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Web tool for quantitative sustainability evaluation of hygro-thermally optimized insulation solutions

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Abstract. This study is part of the EU funded project RiBuild and aims to create a web tool for supporting decisions relating to energy retrofits of historic buildings. The web tool provides a quantitative sustainability evaluation of hygro-thermally optimized insulation solutions through a greenhouse gas (GHG) emissions indicator. The study presents LCAs of five insulation systems for installation in historic buildings. The web tool accommodates 160 locations in seven countries and generates 210,180 impact profiles by combining insulation system, installation location, and heating systems. In 2 % of the scenarios, the induced impacts exceed the avoided impacts. Across all analyses, the mineral wool insulation system is the least GHG intensive solution. This study illuminates that the environmental justification of internal insulation depends on the geographical location of installation and the installed heating system in the retrofitted building. To further improve the sustainability performance of energy retrofits in historic buildings, the implementation of insulation recycling solutions and measures for reducing production impacts of insulation systems are needed.

1. Introduction

The potential consequences of climate change and the concomitant rise in global mean temperatures has received global attention and priority. The European Council [1] has set a target of 40 % reduction in GHG emissions by 2030 compared to 1990 levels. As the existing building stock accounts for 40 % of the energy use and 36 % of the GHG emissions [2, 3], energy retrofits for improvement of the energy efficiency of existing buildings offer a great potential to reduce the European GHG emission levels.

Historic buildings are part of the existing building stock and represent architectural, as well as historical and cultural values, that need to be preserved. Consequently, energy retrofits of historic buildings pose different constraints and challenges than traditional insulation retrofits, as their visual character and building fabric must be considered [4, 5]. External insulation retrofit measures impact the aesthetic appearance of a building, why these solutions are not always a possible option when renovating historic buildings. In this light, different approaches such as internal insulation retrofits, must be considered. However, these solution options are less favorable from a hygro-thermal point of view, as the temperature of the external wall is decreased when applying insulation internally. The subsequent lowered dew point and increase



in relative humidity between insulation and the external wall aggravate the risk of condensation and mold growth [6].

The Horizon 2020 project "*Robust Internal Thermal Insulation of Historic Buildings*" (RiBuild) is a research project which aims to develop comprehensive guidelines for improving energy performance of historic buildings while maintaining a minimal risk of mold growth through hygro-thermal optimization of internal insulation retrofits. RiBuild is a collaboration between research institutions across seven European countries: Belgium, Denmark, Germany, Italy, Latvia, Sweden, and Switzerland. In the RiBuild project, historic buildings are defined as all protected and non-protected buildings constructed before 1945 [6].

1.1. Objective and scope

With this study, a quantitative sustainability assessment web tool is created for the RiBuild project to assess the climate burden impact of insulation systems for energy retrofits of historic buildings. The sustainability assessment provides an additional angle to the hygro-thermal optimization to support decision-making of the most appropriate internal insulation solution in a renovation scenario. This study will provide a quantitative life cycle assessment (LCA) of hygro-thermally optimized insulation solutions for historic buildings. In practice, the web tool accommodates a range of unit climate burdens (kg CO₂-eq) for a range of unit operations on induced impacts (i.e. from production, transport, installation, and disposal of the insulation systems) and avoided impacts (i.e. from saved energy consumption), which through the user interface can be combined with a multitude of application scenarios (geographic locations, heating systems, and wall types in the existing building). The study covers five project tailored insulation systems with various thickness (consisting of the insulation materials calcium silicate, polyurethane, phenolic foam, mineral foam, and mineral wool) for installation in 160 locations across the seven participating countries with a lifespan of 30 years from 2020-2050.

2. Method and materials

The LCA of the insulation systems in this study follows the ISO14040 and ISO14044 standards [7, 8], and covers the following steps: *goal and scope definition*, *life cycle inventory analysis*, *life cycle impact assessment*, and *interpretation*.

The intended application of this study is a comparative LCA of five project tailored insulation systems selected on their hygro-thermal performance for an internal insulation retrofit of historic buildings.

The system boundaries of the insulation systems covered, are in accordance with EN15804:2013 [9]: the production stage (A1-A3), the assembly stage (A4-A5), the operation energy use stage (B6), and the end-of-life stage (C1-C4), thus, making this a 'cradle-to-grave' simplified LCA. The impacts from the life cycle stages A1-A5 and C1-C4 are considered induced impacts, whereas the impacts from the life cycle stage B6 are considered avoided impacts via saved energy consumption for space heating. The saved energy consumption is calculated using the Heating Degree Days (HDD) method. only transmission losses are considered, and infiltration losses are disregarded. Maintenance (B2) and replacement (B4) have been excluded from this LCA, as the projected service lives of the materials for the insulation systems are longer than the life cycle defined in this assessment. The life cycle inventories (LCI) are modeled as attributional with allocation at the point of substitution, as this assessment is a comparison of specific goods which is in accordance with the ILCD guidelines [10]. LCIs have been modeled using the *SimaPro 8.5.2.0* software. The functional unit (F.U.) for the web tool is defined in alignment with the intended application of the study as:

1 m² insulation system with the equivalent U-value installed as a part of an energy retrofit of a historic building with the lifespan of 30 years from 2020 to 2050.

The LCIA method used is CML-IA baseline 3.05 with normalization factor EU25+ 2000.

2.1. Life cycle inventory

The five insulation systems and their variations for assessment in the web tool were chosen by the RiBuild research team based on their hygro-thermal properties (Table 1).

Table 1: Overview of material properties of the insulation systems included in the web tool. Insulation system S1 has four thickness variations, S3 has six, while S1, S4, and S5 have three each

System ID	Thickness [mm]	Material	λ [W/mK]	ρ [kg/m ³]	Manufacturer
S1	10	Lime Plaster	0.68	1480	Calsitherm
	25, 30, 50, 80	Climate Board	0.059	187	Calsitherm
	5	Glue Mortar	0.6	1410	Calsitherm
S2	10	iQ-Top	0.111	700	Remmers
	30, 50, 80	iQ-Therm	0.031	45	Remmers
	8	iQ-Fix	0.497	1500	Remmers
S3	20, 45, 65, 80, 90, 110	Phenolic Foam	0.018	40	Kingspan
	12.5	Gypsum Board	0.25	712	Knauf
S4	10	Climate Plaster	0.68	1480	Calsitherm
	60, 80, 100	Mineral Foam	0.045	115	Xella
	5	Glue Mortar	0.6	1410	Calsitherm
S5	0.22	Vapor Barrier	-	363.63	Saint-Gobain Isover
	70, 95, 120	Mineral Wool	0.032	33	Saint-Gobain Isover
	22	Air	-	-	-
	12.5	Gypsum Board	0.25	712	Knauf

The study seeks to assess product-specific systems by using country and manufacturer-specific data through environmental product declarations (EPDs) and data sheets when possible. Background data and additional data was derived from the *ecoinvent 3.4* database. The inventory modeling of phenolic foam insulation was based on Densley Tingley et al. [11]. No information was found on the Climate Plaster and the Glue Mortar, both in S4, and these system parts were assumed to be identical with the Calsitherm Lime Plaster and Glue Mortar in S1. The remaining production processes and background processes were modeled using existing *ecoinvent 3.4* processes. In the end-of-life stage, all materials were assumed to be landfilled.

The reduced transmission losses occurring as a result of an internal insulation retrofit lead to savings in energy consumption and consequently avoided GHG emissions. For each country, the three most common heating systems for residential space heating have been chosen based on data from the Heat Roadmap Europe and the Swiss Energy Department [12, 13] (Table A1). For the biomass furnace, country-specific modeling was only possible for Switzerland due to limitations of *ecoinvent 3.4*. For the remaining countries, Europe was chosen as representation. The energy carrier composition for district heating and electricity were based on country specific mixes. The remaining heating systems were modeled using country-specific processes from *ecoinvent 3.4*. The web tool accomodates five choices of existing wall types for calculating reduced transmission losses (Table A2).

Weather data for calculating HDD profiles for retrofit locations for the period 2020-2050 were obtained from the European research project Climate for Culture. These weather data were derived from climatic simulations based on the Intergovernmental Panel on Climate Change (IPCC) AR₄ A₁B climate change scenario and was subsequently adjusted for these projections of future GHG emissions scenarios [14, 15].

3. Results

The sustainability web tool provides a climate burden indicator to assist selection of the most appropriate insulation system for retrofits of historic building. In the user interface part, the user is requested to define the renovation scenario through specification of the renovation location, the heating system of the building, and the composition of the existing wall (Figure 1). Based on these choices, the web tool generates the climate burden indicator for the insulation systems in terms of induced impacts from 1 m^2 insulation systems and avoided impacts via the saved energy consumption for 1 m^2 wall section. For the specific scenario defined by the user, the results for all insulation solutions options are displayed. A mock-up of the web tool has been developed using Microsoft Excel and generates 213,180 possible impact profiles for application solutions.

User input page

Here, you define the properties of the historic building that needs an internal insulation retrofit. These choices affect the sustainability performance of the insulation solution.

Choose the country for your renovation project here ↓	Choose the nearest located city for your renovation project here ↓	Choose the heating system of the building here ↓	Choose the stone type which the existing wall consists of here ↓	Choose the thickness of the existing wall here ↓
Country	City	Heating system	Existing wall stone type	Existing wall stone thickness
Belgium Denmark Germany Italy Latvia Sweden Switzerland				

Figure 1: Screenshot of the user input page of the web tool

In order to determine the most appropriate insulation system for a renovation project, the insulation systems are compared based on their induced impact, the avoided impacts and their net impact profiles. For equal comparison of the insulation systems, the F.U. has been adjusted to:

1 m² insulation system with U-value 0,5 W/m²K installed as a part of an energy retrofit of a historic building with an existing wall of Wienerberger brick with thickness 400 mm and $\lambda = 0,801 \text{ W/mK}$ and a lifespan of 30 years from 2020 to 2050.

For all application scenarios, S5 (mineral wool) has the smallest induced impact profile and S1 (calcium silicate board) has the biggest (Figure 2).

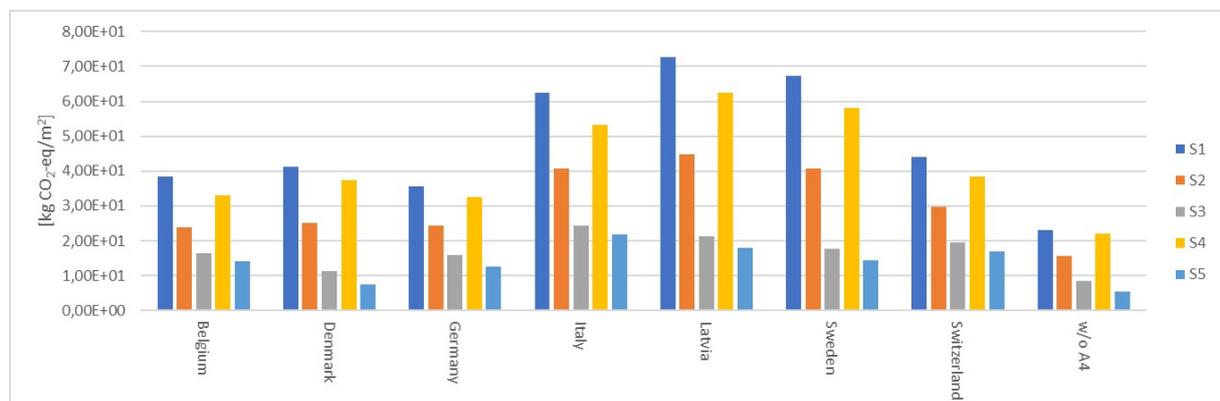


Figure 2: Induced impact profiles (A1-A5 and C1-C4) for all insulation systems for each country and excluding the transportation stage A4

The transportation impact can potentially double the induced impacts depending on the distance. Most of the materials contained in S5 are produced in Denmark resulting in a small contribution to the total induced impact when comparing with the scenario excluding the transportation stage. For S5 installed in Italy, the transportation contributes with approximately 75 % of the total induced impact of S5.

The avoided impact from saved energy consumption consists of the avoided transmission loss through the wall section with and without a retrofit, the climatic profile of the location, and the GHG emission intensity of the heating system. The comparison of the avoided impacts is based on the average HDD profile for each country (Figure 3).

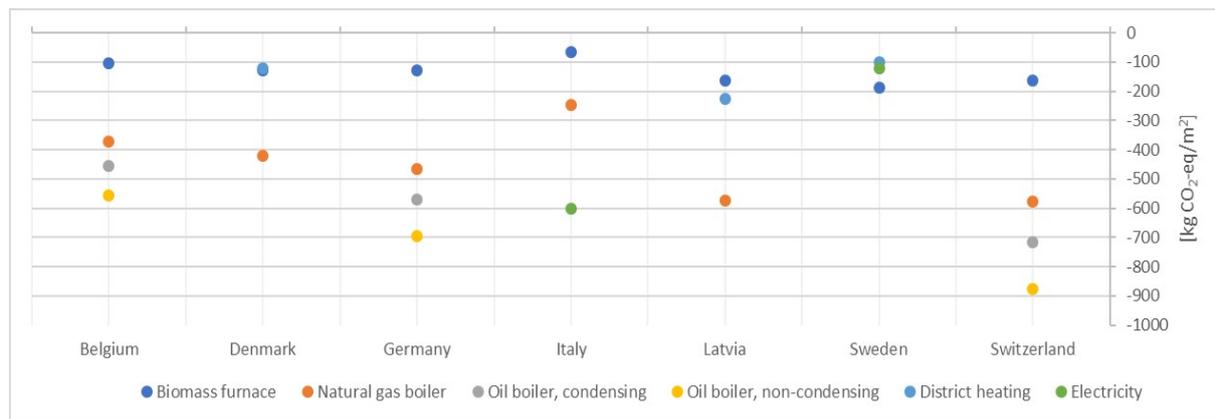


Figure 3: Avoided impacts (in kg CO₂-eq/F.U.) for each heating systems within each country for the entire period 2020-2050

The avoided impacts based on the saved energy consumption for space heating for each country changes with the type of heating system used. For all countries except Sweden and Denmark, the biomass furnace results in the smallest avoided impact. For these two countries, the smallest avoided impact came from district heating. For Sweden, the biomass furnace resulted in the largest avoided impact, highlighting the low GHG emission intensity of the Swedish district heating and electricity production. For the countries with oil boilers as an option (Belgium, Germany, and Switzerland), the non-condensing oil boiler results the largest avoided impact. For Denmark and Latvia it is the natural gas boiler which results in the largest avoided impact. Electricity results in the largest avoided impact in Italy which highlights the high GHG emission intensity of the Italian electricity production.

The insulation systems' net impact profiles follow the trend of the avoided impacts (Figure 4). All net impact profiles show negative values which indicates that the GHG emissions savings from saved energy consumption are greater than the induced impacts from the insulation systems throughout the life cycle. The heating systems with the highest GHG emission intensity result in the biggest GHG emissions savings for the insulation systems. For all application scenarios S5 (mineral wool) performs best and S1 (calcium silicate board) performs worst.

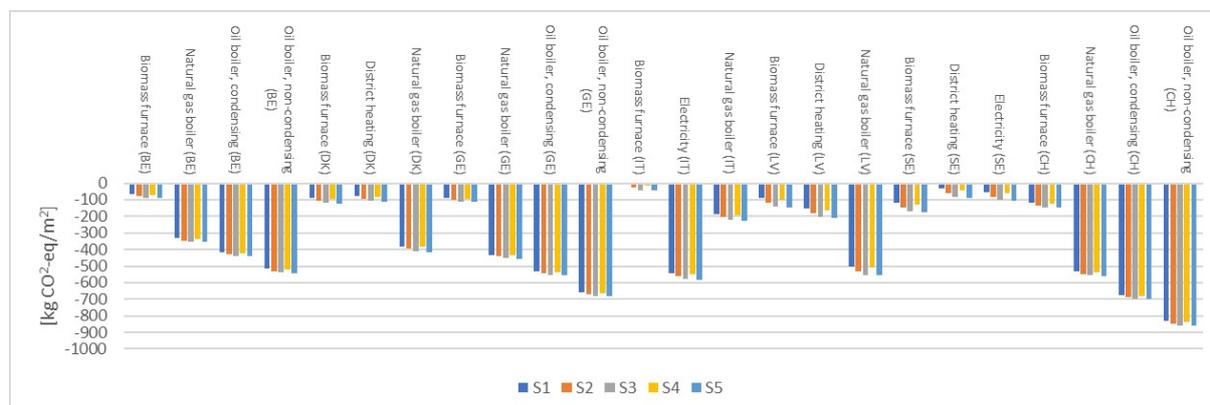


Figure 4: Net impact profiles for all insulation systems for each country specific heating system

3.1. All net impact profiles generated in the web tool

Some of the 213,210 net impact profiles generated from the application scenarios in the web tool result in positive net impact profiles (Table 2). Positive net impact profiles occur when the insulation systems impact with a higher GHG emission intensity than what is avoided due to saved energy consumption over the 30-year lifespan. The frequency of application scenarios with a positive net impact is most pronounced for Italy, followed by Sweden. Italy has the smallest average saved energy consumption and Sweden has the least GHG emission intensive heating systems (Figure 3). No scenarios produced a positive net impact in Latvia.

Table 2: Number of net impact results for each country and the number and percentage within these with a positive net impact

Country	n	n > 0	% > 0
Belgium	6080	8	0.13
Denmark	4560	1	0.02
Germany	91200	7	0.01
Italy	54720	4121	7.53
Latvia	2280	0	0
Sweden	28500	141	0.49
Switzerland	25840	16	0.06
Total	213180	4294	2.01

4. Discussion

The comparison of the insulation systems' induced impacts for the seven countries did not yield differences in the ranking of the most appropriate insulation solution. However, the transportation distance's contribution changes the performance of the individual insulation system when comparing between the countries. Thus, when deciding on materials for an internal insulation retrofit, the location of the production site should be taken into consideration.

For the avoided impacts, a large avoided impact was associated with either a cold climate, a GHG emission intensive heating system or a combination of the two. Sweden yielded the largest average saved energy consumption, but the smallest distribution range values of avoided impact for the heating systems, showing that the energy grid supplying heating has a considerable influence on the sustainability benefit of a retrofit in a renovation scenario. A study conducted by Ghose et al. [16] concluded that maximum benefits only occur if the post-retrofit energy grid is based on high coal generation, supporting the findings of this study.

2 % of all net impact results were positive (i.e. an excess of induced impacts). In these scenarios insulation retrofit measures would not be sustainable solution as the avoided impacts associated with energy consumption savings do not cover the induced impacts associated with the insulation systems. The occurrence of positive impact profiles was most pronounced for Italy, followed by Sweden, and shows that in general, the energy retrofits are most sustainable for colder climates with heating systems of high GHG emission intensity. Dylewski & Adamczyk

[17] find that the most ecological cost-effectiveness was found for the scenario of worst performing heat source in the coldest climate zone and the least ecological cost-effective solution was found for the scenario including the best performing heat source in the warmest climate zone. In addition, Oregi et al. [18] (cited in Karimpour et al. [19]) note that the induced impact from embodied energy of building materials can account for up to 35 % of future emission targets of a building constructed in a mild climate.

With the development towards more sustainable and less GHG emission intensive energy grids, the avoided impacts are diminished and the induced impacts become more influential of the insulation systems' overall performance. However, a decreased avoided impact implies a less GHG intensive energy grid for heating which in itself is a more sustainable scenario. Sohn et al. [20] emphasized that integrating a dynamic energy mix in building LCAs is preferable to a static energy mix, as future projections are available and this provides an indication of the building's overall environmental performance against possible future energy mix scenarios. When taking this development towards more sustainable technology into account, measures towards reducing induced impacts from production are needed to improve the overall sustainability performance of the insulation systems [21, 22]. Another approach would be introducing recycling solutions, either through the use of recycled materials or improving the recycling potential when carrying out energy retrofits. Ingraio et al. [23] highlighted the improvement of insulation systems' environmental performance by using recycled insulation materials compared to conventional (i.e. straight from the plant) insulation materials.

In this study, the best performing insulation system consisted of mineral wool as insulation material (S5). As the only system, S5 needs a vapour barrier which implies a risk of condensation from cooling of the existing wall. Therefore hygro-thermal simulations are essential when choosing an internal insulation solution for energy retrofits of historic buildings. The hygro-thermal performance and the climate burden impact profile might potentially result in opposing recommendations for decisions regarding the most appropriate choice of insulation system.

5. Conclusion

A web tool for assessing the most appropriate insulation solution for energy retrofits of historic buildings based on their climate burden impact has been created. The web tool generates a total of 213,210 impact profiles. This study compares the life cycle performance of the five project tailored insulation systems included in the web tool based on the same U-value of $0,5 \text{ W/m}^2\text{K}$.

Of the five insulation systems, S5 performed best across all analyses. However, as this insulation system needs a vapour barrier, it might not be the most appropriate insulation system when taking the hygro-thermal performance into account. For decision-makers who commission the LCA of insulation systems for energy retrofits of historic buildings, these conditions must be carefully considered as they will affect recommendations regarding the most appropriate solution for renovation of historic buildings.

Analysis of the avoided impacts showed that the combination of a large saved energy consumption and low GHG intensity heating system resulted in minor avoided impacts, whereas the combination of small saved energy consumption and high GHG intensity heating system resulted in a large avoided impact.

In some scenarios, insulation retrofit measures did not provide a sustainable solution as the induced impacts exceeded the avoided impacts. This situation was most pronounced for Italy, followed by Sweden, and showed that in general, energy retrofits are most sustainable for the combination of colder climates and GHG intensive heating systems. In combination with the projected development towards more sustainable energy grids, these findings elucidate that the environmental justification of internal insulation in energy retrofits depends on the geographical location of installation and the type of heating system supplying the building being retrofitted. Therefore, the implementation of recycling solutions and measures for reducing production

impacts are needed to further improve the sustainability performance of energy retrofits in historic buildings.

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Appendix A.

Table A1: Heating systems for space heating

Heating system	Countries
Biomass furnace	All countries
Natural gas boiler	CH, BE, DK, GE, IT, LV
Oil boiler, cond.	CH, BE, GE
Oil boiler, non-cond.	CH, BE, GE
District heating	DK, LV, SE
Electricity	IT, SE

Table A2: Stone types and thickness variations for the existing walls and their thermal conductivity coefficient

Stone type	Thickness [mm]	λ [W/mK]
Brick Weinerberger	300, 400, 500, 600	0.801
Lime Sand Brick	300, 400, 500, 600	1.0
Sandstone Monte Merlo	300, 400, 500, 600	0.956
Tuff Ettringen	300, 400, 500, 600	0.481
Granite	300, 400, 500, 600	1.7

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