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A carbon-focus parametric study on building insulation materials and thicknesses for different heating systems: A Swiss case study

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Abstract. To tackle the problem of climate change, Swiss energy strategies aim to reach the carbon neutrality by 2050. However, this challenge cannot simply be solved by focusing on the operational energy performance and instead, on a lifecycle evaluation. Thus, in order to reduce the sector's carbon footprint, building stakeholders need to consider embodied GHG emissions of construction materials. In this study, a parametric method was developed to balance operational and embodied impacts of insulation strategies on GHG emissions according to the material and heating system choices. The methodology is split into two for the computation of the overall carbon emissions of the heating plus insulation system. Firstly, the calculation of the embodied emissions, which relies on Environmental Product Declarations of different construction materials. Secondly, the calculation of the operational emissions, which is the product between the thermal energy needs and the energy carbon content of the respective heating system. Thereafter, the methodology was applied to two case studies: an existing building and a brand-new building. The first main finding was that, for high-carbon insulation materials, there was clearly an optimal thickness after which, adding insulation would only increase the lifecycle impact of the system. For instance, in the heat-pump equipped case study, installing 35 cm of extruded polystyrene insulation (XPS) is more harmful towards global warming than installing 17 cm of XPS. This trend was not present for low-carbon materials whatsoever. The building's carbon emissions benefitted from their addition of insulation up to the maximum thicknesses studied. To conclude, it is also important to highlight that aimlessly targeting energy efficiency can be a step back towards the goal of carbon neutrality. Indeed, it is possible to claim that for energy efficient buildings, fossil fuel-based insulation should be carefully used. This study allowed the development and application of a method that identifies optimal insulation thickness and material for a given heating system and hopefully, highlight the importance of considering both embodied and operational emissions of construction materials and systems.

Keywords: building insulation material, building LCA, embodied impacts, parametric analysis.



1. Introduction

The effects of the climate crisis due to the excess emissions of greenhouse gas (GHG) into the atmosphere are already affecting life on Earth. As global warming temperatures reach upwards of 1.3°C [1], the importance of mitigating these emissions has been a recent priority of the United Nations' with the creation of the Climate Change Conference (COP). Notably, during 2015's COP, 196 countries engaged themselves into limiting global warming to 2°C with nationally determined contributions [2]. The construction and subsequent operation of buildings is a great contributor towards the global warming process, accounting for 38% of carbon dioxide (CO₂) emissions in recent years [4]. Ever since the Yom Kippur War and the oil crisis of 1973, a global focus on energy efficiency has taken place, including on the building sector. Indeed, the first regulation focused on insulation and ventilation of residences took place in France in 1974, followed by other Western European nations in the years that followed [5].

This global effort still exists today. Focusing on increasing energy efficiency and promoting the implementation of renewable energy sources [6], the term Net Zero-Energy Buildings (nZEB) has been widely used by sector specialists since 2010 [7]. The goal with such standards is to achieve energy and carbon neutrality during the operational phase of buildings' lifecycle. However, a portion a building's carbon footprint is linked to its embodied emissions and as buildings become more energy-efficient, the more relevant embodied emissions are [8]. In fact, the importance of the embodied GHG in building's lifecycle Global Warming Potential (GWP) have been trending upwards, reaching a ratio of 1:1 between operational and embodied emissions [6].

The objective of this study is to explore this relationship between embodied and operational GHG emissions, notably when designing the building's heating system and its performance, specifically in the Swiss context. For such, a parametric study was made on a case studies of a typical residential building in order to determine the impacts of insulation material and thickness on the lifecycle GWP.

In the following chapter, this paper will justify the feasibility and necessity of this parametric study in the Swiss context. Thereafter, a new methodology that better allows the comparison of GHG emissions between the different scenarios of this case study will be presented. Thirdly, the case study will be fully described, along with the modifiable parameters of the parametric methodology. Finally, the results will be shown with a discussion on them and on the limits of this research.

2. State of the Art

Life Cycle Assessment (LCA) is a methodology that allows for an environmental evaluation of different phases in a product's lifetime, standardized by the ISO14040/44 [9]. Between various environmental impacts (eg. ozone layer and resource depletions, acidification, water consumption and eutrophication [10]), LCA evaluates the Global Warming Potential (GWP) of all GHG emissions of a given product in equivalent kilograms of carbon-dioxide (kgCO₂-eq). As embodied impacts become more relevant, LCAs have been more widely used as a decision-making tool for building design.

For the building sector, the norm EN15804 defines Environmental Product Declarations (EPDs) [11], which describe an LCA of a given construction product or service. In Switzerland, the KBOB (Conference for the Coordination of Building Organizations and of the Property of Public Clients) [12] assembles a database (DB) of EPDs for materials used in the Swiss territory. With this DB, it is possible to calculate the embodied GWP of a building while, for the operational GWP calculations, an energy simulation is needed. For that, Lesosai [13], a simulation software that uses the Swiss SIA 380 [14] was chosen.

The optimization of insulation material and thickness is a recurrent topic of research using lifecycle cost analysis [15] or lifecycle primary energy [16], for example. Meanwhile, some studies do indeed consider GHG emissions. In [17], a case study is done for Norway, where the authors optimise insulation thickness by computing lifecycle emissions. However, in this study, only insulation thickness was

modelled, while material and heating type was fixed. In [19], the authors do a multi-objective optimisation of energy consumption and environmental impact through a Pareto front on an Iranian residential building. But in this case, the authors do not compare the relationship between insulation thickness and environmental performance. In [20], Amiri optimises thicknesses and material types by using an indicator that takes economic, environmental and energy factors into account. The authors do study the environmental impact of a building as function of insulation thicknesses; however, it is difficult to compare and interpret the different results of the parametric study uniquely for carbon emissions. For this reason, a GWP mitigation potential calculation was introduced in this paper, which will be fully described in the following sections.

It is also important to highlight that the insulation material optimization is highly contextual and thus, the results found in different publications cannot be directly compared. The GHG emissions of a building highly depend on the country's weather conditions, electricity mix and construction material's EPDs, for instance. To the best of the author's knowledge, only [18] has done a similar study on the Swiss context, however this paper was published in June 2013 and the author used the Ecoinvent database for a renovation case study. Moreover, this article studies different electricity power mixes, instead of varying the heating system types. As will be explained in the following chapter on the methodology, the two papers also differ on that front.

3. Methodology

The focus of this paper is on insulation materials and heating systems. Thus, only the lifecycle GWP of these two parameters will be considered for the LCA calculations. We assume that changing the insulation material or the heating system does not affect the other building components. For the energy modelling, the changes between the distinct variants will be described in the following chapter: Case Study. Here, the methodology will be described through three main steps on the subsections below: calculation of embodied GWP; calculation of operational GWP and the calculation of the lifecycle GWP mitigation potential.

3.1 Embodied GWP

Firstly, embodied GWP is characterized by the environmental impacts of the fabrication and end of life of given materials (modules A1 through A3 and C3 through C4, respectively), as defined in EN 15978 [9]. This impact is given by the KBOB for a functional unit, in the case of insulation, for the kilogram of material installed. Before that however, thermal bridges are considered according to the following equation:

$$U_{wall} = U_{target} - Thermal\ Bridging$$

Where U_{wall} is the wall conductivity and U_{target} is the target conductivity without thermal bridging that will be used subsequently for insulation quantity calculations. Insulation thickness is then calculated with the equation:

$$e = \left(\frac{1}{U_{target}} - \frac{1}{U_{structure}} \right) \times \lambda_{insulation}$$

Where e is insulation thickness in meters, $U_{structure}$ is the conductivity of the structural sections of the walls and $\lambda_{insulation}$ is the thermal conductance of the insulation material. Once the insulation is quantified, the insulation's embodied GWP is calculated through the equation below:

$$GWP_{Insulation} = m \times GWP_{unit} \times \frac{LB}{LM}$$

On the KBOB's database of EPDs, insulation material's functional units are in kilograms and thus, the variable m in the equation above is the mass of insulation required to achieve a given target conductivity. GWP_{unit} is the kgCO₂-eq emissions for every kilogram of insulation material used. LB is

the regulatory building lifetime of 60 years, according to the Swiss norm SIA 2032 [21] and LM is the lifetime of the insulation. This factor in the equation represents the future renovations to the building as materials reach the end of their service lives. As for the embodied GWP of the heating systems, the equation below is used:

$$GWP_{HS} = P \times GWP_{HS} \times \frac{LB}{LM_{HS}} + l \times GWP_{geo} \times \frac{LB}{LM_{geo}}$$

Where GWP_{HS} is the heating system's embodied GHG emissions, P is the quantity of a given heating system required to heat the thermal volume, which is the nominal power for heat pumps and the reference surface for all other heating systems. The second part of the equation only applies to the embodied emissions of the geothermal heat pump, where l is the length of the geothermal pipes and GWP_{geo} is the GHG emissions per meter of piping. Finally, the embodied GWP is calculated as shown below:

$$GWP_{Embodied} = GWP_{HS} + GWP_{Insulation}$$

3.2 Operational GWP

In this study, operational GWP is limited to energy use for heating, under module B6 of the EN 15978 [9]. The heating needs for every targeted thermal conductivity are simulated in the software Lesosai and then entered into the equation below as Heating Needs (HN). $CF_{heating}$ is the equivalent carbon dioxide emission per kWh of final energy and LB is the lifetime of the building.

$$GWP_{Operational} = HN \times CF_{heating} \times LB$$

3.3 GWP mitigation potential

Finally, to compare the different variants of this parametric study to a reference case, a GWP mitigation potential per reference surface and per year is calculated, according to the equations below.

$$GWP_{Overall} = GWP_{Embodied} + GWP_{Operational}$$

$$GWP_{reduction} = \frac{(GWP_{Overall,i} - GWP_{Overall,ref})}{LB \times S_{ref}}$$

In it, GWP_i is the lifecycle emission for each variant, GWP_{ref} is the lifecycle emission of the reference case and S_{ref} is the reference surface of the thermal envelope of the case study. For reference, in the Swiss environmental regulation SIA 2040 [22], the target lifecycle GWP of a new building of the same type is 12 kgCO₂/(m².year). This value includes all construction elements of the building, whereas $GWP_{Overall}$ only takes the heating system and insulation into account.

Finally, the reference building and the simulation parameters with which this study was done will be presented in the following chapter.

4. Case Study

The case study of the Swiss residence shown in Figure 1 was chosen according to a recommendation by an industry practitioner when asked for a representative Swiss residence.



Figure 1. Picture of Typical Swiss residence used for both case studies.

For the parametric study, the model changes are restricted to wall insulation thickness and the heating system and they do not affect other building characteristics, aside from thermal bridging and the ventilation systems, which will be detailed further in this section.

Target U-values studied ranges from 0.1 W/(m².K) to 1.0 W/(m².K), corresponding to a thermal resistivity from 1 to 10 m².K/W with a 1 m².K/W step. As for the material choices, Table 1 shows all insulation types simulated, based on the available EPDs.

Table 1. Insulation materials used for the parametric study.

Insulation material	Functional Unit	GWP _{insulation} [kgCO ₂ eq]
EPS-Expanded Polystyrene	Kg of insulation	7.64
XPS-Extruded Polystyrene	Kg of insulation	14.5
PUR-Polyurethane	Kg of insulation	7.52
Glass Wool	Kg of insulation	0.203
Woodfibre boards	Kg of insulation	0.445
Cellulose Fibre	Kg of insulation	0.257
Rock Wool	Kg of insulation	1.06

Meanwhile, the heating systems studied are listed in Table 2 with the respective GHG emissions for every kWh of energy needs for heating.

Table 2. Heating systems used for the parametric study.

Heating system	Functional Unit	Conversion Factor [kgCO ₂ -eq]
Oil Boiler	Heating needs in kWh	0.301
Air-Water Heat Pump	Heating needs in kWh	0.078
Geothermal Heat Pump	Heating needs in kWh	0.057
Wood Pellet Boiler	Heating needs in kWh	0.027

For both studies, the following simulation hypotheses were made:

- A double-flow ventilation with a heat exchanger is added when the model variant has a lower wall conductivity than $0.33 \text{ W}/(\text{m}^2.\text{K})$.
- Thermal bridging is a linear function of the wall conductivity of the model. For instance high-performance models with $0.1 \text{ W}/(\text{m}^2.\text{K})$ have $0.01 \text{ W}/(\text{m}^2.\text{K})$ of thermal bridging. While low-performing models at the other extreme, with $1 \text{ W}/(\text{m}^2.\text{K})$, have $0.1 \text{ W}/(\text{m}^2.\text{K})$ of bridging.

Finally, this study depends on a reference scenario, which is also based also on a typical Swiss building. Its main characteristics are shown in Table 3.

Table 3. Reference model's characteristics for the case study.

Parameter	Value
Insulation material	EPS
Building's target U-value	$0.14 \text{ W}/(\text{m}^2.\text{K})$
Insulation thickness	37 cm
Air-Water Heat-Pump's COP (if applicable)	2.8
Geothermal Heat-Pump's COP (if applicable)	3.9
GWP _{overall}	$5.4 \text{ kgCO}_2/(\text{m}^2.\text{y})$

With the case study and its respective references defined and the parameters identified, it is now possible to present and discuss the results obtained from the methodology.

5. Results and discussions

Here, the results of the parametric study will be illustrated by plotting the potential mitigation of GHG emissions as a function of the targeted thermal conductivity, varying from 1 to $0.1 \text{ W}/(\text{m}^2.\text{K})$. This U-value, as aforementioned, does take thermal bridging into account. A curve has been traced for every insulation material shown in Table 1.

For the graphics in Figure 2 through Figure 89, positive values signify a variant that performs worse than the reference, whereas the negative points are improvements from the reference scenario, described in Table. It must be noted that the scales of the different graphics shown in this section are not the same.

In Figure 2, each point represents the yearly GWP mitigation potential per square metres with an air-water heat pump system when compared to the reference. For instance, the yellow curve shows that the installation of XPS insulation never is more viable than the reference (EPS insulation, $U = 0.14 \text{ W}/(\text{m}^2.\text{K})$), since the yellow curve never dips under zero. Namely, in a low-efficiency building, with $1 \text{ W}/(\text{K}.\text{m}^2)$, using XPS will increase the carbon footprint of the construction by $5.8 \text{ kgCO}_2/(\text{m}^2.\text{year})$ and in the other extreme, with $0.1 \text{ W}/(\text{K}.\text{m}^2)$, it would increase it by $5 \text{ kgCO}_2/(\text{m}^2.\text{year})$. Finally, it is clear that for an EPS insulation (blue curve), the optimal target U-value would be closer to $0.25 \text{ W}/(\text{K}.\text{m}^2)$ or 18 cm in thickness, which would decrease the GWP_{Overall} by $1.1 \text{ kgCO}_2/(\text{m}^2.\text{year})$.

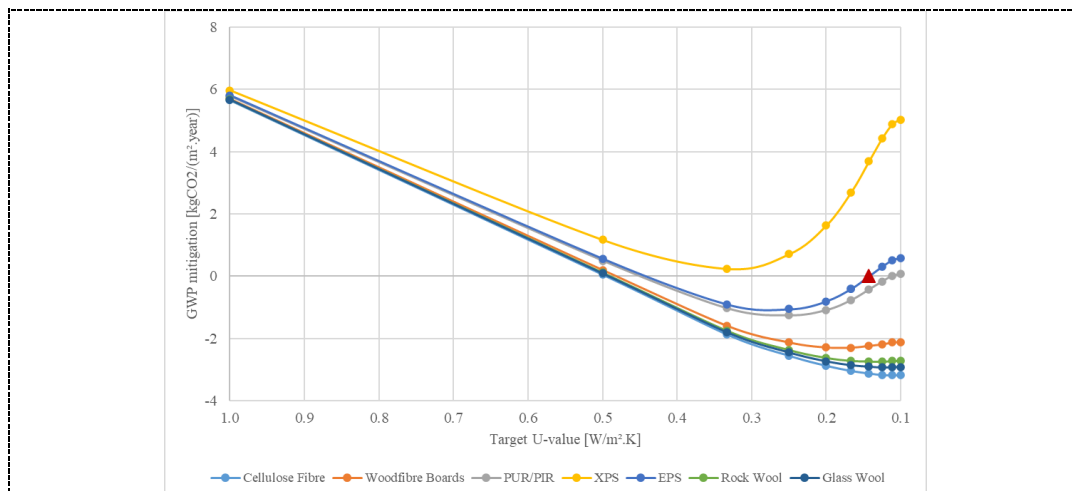


Figure 2. GWP mitigation per m² for different insulation materials and U-values with Air-water Heat pump. Reference: Heat pump system with EPS insulation and Target U-value of 0.14 W/m².K represented by the red triangle.

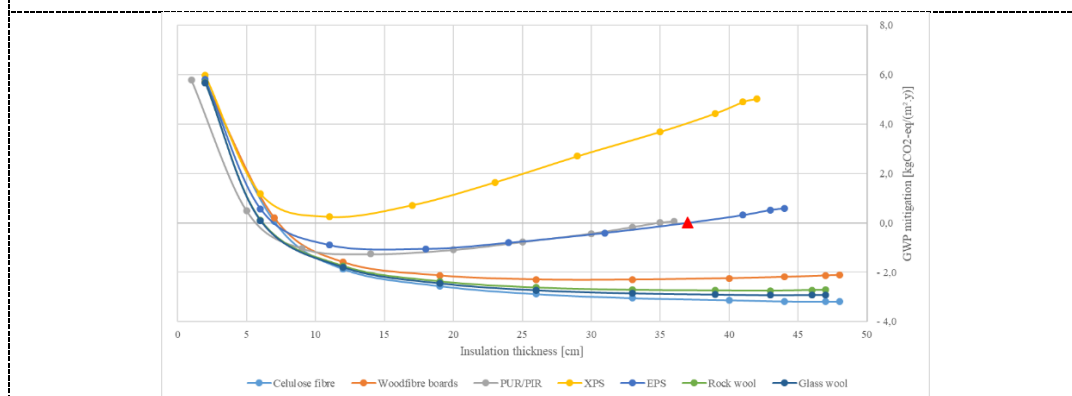


Figure 3. GWP mitigation per m² for different insulation materials and thicknesses with Air-water Heat pump. Reference: Heat pump system with EPS insulation and Target U-value of 0.14 W/m².K represented by the red triangle.

In Figure 4. GWP mitigation per m² for different insulation materials and U-values with Geothermal Heat pump. Reference: Heat pump system with EPS insulation and Target U-value of 0.14 W/m².K represented by the red triangle. 4 and 5, an analogous result is shown, but this time with geothermal heat-pump, while the reference still is the air-water heat-pump. As shown in Table 3. Reference model's characteristics for the case study., the coefficient of performance of the geothermal heat-pump is higher, however, additional embodied emissions linked to the geothermal piping make the difference in terms of GWP between the two systems almost indistinguishable. For instance, the GWP mitigation from changing the heating system of the reference case is only 0.1 kgCO_{2eq}/(m².year).

Furthermore, on the heating systems, the more emitting the fuel per kWh is, the greater benefits of adding insulation will be. Notably, for the oil boiler, the results in Figure 66 and 7 show that a badly insulated building will emit upwards of 45 kgCO_{2eq}/(m².year) more than the reference. Despite that, a rock wool insulation sufficient to achieve a U-value of 0.125 W/m².K would only increase the GWP by 0.6 kgCO₂/(m².year).

Finally, in Figure 88 and 9 the least emissive heating system was simulated in the wood-pellet boiler. For a house with said heating system and an XPS insulation, the installation of 39 cm of insulation has

a larger contribution towards global warming than installing only 6 cm. This highlights the inflexion point that exists for certain materials, particularly visible for XPS, EPS and PUR in this graphic.

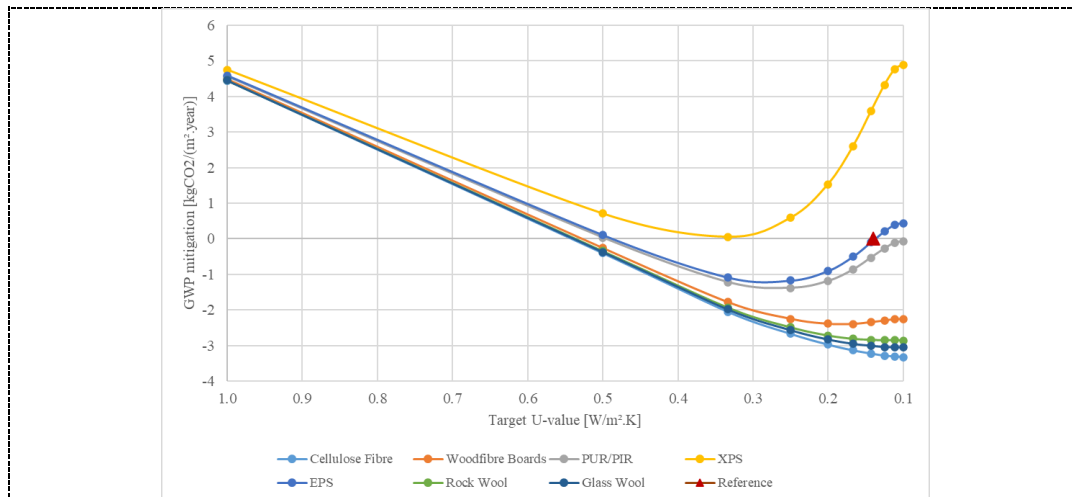


Figure 4. GWP mitigation per m² for different insulation materials and U-values with Geothermal Heat pump. Reference: Heat pump system with EPS insulation and Target U-value of 0.14 W/m².K represented by the red triangle.

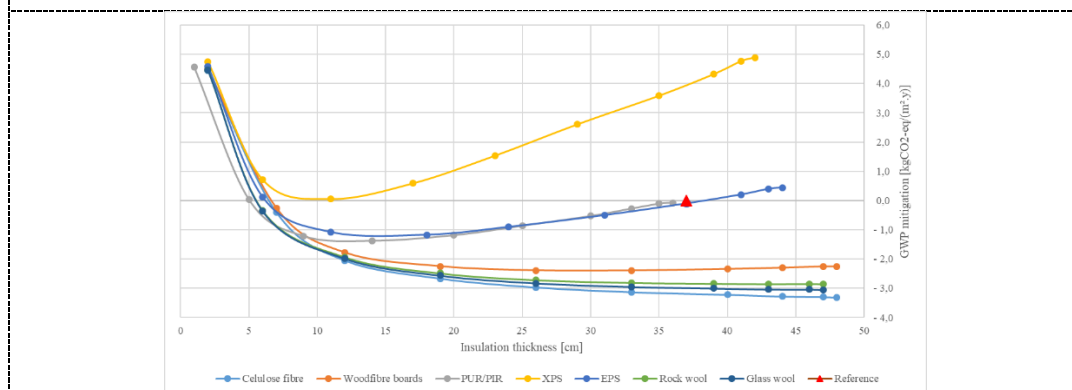


Figure 5. GWP mitigation per m² for different insulation materials and thicknesses with Geothermal Heat pump. Reference: Heat pump system with EPS insulation and Target U-value of 0.14 W/m².K represented by the red triangle.

For all heating systems, Cellulose fibre was the best performing insulation material at a conductivity of 0.1 W/m².K. However, it is also clear that there is always a point of diminishing return, where the addition of insulation is less impactful on the GWP. Combined with a wood pellet boiler, said insulation material results in the best lifecycle performance in terms of GHG emissions.

Moreover, it is also possible to conclude that the lower the performance of the building, that is to say, the higher its target conductivity, the less relevant the choice of insulation material is. Inversely to that, the importance of the GWP reduction potential at lower conductivity values are aggravated and two main classes of insulation are identified: (1) EPS, PUR and XPS, which have a clear inflexion point above the U-value of 0.1 W/(m².K) for most heating types. These materials have the highest embodied GWP amongst the materials listed in Table 3; and (2) Rock wool, Woodfibre boards, Glass wool and Cellulose fibre. In turn, these have the lowest embodied emissions and present no inflexion points, at least within the limits of this study.

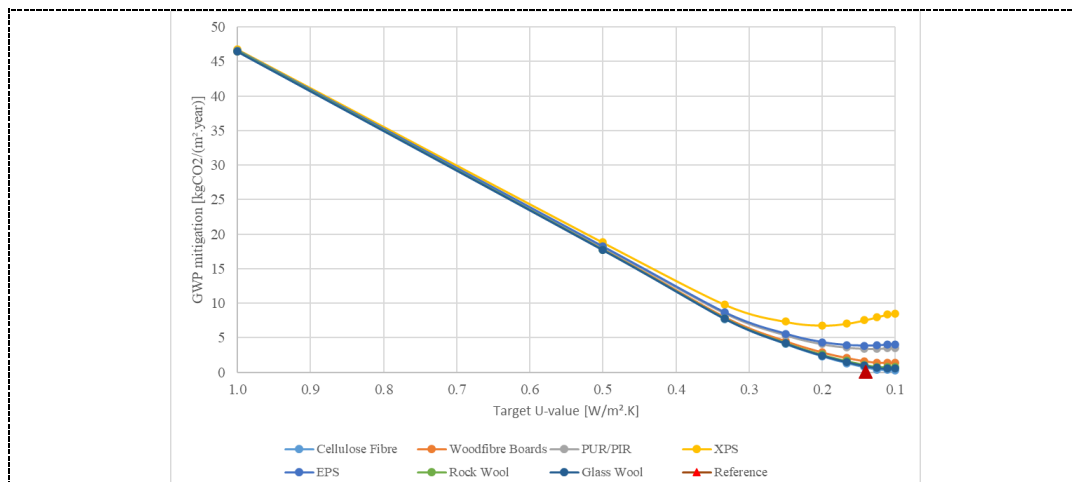


Figure 6. GWP mitigation per m² for different insulation materials and U-values with Oil boiler. Reference: Heat pump system with EPS insulation and Target U-value of 0.14 W/m².K represented by the red triangle.

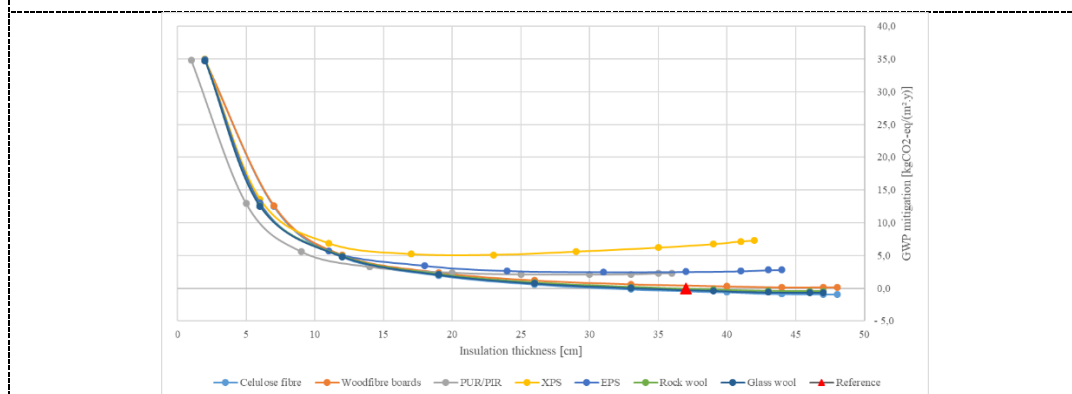


Figure 7. GWP mitigation per m² for different insulation materials and thicknesses with Oil boiler. Reference: Heat pump system with EPS insulation and Target U-value of 0.14 W/m².K represented by the red triangle.

To simplify the methodology and simulation process of this parametric study, a couple of simplifications were made, however, they could have an impact on the results, notably:

- The financial and architectural constraints during a building design or renovation process should be considered. Indeed, optimal insulation thickness for minimizing Lifecycle Cost has been studied in [23] and [24], for instance.
- Technical characteristics of the different insulation materials have been neglected but are also impactful choices, such as the flammability, toxicity, smoke production and water-vapor permeability[25].
- This study only calculated the GWP of insulation plus heating system during the building's lifecycle. However, openings' characteristics and infiltration are also impactful parameters in a building's heating needs [15].
- The KBOB database does not yet take the carbon sink potential of bio-based insulation. However, this is a major advantage of bio-based materials that simultaneously store carbon and improve a building's thermal performance. This important mechanism is believed to be a key factor for the adhesion to the 2°C global warming budget [26].

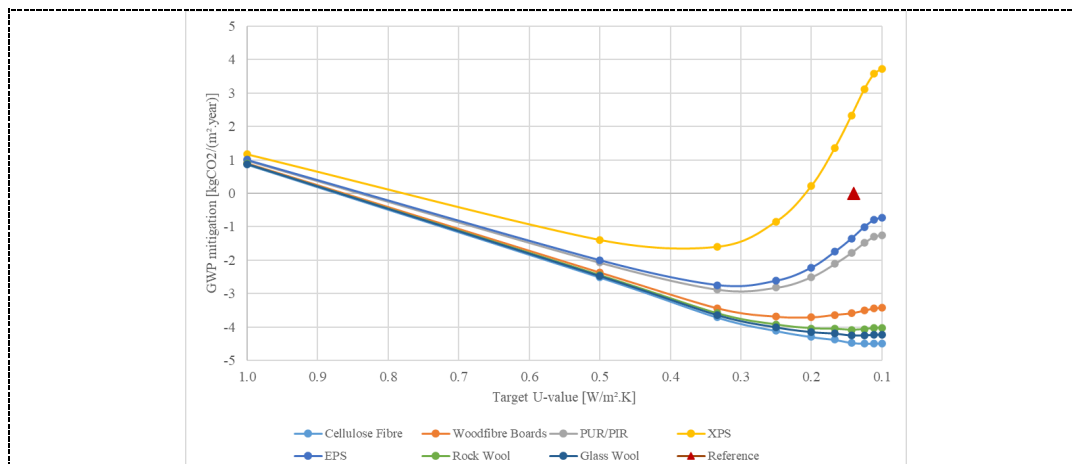


Figure 8. GWP mitigation per m² for different insulation materials and U-values with Wood-pellet Boiler. Reference: Heat pump system with EPS insulation and Target U-value of 0.14 W/m².K represented by the red triangle.

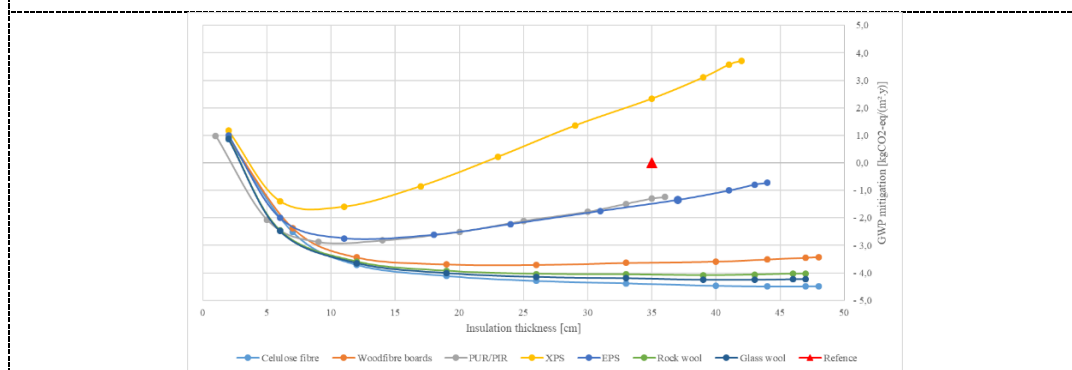


Figure 9. GWP mitigation per m² for different insulation materials and thicknesses with Wood-pellet Boiler. Reference: Heat pump system with EPS insulation and Target U-value of 0.14 W/m².K represented by the red triangle.

In order to further improve the methodology, these points should be further explored together with other subjects outside the scope of this study, such as recircularity of materials or rehabilitation of buildings.

6. Conclusions

This study demonstrates the relationship between embodied GHG emissions. Specifically, between the initial GHG investments on thermal insulation and the consequent mitigations throughout the operational phase of a building's lifecycle. The main findings from the results are as follows:

- An increase in embodied emissions through the addition of insulation does not necessarily decrease the overall GHG emissions of the building. This is the same conclusion reached close to 10 years ago on the same context by [18]. Indeed, EPS (Business as usual case study) has an optimum $GWP_{Overall}$ at $U=0.25 \text{ W/(K.m}^2\text{)}$. Despite that, Swiss SIA norms 380/1 demands for a $U < 0.2 \text{ W/(K.m}^2\text{)}$ which increases the $GWP_{Overall}$ by $1.1 \text{ kgCO}_2/(\text{m}^2.\text{year})$. Then, a change in the norms should demand a lifecycle overview of insulation or a more widened view of targeted U-value that would take the interaction between insulation and heating systems into account.

- Two classes of insulation material were observed: high-carbon materials, namely EPS, PUR and XPS and low-carbon materials composed of Rock wool, Glass wool, Woodfibre boards and Cellulose fibre. The former class have an inflexion point, after which, the addition of insulation would increase the overall GWP of the building, whereas the latter, were not concerned by such phenomenon. This highlights the special attention required when designing a building's thermal envelope with high-carbon insulation materials. In [25] and in [27], the authors grouped them into similar categories, namely synthetic-based (or non-bio-based) and bio-based materials.
- For energy-efficient buildings, the choice of insulation material is incredibly important. Thus, special attention needs to be paid to the embodied carbon emissions, so that they can be effectively balanced by lowering the operational heating emissions.
- The geothermal heat pump has close to 40% greater coefficient of performance than the air-water heat-pump. However, the extra investments required in the form of geothermic piping is barely balanced during the operational phase.

As mentioned above, the conclusions of this study can only be applied to Switzerland. It can be presumed that countries with drastically different conditions and contexts would have very different results. Thus, the application of a similar study in other countries would be very helpful to a better understanding of the importance of LCAs in building design. The presented methodology could be easily be applied to different contexts only by changing the climate context of the energy model and the database for EPDs of a given country, such as the Ökobaudat in Germany [28] or the INIES in France [29].

Since the oil crisis of the 1970s, energy regulations had had a heavy impact on the building sector. However, as global warming becomes an emergency, there needs to be a clear shift in focus from energy to environmental performance. This study helps shine a light on the unfortunate possibility of increasing building's GHG emissions in case of an exclusive focus on reducing energy demand, without considering embodied emissions. The results of this research might be of high value for policymakers and the development of future environmental regulations.

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