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To cite this article: Licia Felicioni *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1085** 012056

Sustainability assessment of waterproof membranes for radon mitigation in buildings

Licia Felicioni[1,2,3], Martin Jiránek[1], Antonín Lupíšek[1,2]

[1] Czech Technical University in Prague, Faculty of Civil Engineering, Thákurova 2077/7, 166 29 Prague, Czech Republic
[2] Czech Technical University in Prague, University Centre for Energy Efficient Buildings, Třinecká 1024, 273 43 Buštěhrad, Czech Republic

[3]licia.felicioni@cvut.cz

Abstract. Gas radon is the main source of ionising radiation for humans and the second cause of lung cancer, just after smoking. Radon is present in the ground, and its concentration differs soil by soil according to the permeability and the mineral composition. Since radon mainly penetrates a building through cracks and fractures at the foundation level, it is necessary to focus on that area. The problem of high radon indoors concentration is present largely in Europe and in those countries where the heating indoors is privileged since there is a high-temperature difference between outdoors and indoors in winter. The waterproof membranes placed continuously in the structures that are in contact with the soil are one of the cheapest and easy-to-install radon mitigation solutions. Membrane-based measures, like all remedial measures, represent operational and embodied environmental impacts; the lasts were more or less ignored so far. Still, as buildings are becoming energy-efficient and should ensure a high level of indoor comfort, the environmental impacts of these membranes are recognised as being noteworthy and shall be methodically examined. The paper aims to assess the contribution of embodied impacts of five macro-categories of membranes that could be installed to protect buildings against radon. The embodied impacts are calculated for the A1-A3 LCA stages and compared against each other in relation to one square meter and the radon resistance.

1. Introduction

Radon in buildings is considered the most present indoor air pollutant that leads to harmful effects on the health of the general population. Indeed, inhalation of radon and its short-living decay products increases the risk of lung cancer [1]; it is the second most frequent cause of lung cancer after tobacco smoke [2]. This radioactive noble gas from soil, considered the most critical radon source, enters buildings mainly through cracks, pipes, and fractures at the foundation level [3]. Once radon is inside the building, it accumulates in the spaces directly in contact with the ground (ground floors, underground floors, cellars) [4,5].

Investigating the topic of environmental impacts of radon protective/preventive measures through literature research conducted in research engines and databases (specifically Web of Science, Scopus, and Google Scholar), it has been highlighted that there is still a gap in the literature about this topic. Still, studying different measures or components from a sustainability perspective is already presented in the literature; for example, basic radon control techniques are the waterproofing materials usually used in roofs and have already been studied in other works for slightly different purposes [6]. However, this work's originality is that the embodied impacts are presented for different kinds of waterproof membranes usually used at the foundation level and compared with their radon resistance (R_{Rn}) (defined in Ms/m). Indeed, this work aims to highlight the embodied impacts of acidification potential (AP) (defined in kg - SO_2 eq.), ozone depletion potential (ODP) (defined in kg – CFC-11 eq.), and global warming potential (GWP) (defined in kg - CO_2 eq.) for five macro-categories of waterproof membranes (bituminous membranes and coatings, polymeric membranes, polymer cement coatings, and composite

IOP Conf. Series: Earth and Environmental Science 1085 (2022) 012056 doi:10.1088/1755-1315/1085/1/012056

membranes), as they are one of the easiest and cheapest control technologies to reduce radon hazard [7,8], and compare each other to one square meter and the radon resistance. When a membrane is able to reduce radon transport by diffusive effect, it is considered a radon barrier.

This manuscript considers the "cradle-to-gate" boundary, strictly connected to the material production stream (from raw material supply to delivery to the gate). Based on these premises, the analysis proposed aims to define three indicators for the A1-A3 product stage (AP, ODP, and GWP) for five membranes of different chemical compositions. The manuscript aims to understand which kind of membrane is more environmentally friendly in relation to providing sufficient protection against radon by its thickness and radon resistance. The assessment compares the five membranes in the range of the environmental indicators per m^2 (e.g. GWP/m^2) and the radon resistance. It has been taken as a functional unit 1 m^2 because it is the basic unit when considering membranes and is easily understandable.

2. Aim and scope

This paper is a part of a broader study for the EU RadoNorm project [9] under the umbrella of the Horizon 2020 framework programme (H2020). The project's scope looks toward effective radiation protection based on improved scientific evidence and social considerations. The authors' task is related to assessing the impact of various types of buildings' radon protective and remedial measures on the environment.

This project comes from the European Union's willingness to reduce the exposure to radon in buildings with the Directive 2013/59/Euratom [10]. Moreover, this Directive aims at increasing the awareness of radon risk indoors by implementing rules in every European country since 2018 with consequent monitoring and mitigating actions [11]. New buildings should be designed and built using preventive measures to reach a radon concentration as low as plainly obtainable [12], but at the same time, do not omit the energy spent and the greenhouse gases emitted during the materials production stages (e.g. materials extraction and manufacturing).

3. Materials and method

3.1 Macro-categories and selection of membranes

This work selected the following five types of waterproof membranes among five macro-categories different due to their chemical composition as a case study because they could be representative and easily replicable (Table 1).

Table 1. List of waterproof membranes selected for this work

Acronym	Composition	Macro-category	Range of typical thicknesses
MAP	Membrane made of SBS (styren-butadien-styren) modified bitumen	Bituminous membrane	2/5 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
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.

3.2 Radon resistance calculation for each membrane

The radon resistance values (R_{Rn}) have been determined for five widely-used waterproofing materials divided into five groups according to their chemical composition. Equation (1) has been considered as the definition for calculating R_{Rn} for each waterproofing material [13].

$$R_{Rn} = \frac{\sinh\frac{d}{l}}{\lambda . l} \qquad (1)$$

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 waterproofing material [m^2/s].

For each macro-category, the average radon diffusion coefficients (D) were taken from the database of the Faculty of Civil Engineering of the Czech Technical University in Prague [14] according to the method developed in cooperation with the National Radiation Protection Institute in Prague that follows the ISO/TS 11665-13 standard [15]. Table 2 shows the number of tested materials for each membrane type and the calculations conducted. Only the values concerning a 2mm-thickness of each membrane are shown to ease the process.

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

Typology	No. of tested materials	avg. D [m^2/s]	λ [s^{-1}]	avg. l [m]	avg. R_{Rn} [Ms/m]
MAP	98	1.71×10^{-11}	2.1×10^{-6}	2.85×10^{-3}	127
SMA	52	2.67×10^{-11}	2.1×10^{-6}	3.57×10^{-3}	79
SPC	36	1.96×10^{-10}	2.1×10^{-6}	9.65×10^{-3}	10
PVC	72	1.72×10^{-11}	2.1×10^{-6}	2.86×10^{-3}	126
MA-PE	19	1.54×10^{-11}	2.1×10^{-6}	2.71×10^{-3}	142

The same calculations have been done for other thicknesses (0.6mm, 1mm, 3mm, 4mm, 5mm) to better understand how the radon resistance, and even the environmental impacts, change in relation to the thickness. Those values have been selected according to the values that are usually used at the foundation level. For example, as mentioned in Table 1, PVC membranes are available in a range of thickness 0.6/2mm, while MAP membranes are in the range of 2/5 mm.

3.3 Environmental impact categories

After selecting the five macro-categories and choosing the proper kind of membrane for each of them, the Environmental Product Declarations (EPDs) collection for the environmental data for the LCA product stage (A1-A3) was done. Data sets for the embodied impacts were found in online and open-source databases, such as EPD International [16], Ökobaudat [17], EPD Online Tool [18], and EPD Ireland [19]. A potential constraint using the presented method is given using the construction options available in these LCA open-source databases. Table 3 shows which environmental parameters were considered for each building element in the A1-A3 product stage:

Table 3. Impact categories and their unit of measurement.

Impact categories	Acronym	Unit measure
Acidification potential	AP	[kg - SO_2 eq.]
Ozone depletion potential	ODP	[kg – CFC-11 eq.]
Global warming potential	GWP	[kg - CO_2 eq.]

The embodied impact calculation was not conducted in any specific LCA software but directly in MS Office Excel. Needed data were imported from the EPDs collected from LCA open-source databases. Every membrane was converted to the same thickness to compare the results properly.

4. Results

4.1 Radon resistance calculation for each membrane

First, the calculation of the radon resistance for each membrane and each selected thickness has been made following the method reported in the Methodology section. Figure 1 shows the results. As of today, the European Union has yet to define a uniform R_{Rn} value; instead, each country has different specifications based on the national building code. In Sweden, for example, there is a limit value of 50 Ms/m, whereas, in Czechia, the values vary based on the type of building.

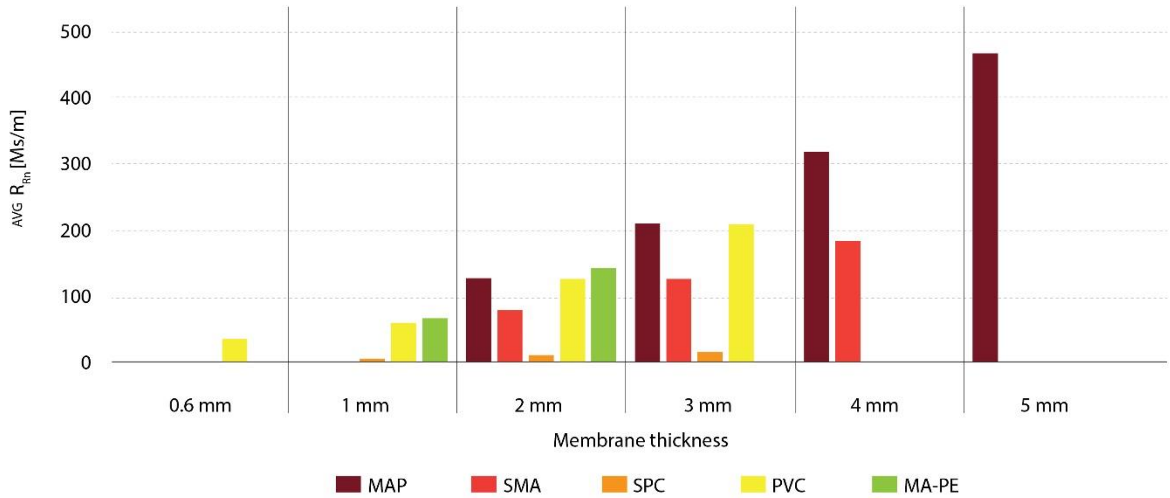

Figure 1. Overview of average R_{Rn} for different membrane thicknesses. A few values of radon resistance cannot be reached since it is not realistic to have those specific thicknesses for certain types of waterproof membranes.

As Figure 1 showcases, in some thickness ranges, the values of R_{Rn} can never be reached because the production of that membrane in that specific thickness is not available because it would not be effective in its scope – for example, it is not possible to produce 1-mm thickness membrane for the SMA and MAP. The 2-mm thickness is the most common among the selected membranes; indeed, considering a 2-mm thickness, the MA-PE membrane presents the highest R_{Rn} value (142 Ms/m) while the SPC membrane has the lowest rate (10 Ms/m).

4.2 Assessment of the environmental impact of radon barriers

Then the same process described in Section 4.1 was done for the environmental impacts (AP, ODP and GWP) in order to understand which membrane is the finest in terms of environmental impacts and radon protection; a comparison between the selected environmental parameters (AP, ODP and GWP) and the radon resistance has been made for each membrane and each of its potential thicknesses. Figure 2 shows the specific calculation for the AP indicator.

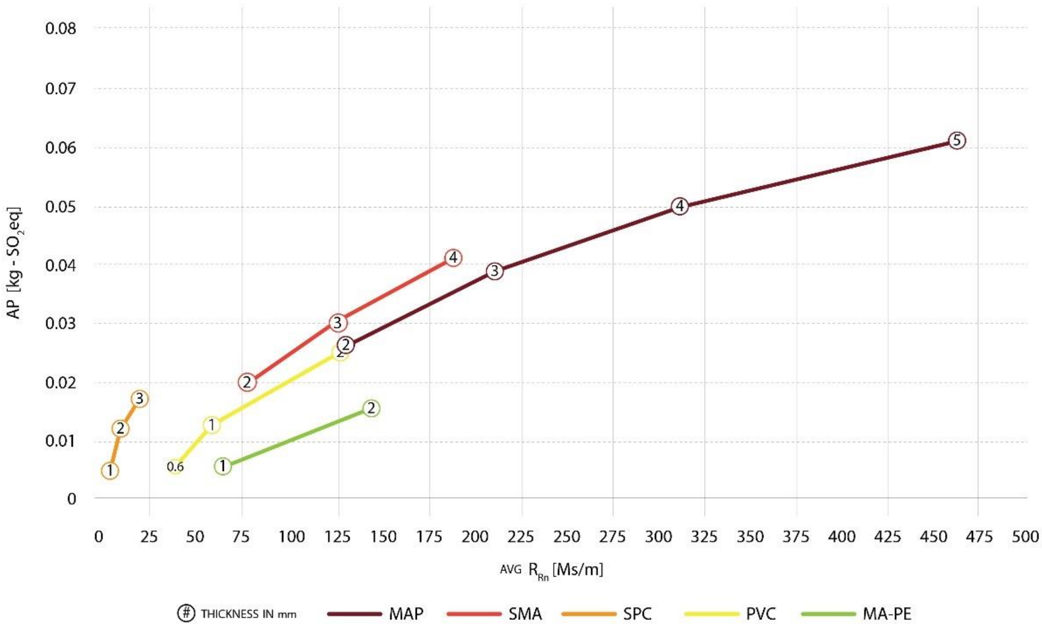

Figure 2. Overview of AP embodied impacts on five kinds of membranes in relation to radon protection and their thicknesses.

The embodied AP increases for every thickness from 0.6mm to 5mm for every kind of membrane. These impacts derive from the thickness of the membrane; for this reason, the thickness of 5 mm presents the highest embodied impacts, but this thick membrane is available only for the bituminous membrane; thus, in the case of PVC and MA-PE, the most significant impacts derive from 2mm-thick membranes.

The same outcomes shown in Figure 2 are visible in Figure 3 and Figure 4 that represent, respectively, the embodied impacts for ODP and GWP; even in these cases, there is linearity in the increase of emissions when the membrane thickness grows but, simultaneously, it can be noticed a rise in radon resistance. Indeed, considering a PVC membrane, for example, a greater thickness leads to higher GWP impacts but a better performance in terms of R_{Rn}. The same argument is valid for the other membranes.

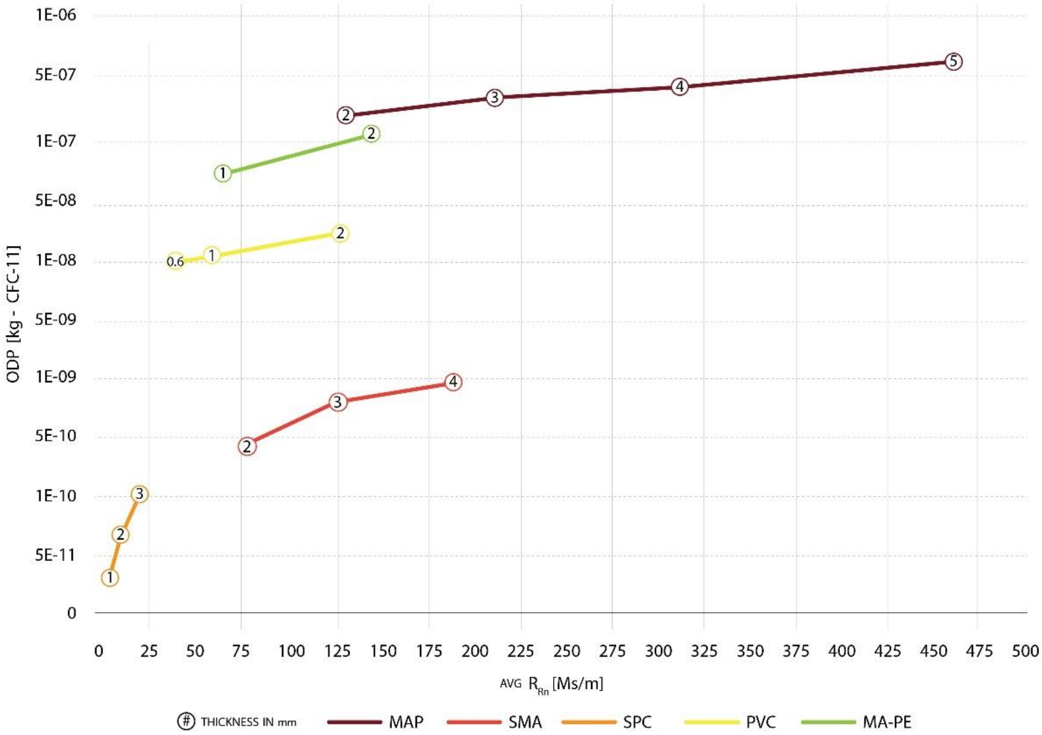

Figure 3. Overview of ODP embodied impacts on five kinds of membranes in relation to radon protection and their thicknesses.

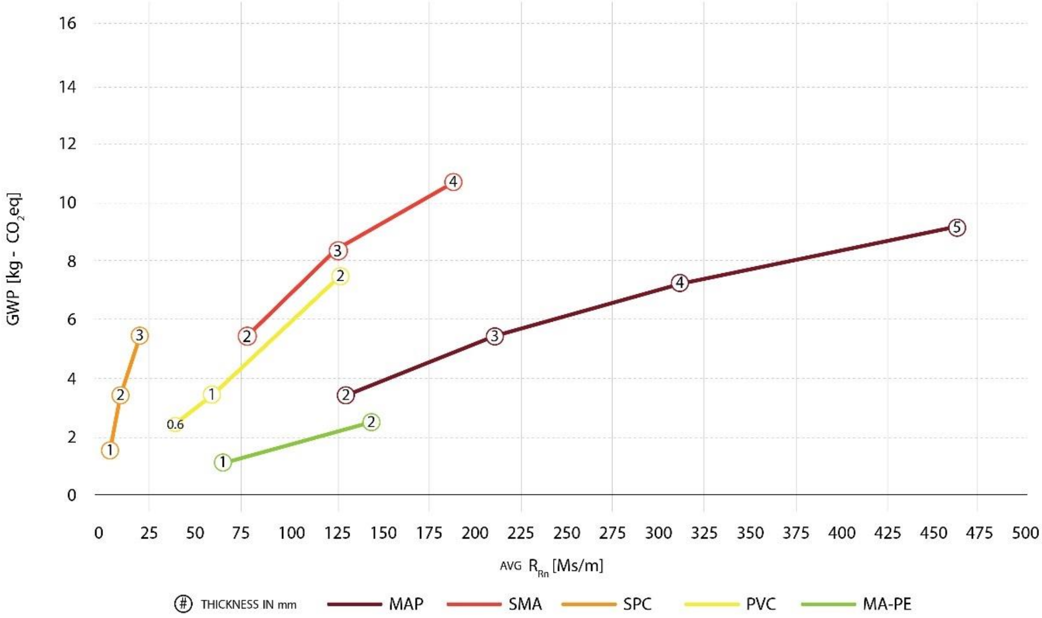

Figure 4. Overview of GWP embodied impacts on five kinds of membranes in relation to radon protection and their thicknesses.

5. Discussion

The results on embodied impacts for different membranes and their thicknesses allow observing how waterproof membranes produce more or less evident effects during the "cradle-to-gate" stage. One of the relevant outcomes of this study is that radonproof membranes bring additional embodied impacts if used in high thicknesses but, in contrast, if used thinner membranes, the radon resistance values decrease, leading to a lower-efficient performance. The graphs clearly show that as the radon resistance of the membrane increases, the values of all three impact categories (AP, ODP and GWP) rise, which means that the environmental impact worsens. However, significant differences can be found between individual material types of membrane. The selection of suitable insulation is complicated by the fact that individual material types of membrane are produced in different thicknesses and achieve different values of radon resistance. For example, for radon resistance from 75 to 125 Ms/m, three material types of membrane are available - PVC, SMA and MA-PE. If the task is to reduce AP or GWP as much as possible, MA-PE membrane will be the right choice. Conversely, if the aim is to reduce ODP as much as possible, SMA should be used. However, if a radon resistance greater than 200 Ms/m is required, then only MAP is available among the studied barriers. This means that the choice of a membrane cannot affect the environmental impact in this area.

The waterproofing, which performs radon barrier, must have a greater radon resistance than its minimum value prescribed by national building standards or codes. For example, according to SINTEF [20], the minimum value of radon resistance is 50 Ms/m. According to the Czech technical standard CSN 73 0601 or [21], the values of the minimum radon resistance range from 2 to 300 Ms/m depending on several parameters, such as the type of building, category of radon prone area, ventilation intensity, the required indoor radon concentration or the existence of other radon control technologies. Higher values of radon resistance are required for houses with lower ventilation intensity in high radon-prone areas and in the absence of any other radon control measures.

Therefore, the impact of the radon barrier on the environment can be reduced in three ways, (i) by choosing the insulation material that has the least impact, (ii) by not using membranes with radon resistances unnecessarily exceeding the minimum resistance value and by overall optimization of the radon protection design, (iii) it is necessary to verify whether the minimization of the insulation impact is not offset by the impact caused by the increase in the ventilation or by installing other measures. The study of the impact of combined measures on the environment will be the subject of further research. Similarly, the environmental evaluation of other types of waterproofing materials will be investigated.

6. Conclusion

This paper was created as a part of the EU RadoNorm project under the umbrella of the Horizon 2020 framework programme (H2020). This project aims to reduce the indoor radon concentration level, but one task is to analyse the additional embodied impacts of radon control techniques for three indicators (AP, ODP, and GWP).

The research confirmed that the insulation design methodology, based on several minimum values of radon resistance instead of a single value, allows minimizing the impact of insulation on the environment significantly.

Acknowledgements

This work has been funded by the project RadoNORM, which has received funding from the European Union’s H2020 framework programme for research and innovation under grant agreement No. 900009 and SGS22/084/OHK1/2T/11 project from the Czech Technical University in Prague.

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