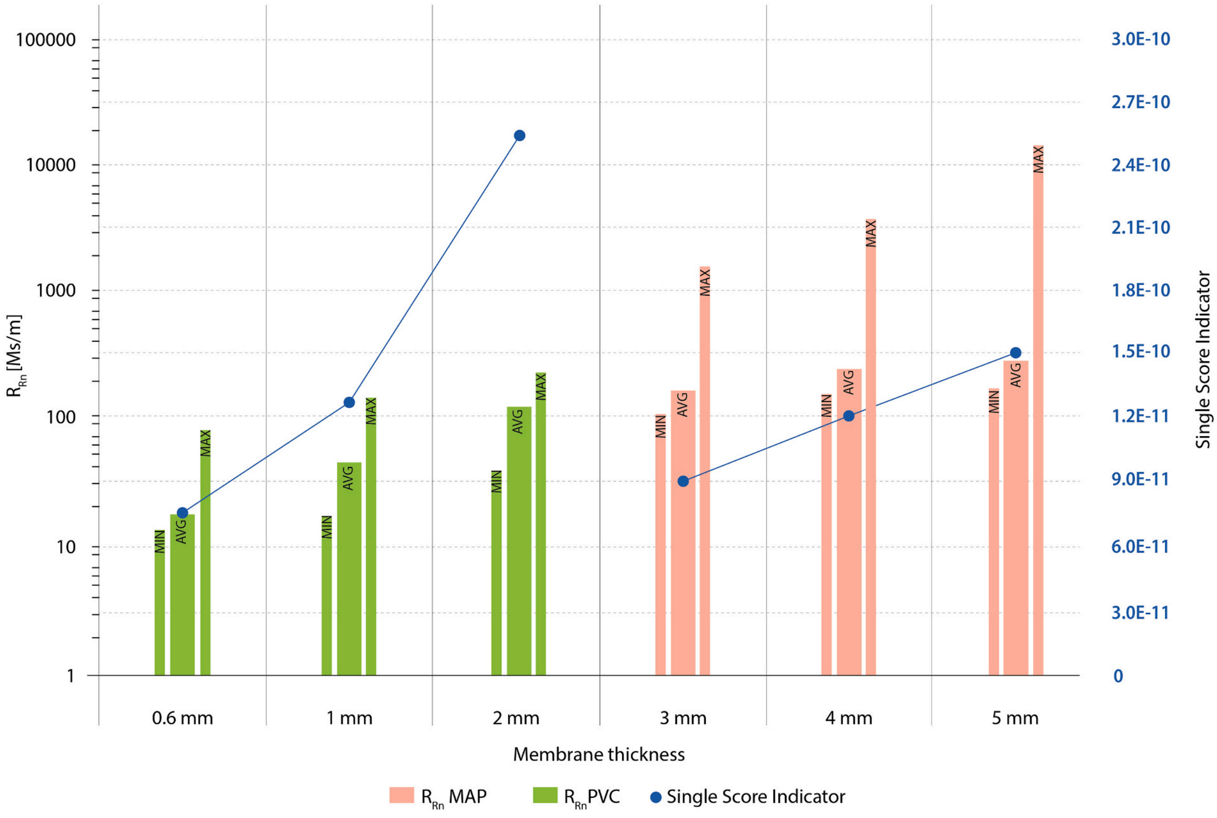

Fig. 9. Comparison between a bituminous membrane (MAP - pink) and a polymeric membrane (PVC - green) considering the maximum and minimum values for radon resistance and the single-score indicator for embodied environmental impacts (blue dots).

Table 5
Value of D (m^2/s) for bituminous and polymeric membranes.

Typology	min D [m^2/s]	avg D [m^2/s]	max D [m^2/s]	Error [m^2/s]
MAP	3.00×10^{-12}	1.71×10^{-11}	3.72×10^{-11}	1.41×10^{-11}
PVC	7.30×10^{-12}	1.72×10^{-11}	2.71×10^{-11}	9.90×10^{-12}

4. Discussion

The embodied impacts for different membranes and their thicknesses enable us to observe how waterproof membranes produce more or less evident effects during the ‘cradle-to-gate’ stage (LCA A1-A3). One of the relevant outcomes of this study is that radon-proof membranes possess additional embodied impacts if used at high thicknesses; however, if thinner membranes are used, the radon resistance values decrease, leading to lower efficiency. The graphs clearly show that as the radon resistance of the insulation increases, the values of the environmental impact categories increase, thereby indicating that the environmental impact worsens.

Waterproofing, which provides radon-proof insulation, must have a radon resistance greater than the minimum value prescribed by the national building standards or codes. For example, according to SINTEF [44], the minimum R_{Rn} is 50 Ms/m. According to the Czech Technical Standard CSN 730601 or [45], the values of the minimum R_{Rn} range from 2 to 300 Ms/m depending on several parameters, such as the type of building, category of radon-prone area, ventilation intensity, required indoor radon concentration, or the existence of other radon control technologies. Higher values of R_{Rn} are required for houses with lower ventilation intensity in high radon-prone areas and in the absence of any other radon control measures.

Isolation materials vary substantially depending on the type of material from which they are made. The selection of suitable insulation material is challenging because individual insulation material types are manufactured at varying thicknesses and achieve varying degrees of radon resistance. For example, for R_{Rn} values ranging from 100 to 150 Ms/m, five insulation materials are available: SMA, LDPE, HDPE, PVC, and MA-PE. If the task is to reduce as much AP or GWP as possible, HDPE insulation is considered to be the right choice, as discussed in Section 3.2. However, if the score indicator is computed by normalising and weighing the environmental parameters, HDPE and PVC membranes are the most environmentally friendly and unfriendly membranes in the R_{Rn} range of 100 to 150 Ms/m, respectively.

Furthermore, HDPE should also be used if the aim is to reduce as much ADPf as possible. However, if a radon resistance >300 Ms/m is required, the OAP membrane would be a suitable choice among the studied insulation materials. However, according to the single-score indicator, HDPE is the most suitable insulation material to achieve a R_{Rn} of >300 Ms/m, whereas SPC is the best insulation material for a R_{Rn} of up to approximately 10 Ms/m. Additionally, considering the embodied energy, PVC shows the highest values for both renewable and non-renewable energy. Thus, to select the most environmentally friendly membrane considering the embodied energy and effectiveness in terms of radon protection, in a hypothetical range between 25 and 75 Ms/m, the HDPE membrane with a thickness of 1 mm is the best available option.

The analysis of the single-score indicator enables us to evaluate the membrane with fewer embodied impacts (the use of resources is excluded). If the outcomes are compared to radon resistance, it is possible to choose the most environmentally friendly and radon-resistant membrane available within a specific range. For instance, for a radon range between 150 and 200 Ms/m, only two types of membranes are available (HDPE and SMA), and the single-score indicator highlights which among them should be chosen to achieve low embodied impacts (the HDPE membrane). The ranges consider the calculated average radon resistance values of each membrane; however, the minimum and maximum values can be registered and depend on the maximum and minimum values of D (m^2/s).

Owing to the potential risk of radon concentration in a particular area, the selection of a membrane cannot be solely based on environmental parameters. Alternatively, the selection must also consider the radon resistance of the membrane. Thus, the level of radon resistance needs to be determined before choosing the correct membrane by considering the area and concentration of indoor radon, as well as the environmental impacts.

4.1. Limitation of the study

There is a limitation in this study due to the fact that the EPDs and products selected for obtaining the embodied impact results could differ if other open-source LCA databases had been used. However, the methodology is representative and can be replicated using other EPDs or different life-cycle inventory databases.

5. Conclusions

This paper was created as a part of the EU RadoNorm project under the umbrella of the Horizon 2020 Framework Programme (H2020). The project aims to reduce indoor radon concentration levels, and a specific task aims to analyse the embodied impacts of radon control technologies on the environment.

Life cycle assessment, normalisation, and weightings achieved through CML2001 were used to compare the environmental impacts of ten types of radon-proof membranes with different chemical compositions after calculating the single-score indicator. This environmental assessment was combined with radon resistance (the efficiency of a membrane in reducing radon risk). The results highlight that membranes with higher thicknesses have higher embodied impacts but simultaneously show greater radon protection.

The results highlight that membranes such as HDPE membranes can be used for different radon-resistance ranges according to their thicknesses; the impact of HDPE membranes in terms of embodied energy is the lowest among the selected membranes. Conversely, if the goal is to reduce the GWP, membranes made of materials such as MA-PE or LDPE should be used because of their low emissions. Finally, the single-score indicator should be considered to obtain a wider overview of the best radon-proof insulation materials according to their environmental impacts and radon protection abilities. For instance, according to the single-score indicator, HDPE is the most suitable insulation material in terms of the environmental impacts, with a radon resistance of >300 Ms/m; however, SPC is the best insulation material with a radon resistance of up to approximately 10 Ms/m.

Therefore, the environmental impacts of radon-proof insulation can be substantially minimised in the following three ways: (i) choosing insulation materials with minimal environmental impact; (ii) avoiding insulation materials with radon resistances that are unnecessarily higher than the minimum resistance level and by optimising the overall radon protection design; and (iii) considering whether the reduction in insulation impacts is offset by the increase in the ventilation or other measures. Additional research will be conducted to examine the impact of combined radon-proof measures on the environment. Future studies would certainly benefit from the inclusion of a comprehensive life cycle analysis that encompasses the production, construction, use, and end-of-life stages.

Nomenclature

ADPf	Abiotic fossil fuel depletion
ADPe	Abiotic depletion potential elements
AP	Acidification potential
CO_2	Carbon dioxide
EPD	Environmental Product Declaration
EPDM	Ethylene propylene diene terpolymer rubber membrane

EP	Eutrophication potential
EU	European Union
FW	Fresh water consumption
GWP	Global warming potential
HDPE	High density polyethylene membrane
LDPE	Low density polyethylene membrane
LCA	Life-cycle assessment
MAP	Membrane made of SBS modified bitumen
MA-PE	Polyethylene foil coated with SBS modified bitumen
OAP	Membrane made of oxidised asphalt
ODP	Ozone depletion potential
PERT	Renewable primary energy
PERNT	Non-renewable primary energy
POCP	Photochemical ozone creation potentials
PVC	Plasticised polyvinylchloride
R_{Rn}	Radon resistance
SMA	Coating made of SBS modified bitumen
SBS	Styren-Butadien-Styren
SPC	Polymer-cement coating
TPO	Thermoplastic polyolefin

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

Data will be made available on request.

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References

[1] S. Darby, D. Hill, A. Auvinen, J. Barros-Dios, H. Baysson, F. Bochicchio, H. Deo, R. Falk, F. Forastiere, M. Hakama, I. Heid, L. Kreienbrock, M. Kreuzer, F. Lagarde, I. Mäkeläinen, C. Muirhead, W. Oberaigner, G. Pershagen, A. Ruano-Ravina, E. Ruosteenoja, A. Schaffrath Rosario, M. Tirmarche, L. Tomásek, E. Whitley, H.-E. Wichmann, R. Doll, Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies, BMJ. 330 (2005) 223, https://doi.org/10.1136/bmj.38308.477650.63.

[2] World Health Organization, WHO Handbook on Indoor Radon: A Public Health Perspective., Geneva. https://www.ncbi.nlm.nih.gov/books/NBK143216/, 2009.

[3] R.M. Amin, A study of radon emitted from building materials using solid state nuclear track detectors, J. Radiat. Res. Appl. Sci. 8 (2015) 516–522, https://doi.org/10.1016/j.jrras.2015.06.001.

[4] A. Cucoş, C. Cosma, T. Dicu, B. Papp, C. Horju-deac, Ventilation systems for indoor radon mitigation in energy-efficient houses, Ecoterra - J. Environ. Res. Prot. 12 (2015) 14–20.

[5] International Atomic Energy Agency, Protection against Exposure Due to Radon Indoors and Gamma Radiation from Construction Materials — Methods of Prevention and Mitigation, Vienna, Austria, 2021.

[6] Government of Canada, Summary Report on Active Soil Depressurisation (ASD) Field Study, Ottawa, Canada. https://www.canada.ca/en/health-canada/services/environmental-workplace-health/radiation/radon/summary-report-active-soil-depressurization-field-study.html, 2016 (accessed February 8, 2021).

[7] L. Grace Zhou, J. Berquist, Y. Ethan Li, J. Whyte, J. Gaskin, M. Vuotari, G. Nong, Passive soil depressurisation in Canadian homes for radon control, Build. Environ. 188 (2021), 107487, https://doi.org/10.1016/j.buildenv.2020.107487.

[8] M. Jiránek, V. Kačmaříková, Dealing with the increased radon concentration in thermally retrofitted buildings, Radiat. Prot. Dosim. 160 (2014) 43–47, https://doi.org/10.1093/rpd/ncu104.

[9] M. Stietka, A. Baumgartner, C. Seidel, F.J. Maringer, Development of standard methods for activity measurement of natural radionuclides in waterworks as basis for dose and risk assessment-first results of an Austrian study, Appl. Radiat. Isot. 81 (2013) 294–297, https://doi.org/10.1016/j.apradiso.2013.03.027.

[10] H. Arvela, O. Holmgren, P. Hänninen, Effect of soil moisture on seasonal variation in indoor radon concentration: modelling and measurements in 326 Finnish houses, Radiat. Prot. Dosim. 168 (2016) 277–290, https://doi.org/10.1093/rpd/ncv182.

[11] B. Collignan, E. Le Ponner, C. Mandin, Relationships between indoor radon concentrations, thermal retrofit and dwelling characteristics, J. Environ. Radioact. 165 (2016) 124–130, https://doi.org/10.1016/j.jenvrad.2016.09.013.

[12] L. Felicioni, A. Lupíšek, M. Jiránek, Embodied energy and global warming potential of radon preventive measures applied in new family houses, in: Smart Innov. Syst. Technol., Springer, Singapore, 2022, pp. 57–68, https://doi.org/10.1007/978-981-16-6269-0_5.

[13] European Commission, Directive 2013/59/Euratom, 2013.

[14] F. Bean, J. Volt, V. Dorizas, E. Bourdakis, D. Staniaszek, A. Roscetti, L. Pagliano, Future-proof buildings for all Europeans. A guide to implement the energy performance of buildings directive, Build. Perform. Inst. Eur. 844 (2018) 76.

[15] European Parliament, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings, 2010.

[16] M. Hu, D. Milner, Visualising the research of embodied energy and environmental impact research in the building and construction field: a bibliometric analysis, Dev. Built Environ. 3 (2020), 100010, https://doi.org/10.1016/j.dibe.2020.100010.

[17] M. Abouhamad, M. Abu-Hamd, Life cycle assessment framework for embodied environmental impacts of building construction systems, Sustainability. 13 (2021) 1–21, https://doi.org/10.3390/su13020461.

[18] M. Gonçalves, J.D. Silvestre, J. de Brito, R. Gomes, Environmental and economic comparison of the life cycle of waterproofing solutions for flat roofs, J. Build. Eng. 24 (2019), 100710, https://doi.org/10.1016/j.jobe.2019.02.002.

[19] M. Jiránek, V. Kačmaříková, Radon diffusion coefficients and radon resistances of waterproofing materials available on the building market, J. Environ. Radioact. 208–209 (2019), 106019, https://doi.org/10.1016/j.jenvrad.2019.106019.

[20] H. Arvela, O. Holmgren, H. Reisbacka, Radon prevention in new construction in Finland: a nationwide sample survey in 2009, Radiat. Prot. Dosim. 148 (2012) 465–474. doi:https://doi.org/10.1093/rpd/ncr192.

[21] J.B. Guinée, M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. de Koning, L. van Oers, A. Wegener Sleeswijk, S. Suh, H.A. Udo de Haes, H. de Bruijn, R. van Duin, M. A.J. Huijbregts, Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background, Kluwer Academic Publishers, Dordrecht, 2002. https://www.universiteitleiden.nl/en/research/research-projects/science/cml-new-dutch-lca-guide.

[22] CML - Department of Industrial Ecology, CML-IA Characterisation Factors. https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors, 2016 (accessed October 20, 2022).

[23] O. Holmgren, H. Arvela, B. Collignan, M. Jiránek, W. Ringer, Radon remediation and prevention status in 23 European countries, Radiat. Prot. Dosim. 157 (2013) 392–396, https://doi.org/10.1093/rpd/nct156.

[24] F. Bochicchio, J. Hulka, W. Ringer, K. Rovenská, I. Fojtikova, G. Venoso, E. J. Bradley, D. Fenton, M. Gruson, H. Arvela, O. Holmgren, L. Quindos, J. McLaughlin, B. Collignan, A. Gray, B. Grosche, M. Jiranek, K. Kalimeri, S. Kephalopoulos, M. Kreuzer, D. Schlesinger, H. Zeeb, J. Bartzis, National radon programmes and policies: the RADPAR recommendations, Radiat. Prot. Dosim. 160 (2014) 14–17, https://doi.org/10.1093/rpd/ncu099.

[25] R. Obenchain, S.S. Young, G. Krstic, Low-level radon exposure and lung cancer mortality, Regul. Toxicol. Pharmacol. 107 (2019), 104418, https://doi.org/10.1016/j.yrtph.2019.104418.

[26] N.M. Rahman, B.L. Tracy, Radon control systems in existing and new construction: a review, Radiat. Prot. Dosim. 135 (2009) 243–255, https://doi.org/10.1093/rpd/ncp112.

[27] M. Abdelouhab, B. Collignan, F. Allard, Experimental study on passive soil depressurisation system to prevent soil gaseous pollutants into building, Build. Environ. 45 (2010) 2400–2406, https://doi.org/10.1016/j.buildenv.2010.05.001.

[28] M. Jiránek, V. Kačmaříková, Applicability of ventilation systems for reducing the indoor radon concentration, Radiat. Prot. Dosim. 191 (2020) 202–208, https://doi.org/10.1093/rpd/ncaa148.

[29] H. Arvela, O. Holmgren, H. Reisbacka, J. Vinha, Skip Nav destination article navigation review of low-energy construction, air tightness, ventilation strategies and indoor radon: results from Finnish houses and apartments, Radiat. Prot. Dosim. 162 (2014) 351–363, https://doi.org/10.1093/rpd/nct278.

[30] W. Ringer, Monitoring trends in civil engineering and their effect on indoor radon, Radiat. Prot. Dosim. 160 (2014) 38–42, https://doi.org/10.1093/rpd/ncu107.

[31] RadoNorm.EU, RadoNorm - Managing risks from radon and NORM. https://www.radonorm.eu/, 2021 (accessed February 2, 2021).

[32] C.R. Scivyer, M.P. Jaggs, Radon Sumps: A BRE Guide to Radon Remedial Measures in Existing Dwellings, 2010.

[33] M. Jiránek, Z. Svoboda, A new approach to the assessment of radon barrier properties of waterproofing materials, Radiat. Prot. Dosim. 177 (2017) 116–120, https://doi.org/10.1093/rpd/ncx140.

[34] ISO/TS 11665—13:2017, Measurement of Radioactivity in the Environment — Air: radon 222 — Part 13: Determination of the Diffusion Coefficient in Waterproof Materials: Membrane Two-side Activity Concentration Test Method, 2017.

[35] EN 15978:2011, Sustainability of Construction Works - Assessment of Environmental Performance of Buildings - Calculation Method, 2011.

[36] International EPD, The International EPD System. https://www.environdec.com/library, 2021. (Accessed 8 February 2021).

[37] German Federal Ministry of the Interior Building and Community, Ökobaudat, (n.d.). https://www.oekobaudat.de (accessed February 8, 2021).
[38] Institut Bauen und Umwelt e.V., EPD Online Tool, (n.d.). https://ibu-epd.com/en/ (accessed February 8, 2021).
[39] Irish Green Building Council, EPD Ireland, (n.d.). https://www.igbc.ie/epd-search/ (accessed February 8, 2021).
[40] BS EN 15804:2012+A1:2013, Sustainability of Construction Works. Environmental Product Declarations. Core Rules for the Product Category of Construction Products, 2014.
[41] International Organization for Standardization, ISO 14025 - Environmental labels and declarations - Type III environmental declarations - Principles and Procedures, 2006.
[42] A.F.A. Rashid, J. Idris, S. Yusoff, Environmental impact analysis on residential building in Malaysia using life cycle assessment, Sustainability. 9 (2017), https://doi.org/10.3390/su9030329.
[43] J. Pešta, T. Pavlů, K. Fortová, V. Kočí, Sustainable masonry made from recycled aggregates: LCA case study, Sustainability. 12 (2020), https://doi.org/10.3390/su12041581.
[44] SINTEF, Guidelines for SINTEF Technical Approval for Radon Membranes, 2012.
[45] M. Jiránek, New, efficient and generally applicable Design of Radon-proof Insulations — a proposal for a uniform approach, Radiat. Prot. Dosim. 177 (2017) 121–124, https://doi.org/10.1093/rpd/ncx139.