Study of environmental impact: Insulation materials in Gothenburg

Master's thesis in Structural Engineering and Building Technology

JAVIER MARTÍNEZ SÁNCHEZ

Department of Architecture and Civil Engineering
Building Technology
Sustainable development
CHALMERS UNIVERSITY OF TECHNOLOGY
Master's Thesis ACEX30-18-108
Gothenburg, Sweden 2018

MASTER'S THESIS ACEX30-18-108

Study of environmental impact: Insulation materials in Gothenburg

Master's Thesis in the Master's Programme Structural Engineering and Building Technology

JAVIER MARTÍNEZ SÁNCHEZ

Department of Architecture and Civil Engineering
Building Technology
Sustainable development
CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2018

Study of environmental impact: Insulation materials in Gothenburg

Master's Thesis in the Master's Programme
Structural Engineering and Building Technology

JAVIER MARTÍNEZ SÁNCHEZ

Examensarbete ACEX30-18-108
Institutionen för arkitektur och samhällsbyggnadsteknik
Chalmers tekniska högskola, 2018

Department of Architecture and Civil Engineering
Building Technology
Sustainable development
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover:
Figure text for the cover picture (if applicable), possibly with reference to more extensive information in the report.

Department of Architecture and Civil Engineering
Göteborg, Sweden, 2018

Study of environmental impact: Insulation materials in Gothenburg

Master's thesis in the Master's Programme
Structural Engineering and Building Technology

JAVIER MARTÍNEZ SÁNCHEZ

Department of Architecture and Civil Engineering
Building Technology
Sustainable development
Chalmers University of Technology

ABSTRACT

A study was carried out on insulation materials for residential buildings, considering their main properties, both technical and environmental. A wall model that is thermally insulated with four different insulation materials was used as reference. With the wall variants designed, a comparison of the environmental impacts and of the insulation materials required to meet the thermal insulation requirements established in the regulations was carried out. For this, Life Cycle Analysis was used as a tool to assess the environmental impacts and the EDIP and ELU methods to calculate the global environmental performance. The results showed that the material with the best behaviour in terms of environmental impact is the insulation based on cellulose fibre, while aerogel blankets are still not recommended according to the results, despite its better technical conditions, showing the worst results in almost all the impact categories analyzed. The performing of the most used materials in construction in Europe today (rockwool and glasswool) is in between of the other materials, being lower in both cases relative to aerogel and higher than that associated with the use of solutions based on the cellulose fibre. Glasswool shows an environmental performance worse than rockwool because of its much greater impact in terms of depletion of abiotic resources due to elements. In this category is the material that gets the worst result.

Contents

Preface

In this study, a comparative analysis of different insulation materials was carried out. At an early stage, a literature review and study of the best analytical techniques to compare the environmental performance of insulation materials was conducted. Subsequently, once the materials part of the comparison were selected, a life cycle analysis of them was carried out, to later compare the results obtained. The project was done between January 2018 to August 2018.

I would like to thank my supervisor Sjouke Beemsterboer for much appreciated support and feedback during this thesis work and my examiner Holger Wallbaum for his valuable input.

Göteborg August 2018

Javier Martínez Sánchez

Notations

CO2 eq.	Carbon dioxide equivalents
EPD	Environmental Product Declaration
EU	European Union
GHG	Green House Gases
GWP	Global Warming Potential
AP	Acidification Potential
EP	Eutrophication Potential
OP	Ozone Depletion Potential
ADPF	Abiotic Depletion Potential-Fossil Fuels
ADPE	Abiotic Depletion Potential-Elements
POCP	Photochemical Ozone Creation Potential
ISO	International Organization of Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
EDIP	Environmental Development of Industrial Products
ELU	Environmental Load Unit

1 Introduction to the project

The revolution triggered by the industrial age and the inherent burning of fossil fuels such as coal and natural gas has led to a situation of adverse climate change, motivated by the high levels of carbon dioxide and other greenhouse gases in the atmosphere caused by the increase in industrial activity. Subsequently, this situation has enhanced the world's natural greenhouse effect, leading to higher overall temperatures.

Because of this, The International Panel on Climate Change urged the need for direct and regular action to regulate the adverse effects of climate change since we are facing a turning point in the global climate (IPCC, 2014). Focusing on the building industry, the massive use of materials such as cement, aluminum, concrete and PVC has caused a significant increase in energy and environmental costs, strictly related with the increase of greenhouse gases emissions (Adalberth, 2000). The emissions of the construction industry have been estimated at 30 or 40% of the total global emissions of GHG (United Nations Environment Programme, 2018).

The reduction of this massive use of materials and energy can be reached acting directly over the way buildings are conceived, built, and maintained. These emissions are related to the construction, operative phase (heating, lighting, etc.) maintenance and demolition of the buildings. According to (Gielen, 1997) 20 years ago, the distribution of emissions throughout the life of a multi-family residential building was 20% during the construction phase, with the remaining 80% corresponding to its operational life. The priority in that scenario was to improve heat losses by incorporating better insulation materials. Today, with better insulation solutions the impact of both phases can be considered 50% each (Aditya, et al., 2017). This shows that is becoming more interesting to reduce the emissions and impacts associated with the production of the insulation materials, and not only on the insulation capacity of the buildings.

Therefore, in the present, the search should focus on finding sustainable insulation materials in the production phase. The objective of this work will be to compare some insulation materials, based on environmental indicators that allow a preliminary idea of what material is more advisable from the environmental point of view for its large-scale use in the construction of multifamily residential buildings.

1.1 Project aim and purpose

The main objective of this thesis is to try to find the most appropriate insulation material for its recurrent use in construction, that is, adapting to the characteristics of current architecture, improving the carbon footprint of the building of which it forms part, trying to minimize also the effects associated with other environmental impacts.

1.2 Problem statement

The high amount of greenhouse gasses emissions and environmental impacts associated with the construction industry makes it necessary to look for alternative materials to those currently used. Numerous studies have been carried out comparing the impact in terms of greenhouse gasses, but in many cases, the selection of those associated with lower global emissions may result in a worse performance in other categories of environmental impact. Therefore, the main problem to be investigated in this thesis is if the material that leads to lower global emissions shows a good performance in other environmental indicators. That is, look for material that ensures better performance than materials traditionally used in the construction of multifamily housing buildings without causing poor performance in other environmental indicators.

1.3 Research questions

Based on the aim of the project, the report should answer the following questions:

- What is an appropriate technical insulation material?
- What makes a better insulation material in terms of environmental impact?
- Which one of the materials analyzed has a better performance?
- Are the different environmental impacts of the insulation materials related?

1.4 Working hypotheses

- The use of some alternative thermal insulation materials can decrease the environmental impact of a building.
- The building construction sector can improve its environmental performance levels by modifying the traditional thermal insulation materials.
- It can be efficient to use eco-friendly materials.

1.5 Limitations

The field is too wide to carry out a complete study, so some limitations will be necessary.

- All the materials cannot be analyzed, so representatives of different types of insulation materials will be chosen. These categories are typical insulators of the construction industry (Rock and mineral wool), the modern superinsulation materials (Aerogel) and recycled materials (cellulose fibers).
- The architectural concept of multifamily housing varies a lot, so to make the comparison between the performance of the materials, a common wall for a multifamily residential building has been chosen.
- The impact categories studied are not all the possible ones, just a combination of them considered interesting for the project, based mainly on the most common impacts studied when studying the environmental impact in other LCA studies.

1.6 Disposition of the report

The report starts with a description of the methodology followed to do this thesis, to continue with a literature study that pretends to solve the two first research questions. After the literature review concerning the insulation materials, the scenario analyzed is showed, describing the structure of the wall used as a reference as well as the materials used for each of the case studies. In this part of the study the LCA method is explained, and the assumptions required for the analysis are stated. The next part of the report is the one related to the proper analysis and results, finishing with the discussion and the conclusions of the thesis.

2 Methodology

Since the aim of the thesis is the study of the environmental impact of the insulation materials, it will be structured in these different phases:

1. Research and literature study about insulation materials in order to get different alternatives to the traditional thermal insulation materials.
2. Get carbon footprints and other environmental indicators of a wall defining the impacts resulting from materials and activities for the alternatives defined before using LCA.
3. Comparison between the results obtained with alternative materials and construction procedures and the ones reached using classic insulation materials, comparing their performance in this field with the other indicators calculated, trying to find tradeoffs between them.

Ideally in this case, given the wide variety of insulation materials that exist in the market and the potentials that are to come, would be to make a comparison of many of them to have a large amount of data to make a contrasted answer to the main question of the thesis. However, adapting the comparison to the temporary period of a master thesis, the materials studied should be limited. The choice of materials was carried out taking into account the information, both qualitative and quantitative, found in studies and books that are detailed in the literature study. It is difficult to select only a few materials to perform the analysis, so a literature review was carried out on the current situation in the market of insulation materials for residential buildings, also considering the potential materials that can be a viable alternative to the ones that are currently used. Therefore, the analysis of reference materials of three large groups of insulation materials will be carried out, allowing a broad comparison between these four different categories. These three groups are:

- **Standard materials:** This group includes the materials that the construction industry has been used during the last years in a generalized way. In this group can be highlighted the mineral fibers (glasswool, sand mineral wool, and rock wool) and also the plastic foams (expanded polystyrene (EPS), extruded polystyrene (XPS) and polyurethane foam (PU)), that will not be studied due to be oil-based products. In this category the materials chosen are the mineral wool based materials, analyzing both rockwool and glasswool.
- **New materials:** In this field, newly created materials are included, or that have not yet been used generically in the field of construction, in many cases because the scale of production is still small. Examples of this category are the VIPs (Vacuum insulation panels) and Aerogel. The Aerogel was the material chosen in this category.
- **Recycled materials:** This category includes those insulation materials formed from recycled products. The material included in the analysis was the cellulose loose fill fibers.

To make the comparison of the materials, it is necessary to establish some common parameters that allow a direct comparison between them. For this reason, a wall was defined and associated to each of the materials looking for the alternatives analyzed to respond to the same thermal characteristics, so that the same coefficient of heat transmission was fixed for all the wall structures analyzed. With the materials chosen, a comparative analysis of their performance, combined with the other materials that compound the wall, as insulation materials in a standard wall was performed, obtaining the thickness of each one needed to fulfill the specifications set by the authorities in Sweden for the thermal envelope of the residential buildings.

After having all the alternatives set and the preliminary conditions detailed, the next step was to look for information about the environmental impacts associated with each of the materials that make up the wall, as well as establish the methodology and the LCA characteristics (Baumann & Tillman, 2004). The information related to the environmental impacts of the materials was found in EPDs provided by the companies and specialized institutions. However, the information found sometimes was not complete, so it was completed using the Simapro software and the database (Ecoinvent, 2013). Also, the information found in the EPDs was related to different functional units, and because of that, a standardization process was carried out in order to compare the different alternatives. The information and the processes used are detailed in the dedicated chapter to the LCA analysis.

For the analysis, the alternatives considered were compared. To do that, the impact of each of the wall configurations were analyzed taking into account different environmental impacts. After having all the impacts measured, the materials were compared trying to find tradeoffs between them, and ultimately compare the global impact of each of the materials used following the EPS method (Steen, 2015). The consistency of the data was tested by comparing data from different product EPDs in the European market.

3 Study of insulation materials

This chapter will seek to respond to the research questions mentioned before by reviewing the literature corresponding to the aim of the thesis. These questions are presented as sections.

3.1 What is an appropriate insulation material?

The sector of large-scale construction, one of the most energy-intensive in the world, demands the search for adequate insulation materials to help reduce the environmental footprint to its maximum. In this sense, in the last years, several studies have focused on the key factors that constitute good insulation materials, establishing some guidelines to help decide on the optimal materials to be applied for construction.
From a technical point of view, the definition of a good insulation material comprises numerous factors, resumed in Figure 1. The following sections provide a more detailed description of the main technical aspects of insulation materials as defined in the recent literature on this type of materials.

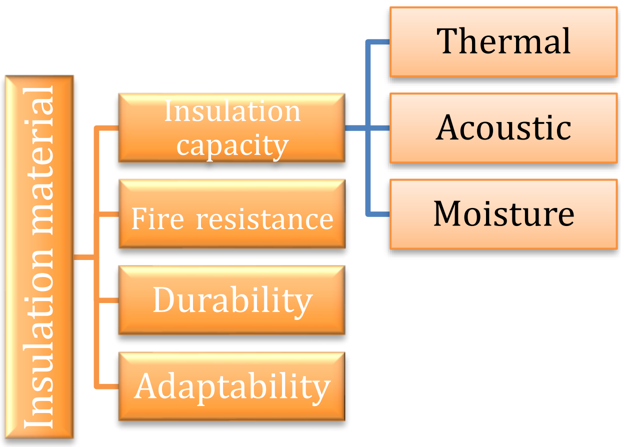


Figure 1 Insulation materials properties

3.1.1 Insulation capacity

The insulation capacity is the main factor when designing the thermal insulation of a building, and hence, one of the main factors when choosing the material used for this purpose. To explain what means to thermally insulate a building, it is first necessary to define the main factors that determine the insulation capacity.

Thermal conductivity, thermal resistance, and thermal transmittance are some of the properties that define the insulation materials. Typically, the most popular variable to measure a material's insulation capacity is thermal conductivity, measured in unit Watt per meter thick and Kelvin. It is also common to use the R-value as a measure of the thermal conductivity of a material per unit area. The inverse of the R-value is the U-factor, that measures the heat flow through a material. (Straube, 2007).

In spite of the importance of thermal insulation capacity in a material's insulation capacity, there are other properties of insulation that can be complementary to thermal insulation, avoiding the use of a second material for that purpose. The most important ones are the acoustic insulation and vapor/moisture permeability.

Although it cannot be directly associated that greater thermal insulation causes greater acoustic insulation, some materials have a good performance in both fields. The products made from mineral wool, thanks to its internal structure, can provide good acoustic insulation. The mineral wools behave as shock absorbers so that when the sound energy passes through its structure, it dissipates. (Ballagh, 1996).

Also, moisture and the problems derived from it constitute important phenomena present in many residential buildings. The issues related to moisture not only affect the aesthetics of the buildings, inside or outside depending on where it appears, but is also harmful to health and deteriorates the elements that make up the building, worsening its properties (Thermal Insulation Association of Canada, 2013). The humidity promotes the appearance of mold, fungi, and bacteria. For example, reflective thermal insulators (Lee, et al., 2016) solve the problems that appear on the walls or interior partitions of buildings.

3.1.2 Fire resistance

Fire resistance is an important parameter, given it is a mandatory characteristic established by the building regulations to keep the structures safe from fire. The materials with better behavior against fire are those composed of inorganic substances, like the ones based on mineral wool. The organic compounds, more susceptible to the effect of fire, must be treated with retardant substances to improve their properties against it. As an example, products based on cotton and cellulose, are treated with boron compounds and other fire retardants (Hidalgo, et al., 2017).

3.1.3 Durability

The durability of an insulation material is an important feature to consider, as the properties of an insulating material are not constant over time, given the reduction of performance that occurs in the R-value or the thermal conductivity resistance throughout the useful life of the product in most cases. A material with a shorter useful life implies a higher replacement and maintenance rate increasing, in most cases, the economic costs and its environmental impact.

To maintain the insulation performance as constant as possible, the insulating material must be resistant or protected against agents that can adversely affect the useful life of the material, such as water, corrosive elements or solvents. Also, it is important to maintain conditions in the environment of the insulating material that guarantee the correct performance of its functions (Thermal Insulation Association of Canada, 2013). According to (Aditya, et al., 2017), when the fiberglass, the rockwool or the Polyethylene are produced as blankets (batts or rolls), the R-value is reduced by the compression. Here, it is important not to cause the insulating material to receive part of the load of the structure to maintain the thermal properties.

3.1.4 Adaptability

When selecting a material to be used in the construction industry, it is important that this material is not highly compromised by the circumstances of the buildings. In this sense, a material that can be used in various configurations or surfaces has greater possibilities of use than another with a more rigid structure or a specific configuration. One of the best examples is the aerogel, which can be sprayed on almost any surface or used as semirigid panels, while with vacuum or gas-filled panels its use is more restricted by the typology of the wall or the roof since they are sold as prefabricated panels with standardized dimensions (Schiavoni, et al., 2016).

3.2 What parts of the building are thermally insulated?

The improvement of the thermal envelope has been one of the most important factors that have led to the progress of construction towards sustainability. The thermal envelope can be defined as all the construction elements that separate the inside of the building from the outside. In the last decades in Europe, the residential buildings have improved their insulation considerably, reducing the thermal transmission and achieving a greater thermal stability inside the building. In order to achieve the efficient thermally insulation of a building, and focusing on the insulation materials, the fields of action can be separated in three parts of the envelope (Fundación de la Energía de la Comunidad de Madrid, 2012):

- **Facade insulation:** From the point of thermal and acoustic insulation in most residential buildings, the facade is one of the key points to be considered since it is one of the main barriers against thermal transmission and external noise. This resistance can be maximized by installing insulation materials in the walls, either by the outside, inside or by injecting into the wall.
- **Insulation of Covers:** With the facade, the insulation covers is another main surface of contact with the outer conditions, both thermal and acoustic. It's also a critical point in terms of water insulation. To assure a good performance in these fields, the covers should be insulated on the roof, between beams, battens, with tile adhered on the insulator, with floating pavement, etc.
- **Insulation of Floors and Ceilings**: The ceilings in contact with living spaces, floors in contact with non-habitable spaces, supported on the ground or in contact with the outside air should be insulated. The floor is a part with a relatively small surface of the envelope, but its importance lies in the fact that it is in contact with the ground, which is generally at a constant temperature well below the comfort temperature of the dwelling.

The objective behind the improvement of the thermal envelope is not only to achieve a better thermal resistance in the aforementioned parts, but it is also important to eliminate the thermal bridges that exist between them. These thermal bridges are usually the least insulated parts of the building envelope. In

this sense, a solution must be designed specifically to minimize the heat losses, trying to make the thermal behavior of these points remain as similar to the rest of the envelope (Christianson & Nsofor, 2014).
The design and construction of these points are transcendental since its execution determines the thermal behavior and also the possible appearance of issues due to its special characteristics. These thermal bridges usually arise where the placement of the insulation is compromised by other building elements (Petránek, et al., 2013). Hence, achieving the total elimination of these thermal bridges is one of the main objectives when trying to avoid unnecessary energy losses.

3.3 What makes an insulation material sustainable?

Once the technical characteristics of insulating materials and insulation of residential buildings are defined, the next step is to define what it is considered as a sustainable insulation material. For several years, it has been a tendency to look for more sustainable materials and sustainable systems. The Green Paper on Integrated Product Policy is one example of this search, as it encourages the need to establish a "new growth paradigm and a higher quality of life through wealth creation and competitiveness on the basis of greener product" (COMMISSION OF THE EUROPEAN COMMUNITIES, 2001, p. 2) and states that "products of the future shall use fewer resources, have lower impacts and risks to the environment and prevent waste generation already at the conception stage" (COMMISSION OF THE EUROPEAN COMMUNITIES, 2001, p. 2). Given the broadness of sustainability as a concept, the definition of sustainable insulation materials is a controversial matter. In this sense, the same material can be perceived as more or less sustainable depending on the factors considered.

Although the term is broad and subject to discussion, there are factors that can lead to the characterization of a sustainable material. A material has more possibilities of being considered sustainable when, in environmental terms, it comes from renewable, abundant and close sources, consumes little energy or is not polluting during its life cycle. In economic terms, a material is sustainable if it has a model of fair development, it has an accessible price, it has a percentage of recycled material, it is durable, it is recyclable and/or biodegradable. In social terms, it comes from a fair production, promotes cultural value in its environment or generates community development (Czarnecki & Van Gemert, 2017). In summary, the main factors are:

- Materials that come from renewable sources
- Materials of the near environment, with few transport costs
- Non-polluting materials
- Recycled and recyclable materials
- Long-lasting materials
- Materials that consume less energy
- Fair produced materials
- Versatile materials

It's easy to think that a material resultant of combining all these features is sustainable but, in most of the cases, this is not possible. The greatest difficulty in defining if a material is sustainable lies in the weight given to each one of these factors (or subcategories) within the common sustainability indicator, since not all of them exert the same influence in the degree of sustainability of a material. (Govindan, et al., 2015).

All of these factors, among others, are part of the “articulations” to reach the sustainability. Depending on these, the situation and the material analyzed, some of them will have more influence than others in the materials sustainability definition. It’s not the same analyze timber as a structural component or as an insulation material (Mulder, et al., 2011)

For this reason, in the last century tools have been developed trying to parameterize and compare these impacts. One of the most important and used is the Life Cycle Analysis (LCA). It was created in the sixties and it is a methodological framework for estimating and evaluating the environmental impacts attributable to a product or service during all stages of its life. The basic principle of the tool is the identification and description of all the stages of the life cycle of the products, from the extraction and treatment of the raw materials, the production, the distribution and use of the final product until its possible reuse, recycling or product waste (Baumann & Tillman, 2004). Some of the most influential factors for finding sustainable insulation materials from the environmental point of view are explained in more detail in the following paragraphs.

3.3.1 Materials that come from renewable sources

The use of products and materials that come from renewable sources is a necessary step to avoid the depletion of natural resources. In this sense, insulation materials coming from non-renewable sources such as those derived from plastic products are not considered sustainable materials and, therefore, should be avoided. (Campos-López, 1980).

3.3.2 Materials of the near environment

The proximity of materials to their source of production is a key element in terms of sustainability. In general terms, the transportation of building materials, especially those with low density requires a big waste of energy and resources. Given the adverse environmental impact of materials’ transportation, the closer the material to their final destination the less transportation costs (oil, CO2, energy) leading to a lower environmental damage. (Horvath, 2004)

3.3.3 Long-lasting materials

Longer useful life is a property that can make a material more sustainable than others, by having a higher replacement rate or with a greater need for maintenance. This is the case of some SIMs (Super insulation materials), such as the Vacuum Panels. Their thermal properties are much better than those of traditional insulators, but since they are more delicate, their need for maintenance and replacement is also much higher (Kim, et al., 2017). The developing objective is to create more durable materials while maintaining the outstanding thermal insulation capabilities.

3.3.4 Recycled and recyclable materials

Reusing the building wastes in their original form can be a way to reduce the amount of energy and new materials demanded by the sector (for example, bricks), reducing its environmental impact. But not only materials from the building industry can be reused in the construction of new buildings. The use of thermal insulation manufactured from textile fibers remnants of clothing is an example (Briga-Sá, et al., 2013).

3.3.5 Non-polluting materials

Using non-polluting materials (neither during their production nor during their useful life) in construction should be one priority to achieve the objective of sustainable development. Around 80,000 chemicals are used in the building industry, making so difficult the material pollution's characterization.
The building industry has a great impact on the Global Climate Change since the sector produces around the 30-40% of the total global emissions of greenhouse gases.
In this sense, several strategies can be followed to reduce the polluting materials. Related with the production of materials phase, the reduction of resources needed is a primary objective, but is also important the gradual substitution to "clean" (or non-fossil based) energy sources for extraction of raw materials and posterior production processes (Berge, et al., 2009).

3.3.6 Materials that consume less energy

One of the key factors to consider when analyzing the level of sustainability and environmental performance of a material is the amount of energy used in its production phase.
The production phase of most construction materials is highly reliant on fossil fuels that are scarce by nature and, hence, the energy used to produce them does not follow a sustainable rate. (Horvath, 2004). In this sense, the level of sustainability of a construction material will depend, to a great extent, on the reliability of scarce sources of energy.

3.3.7 Fair produced materials

In line with the more economic and social definition of sustainability, the materials used in construction should be oriented towards an integral development, contributing to economic, social and environmental sustainability and respecting cultures, traditions, and basic human rights.

3.3.8 Versatile Materials

Minimizing the use of materials with polyvalent materials can be a solution to reach more sustainable buildings. Climate regulating materials can realize more than one function. For example, timber is an excellent moisture regulator, but also can be a structural component or part of the surface (Berge, et al., 2009).

3.4 Insulation materials

In this chapter, the materials chosen for the analysis are described based on the existing literature, explaining the reasons that justify their selection as good insulation materials. As stated before, four different materials are included in the analysis, covering some of the different alternatives that exist or may exist more extensively in the thermal insulation sector of residential buildings.

Since the creation of the life cycle analysis, many studies were carried out in the construction sector. This section is based on the existing literature on construction materials and elements, and different studies were used as a reference for the selection of methodology and the development of the conclusions.

3.4.1 Mineral wool (Rockwool and Glasswool)

Along with the plastic insulators, mineral wool is an insulating material widely used by the construction sector. With a market share of 57%, mineral wool is the most used insulation material in Europe, above the before mentioned insulators based on plastic derivatives, with a 40% presence in the construction sector of the continent. The percentage of use is even higher in the countries of northern Europe. It is also proved that the mineral wool-based insulation material has a better environmental performance than the solutions based on expanded and extruded polystyrene or polyurethane. (Schmidt, et al., 2004). Mineral wool offers, besides a remarkable thermal protection (it has a specific thermal conductivity of 0,04 W/mK (Berge, et al., 2009)), additional advantages. Among them, it protects against fire the structures of buildings, and their occupants, acting as a fireproof barrier that allows time to evacuate people since it resists temperatures of up to 1000 degrees Celsius and during its combustion, the generation of toxic fumes is very reduced compared to other insulating materials. It also offers good acoustic properties and a long service life (Širok, et al., 2008).

(Sohn, et al., 2017) carried out a mineral wool life cycle analysis. The study is based on the realization of a balance between the environmental impacts induced by the production and construction of thermal insulation facilities, with the amount of energy they save, and the consequent impacts they avoid. The result shows how the energy and the impact avoided throughout its useful life are much greater than those incurred during their production or dismantling.
The conclusions drawn by this study have a special interest as the material analyzed is also in a Nordic country (Denmark), and in a residential building, so it resembles the material and the place of study proposed for the realization of this thesis. The main difference with the one proposed in this project is that it is a single-family house.

Since the mineral wool based materials are the insulating materials of reference in the market of European insulating materials, will be included in the study as a reference when comparing them with those that can potentially replace them in the future or in the present, in the case of those less used but available.

3.4.2 Aerogel

In the market, there are materials whose thermal properties far exceed the traditional thermal insulation materials properties, including those used by the building industry. It is expected that these materials, whose main drawback in comparison with those currently used is their high price, will gain market presence as their introduction in the market and production are higher, leading to a decrease in their cost. In this sense, implementing materials such as aerogel solutions in the construction industry can lead to a considerable reduction in the energy needs of residential buildings (Baetens, et al., 2011).

The paper written by (Sáez de Guinoa, et al., 2017) shows the environmental implications of aerogel-based insulation panels. The main aim of this study is “to estimate the life-cycle environmental benefits linked to the energy efficiency improvement of a nano-technological aerogel-based panel for building insulation and its application in a residential dwelling”. The building selected for the study is a multifamily housing building located in Zaragoza (Spain), but simulations of its behavior were carried out under different climatic conditions, one of them taking the climate of Stockholm (Sweden) as a reference climate.

The study shows that the aerogel can provide net benefits in terms of GWP if the use stage is considered during the analysis. On the other hand, the impacts related to the production stage of the material are significant compared with other conventional insulation materials. The distribution of emissions in the production process is outlined in the following table(Casini, 2016).

Component	Embodied Energy (MJ/Kg)	Embodied CO2 (Kg/kg)	%
Silica precursor and other raw materials	35,5	3,2	75,65%
Fibrous reinforcement	12,1	0,6	14,18%
Production process	3,5	0,4	9,46%
Supercritical extraction	2,1	Recovered from other industrial processes	0,00%
Pollution control equipment	0,7	0,03	0,71%
Total	53,9	4,23	
International transport (from United States to Europe	2,2	0,14	

Table 1 (Casini, 4 – Advanced insulating materials, 2016)

As stated before, the aerogels are one of the most potential insulating materials given their extremely low thermal conductivity (around 0.01–0.02 W/mK). Other properties that make aerogel a material with exceptional characteristics are its lightness and flexibility, which allow it to adapt to different architectural compositions (Baetens, et al., 2011). Due to the potential of aerogel-based solutions, it seems interesting to include this material in the study to check whether its good thermal properties are compatible with an acceptable environmental performance.

3.4.3 Cellulose and textile fibers

Every year large quantities of paper and textile fibers from multiple uses in the world are discarded. Trying to find uses for part of these wastes would help to increase their useful life, besides avoiding the use of other alternative resources. Insulating with fibers, either textile or with cellulose can become a way to reuse a large amount of waste paper or textiles after their useful life as other products. For example, if the textile waste is used in Norway to manufacture thermal insulation, it could cover 25% of the annual demand of insulation materials in the country per year (Berge, et al., 2009). Its thermal conductivity is practically the same as the mineral wool products, 0,04 W/mK (Berge, et al., 2009),This insulating solution is currently used, but much less than solutions based on mineral wool or plastic derivatives, (Schmidt, et al., 2004).

The inventory of coal and energy carried out by the University of Bath (Hammond & Jones, 2006) shows a comparative analysis of the embodied energy associated with different insulation materials. The data established in this inventory for the different insulating materials are shown in the following table.

Insulation material	Embodied energy (MJ/kg)
Cellulose	0.94–3.3
Fiberglass (Glasswool)	28
Mineral wool	16.6
Rockwool	16.8
Woodwool (loose)	10.8
Woodwool (Board)	20
Wool (Recycled)	20.9

Table 2 (Hammond & Jones, 2006)

It can be seen that the embodied energy associated with the cellulose as an insulation material is low compared with the energy of the mineral wool and the glasswool. Converting embodied energy to CO2 emissions cannot be carried out directly, but the embodied energy is a good indicator to estimate the potentiality of emissions associated with a product, especially if the difference between products is high, as it can be in this case, in which the differences with other conventional insulating materials are of the order of 5 to 10 times higher.

(Takano, et al., 2014) performed an analysis using different configurations of insulating material in the external walls of a residential building in Finland. The cellulose fibers solution was compared with glasswool and Rockwool getting these alternatives worse results in terms of GWP.

Original (reference)	Rockwool	Gypsum board + particle board	Wood Planking	Wood Planking	Bitumen
Alternative 1	Glasswool	Particleboard: 10 or 24 mm	Galvanized steel sheet: 0.6 mm	PVC sheet: 2.6 mm	Polyvinyl chloride (PVC): 1.2 mm
Alternative 2	Cellulose fiber	Gypsum board: 13 or 15 mm	Rendering: 20 mm	Parquet flooring: 14 mm	Concrete tile: 15 mm

Table 3 (Takano, Hughes, & Winter, 2014)

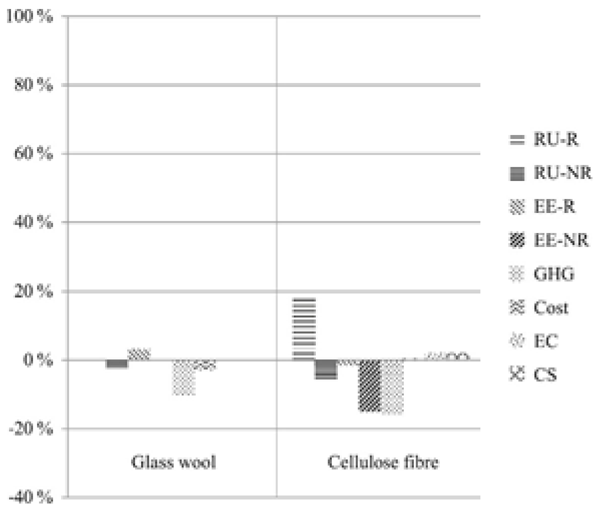


Figure 2 (Takano, Hughes, & Winter, 2014)

The comparison shows that the emissions associated with the insulating material used can be reduced by 15% by exchanging Rockwool (standard material) for insulation based on cellulose fibers.

It is worth asking how this solution does not have a greater reception within the construction industry. As discussed by (Zabalza Bribián, et al., 2011), the inertia and the skepticism of the designers and the lower prices associated with the massive used of the conventional insulators in the sector are behind contractors and decision makers in the construction industry continue to opt for conventional insulating materials, such as plastic derivatives and rock wool.

When analyzing the results of the studies, it seems that cellulose fiber can be a viable alternative to the materials used today. In addition, its origin from recycled materials such as newspaper papers can lead to a better environmental performance than those of mineral or plastic origin. It is therefore interesting to include this kind of material in the study to measure its environmental performance compared to the materials currently used and to check whether a solution based on the reuse of recycled materials can be viable as a substitution.

3.4.4 Insulation materials review

Once the information from the previously conducted studies has been extracted, it is important to highlight the most important facts for the thesis. Rockwool and glasswool are the most used materials in the construction industry globally, and especially in Europe. In addition, compared with other materials used on a large scale (plastic derivatives), they have a lower environmental impact and are the materials chosen to represent the group of standard materials or used materials in the analysis.

The studies show that the change of Rockwool by cellulose fibers can lead to minor impacts. This suggests that alternative materials to those traditionally used by industry can achieve a reduction in the environmental impacts associated with their use. Because of this, the cellulose fiber solution is the one representing the category of recycled materials in the analysis.

Aerogel-based solutions provide technical conditions unattainable for most of the insulating materials currently used by the industry. In addition, its adaptability and maintenance are simpler than other modern products such as VIPs. Also, they can currently have net benefits in terms of GWP applied to contemporary residential buildings. This opens the possibility of its progressive incorporation and proves that research into new materials can lead to getting materials with better technical characteristics. Must be also questioned if it is sustainable studying other impact indicators and compared with other materials. Therefore, aerogel it is the material chosen to represent the group of the newest materials in the analysis.

The studies also show that the most important aspect when selecting the insulating material is in most cases the cost, without considering that a material with a slightly higher economic cost can have a much better environmental performance. Therefore, contractors and people with decision-making power within the industry are urged to develop decision methods that allow a weighting of aspects such as the environmental impact, and in this case, the GWP, when choosing the insulation material for a construction project. This makes also important the figure of the LCA in this process as one of the best tools to compare the impact that each of the different alternatives can have.

4 LCA of the case study

In this chapter, the different proposals for the insulating material are studied from the point of view of life cycle analysis.

4.1 Goal and scope

When parametrizing this situation and the possibilities for improvement regarding the environmental impacts, one of the most useful tools is the life cycle analysis. The first step when performing a life cycle analysis is to specify the goal and the scope (Baumann & Tillman, 2004).

The aim of this thesis is to identify improvements in the impact that residential buildings have on the environment through the use of thermal insulation materials in the construction of multifamily residential buildings (Baumann & Tillman, 2004). The expected audience for this study is those responsible for deciding in the construction industry, mainly in Sweden, since it is the country taken as a reference for the elaboration of the study. It should verify how the use of certain insulation materials can significantly influence reduce the environmental impacts of buildings throughout their useful life and also, to increase the visibility of the need to reduce the emissions and impacts associated to the building sector, to achieve the incorporation of this field as one of the main ones when designing a residential building.

The database used for this study was the EPDs of the products analyzed, completing the lack of information with the Ecoinvent database (Ecoinvent, 2013), and the method used to calculate the equivalent impacts was the EPS (Steen, 2015). Although Sweden is taken as a reference, no environmental data was available for some products in this country. Therefore, some EPDs (in the case of plastic film or aerogel) obtain the information related to the production phase of other countries (Luxemburg and the United States). However, the impacts related to transport to Sweden were considered. In the following points the materials chosen, and the wall selected are described.

4.1.1 Layer definition

Since the objective of the analysis is to compare the environmental performance of different insulation materials, some fixed conditions must be established in each scenario to achieve results that can be compared with each other. For this, it was used as a basis for the definition of the components of the facade the study carried out by (Peñaloza, Norén, & Eriksson, Life Cycle Assessment of Different Building Systems: The Wälludden Case Study, 2013) and showed in Figure 3.

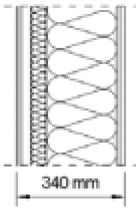
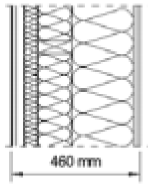
Exterior walls	
Standard Design	**Passive House Design**
 Ventilated plaster facade system28 x 70 mm wood lath C600 mm 50 mm stone wool, 45 kg/m^3 220 mm stone wool, 28 kg/m^3 45x220 mm timber studs, C 600 mm 0.2 mm plastic film, PE 2 x13 mm gypsum plasterboard, 720 kg/m^3	 Ventilated plaster facade system28 x 70 mm wood lath C600 mm 50 mm stone wool, 45 kg/m^3 120 mm stone wool, 28 kg/m^3 45x120 mm timber studs, C 600 mm 220 mm stone wool, 28 kg/m^3 45x220 mm timber studs, C 600 mm 0.2 mm plastic film, PE 2 x13 mm gypsum plasterboard, 720 kg/m^3

Figure 3 (Peñaloza, Norén, & Eriksson, Life Cycle Assessment of Different Building Systems: The Wälludden Case Study, 2013)

Using as reference the configuration of the "standard design" of the study carried out by (Peñaloza, et al., 2013), the data to develop the wall layer was obtained from information provided by the company PAROC (Paroc Group oy, 2018). This company manufactures energy-efficient and fireproof insulation solutions for new and renovated buildings (Figure 4). The solution chosen is that commercialized for residential buildings in Nordic countries.

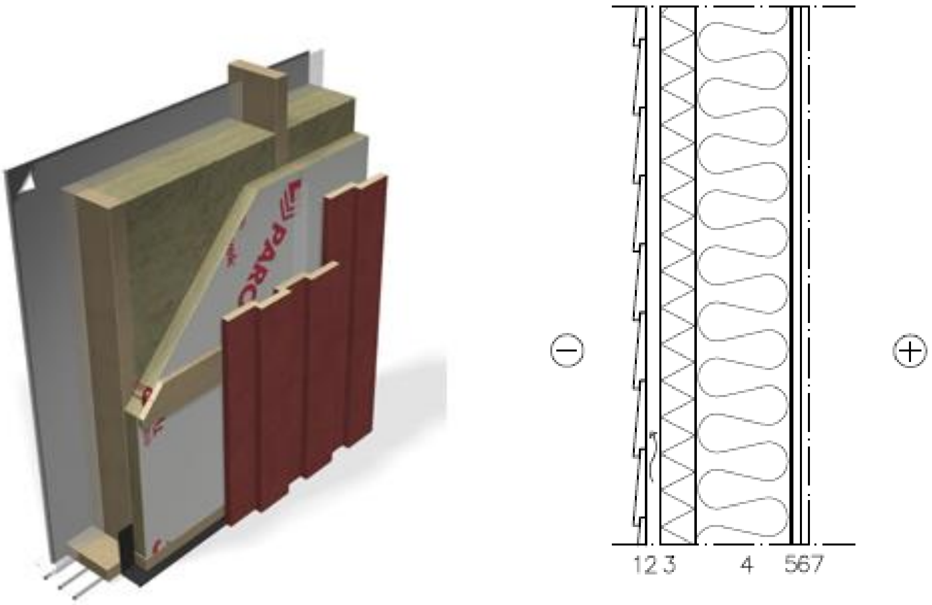


Figure 4 (Paroc Group oy, 2018)

Layer		Thickness mm	Conductivity W m^{-1} K^{-1}
1	Cladding	22	Not needed
2	Ventilated gap	50	Not needed
3	Wind protection	55	0,032
4	Insulation material/Timber studs	Defined	Material properties
5	Plastic film (Vapour barrier)	0,2	0,12
6	Gypsum plasterboard	12,5	0,57
7	Surface finishing	-	-

Table 4 Wall configuration

The aim was to achieve the same U-value using the different insulation materials, permitting the comparison between them. The chosen U-value is established by Boverket for the city of Goteborg, 0,18 W/ m2K (Association, European Insulation Manufacturers, 2018). The U-values were obtained from the Ecoinvent database manuals (Ecoinvent, 2013) and the EPDs. The insulation layer also includes the timber studs, but since the major component of the layer is the insulation material, the assumed U-value is the one related to the insulation material. The surface finishing was neglected since the building board selected can be used without it. The thickness values of the layers related to construction elements will remain fixed, with the value of the insulation layer being changed until reaching the previously established U-value (layer number 4). With this, the amount of material needed for each square meter of wall is calculated by applying the density of the materials to the dimensions obtained. The Figure 5 shows the thickness results got for the different insulation materials after completing an iterative process to solve the free parameter (The detailed results are in 10.1).

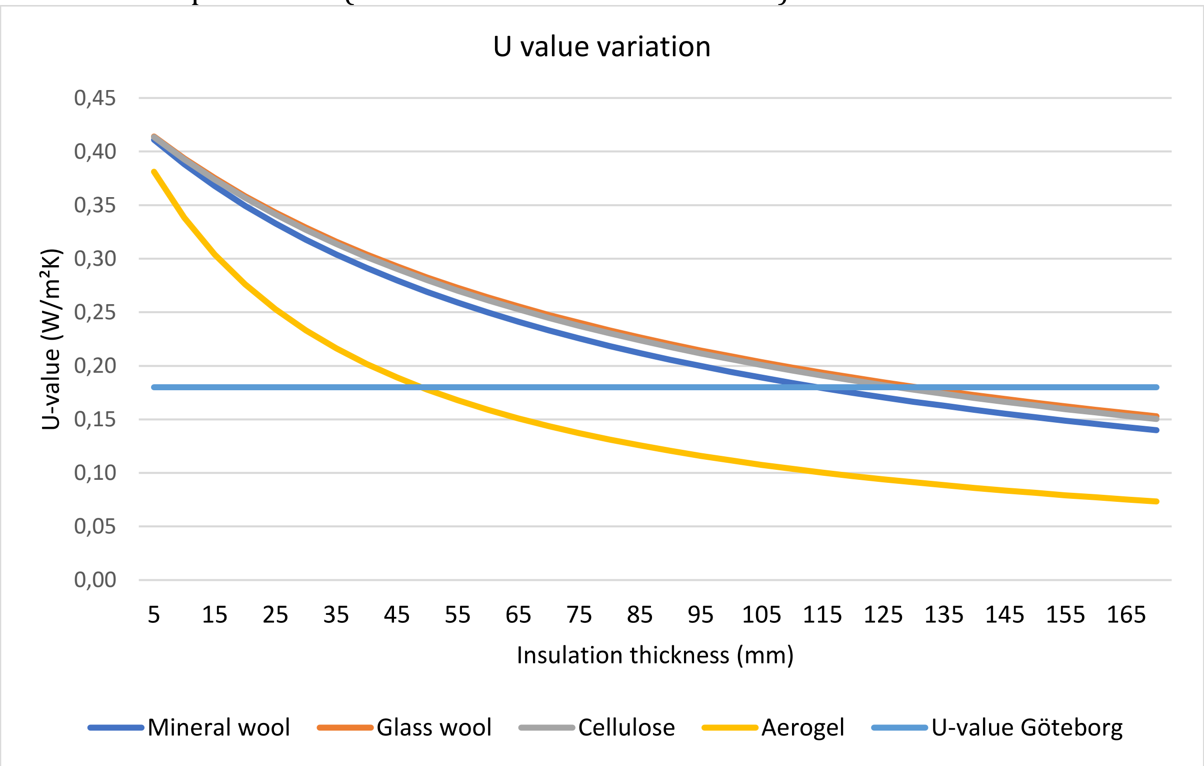


Figure 5 U value variation wall

Once the thickness of the layers of each material has been defined to ensure the predetermined transmission coefficient, using the densities of the materials, the amount of material needed per square meter of facade can be calculated. It can be observed how the thickness of aerogel necessary to achieve the U-value needed to comply with the regulations in Sweden is much lower than that of the other solutions analyzed. The solutions based on insulation with cellulose, mineral and glasswool require a similar thickness, differing the amount of material necessary because of the different density (Table 5).

Material	Thickness mm	Density Kg/m3	Weight Kg/m2
Wind protection	55	45	2,48
Cladding	148	-	7,7
Glasswool	145	40	5,80
Rockwool	125	28	3,50
Plastic film	0,2	900	0,18
Aerogel	55	150	8,25
Cellulose and textile	140	50	7,00
Gypsum plasterboard	12,5	735	9,19

Table 5 Materials

4.1.2 Functional unit

When performing a life cycle analysis, a functional unit must be selected. In this case, the functional unit must also allow not only to carry out the study for each of the insulation materials but also to compare the different materials used. According to what has been established in the previous analysis, the functional unit most in agreement when making this comparative for insulation materials is the square meter of the wall that provides a U value of 0,18 W/ m2K. This indicator, being general, also allows associating it with a wide range of residential buildings, helping to achieve one objective of the study, which is the search for a material to be applied on a large scale in the construction of residential buildings.

4.1.3 Impact categories

The environmental impacts were selected according to the studies and LCAs studied in the literature review that was present in most of the environmental declarations of the materials, as stated before in the section 3.4.4. The impact categories selected for the study of the different alternatives are:

- Global warming potential
- Ozone depletion
- Acidification
- Eutrophication
- Photochemical ozone creation
- Depletion abiotic resources – elements
- Depletion abiotic resources – fossil fuels

4.1.4 System boundaries

As a starting point, the design of a diagram (Figure 6) can help to establish the limits of the system to be analyzed in terms of life cycle analysis, more commonly known as system boundaries.

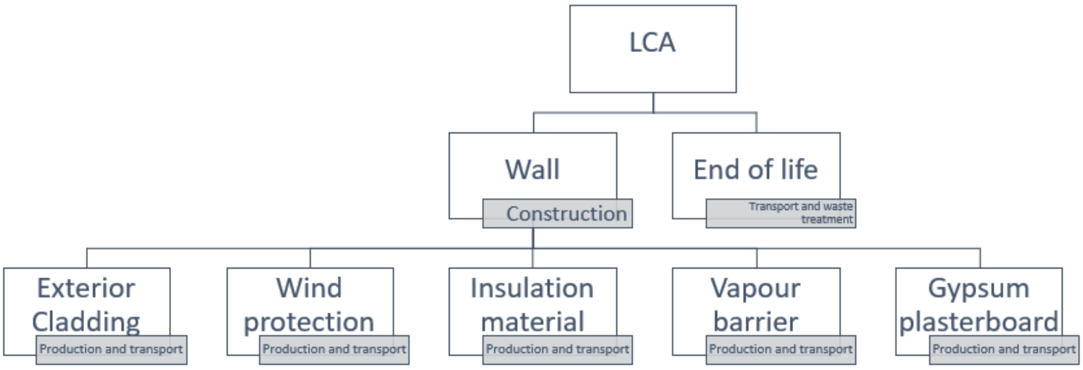


Figure 6 LCA of the wall

In the analysis, the constructive elements of the wall must consider the processes associated with its production or manufacture, and the transports, both intermediate and to the place of final construction. The processes associated with the construction of the wall and those related to its dismantling and the end of its useful life will be considered as well. In Table 6, the modules considered for the study are marked in green, while the modules neglected are in red.

PRODUCT STAGE			CONSTRUCTION PROCESS STAGE		USE STAGE							END-OF-LIFE STAGE				BENEFITS AND LOADS BEYOND THE SYSTEM BOUNDARIES
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport from the gate to the site	Construction, installation	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction, demolition	Transport	Waste processing	Disposal	Reuse- Recovery- Recycling- potential
[green]	[green]	[green]	[green]	[green]	[red]	[red]	[red]	[red]	[red]	[red]	[red]	[red]	[green]	[red]	[green]	[red]

Table 6 LCA stages

The limits of the study must be defined to achieve an adequate analysis. The main dimensions that must be specified and bounded according to (Baumann & Tillman, 2004) are *Natural boundaries*, *geographical boundaries*, *time boundaries*, *boundaries within the technical system.*

The time horizon studied will be that of the useful life of the building, assumed in 50 years, from producing the materials that make up the wall studied to the processes that mark the end of its useful life, such as the dismantling and its subsequent reuse or disposal.

As a geographical reference, the situation of the wall in Sweden, and more specifically in Gothenburg, will be taken. This influences the transport phases of the materials, relating to the selection of suppliers and transport distances with the building's location. Selecting another location involves recalculating and rethinking both the suppliers of the materials and the distances or means of transport used.

4.2 LCI

4.2.1 Inventory list of materials

The main database used to obtain the data needed to carry out the Life Cycle Analysis was the information extracted from EPDs (Table 7), but not all the materials and processes were defined or accurate to the production or construction processes of the structures analyzed. To solve this, the Ecoinvent database was used to cover the lack of information, especially concerning the transport stages (A4 and C2). In the following tables, these documents are shown:

Material	Product	Data in
Cladding	Exterior cladding	(Tellnes, 2015)
Wind protection	Paroc WPS 3n	(Paroc Group oy, 2018)
Cellulose loose fill	Loose fill cellulose insulation	(Werner, 2018)
Aerogel	Aeropan Spaceloft	(Hill, 2015)
Rockwool	Rockwool	(ROCKWOOL International A/S, 2016)
Glasswool	Glasswool slabs	(Boogman, 2018)
Plastic film	Tyvek® DuPont™	(Institut Bauen und Umwelt e.V. (IBU) , 2017)
Building board	Plasterboard Gyproc	(Gyproc Saint Gobain, 2013)

Table 7 Inventory of materials

The amount of material per square meter of the wall is set on Table 8, based on the need of material calculated to establish the U-value of 0,18 in the previous section:

Material	Weight Kg/m²
Wind protection	**2,48**
Cladding	**7,7**
Glasswool	**5,80**
Rockwool	**3,50**
Plastic film	**0,18**
Aerogel	**8,25**
Cellulose and textile	**7,00**
Gypsum plasterboard	**9,19**

Table 8 Material use

The consulted EPDs provide most of the information necessary to define the phases covered by this life cycle analysis. In the case of transport phases, either they were not included given the general character of the EPDs, or they did not adhere to the distances calculated for this project. Therefore, were calculated using Simapro and the Ecoinvent database, using the Recipe method (Ecoinvent, 2013). The final phase of disposal was also calculated using this system for aerogel, Rockwool and glasswool products since the EPD consulted only considered the phases of production and construction of the material. The data sources are detailed in Table 9.

	PRODUCT STAGE			CONSTRUCTION PROCESS STAGE		USE STAGE							END-OF-LIFE STAGE				BENEFITS AND LOADS BEYOND THE SYSTEM BOUNDARIES
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
	Raw material supply	Transport	Manufacturing	Transport from the gate to the site	Construction, installation	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction, demolition	Transport	Waste processing	Disposal	Reuse- Recovery- Recycling- potential
Cladding						-	-	-	-	-	-	-	-		-		-
Wind protection						-	-	-	-	-	-	-	-		-		-
Cellulose loose fill						-	-	-	-	-	-	-	-		-		-
Aerogel						-	-	-	-	-	-	-	-		-		-
Rockwool						-	-	-	-	-	-	-	-		-		-
Glasswool						-	-	-	-	-	-	-	-		-		-
Plastic film (Vapour barrier)						-	-	-	-	-	-	-	-		-		-
Building board (Plaster board)						-	-	-	-	-	-	-	-		-		-

	Data from the EPD
	Data from the Ecoinvent Database

Table 9 LCA data distribution

The wind barrier is based on the product Paroc WPS 3n (Paroc Group oy, 2018), composed by a mineral wool layer and a windproof Tyvek® membrane (Institut Bauen und Umwelt e.V. (IBU) , 2017). The cladding is a wood-based product, made using nordic sawn woods as raw materials. Also, the auxiliary materials were neglected after including some of them in the analysis and observe that their influence was less important than the 1% of the total emissions associated with the construction and production of the materials. Densities were also obtained using the Ecoinvent Database manuals (Ecoinvent, 2013) and the information provided in the EPDs.
The data related to the ventilated facades was obtained from the manufacturer PAROC and the database manuals of Ecoinvent (Ecoinvent, 2013).

4.2.2 Transportation distances

A critical point in terms of transport is the location of the building. In this case, the location established was the city of Gothenburg. Due to the limited amount of aerogel suppliers in the national market of Sweden, the transport distance from the factory in the USA to Gothenburg was considered as an international transportation to Europe (Hill, 2015). The distance to the port in the USA, the distance between the USA and Europe and the transport distance within Europe were considered. For the glasswool, the distance used was the one between Billesholm and Göteborg, where an ISOVER factory is located. The Rockwool was considered produced in the Rockwool factory located in Moss (Norway). The Dupont factory in Luxembourg is where the plastic film is produced, assuming that distance for the calculation. For the cellulose fibers, the distance was calculated to the facilities of Scandinavian Cellulose Production AB, in Tibro. The wind protection distance assumed is the distance between Göteborg and Hässleholm, where the PAROC plant is located. The cladding is transported from Oslo. The transport distances are shown in Table 10.

Material	Transport	Process	km	Tonkm
Aeropan	Transport distance production site to port (USA)	Transport, lorry 16-32t, EURO4	100	0,85
	Transport distance USA to Europe	Transport, transoceanic freight ship/OCE	5600	47,6
	Transport distance within Europe	Transport, lorry 16-32t, EURO4	400	3,4
Glasswool	Transport distance within Europe	Transport, lorry 16-32t, EURO4	213	1,2354
Rockwool	Transport distance within Europe	Transport, lorry 16-32t, EURO4	235	0,8225
Plastic film	Transport distance within Europe	Transport, lorry 16-32t, EURO4	1243	0,2237
Gypsum plasterboard	Transport distance within Europe	Transport, lorry 16-32t, EURO4	412	3,7863
Wind protection	Transport distance within Europe	Transport, lorry 16-32t, EURO4	230	0,5704
Cellulose fibers	Transport distance within Europe	Transport, lorry 16-32t, EURO4	175	1,225
Cladding	Transport distance within Europe	Transport, lorry 16-32t, EURO4	294	2,2638
Utilisation capacity (including return): 75%				

Table 10 Transport definition

4.2.3 End of life scenario

In the case of the end-of-life scenario, since for Aerogel no data were found to characterize this phase, the worst-case scenario was taken, in which the product was landfilled after its use. It considers a transport distance to the landfill site 50 km, and the utilization capacity, including empty trips. The transport was defined as a Transport, lorry 16-32t, EURO4.

For the plastic film, the distance and the transport at the end-of-life stage were not included in the EPD. Because of that, the impact of this stage was calculated taking the amount of plastic film needed per square meter and using the process Transport, lorry 16-32t, EURO4, and assuming 50km.

In the case of the cellulose insulation, 50 km to sorting installation and 100 km from sorting location to final waste processing were assumed. The transport was defined as Transport, lorry 16-32t, EURO4. For the waste processing, even though the cellulose is recyclable and reusable, the waste scenario after demolition, incineration with energy recovery and landfilling was assumed, as stated on the EPD (Institut Bauen und Umwelt e.V. (IBU) , 2017).

For the glasswool was used the method "Disposal, building, mineral wool, to final disposal/CH S" of the (Ecoinvent, 2013) database, that covers both C2 and C4 phases of the end of life stage. In the case of the mineral wool the landfill was also the end life scenario selected.
For the wind barrier, composed of Rockwool and a plastic barrier, the data used was the combination of the impacts of the two different materials.

4.3 LCIA-Results of the study

Based on the structure analyzed for the wall and data extracted from the environmental product declarations and the database (Ecoinvent, 2013), associated with its determined functional unit were weighted in such a way they were adapted to the amount of insulation needed per square meter to satisfy the thermal resistance required established by the regulations. After having all the data collected associated with the amount of each material needed to insulate the wall, the environmental indicators listed before were calculated for the 4 alternatives. The results show the values obtained considering the entire wall in all cases. The percentage of influence of each of the materials that make up the wall analyzed in the different phases is also calculated. The results are shown in the following sections.

4.3.1 Global warming potential

In this section the Global Warming Potential of the alternatives is shown, separated by phase of the life cycle.

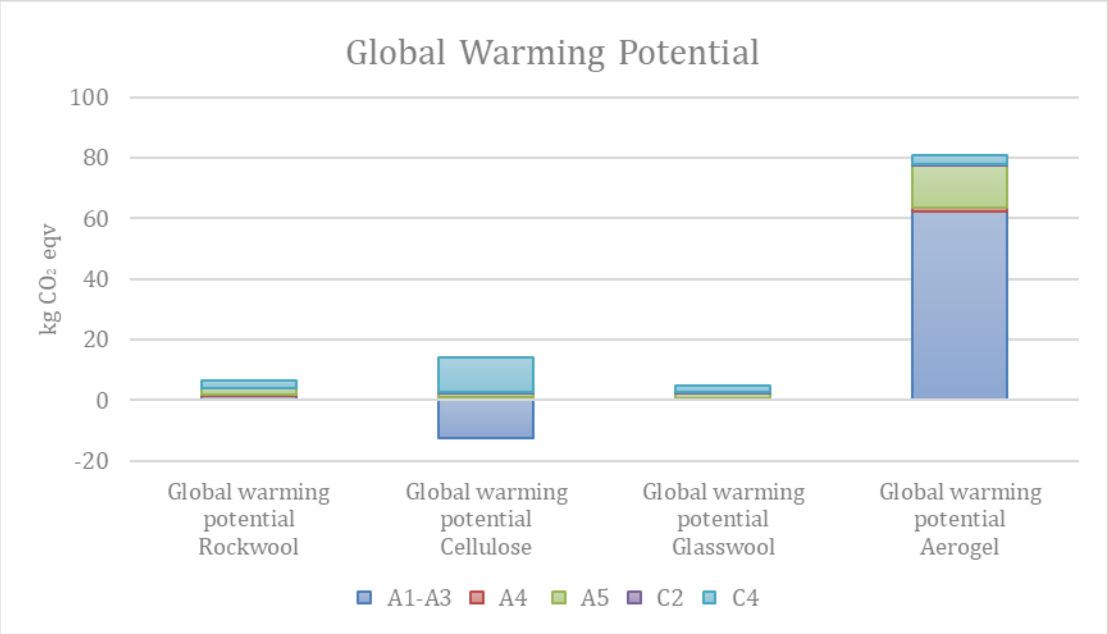


Figure 7 GWP

In the Figure 7 can be seen how the wall that uses aerogel as insulation material is the one with the highest emissions of greenhouse gases. In the case of the wall insulated with cellulose, a strange effect occurs, and that is the positive impact of the production phase. This is because cladding and cellulose fibers are made of wood and paper fibers from recycled newspapers respectively, so the sum of CO2 in this case is considered an advantage and is translated into a negative weighting.

Can be seen in this case how the most negative phase is C4, given that the scenario used in the LCA was that of incineration.

4.3.2 Ozone depletion

In this section the Ozone Depletion Potential of the alternatives is shown, separated by phase of the life cycle.

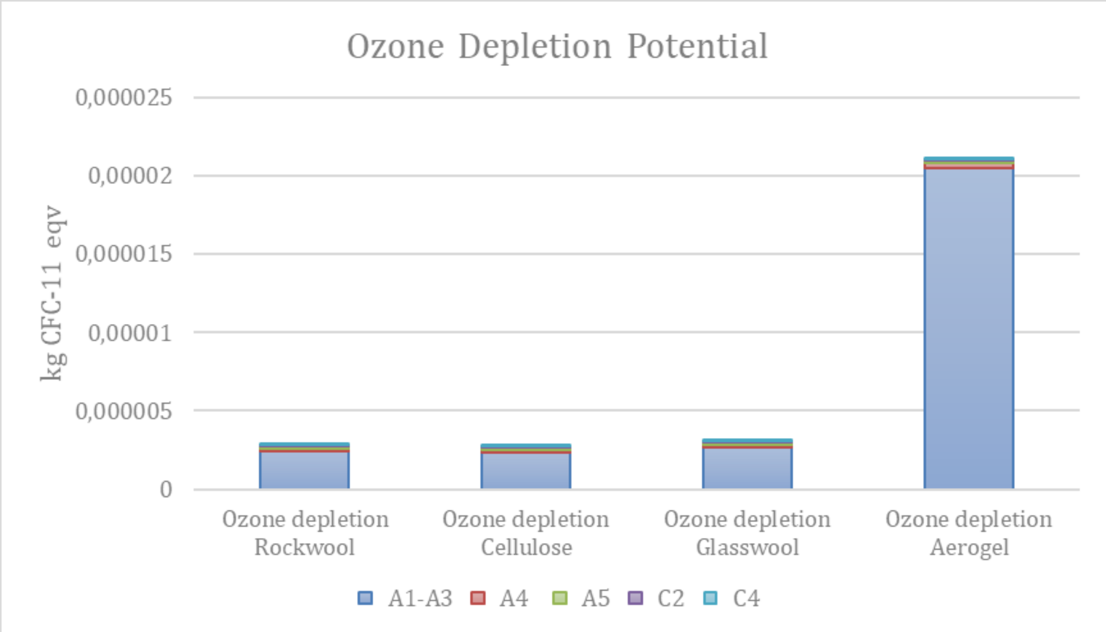


Figure 8 ODP

In the case of the ODP, it can be observed in Figure 8 how the first three alternatives show similar results, even in the distribution of the impacts throughout their useful life. In the case of Aerogel, the impact is approximately 10 times greater than the obtained by the other products. The stage with the greatest impact of the life cycle is the production of materials, which is approximately 95% of the associated emissions in the case of aerogel and 80% in the other solutions.

4.3.3 Acidification

In this section the Acidification Potential of the alternatives is showed, separated by phase of the life cycle.

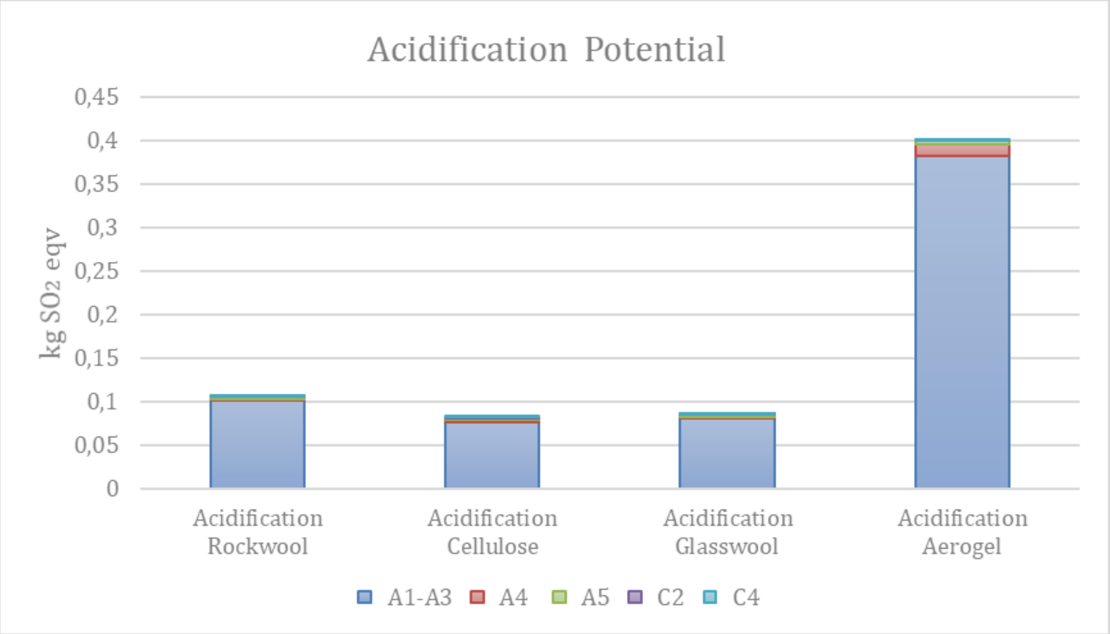


Figure 9 AP

Can be observed in Figure 9 how the aerogel solution is the one with the greatest impact in terms of acidification potential. In all solutions, the stage with the biggest impact is the production phase of the materials, representing the other stages approximately the 10% of all the impact. The other three solutions obtained even results, four times lower than those obtained by the insulated wall with aerogel. The best performance is achieved with cellulose insulation.

4.3.4 Eutrophication

In this section the Eutrophication Potential of the alternatives is showed, separated by phase of the life cycle.

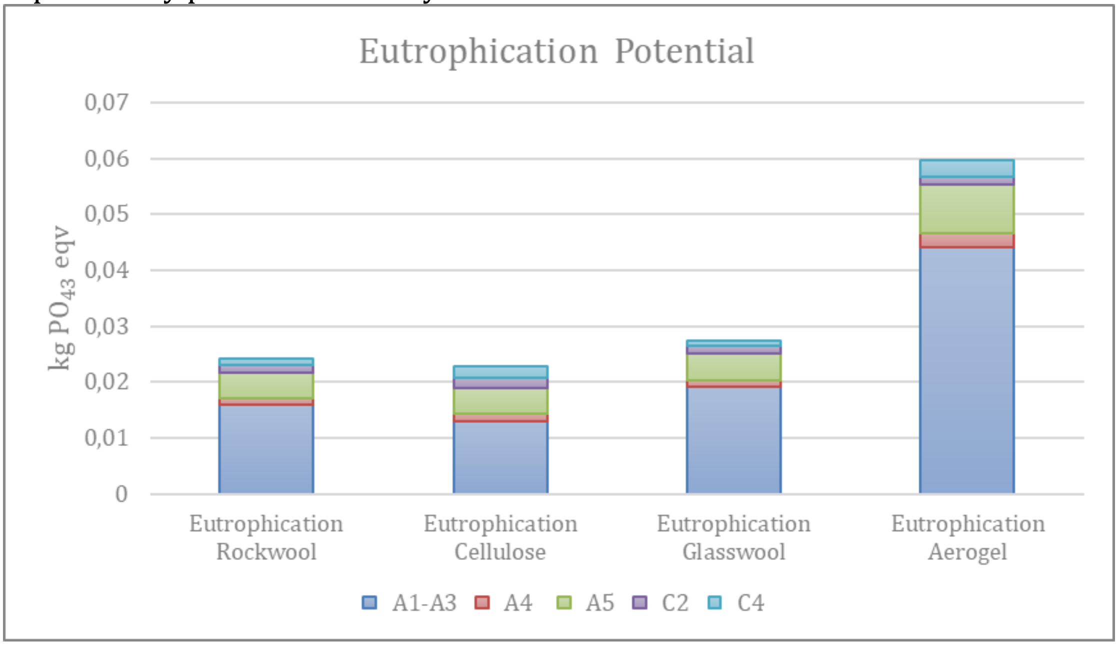


Figure 10 EP

In the case of Figure 10, can be seen how the aerogel solution has associated the greatest impact in terms of Eutrophication Potential. In all solutions, the stage with the biggest impact is the production phase of the materials, representing approximately the 70% of the global impact. The other three solutions obtained even results, two times lower than those obtained by the insulated wall with aerogel. The best performance is achieved with cellulose insulation.

4.3.5 Photochemical ozone creation

In this section the Photochemical Ozone Creation Potential of the alternatives is showed, separated by phase of the life cycle.

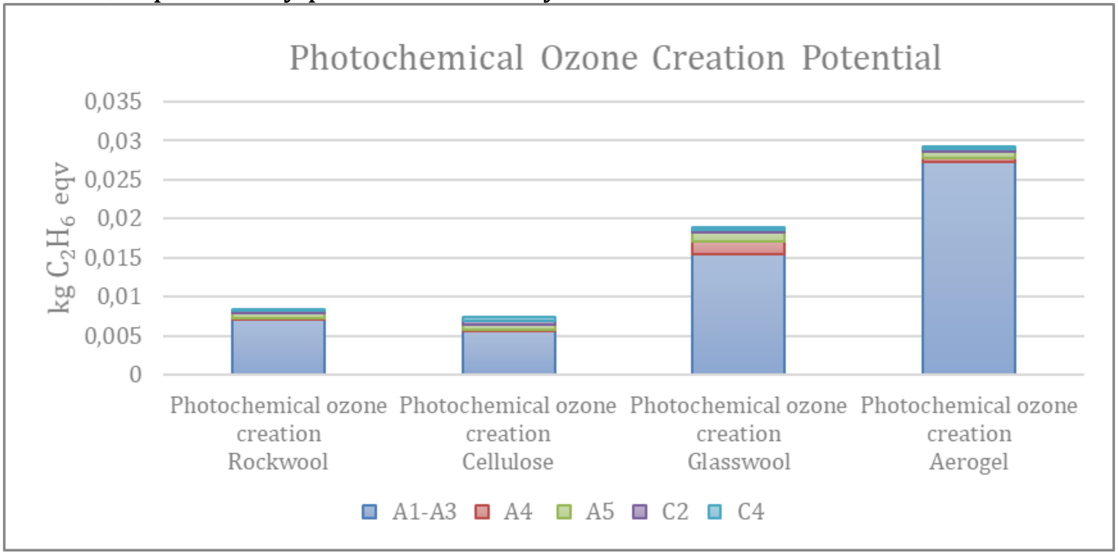


Figure 11 POCP

Contemplating the photochemical ozone depletion potential in Figure 11, seems clear that the aerogel solution has associated the greatest impact. The cellulose fibers solution obtained the best performance, is better than the glasswool and the rockwool on this indicator. In this case, the glasswool is in between the impact of the aerogel and the other two solutions, and not approximated to the value of the rockwool and the cellulose as it was in previous indicators.

4.3.6 Depletion abiotic resources – elements

In this section the Depletion of the abiotic resources due to elements of the alternatives is showed, separated by phase of the life cycle.

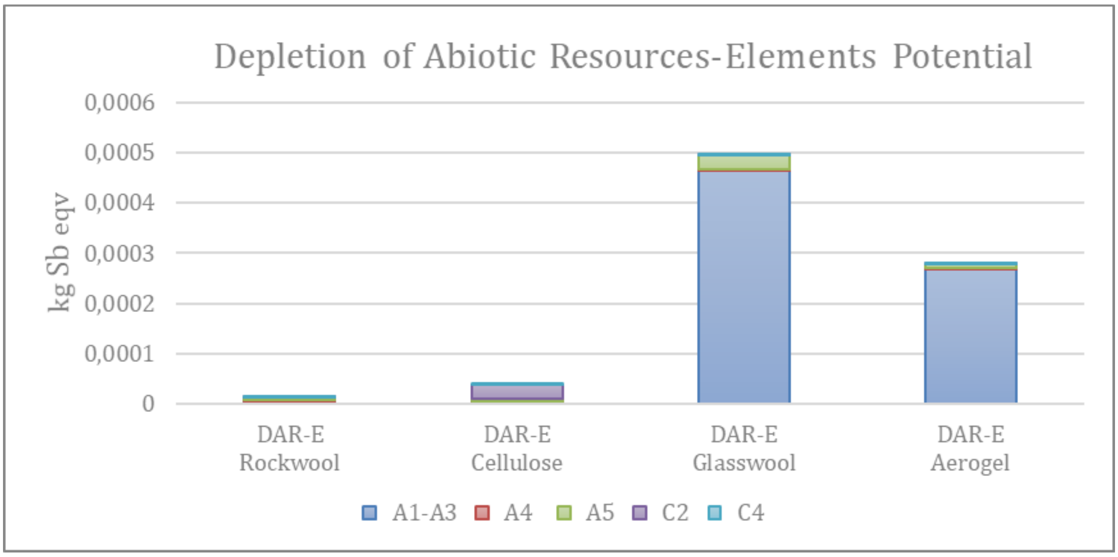


Figure 12 ADPE

Figure 12 shows the ADPE, the indicator with the greatest disparity. The most relevant impact is associated with glasswool, being the second the impact related to the aerogel solution. The impact of these two materials is well above the best materials in this field. Cellulose and rockwool, the best material according to this indicator, are far below the glasswool and aerogel results.

4.3.7 Depletion abiotic resources – fossil fuels

In this section the Depletion of abiotic resources potential associated with fossil fuels of the alternatives is shown, separated by phase of the life cycle.

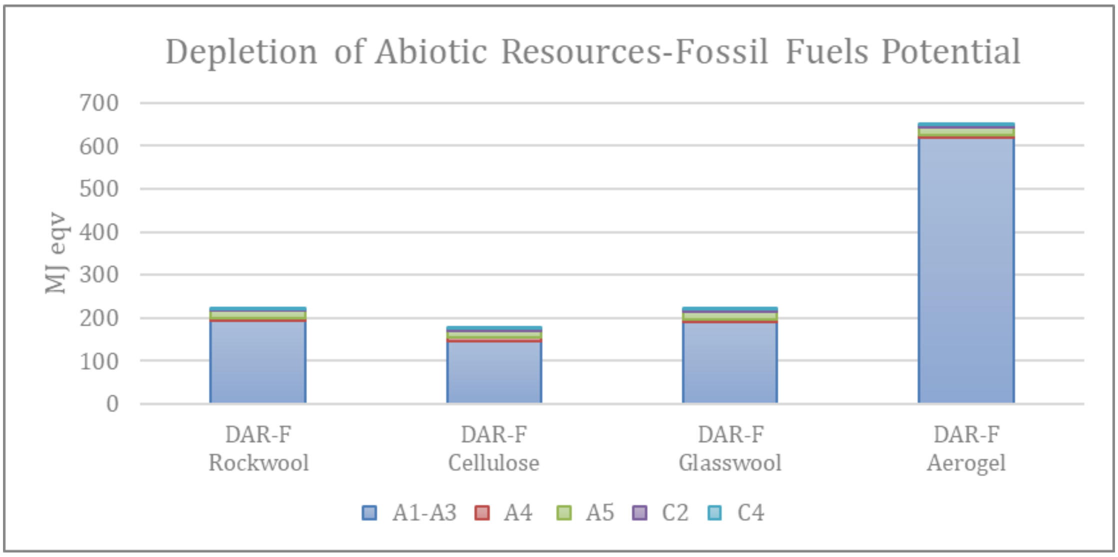


Figure 13 ADPF

In the case of Figure 13, can be seen how the aerogel solution has associated the greatest impact in terms of Depletion of Abiotic Resources due to Fossil Fuels. The distribution of impacts looks like the Figure 10, but with more influence of the production phase (A1-A3). In all solutions, the stage with the biggest impact is the production phase of the materials. The other three solutions obtained even results, three times lower than those obtained by the insulated wall with aerogel. The best performance is achieved with cellulose insulation.

4.3.8 Insulation materials analysis

A dominance analysis was carried out for the different configurations of the wall. The dominance analysis permits investigate which parts of the life cycle *gives rise to the greatest (dominant) environmental impact* (Baumann & Tillman, 2004). The results of the dominance analysis allow identifying where are the improvements are needed. The dominance analysis is done for the four insulation materials analyzed, considering all the phases of the LCA.

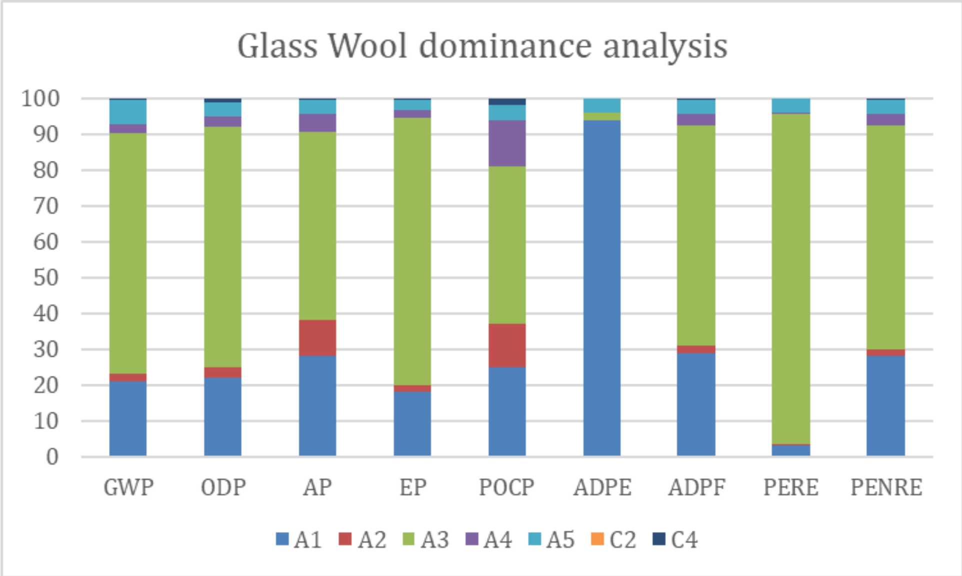


Figure 14 Glasswool dominance analysis

In the case of the glasswool (Figure 14), can be easily seen that the stage with a higher impact is the A3 stage in almost every category. The exception is the Abiotic depletion potential for non-fossil resources. Here, the stage with a higher impact is the phase of production of the raw materials.

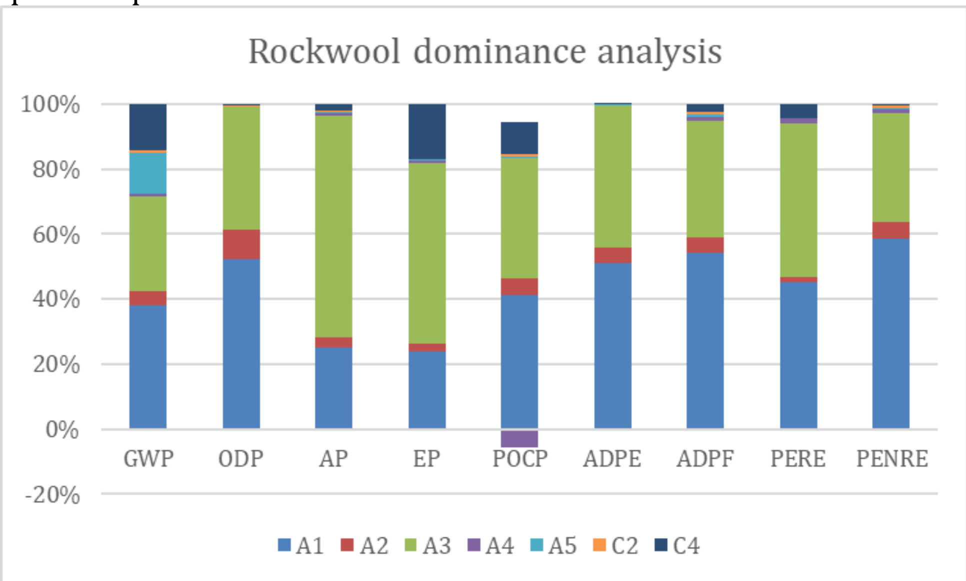


Figure 15 Rockwool dominance analysis

For the Rockwool (Figure 15), the most important phase in CO2 terms is related to the raw material supply. The phase A1 and A3 are the ones with the biggest environmental impact, alternating in the various indicators.

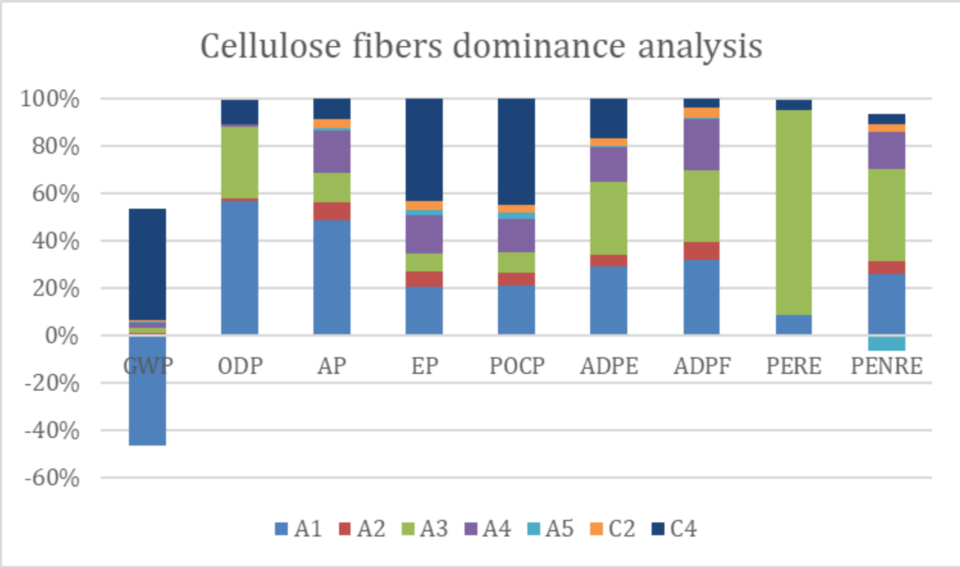


Figure 16 Cellulose dominance analysis

The greatest peculiarity of the distribution of impacts in the solution based on cellulose fibers (Figure 16) is, as mentioned above, the positive impact of the raw material supply phase in terms of global warming potential. Can be also seen how in the other environmental impacts, the end-of-life phase has a greater relative impact than that found when analyzing other materials. This is because the impacts of the minor production and construction phases in absolute terms, the end-of-life phase increases its percentage.

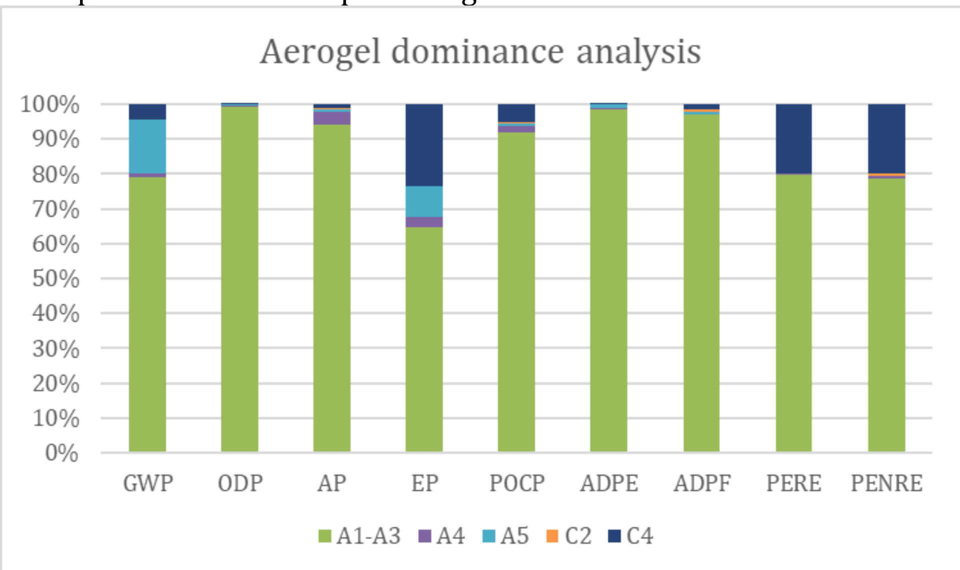


Figure 17 Aerogel dominance analysis

For the aerogel analysis, no concrete information is available for the construction phases, so that each of the processes of the production phase can be individualized. However, it can be verified that, as in the other insulation materials analyzed, the greatest impact is found in this phase. It can also be observed in Figure 17 that despite being the product with the greatest distance to the construction site, the impacts related to transportation (A4) are almost negligible compared to those of the phases (A1-A3).

5 Discussion

To compare the results, an analysis was done fixing the impact of the aerogel as a reference (Figure 18). The reason for choosing the aerogel as a reference is to improve the visualization of the graphic since the logical decision to reference the rockwool or glasswool provides variations that make it practically illegible.

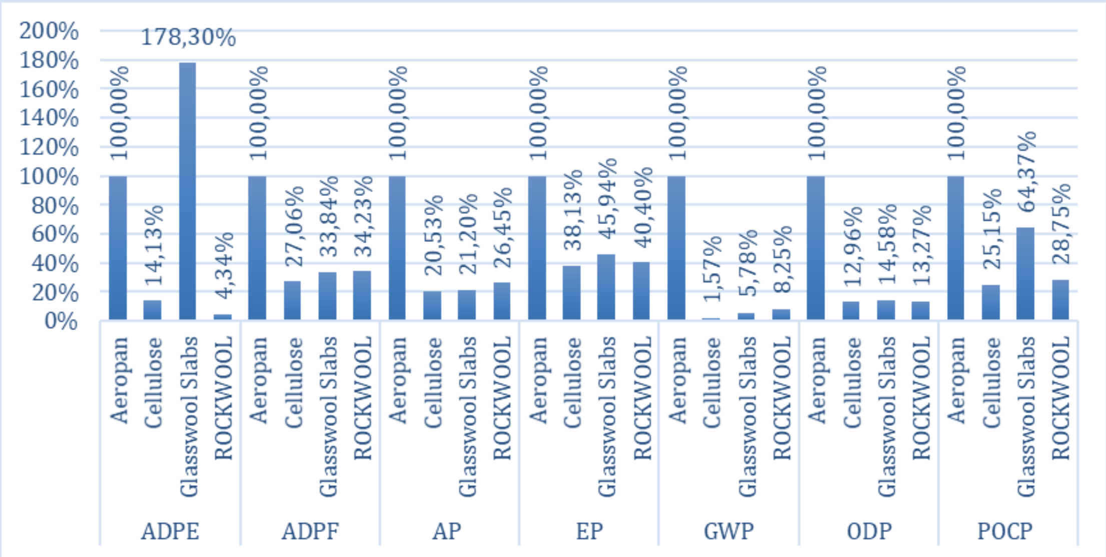


Figure 18 Impact comparison

	Aerogel	Cellulose	Glasswool	Rockwool
ADPE	3	2	4	1
ADPF	4	1	2	3
AP	4	1	2	3
EP	4	1	3	2
GWP	4	1	2	3
ODP	4	1	3	2
POCP	4	1	3	2

Table 11 Position by material and indicator

Can be seen on the Table 11 how the best performance in almost each of the impact categories is associated with the use of cellulose fibres. The worst position is for the aerogel in six of the seven categories. The glasswool and the rockwool occupy the second and third positions in almost all the indicators.

It seems clear, based on this analysis, that the insulation solution based on cellulose fibers is the one with the best environmental performance achieved in the global warming potential parameter (Figure 19). The lower value of this product is achieved by using recycled newspaper, so the difference between GWP Climate change excluding biogenic and GWP C-content leaves a negative balance in terms of equivalent CO2 emissions during the raw material supply phase. The cellulose fibers solution analyzed also included the inorganic flame retardants (as boric acid) needed to allow its use as insulation material (between the 5-15% of the total product in mass).

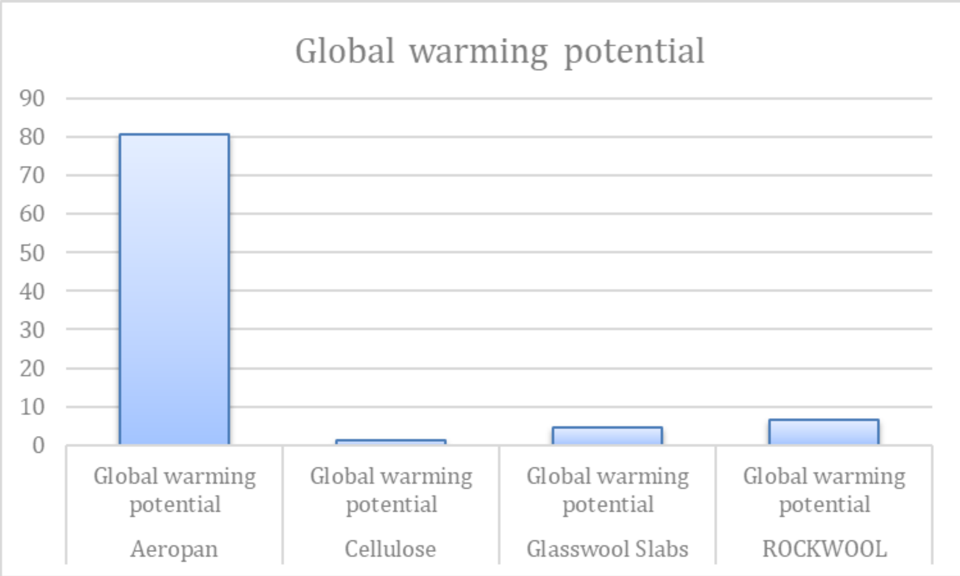


Figure 19 Global Warming Potential

In the case of acidification, the classification of impacts follows the same trend as, the highest being that of the phase associated with the obtaining of raw materials and manufacture of the aerogel. The acidification related to the other insulation materials analyzed is 4 or 5 times smaller.

The eutrophication, ozone depletion, photochemical depletion and the depletion of abiotic resources related to fossil fuels graphs follow a similar distribution, being the aerogel the one that entails a greater impact, and the solution with cellulose the one that has the minor, alternating the glasswool and the Rockwool as the options in second and third position. The case of the depletion of the abiotic resources related to the extraction of elements is different, being the glasswool the product with the higher impact, mainly because of the extraction of the raw materials.

The selection of cellulose fibers as an insulating material implies an improvement over the other products used in terms of greenhouse emissions. However, this decision implies a greater relative impact on the indicator of abiotic depletion potential for non-fossil resources, where the selection of the alternative based on Rockwool would imply an impact three times lower.

It seems clear that the aerogel is not an option to be considered in any of the impacts analyzed, given that it has the greatest impact on all the indicators except for abiotic depletion potential for non-fossil resources, in which the glasswool is the material with the greater impact (70% greater than that of aerogel). Must be considered that the analysis was made only considering the panel-based solution for the aerogel. According to (Berardi, 2018), the aerogel blankets have shown potential in retrofitting projects, while the solutions based on aerogel glazing systems and aerogel-embedded renders are still object of research, therefore, no environmental data on its commercial application was found for inclusion in the project. According to (Berge, et al., 2009), the use of the aerogel on the southern walls of the buildings can lead to a lower use of energy associated with the heating of the building, since it allows the entry of solar radiation. This fact gives to the aerogel an advantage over other insulating materials that do not allow to take advantage of solar energy, this is, bi-directionally insulating.

These are the results obtained when comparing each of the indicators among themselves, but to compare the general impact of the materials, the use of a method of impact weighting is needed. The EPS 2015 was the method chosen (Steen, 2015). The EPS impact assessment method results are the damage costs for emissions and use of natural resources expressed as ELU (Environmental Load Units). One ELU represents an externality corresponding to one Euro environmental damage cost. Impact categories are identified through five areas of protection: human health, the capacity to produce ecosystems, resources, biodiversity, and cultural and recreational values. The default approach is expressed in terms of environmental philosophy and the principles of "causality" and "precaution". The environmental impacts analyzed were the ones used for the comparison of the wall, crossing the data from the study with the ELU characterization factors using Excel. The data used was the one developed by the Swedish Life Cycle Center in the last version, the EPS 2015 (Steen, 2015). The data used is detailed in 10.2. The characterization factors are shown in Table 12:

	Parameter	**Unit**	**ELU/Unit**
Global warming potential	Carbon dioxide	kg	0,135
Ozone depletion	R 11 (trichlorofluoromethane)	kg	716,889
Acidification	Sulphur dioxide	kg	0,118
Eutrophication	Phosphate	kg	0,012
Photochemical ozone creation	Ethene (ethylene)	kg	17,633
Depletion abiotic resources – elements	Antimony	kg	18190
Depletion abiotic resources – fossil fuels	Crude oil (in MJ)	MJ	0,011

Table 12 Environmental Load Units

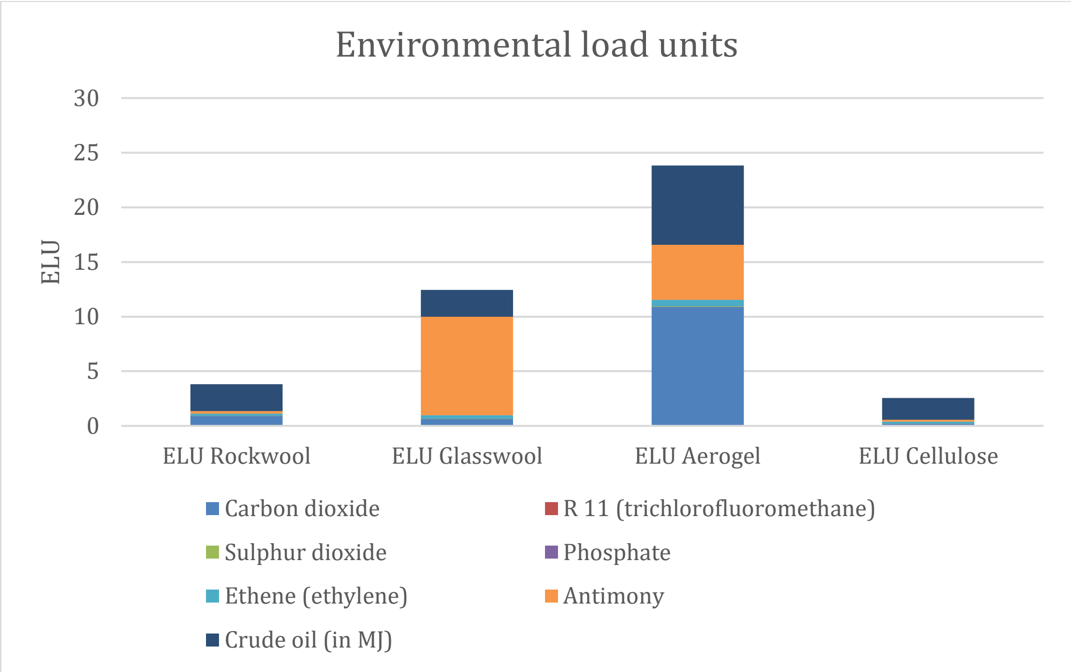


Figure 20 EPS

It can be observed in Figure 20 how the environmental load associated with the configuration with aerogel is much greater than that of the other types of wall. The option that brings a better environmental performance according to these categories is based on a cellulose solution. The options based on Rockwool got better performance than the glasswool, due to the great impact associated with the depletion of abiotic resources that have the glasswool. This is due to the use of silica and felspar. For the extraction of silica, the open surface mining with shovel excavators is used. After that, it is attrited, washed, hydro classified and sifted. Felspar is the second important raw mineral in glass wool production. It is created as a by-product in open surface mining of silica sand. These processes have a great impact in terms of abiotic depletion (Boogman, 2018).

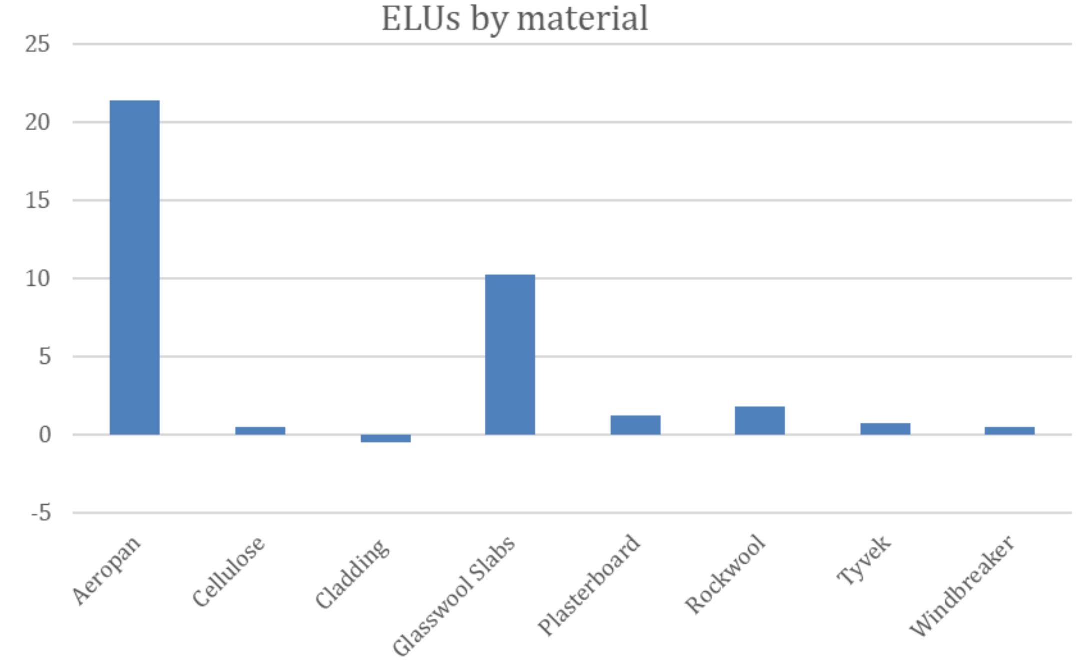


Figure 21 ELUs by material

Can be easily seen in Figure 21 how the greatest impact is associated with the use of the aerogel when compared with the other elements of the analysis.

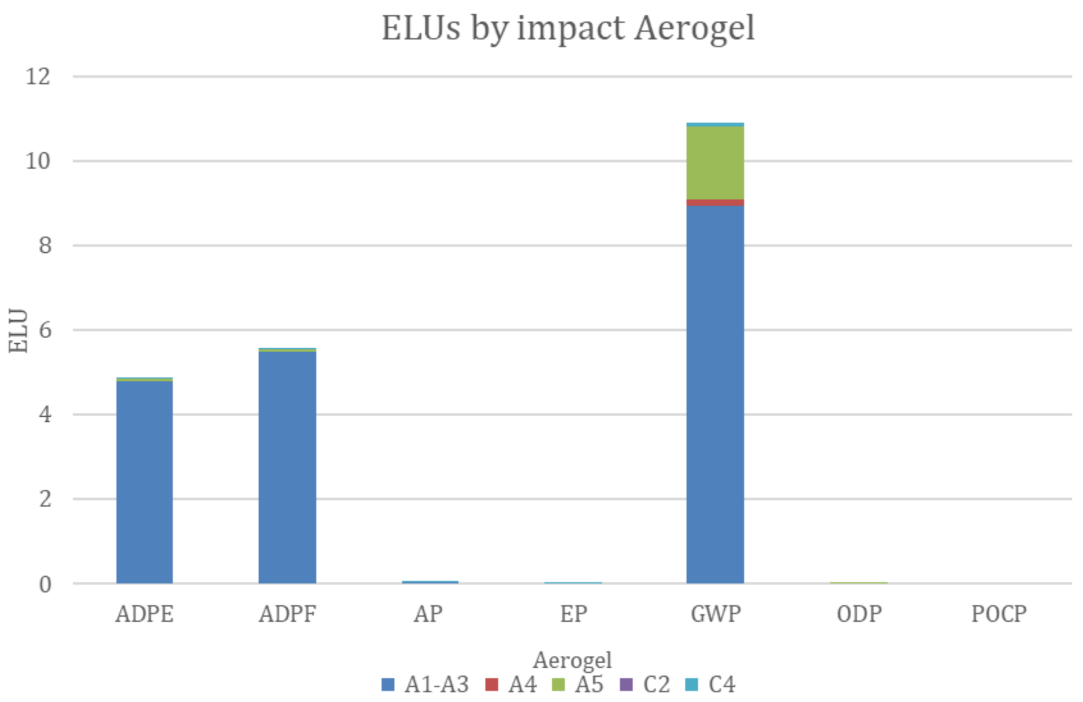


Figure 22 ELUs by impact Aerogel

By observing the aerogel individually on Figure 22, it can be verified that the most important category of environmental impact is that of global warming potential, well above the second most important, the abiotic depletion potential due to fossil fuels. The most demanding stage of the life cycle is clearly the production phase, to which corresponds up to the 85% of the ELUs of the material

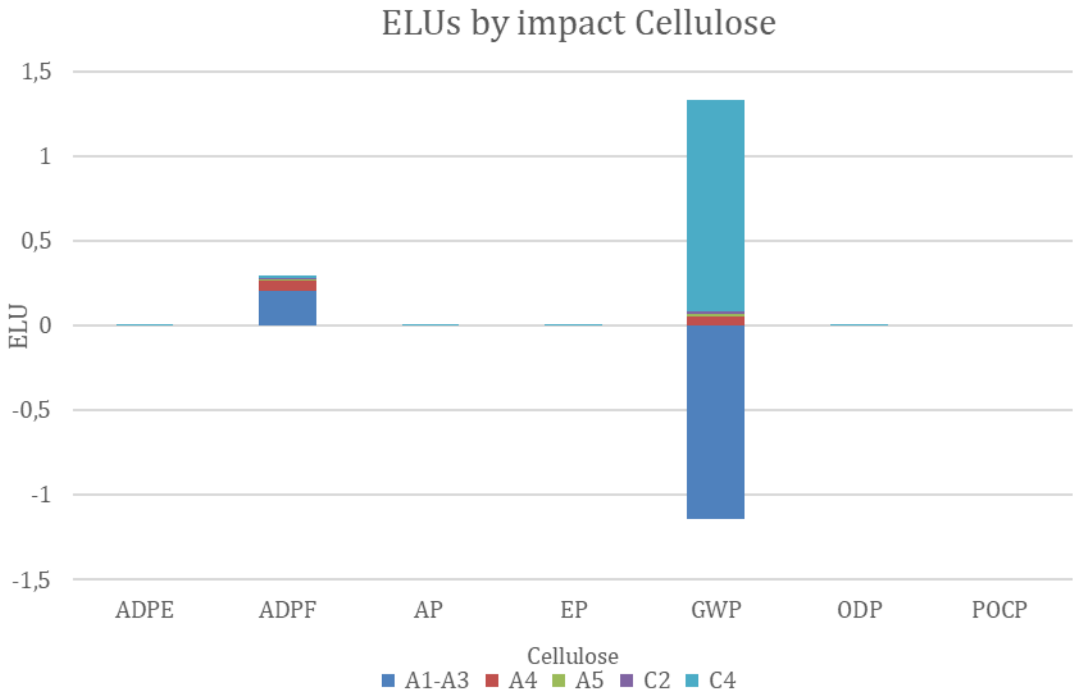


Figure 23 ELUs by impact Cellulose

For the cellulose (Figure 23), the most important impact is that of the abiotic depletion due to fossil fuels, being the global warming potential the second in importance. It can be seen how the impact scale for cellulose is much smaller in comparison to the values got by the aerogel. Can be seen studying the life cycle stages how the production phase has a net gain of 1 ELU since the raw material used to make the insulation products is recycled paper. This provides an improvement in terms of CO2 emissions. The most demanding phase is C4, mainly due to the estimated emissions of greenhouse gases assuming an incineration process for the material as the end of life.

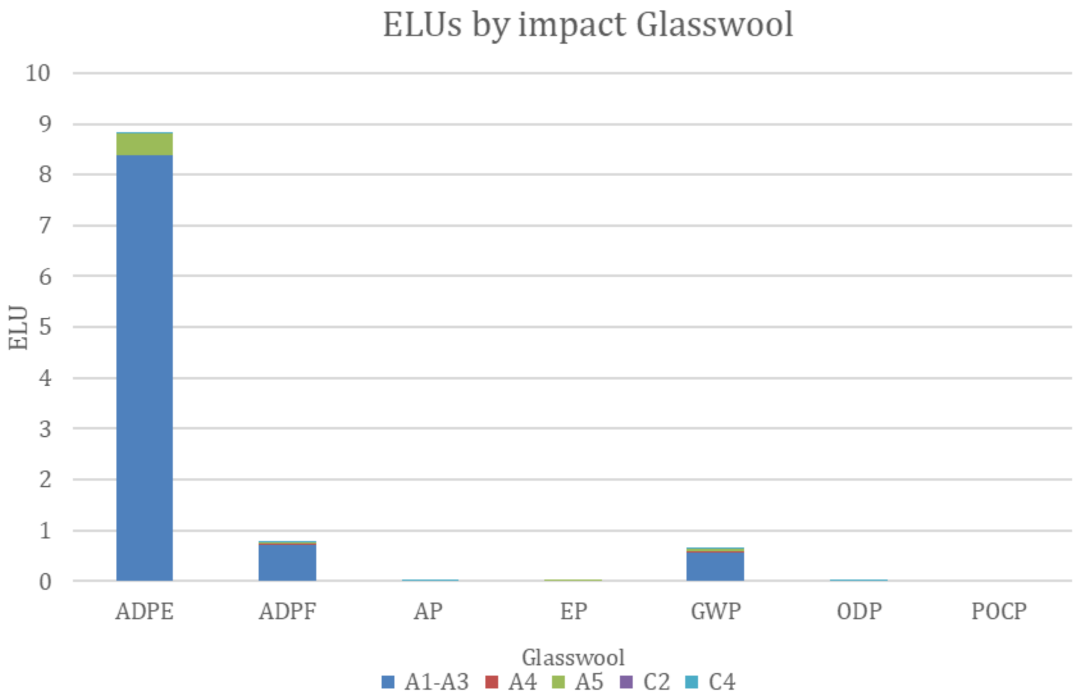


Figure 24 ELUs by impact Glasswool

In the case of the glasswool (Figure 24), can be seen how the most demanding phase of the life cycle is the production stage. The biggest impact is associated with the Abiotic depletion due to elements, being ten times the value of the second biggest impact, the abiotic depletion due to fossil fuels.

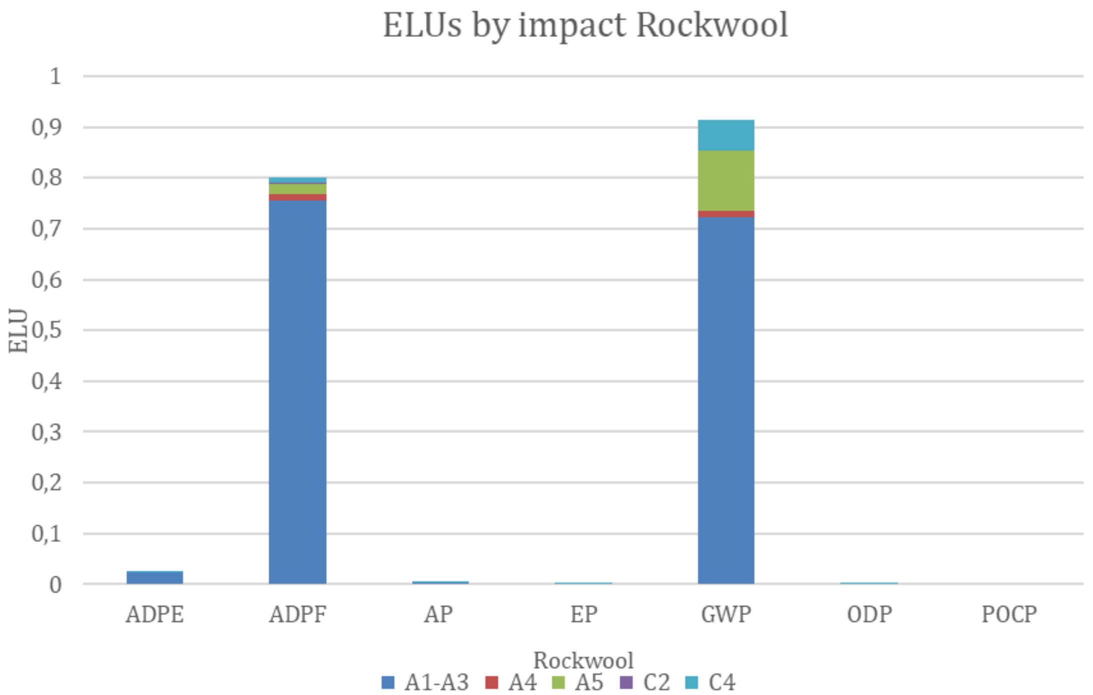


Figure 25 ELUs by impact Rockwool

In the case of the Rockwool (Figure 25), the most demanding phase of the life is the production phase, clearly above the other ones. The most important impact for this material is associated with the global warming potential, but the impact associated with the abiotic depletion due to fossil fuels is almost as important.

5.1 Validation of results

To compare the results, the study was contrasted with the EDIP method. The Environmental Development of Industrial Products is a method developed by the Institute for Product Development (IPU) at the Technical University of Denmark in Lyngby (Hauschild, et al., 2006). The data from the study with the EDIP characterization factors were treated using Excel The characterization factors (Table 13) were extracted from (Potting & Hauschild, 2004) and (Baumann & Tillman, 2004). The results are detailed in 10.3.

	Parameter	Unit	EDIP/Unit
Global warming potential	Carbon dioxide	kg	0,000000149
Ozone depletion	R 11 (trichlorofluoromethane)	kg	0,113861
Acidification	Sulphur dioxide	kg	0,0000109
Eutrophication	Phosphate	kg	0,0000421
Photochemical ozone creation	Ethene (ethylene)	kg	0,00006
Depletion abiotic resources – elements	Antimony	kg	0,016814
Depletion abiotic resources – fossil fuels	Crude oil (in MJ)	MJ	8,30E-07

Table 13 EDIP characterization

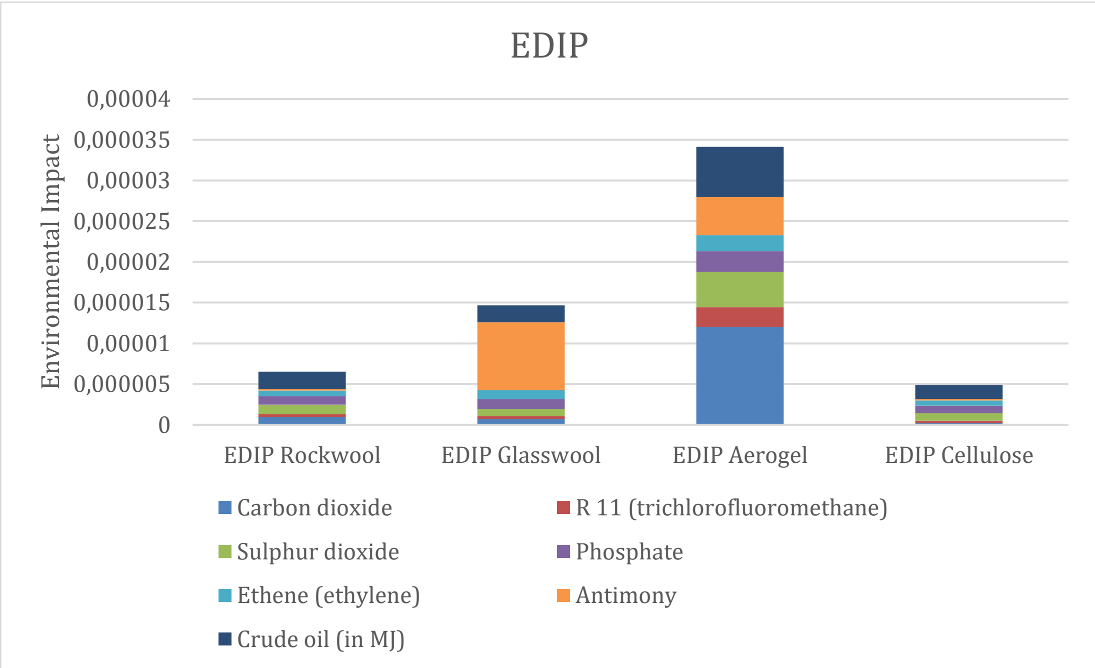


Figure 26 EDIP Results

The results obtained and showed in Figure 26 reinforce the idea that aerogel is the material with the greatest environmental impact, and cellulose fiber the most interesting from an environmental point of view. The analysis also shows the big impact of the abiotic depletion indicator associated with the glasswool production process.

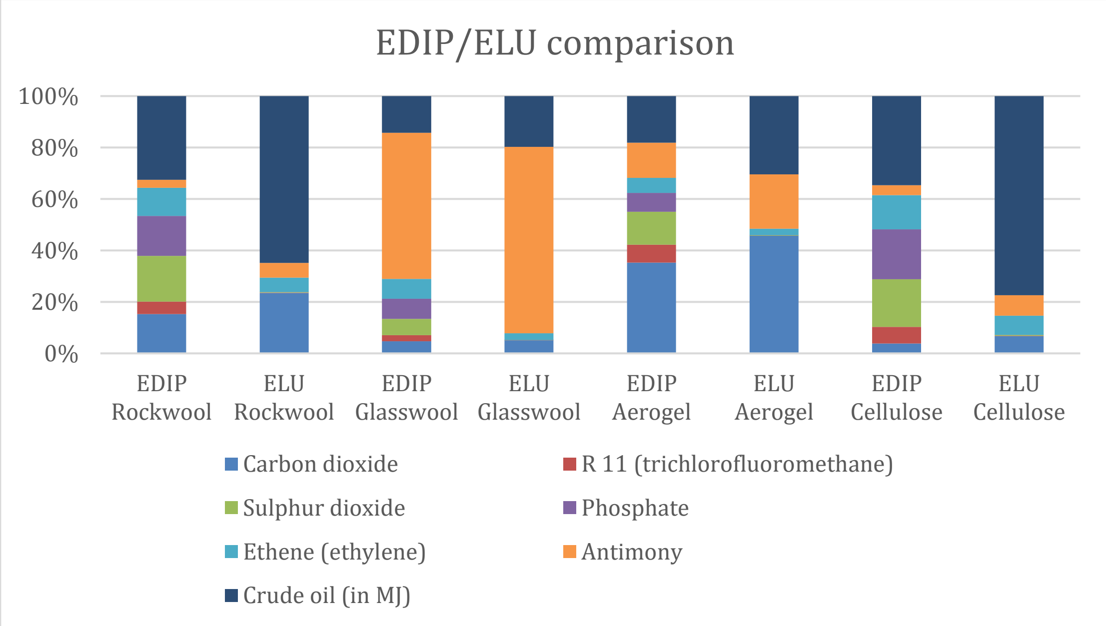


Figure 27 ELU and EDIP comparison

In Figure 27, the EDIP method shows a lower relative importance of the impact due to greenhouse emissions in the case of aerogel, or what is the same, a higher percentage of impact associated to the other environmental impacts than when the ELUs were used. This circumstance reaffirms the importance of measuring different impacts when looking for the most sustainable element in a comparison. The EDIP method distributes more the impacts between the different categories, losing relative importance the abiotic resource depletion due to fossil fuels compared with the results obtained using environmental load units.

A deeper analysis was carried out to show the possible deviations of the data used, using the GWP values obtained, since is one of the most important impacts that both materials share. To validate that, glasswool and Rockwool insulation products Table 14) were compared, showing that the results are similar, but having the Rockwool a bigger impact in terms of CO2.

Type	Name	EPD	Kg C02/m2wall
Glasswool	Isover Glasswool Slabs	(Boogman, 2018)	4,25
Glasswool	Isover Glasswool Rolled	(Boogman, 2018)	4,25
Glasswool	ISOVER InsulSafe	(The Norwegian EPD Foundation, 2018)	2,27
Glasswool	URSA DF 40	(Slovenian National Building Institute, 2013)	2,86
Glasswool	URSA FDP 2 Vf	(Slovenian National Building Institute, 2013)	6,36
Glasswool	URSA FDP 2	(Slovenian National Building Institute, 2013)	5,87
Glasswool	URSA FDP 3 Vf	(Slovenian National Building Institute, 2013)	6,93
Glasswool	URSA SF 32	(Slovenian National Building Institute, 2013)	6,87
Glasswool	URSA SF 35	(Slovenian National Building Institute, 2013)	4,72
Glasswool	URSA TWF 1	(Slovenian National Building Institute, 2013)	3,28
Rockwool	ROCKWOOL® isolering	(The Norwegian EPD Foundation, 2013)	4,57

Rockwool	Stone Wool Thermal Insulation for buildings	(ROCKWOOL International A/S, 2016)	5,76
Rockwool	ROCKWOOL® Stone Wool Thermal Insulation for External Wall	(PE INTERNATIONAL AG, 2103)	5,36
Rockwool	Knauf DP-3	(Institut Bauen und Umwelt e.V., 2013)	7,54
Rockwool	Knauf DP-5	(Institut Bauen und Umwelt e.V., 2014)	9,66
Rockwool	Knauf DP-7	(Institut Bauen und Umwelt e.V., 2018)	8,79
Rockwool	Knauf RMW Insulation 33 - 45 kg/cu.m	(BRE Global, 2016)	9,30

Table 14 Mineral wool samples

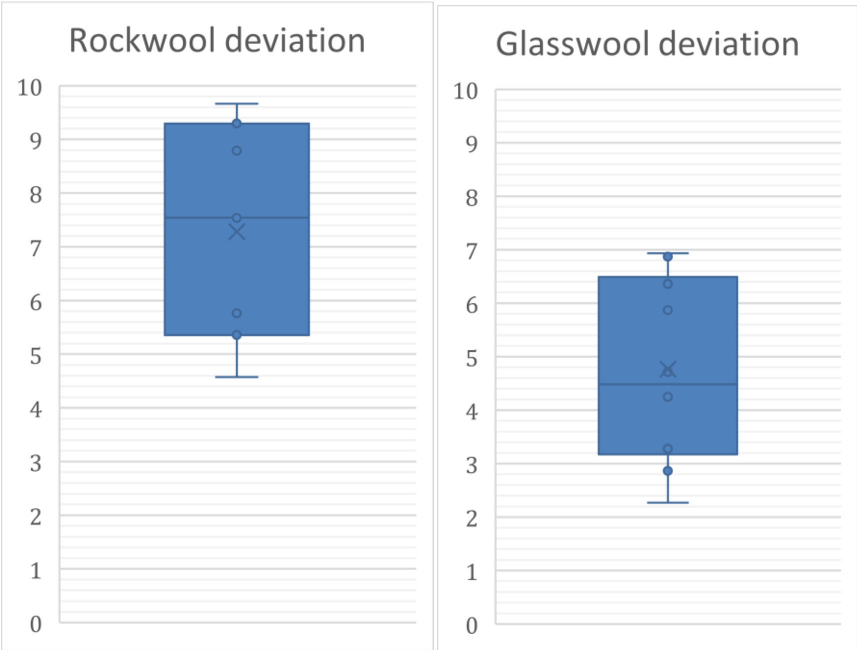


Figure 28 Rockwool and Glasswool deviation

Can be seen in Figure 28 how in function of the product used to do the analysis, that there is no clear winner in terms of CO2 emissions, but based on the EPDs consulted, it seems that the glasswool shows a slightly better behavior in terms of GWP. However, it is a very small sample of materials analyzed, so the reality, seeing the closeness of the intervals, can be different.

6 Conclusions

After the analysis of the different materials chosen for the study, the results based on the EPS and EDIP methods show that the use of insulation solution composed by cellulose fibers can lead to obtaining a better environmental performance. In terms of equivalent CO2 emissions is also better than the conventional insulation materials analyzed and the aerogel. The use of this solution remains residual, largely since the decision-making method when choosing materials by the industry is still mostly opting for the alternative with the lowest material cost. This gives an almost insurmountable competitive advantage to conventional insulation materials due to the economy of scale. The methods of material selection of the construction companies must be modified to increase the specific weight of the environmental criteria, giving more importance to the LCA during the decision process, and not only measuring the economic aspects.

In the case of the aerogel, although its environmental properties are worse than the other insulation materials analyzed, the total result of its use as an insulator continues to provide positive emission savings in terms of GWP. This comparison is not so fair for the aerogel taking into account that its current use is not that of main insulation in residential buildings, so the results obtained are quite influenced by this fact. For its study a retrofitting-oriented material configuration was used, so the results cannot be directly extrapolated to its use as the main insulator. Due to its reduced thickness, it can be an alternative in existing buildings where the installation of other types of insulation in retrofitting solutions is not possible due to lack of space, or in the case of facades of protected historical interest, where the use of other materials would significantly alter them, as well as in new constructions where the thickness is a key element of the structure. It's also interesting as a thermal barrier for the southern walls, because it permits the entrance of the solar radiation into the building, reducing the need for heating.

The emissions associated with the production phase of all the products are in general, significantly higher compared with the other stages of the life cycle analyzed. In the case of the aerogel, it can be observed how more than three-quarters of the emissions associated with the production phase and that the 85% of the ELUs associated to the product are linked to the emission of greenhouse gases. This shows that in the future this should be the process to be improved in terms if a competitive product in this field wants to be reached. If it is possible to improve the environmental performance from the production, the Aerogel can become an interesting material due to its outstanding thermal and fireproof properties.

The transport processes represent all products and stages a small impact considering all the life of the total production, which goes in line with the result obtained in the analysis. This reaffirms that when choosing a supplier is usually more interesting

The mineral wool based solutions, with intermediate results, serve as a reference when comparing the two alternative materials chosen. The results got in terms are in between the two of the other options analyzed, presenting a better performance the rockwool. The glasswool's environmental performance is clearly influenced by the fact that it is the worst option in terms of depletion of abiotic resources. This also shows the importance of including various indicators in an environmental performance comparison (or in any other field) when drawing conclusions about the performance of a material or product in terms of global indicators.

7 Further development

One of the biggest issues during the thesis was to establish the boundaries. Since it is a broad topic, some limits were set to obtain a problem that could be answered in the time horizon of a thesis work. Because of this, an advanced research can be made taking more information into account or including different considerations. For example, include the foam plastic insulation materials, largely used by the industry in some parts of the world. Other modern insulation materials were neglected during the study when selecting the aerogel. The vacuum insulation panels, for example, can be included in the study. The wall layer selected follows a traditional design for the Nordic countries, but it is not a usual type of wall in other parts of the globe. Since the intention of the thesis is to provide a suitable solution for a big scale application, including another kind of wall structures can be a good option to reach solutions for other climatic zones of the earth.

Insulation materials are used in many applications within residential buildings. Only the wall's thermal barriers that protect the building envelope were considered. Insulation of the facilities or internal partitions was not part of this thesis. Also, being part of the external surface, the roof was not included in the study. Elements such as doors or windows are also part of the envelope of the building and were neglected. All these elements should be considered in the next studies if a global vision of insulation in residential buildings is sought.

The study focuses on some environmental impacts looking for correlations and trade-offs between them. Looking for a deeper analysis, more indicators or environmental impact categories should be added to the studio. Also, the EPS and EDIP impact assessments were selected for carrying the comparison between the different materials and impacts. Other methods can verify if the results obtained using these are reliable.

After performing the analysis, a point that catches the attention is the number of associated emissions that the aerogel has compared with the other materials analyzed. This disparity so high that makes it necessary to verify that the analysis makes sense. For this, the procedure should be studied during the production process of the aerogel, where the main impacts are located.

It should be noticed that in the case of the aerogel, its panel-based variant was used as a material for the study. Other variants of the product, such as its potential use as aerogel glazing systems and aerogel-embedded renders, should also be studied before judging it as an unsustainable insulation material. The fact that it can be used as a unidirectional insulator between glass sheets in the south-facing walls can give an advantage when analyzing the phase of use of the material (B) in the life cycle compared to other bi-directional insulating materials. More studies should be conducted focusing also on the phase of use before ensuring that the aerogel is not competitive in terms of environmental impact.

8 References

Adalberth, K., 2000. Energy Use and Environmental Impact of New Residential Buildings.

Aditya, L. et al., 2017. A review on insulation materials for energy conservation in buildings. *Renewable and Sustainable Energy Reviews.*

Association, European Insulation Manufacturers, 2018. [Online] Available at: https://www.eurima.org/u-values-in-europe/

Baetens, R., Jelle, B. P. & Gustavsen, A., 2011. Review: Aerogel insulation for building applications: A state-of-the-art review. *Energy & Buildings.*

Ballagh, K. O., 1996. Acoustical properties of wool. *Applied Acoustics.*

Baumann, H. & Tillman, A.-M., 2004. *The Hitch Hiker's Guide to LCA.* s.l.:s.n.

Berardi, U., 2018. Aerogel-enhanced systems for building energy retrofits: Insights from a case study. *Energy and Buildings.*

Berge, B., Butters, C. & Henley, F., 2009. *The Ecology of Building Materials.* s.l.:s.n.

Boogman, P., 2018. *EPD ISOVER Glasswool,* s.l.: s.n.

BRE Global, 2016. *Rock Mineral Wool EPD,* s.l.: s.n.

Briga-Sá, A. et al., 2013. Textile waste as an alternative thermal insulation building material solution. *Construction and Building Materials.*

Campos-López, E., 1980. *Renewable Resources a Systematic Approach.* s.l.:s.n.

Casini, M., 2016. *4 – Advanced insulating materials.* s.l.:s.n.

Christianson, E. & Nsofor, E. C., 2014. A study on materials for improved energy conservation in buildings. *Energy Engineering: Journal of the Association of Energy Engineering.*

COMMISSION OF THE EUROPEAN COMMUNITIES, 2001. *GREEN PAPER ON INTEGRATED PRODUCT POLICY.* s.l.:s.n.

Czarnecki, L. & Van Gemert, D., 2017. Innovation in construction materials engineering versus sustainable development. *Bull. Pol. Ac.: Tech. BULLETIN OF THE POLISH ACADEMY OF SCIENCES TECHNICAL SCIENCES,* 65(6).

Ecoinvent, 2013. *Ecoinvent Database 3.0.* s.l.:s.n.

Fundación de la Energía de la Comunidad de Madrid, 2012. *Guía sobre Materiales Aislantes y Eficiencia Energética,* s.l.: s.n.

Gielen, D., 1997. *Building materials and CO2: Western European emission reduction strategies,* Petten: ECN Policy Studies .

Govindan, K., Shankar, K. M. & Kannan, D., 2015. Sustainable material selection for construction industry – A hybrid multi criteria decision making approach. *Renewable and Sustainable Energy Reviews,* Volume 55, pp. 1274-1288.

Gyproc Saint Gobain, 2013. *Gyproc Loftplader Environmental Product declaration,* s.l.: s.n.

Hammond, P. G. & Jones, C., 2006. Inventory of Carbon & Energy (ICE). *Mechanical Engineering.*

Hauschild, M. Z. et al., 2006. *Spatial differentiation in the characterisation of photochemical ozone formation: The EDIP2003 methodology.* s.l.:s.n.

Hidalgo, J., Torero, J. & Welch, S., 2017. Experimental Characterisation of the Fire Behaviour of Thermal Insulation Materials for a Performance-Based Design Methodology. *Fire Technology.*

Hill, C., 2015. *Environmental Product Declaration SPACELOFT® AEROGEL INSULATION,* s.l.: Renuables.

Horvath, A., 2004. CONSTRUCTION MATERIALS AND THE ENVIRONMENT. *Annual Review of Environment and Resources.*

Institut Bauen und Umwelt e.V. (IBU) , 2017. *Environmental Product Declaration DuPont™ Tyvek®,* s.l.: The Norwegian EPD Foundation.

Institut Bauen und Umwelt e.V., 2013. *DP-3 Multipurpose Rock Mineral Wool insulation EPD,* s.l.: s.n.

Institut Bauen und Umwelt e.V., 2014. *DP-5 Multipurpose Rock Mineral Wool insulation,* s.l.: s.n.

Institut Bauen und Umwelt e.V., 2018. *DP7 - DP8 Multipurpose Rock Mineral Wool insulation,* s.l.: s.n.

IPCC, 2014. *Summary for Policymakers.* s.l.:s.n.

Kim, J. H., Kim, S. M. & Kim, J. T., 2017. *Simulation Performance of Building Wall with Vacuum Insulation Panel.* s.l., s.n.

Lee, S. W., Lim, C. H. & Salleh, E. @. B., 2016. *Reflective thermal insulation systems in building: A review on radiant barrier and reflective insulation.* s.l.:s.n.

Mulder, K., Ferrer, D. & Lente, H. V., 2011. What is Sustainable Technology? Perceptions, Paradoxes and Possibilities. *Sustainability Responsibility Accountability.*

Paroc Group oy, 2018. *Paroc Group Products.* [Online] Available at: http://www.paroc.se/produkter

Paroc Group oy, 2018. *Paroc WPS 3n.* [Online] Available at: http://www.paroc.com/products/building-insulations/bi-wind-protection-insulations/paroc-wps-3n

PE INTERNATIONAL AG, 2103. *ROCKWOOL® Thermal Insulation for external wall EPD,* s.l.: s.n.

Peñaloza, D., Norén, J. & Eriksson, P.-E., 2013. *Life Cycle Assessment of Different Building Systems: The Wälludden Case Study,* s.l.: SP Technical Research Institute of Sweden.

Petránek, V. et al., 2013. Thermal Bridges in Insulation Systems. *Advanced Materials Research.*

Potting, J. & Hauschild, M., 2004. *Background for spatial differentiation in life cycle impact assessment: The EDIP2003 Methodology,* s.l.: s.n.

ROCKWOOL International A/S, 2016. *Stone Wool Thermal Insulation for buildings EPD,* s.l.: ROCKWOOL Polska SP.

Sáez de Guinoa, A. et al., 2017. Environmental assessment of a nano-technological aerogel-based panel for building insulation. *Journal of Cleaner Production.*

Schiavoni, S., D'Alessandro, F., Bianchi, F. & Asdrubali, F., 2016. Insulation materials for the building sector: A review and comparative analysis. *Renewable & Sustainable Energy Reviews.*

Schmidt, A. C. et al., 2004. A comparative Life Cycle assessment of building insulation products made of stone wool, paper wool and flax. *The International Journal of Life Cycle Assessment.*

Širok, B., Blagojević, B. & Bullen, P., 2008. *Mineral Wool: Production and Properties.* s.l.:s.n.

Slovenian National Building Institute, 2013. *URSA Glasswool EPD,* s.l.: Slovenian National Building and Civil Engineering Institute.

Sohn, J. L., Kalbar, P. P., Banta, G. T. & Birkved, M., 2017. Life-cycle based dynamic assessment of mineral wool insulation in a Danish residential building application. *Journal of Cleaner Production.*

Steen, B., 2015. *The EPS 2015d impact assessment: An overview,* s.l.: Swedish Life Cycle Center.

Straube, J., 2007. Thermal Metrics for High Performance Enclosure Walls: The Limitations of R-Value. *Building Science Corporation, Research Report–0901.*

Takano, A., Hughes, M. & Winter, S., 2014. A multidisciplinary approach to sustainable building material selection: A case study in a Finnish context. *Building and Environment.*

Tellnes, L. G. F., 2015. *Exterior cladding with waterborne paint Environmental Product Declaration,* s.l.: The Norwegian EPD Foundation.

The Norwegian EPD Foundation, 2013. *Rockwool isolering EPD,* s.l.: The Norwegian EPD Foundation.

The Norwegian EPD Foundation, 2018. *Isover Insulsafe page,* s.l.: s.n.

Thermal Insulation Association of Canada, 2013. *Insulation Materials and Properties,* s.l.: s.n.

United Nations Environment Programme, 2018. *United Nations Environment Programme website.* [Online]
Available at: https://www.unenvironment.org/es

Werner, D. F., 2018. *Loose fill cellulose insulation.* [Online]
Available at: http://ecia.eu.com/files/news/20180118%20EPD_Core_ECIA-version%202.4.pdf

Zabalza Bribián, I., Valero Capilla, A. & Aranda Usón, A., 2011. Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Building and Environment.*

9 List of figures

10 Annex

10.1 Layer configuration

ROCKWOOL LAYER	Thickness mm	Conductivity W m⁻¹ K⁻¹	Resistance m² K W⁻¹
Outside thermal resistance			0,13
Cladding	22		
Ventilated gap	50		
Wind protection	55	0,032	1,72
Rockwool	125	0,035	3,57
Plastic film	0,2	0,33	0,001
Gypsum plasterboard	12,5	0,57	0,03
Inside thermal resistance			0,13
			W/m² K
Total thermal resistance			0,18

GLASSWOOL LAYER	Thickness mm	Conductivity W m⁻¹ K⁻¹	Resistance m² K W⁻¹
Outside thermal resistance			0,13
Cladding	22		
Ventilated gap	50		
Wind protection	55	0,032	1,72
Glasswool	145	0,04	3,63
Plastic film	0,2	0,33	0,001
Gypsum plasterboard	12,5	0,57	0,03
Inside thermal resistance			0,13
			W/m² K
Total thermal resistance			0,18

CELLULOSE FIBERS LAYER	Thickness mm	Conductivity W m⁻¹ K⁻¹	Resistance m² K W⁻¹
Outside thermal resistance			0,13
Cladding	22		
Ventilated gap	50		
Wind protection	55	0,032	1,72
Cellulose fibres	140	0,039	3,59
Plastic film	0,2	0,33	0,001
Gypsum plasterboard	12,5	0,57	0,03
Inside thermal resistance			0,13
			W/m² K
Total thermal resistance			0,18

AEROGEL LAYER	Thickness mm	Conductivity W m⁻¹ K⁻¹	Resistance m² K W⁻¹
Outside thermal resistance			0,13
Cladding	22		
Ventilated gap	50		
Wind protection	55	0,032	1,72
Aerogel	55	0,015	3,67
Plastic film	0,2	0,33	0,001
Gypsum plasterboard	12,5	0,57	0,03
Inside thermal resistance			0,13
			W/m² K
Total thermal resistance			0,18

10.2 ELU calculation

	GWP	OP	AP	EP	POCP	ADPE	ADPF	
Parameter	Carbon dioxide	CFC-11	Sulphur dioxide	Phosphate	Ethene (ethylene)	Antimony	Crude oil (in MJ)	
Unit	kg	kg	kg	kg	kg	kg	MJ	
ELU/ Unit	0,13478	716,8894	0,1179148	0,0122613	17,6339	18190	0,01111	
Rockwool	6,66682	2,79E-06	0,1061739	0,0240906	0,011939	1,206E-05	222,893	**Total Rockwool**
ELU Rockwool	0,898557	0,002002	0,0125195	0,0002954	0,210537	0,2193753	2,47659	3,82E+00
Glasswool	4,668642	3,07E-06	0,085056	0,0273945	0,018837	0,0004954	220,326	**Total Glasswool**
ELU Glasswool	0,629241	0,0022	0,0100294	0,0003359	0,332168	9,0109603	2,44806	1,24E+01
Aerogel	80,77842	2,1E-05	0,4012235	0,0596329	0,032788	0,0002778	651,077	**Total Aerogel**
ELU Aerogel	10,88735	0,015087	0,0473102	0,0007312	0,578186	5,0538754	7,23419	2,38E+01
Cellulose	1,271597	2,73E-06	0,0828181	0,022433	0,010824	1,099E-05	177,364	**Total Cellulose**
ELU Cellulose	0,171386	0,001955	0,0097655	0,0002751	0,190863	0,1998253	1,97071	2,54E+00

Parameter	Name	A1-A3	A4	A5	C2	C4	Total
ADPE	Aerogel	4,8E+00	2,0E-02	5,5E-02	2,2E-05	6,7E-05	4,9E+00
ADPE	Cellulose	2,7E-03	6,3E-04	1,5E-05	1,3E-04	7,2E-04	4,2E-03
ADPE	Cladding	6,9E-02	1,1E-02	9,1E-02	9,7E-03	2,1E-04	1,8E-01
ADPE	Glasswool	8,4E+00	1,2E-02	4,2E-01	5,2E-04	5,9E-04	8,8E+00
ADPE	Plasterboard	9,1E-04	1,1E-06	1,1E-04	5,1E-07	0,0E+00	1,0E-03
ADPE	Rockwool	2,3E-02	3,1E-05	9,8E-04	6,9E-06	2,4E-05	2,4E-02
ADPE	Plastic film	6,5E-03	2,9E-05	2,4E-06	9,3E-09	5,4E-05	6,6E-03
ADPE	Windbreaker	6,5E-03	8,9E-06	2,8E-04	2,0E-06	6,9E-06	6,8E-03
ADPF	Aerogel	5,5E+00	1,7E-02	4,1E-02	5,6E-03	1,7E-02	5,6E+00
ADPF	Cellulose	2,1E-01	6,4E-02	1,5E-03	1,3E-02	1,1E-02	2,9E-01
ADPF	Cladding	2,0E-01	3,5E-02	1,3E-01	4,0E-02	1,4E-03	4,1E-01
ADPF	Glasswool Slabs	7,1E-01	2,3E-02	3,6E-02	1,1E-03	4,4E-03	7,7E-01
ADPF	Plasterboard	5,7E-01	1,7E-02	2,3E-02	7,8E-03	0,0E+00	6,1E-01
ADPF	Rockwool	7,6E-01	1,3E-02	2,0E-02	2,7E-03	9,3E-03	8,0E-01
ADPF	Plastic film	4,2E-01	5,5E-03	5,7E-05	1,3E-08	1,1E-03	4,2E-01
ADPF	Windbreaker	2,2E-01	3,6E-03	5,6E-03	7,8E-04	2,7E-03	2,3E-01
AP	Aerogel	3,7E-02	1,5E-03	2,9E-04	1,4E-05	8,7E-05	3,9E-02
AP	Cellulose	8,9E-04	2,3E-04	1,7E-05	4,6E-05	1,1E-04	1,3E-03
AP	Glasswool	1,4E-03	9,3E-05	7,2E-05	4,1E-06	1,1E-05	1,6E-03
AP	Rockwool	3,9E-03	4,3E-05	9,9E-05	9,3E-06	4,9E-05	4,1E-03
AP	Cladding	6,6E-05	3,1E-06	2,7E-05	5,0E-06	8,1E-07	1,0E-04
AP	Plasterboard	6,4E-03	9,0E-05	8,8E-05	4,0E-05	0,0E+00	6,6E-03
AP	Plastic film	5,5E-04	4,8E-05	2,5E-07	8,8E-06	6,4E-06	6,2E-04
AP	Windbreaker	1,1E-03	1,2E-05	2,8E-05	2,7E-06	1,4E-05	1,2E-03
EP	Aerogel	3,9E-04	1,8E-05	5,2E-05	3,2E-07	2,6E-05	4,9E-04
EP	Cellulose	1,1E-05	5,4E-06	7,9E-07	1,1E-06	1,5E-05	3,3E-05
EP	Cladding	1,1E-04	1,0E-05	5,2E-05	1,6E-05	2,1E-06	1,9E-04
EP	Glasswool	8,7E-05	2,3E-06	4,7E-06	1,1E-07	2,8E-07	9,4E-05
EP	Plasterboard	2,1E-05	2,2E-06	1,6E-06	1,0E-06	7,0E-06	3,3E-05
EP	Rockwool	4,8E-05	1,0E-06	1,5E-06	2,2E-07	2,9E-06	5,4E-05
EP	Plastic film	4,6E-06	8,4E-07	1,2E-08	3,2E-09	1,2E-07	5,6E-06
EP	Windbreaker	1,4E-05	2,9E-07	4,4E-07	6,3E-08	8,3E-07	1,5E-05
GWP	Aerogel	9,0E+00	1,3E-01	1,7E+00	4,9E-03	9,0E-02	1,1E+01
GWP	Cellulose	-1,1E+00	5,5E-02	1,7E-02	1,1E-02	1,2E+00	1,9E-01
GWP	Cladding	-1,5E+00	2,9E-02	1,1E-01	3,3E-02	1,8E-01	-1,1E+00
GWP	Glasswool	5,7E-01	2,2E-02	4,8E-02	8,6E-04	2,1E-03	6,5E-01
GWP	Plasterboard	5,1E-01	1,8E-02	1,8E-02	7,7E-03	0,0E+00	5,5E-01
GWP	Rockwool	7,2E-01	1,3E-02	1,2E-01	4,6E-04	6,0E-02	9,1E-01
GWP	Plastic film	2,0E-01	5,0E-03	1,5E-03	1,6E-08	8,5E-02	3,0E-01
GWP	Windbreaker	2,1E-01	3,8E-03	3,4E-02	2,0E-04	1,7E-02	2,6E-01
ODP	Aerogel	1,3E-02	9,7E-05	2,2E-05	4,6E-08	1,6E-06	1,3E-02
ODP	Cellulose	9,9E-05	8,9E-07	-5,9E-07	1,2E-07	1,2E-05	1,1E-04
ODP	Cladding	1,1E-04	2,4E-05	8,5E-05	2,7E-05	8,2E-07	2,5E-04

ODP	Glasswool	3,2E-04	1,4E-05	1,6E-05	7,4E-07	3,4E-06	3,6E-04
ODP	Plasterboard	1,4E-03	6,2E-05	2,5E-05	2,8E-05	0,0E+00	1,5E-03
ODP	Rockwool	1,5E-04	1,2E-07	3,5E-06	2,6E-08	7,8E-07	1,6E-04
ODP	Plastic film	1,6E-07	1,0E-09	2,5E-11	3,9E-09	3,9E-07	5,6E-07
ODP	Windbreaker	4,4E-05	3,3E-08	1,0E-06	7,3E-09	2,2E-07	4,6E-05
POCP	Aerogel	3,4E-07	6,4E-09	3,8E-09	2,4E-10	3,5E-09	3,6E-07
POCP	Cellulose	5,3E-09	2,2E-09	3,8E-10	4,4E-10	6,8E-09	1,5E-08
POCP	Cladding	2,9E-08	2,6E-09	9,1E-09	4,4E-09	6,8E-10	4,5E-08
POCP	Glasswool	1,6E-07	2,4E-08	8,5E-09	9,9E-10	2,6E-09	1,9E-07
POCP	Plasterboard	3,6E-08	2,6E-10	5,9E-10	1,2E-10	0,0E+00	3,7E-08
POCP	Rockwool	2,8E-08	6,2E-10	9,0E-10	1,3E-10	2,3E-09	3,2E-08
POCP	Plastic film	7,7E-09	-9,3E-10	2,2E-11	5,5E-08	8,5E-11	6,2E-08
POCP	Windbreaker	8,1E-09	1,8E-10	2,6E-10	3,8E-11	6,6E-10	9,3E-09

10.3 EDIP calculation

	GWP	**OP**	**AP**	**EP**	**POCP**	**ADPE**	**ADPF**	
Parameter	**Carbon dioxide**	**CFC-11**	**Sulphur dioxide**	**Phosphate**	**Ethene (ethylene)**	**Antimony**	**Crude oil (in MJ)**	
Unit	**kg**	**kg**	**kg**	**kg**	**kg**	**kg**	**MJ**	
EDIP/ Unit	1,49E-07	1,14E-01	1,09E-05	4,21E-05	6,00E-05	1,68E-02	4,10E-04	
Rockwool	6,67E+00	2,79E-06	1,06E-01	2,41E-02	1,19E-02	1,21E-05	2,1202E-06	**Total Rockwool**
EDIP Rockwool	9,93E-07	3,18E-07	1,16E-06	1,01E-06	7,16E-07	2,03E-07	9,14E-02	6,52E-06
Glasswool	4,67E+00	3,07E-06	8,51E-02	2,74E-02	1,88E-02	4,95E-04	2,0958E-06	**Total Glasswool**
EDIP Glasswool	6,96E-07	3,49E-07	9,27E-07	1,15E-06	1,13E-06	8,33E-06	9,03E-02	1,47E-05
Aerogel	8,08E+01	2,10E-05	4,01E-01	5,96E-02	3,28E-02	2,78E-04	6,19E-06	**Total Aerogel**
EDIP Aerogel	1,20E-05	2,40E-06	4,37E-06	2,51E-06	1,97E-06	4,67E-06	2,67E-01	3,41E-05
Cellulose	1,27E+00	2,73E-06	8,28E-02	2,24E-02	1,08E-02	1,10E-05	1,69E-06	**Total Cellulose**
EDIP Cellulose	1,89E-07	3,10E-07	9,03E-07	9,44E-07	6,49E-07	1,85E-07	7,27E-02	4,87E-06