Assessing the environmental impact of using load-bearing reused wood and seaweed insulation in a building construction

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Summary

Purpose: The production of new building materials is behind 11% of the global CO_2 emission, pressuring the construction sector to seek new alternative materials to assist the sector to reduce its Global Warming Potential (GWP). Bio-based material absorbs CO_2 during their lifetime which reduces CO_2 emission to the atmosphere. Wood is the most common bio-based element used nowadays, however, new materials are getting attention from the construction sector, for instance, seaweed. To assist the Danish construction sector to reduce its environmental impact a comparison between a load-bearing structure using wood and seaweed will be made against the conventional concrete load-bearing structure.

Methods: To assess the environmental impact of both load-bearing structures a Life Cycle Assessment (LCA) is conducted for $1m^2$ of load-bearing structure made of wood and seaweed(WSW), and made of concrete and rock wool(CRW). A dynamic LCA (DLCA) approach was chosen to analyse the impact of biogenic carbon since the WSW has bio-based elements in the composition.

Results and discussion: The LCA analysis showed the WSW element emitting 44,85% less GWP when compare to CRW, however, it also presented an increase of 66,67% of land use impact. Significant changes in the results were presented in different LCA approaches, showing that the results are extremely sensitive to the chosen approach. This variation in the results can mislead the benefits of bio-based materials.

Conclusion: For the Indirect Land Use Change(iLUC) approach, WSW showed less impact in 6 out of 7 mid-point categories analysed, only showing a higher impact in land use categories, showing that the use of more wood in the construction sector will require more land to produce more wood. On the other hand, seaweed showed a lower impact in most of the categories, however, the uncertainties about its end-of-life (EoL) demonstrated a higher impact on marine eutrophication when having protein-rich fish feed as a by-product.

Preface

This project has been conducted during the 4th semester of the master's program Environmental Management and Sustainability Science at Aalborg University, as the Thesis final project.
The project was carried out under the supervision of Agneta Ghose, therefore, the writer would like to thank the supervisor for the guidance and support during the project.

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Introduction 1

The construction sector is responsible for about 40% of the total energy-related CO_2 emissions [Dean et al., 2017]. In the European Union, the construction sector consumes 40% of materials and produces annually the same amount of waste [Rinne et al., 2022]. Being responsible for a big amount of CO_2 emissions, the construction sector has a significant potential to minimize the climate change impact through the reduction of greenhouse gas (GHG) emissions [Rinne et al., 2022]. The GHG emission reduction is especially important in light of the main Carbon Neutrality Goal established in the Paris Agreement, which is to reduce the global temperature below 2°C as compared to the 1990 level by 2050 [IPCC, 2018].
According to Hafez et al. [2020] the choice of building materials can significantly affect the GHG emissions of the building, in which the material used can account for 20% to 55% of the total CO_2 emission while the operation stage accounts for 45% to 80% of emissions. In Denmark, the energy consumption for building operations has been declining in the past 50 years from 350kWh/m² per year in 1961 to an estimate of 20KWh/m² per year in 2020 [Birgisdóttir, 2019]. This reduction is due to the fact that Denmark has imposed new rules and regulations for new building construction in the building code. As buildings become more energy-efficient to operate, the focus on savings should shift to the embedded energy of the building materials [Lendager and Pedersen, 2020].
The two most applied materials in the building sector nowadays are concrete and steel [Rinne et al., 2022]. Concrete production accounts for 8% of the global CO_2 emissions, [Andrew, 2018], while steel production accounts for 9%. [Association, 2021]. The European strategy for bioeconomy points out the potential of bio-based products as a substitute for the raw materials connected with fossil fuel production and climate change reduction [Commission, 2018]. The wood from a forest-grown using sustainable methods is an example of bio-based material that can replace traditional concrete or steel structures in building construction. [Lukić et al., 2021]. In addition, wooden structures provide a significant advantage to mitigate climate change, because they have the biogenic capacity to store CO_2 during their life cycle as well as to be reused, recycled or incinerated, replacing the use of fossil fuels when their life service is over [Lukić et al., 2021; Rinne et al., 2022; Dias et al., 2021a].
In Denmark, the use of wood products constitutes more than half of the country's total bioenergy consumption. In particular, the wood pellets, which are the most frequently used type of wood for incineration in Denmark, are primarily imported from Latvia, Estonia, Sweden and Russia - 25%, 23%, 15% and 11% respectively. In addition, waste wood, which includes the wood that comes from the construction sector, is used together with other wood types to produce heat and electricity [Danish Ministry of Climate and Utilities, 2019]. Research shows that having the end of life (EoL) of a wood element as incineration

release the biogenic carbon captured during its life cycle which demonstrates to have a reduction in the environmental impact when compared to the EoL of concrete elements [Lukić et al., 2021] and steel structure [Rinne et al., 2022].
The use of wood as a structure is not a recent idea. However, only in the last decade has the construction sector started to develop more interest in wood as a bio-based element, which can be used to reduce its environmental impact [Lukić et al., 2021]. Through photosynthesis, bio-based elements, such as wood, have the ability to sequestrate carbon from the atmosphere, a process that is commonly referred to as biogenic carbon reducing the CO_2 levels [Prentice et al., 2001]. At the EoL of the element, that is, when it is either decomposed or incinerated, the absorbed carbon is released back into the air [Prentice et al., 2001]. The biogenic carbon released at the EoL as incineration can represent a bigger amount of CO_2 in comparison to black coal. However, burning biomass emits CO_2 that was already part of the biogenic carbon cycle, which was absorbed during the growing life of the bio-based element. On the other hand, carbon that was locked up for millions of years in the ground will be released with the burning of fossil fuels, increasing the amount of CO_2 in the atmosphere, because, this carbon was not part of the biosphere-atmosphere system. The release of CO_2 from biomass shows as being less prejudicial to the environment than the release of fossil fuel, even with the last one showing a smaller amount in weight of CO_2 released [Bionergy, 2022].
To assess the impact of the EoL of an element different Life Cycle Assessment (LCA) approaches can be used to calculate the biogenic carbon uptake and release of bio-based materials, which creates scepticism about the real potential of bio-based elements to decrease the environmental impact in construction [Andersen et al., 2021].
Another concern about the use of bio-based elements in the construction sector is that the sector only focuses on the environmental impact related to GHG emissions [Andersen et al., 2021], concerning the goal to reduce CO_2 emissions from the National strategy to sustainable construction [Housing and Authority, 2021]. Moreover, the use of bio-based can show another type of environmental impact not related to carbon emissions, for instance, it can increase the land-use impact from the use of wood material [Heidari et al., 2019].
However, not all bio-based materials will need to use land in the production phase, that is the case of seaweed, where the production phase occurs in the water, being responsible for the reduction of the water eutrophication impact because of the nutrients uptake [Seghetta et al., 2016a]. Another point of seaweed cultivation is the capacity to absorb more CO_2 than trees and the ability to provide a healthy and safe space for small fish and marine life to flourish [World-Economic-Forum, 2022]. In addition, seaweed is a flexible element that can be turned up into food product [Dias et al., 2021b], fertilizer and bioplastic [World-Economic-Forum, 2022], reinforcement fiber [Stefanidou et al., 2021], and many others [World-Economic-Forum, 2022].
Considering that, this report will analyse the use of seaweed, in combination with wood in a load-bearing element to build a bio-based wall in new building construction. Seaweed will be analysed as wall insulation motivated by its use as roof insulation in the traditional Danish housing, for example in the Læsø island [Visit Læsø] as well as its high potential as a bio-based material [World-Economic-Forum, 2022]. However, the use of seaweed as wall insulation is new and the environmental impact from its cultivation is currently limited, hence needs to be investigated further.

Problem analysis 2

The building and construction sector has an important role to reduce the Global Warming Potential(GWP) since 11% of global CO_2 emissions come from the production of new building materials [GlobalABC et al., 2019]. GWP is an environmental impact indicator used to measure the temperature of the Earth's surface based on the increase in the GHG emissions [Zimmermann et al., 2021]. Minimising CO_2 emissions is the main goal of the construction sector in the transition to a more sustainable industry and to achieve 70% emissions reduction by 2030 compared to 1990 levels [Housing and Authority, 2021; Hansen and Lynge, 2020]. Thus, the reduction of GWP emission represents a step further to achieve carbon neutrality by 2050 [Housing and Authority, 2021].
This section presents a systematic review of the Life Cycle Assessment (LCA) literature on load-bearing and bio-based insulation materials. The goal was to revise the state-of-the-art research on building material alternatives for the construction sector. In the last years, LCA analysis became an important tool to quantify and compare the environmental impacts of a given building to a similar one to assess how the environmental impacts can be reduced [Zimmermann et al., 2021]. In addition, in Denmark from 2023 new buildings with more than 1,000 m^2 will be required to have an LCA analysis, however, the focus will only be on CO_2 emissions as the main environmental impact [Housing and Authority, 2021].
For this reason, LCA articles on wooden buildings and bio-based insulation materials were analysed in the literature review with a focus on their LCA results to assist the building and construction sector. The literature review was based on gathering relevant information, analysing and synthesizing it based on an extensive search in a literature database.
The search used the Aalborg University Library (AUB) platform which provides a wide range of grey and peer-reviewed articles. For the search, only publications in English were included. When no articles with relevance about a specif topic were found, Google searches were added to find grey literature. To gather the latest information about wooden construction and bio-based insulation material a time frame was chosen and included publications after 2017.

2.1 LCA of wood structure

For the LCA of wood structure 10 relevant articles were selected from the literature review analysis made at the AUB platform. Of the selected articles, seven of them analysed buildings with at least 2 floors; six of them had a case study in Europe (3 case studies in the Nordic countries), three from the United States and Canada, and one from Asia. Although the articles were from different countries all of them analysed and assessed CO_2 emissions as the only or the main impact, because carbon emission is the impact category

with the most focus, in regards to the goal of the Paris agreement to keep the global temperature below 2°C [European-Comission, 2020].
The first observation is that wood structure emits less CO_2 in comparison to concrete structures [Balasbaneh and Bin Marsono, 2018; Liang et al., 2021], steel structures [Chen et al., 2020], and hybrid structures made of wood+concrete or wood+steel structure [Rinne et al., 2022; Padilla-Rivera et al., 2018], showing a reduction of 19%, 17%, 20%, 21% and 38% respectively. However, the analysed articles showed results based on LCA of high-rise buildings, that according to Lukić et al. [2021] the embodied impact reduction is easier to achieve while the building height is increased, due to the need for more volume of wood materials, which makes the GHG emissions decrease. Dabaieh et al. [2020]; Chen et al. [2020]; Vidal et al. [2019], arrived at the same result and concluded that more volume of wood will have a bigger carbon stored amount. In this sense the reduction of a wood structure size when in comparison to other structures can achieve rates from 21%-69,5% [Chen et al., 2020] to 88% [Dabaieh et al., 2020].
For Lukić et al. [2021]; Vanova et al. [2021]; Dabaieh et al. [2020], the building envelope was the biggest contributor to the GHG emissions of the building. In addition, for Lukić et al. [2021] the roof and the external wall, together with the door and windows were the second most contributor to the GHG impacts. On the other hand, foundations were the second category with most impact to Vanova et al. [2021] and Dabaieh et al. [2020].
Another factor observed in the literature review was the different ways that the LCA analyses were built, including different life cycle stages from the European Standard DS/EN 15978 [Dansk Standard, 2012]. Figure 2.1 shows the different stages included in the articles.
Chen et al. [2020] concluded that including the benefits beyond boundary (D phase) in the comparison between reinforced concrete and a CLT building shows a 70% reduction in the CO_2 emission in the CLT building scenario when including only the "A" and "C" phases. The difference between the scenarios was of 20% reduction from the CLT building. The difference in the result when including the D phase were pointed by Rinne et al. [2022]; Lukić et al. [2021]; Liang et al. [2021], however the "D phase" was only included in Chen et al. [2020] article.

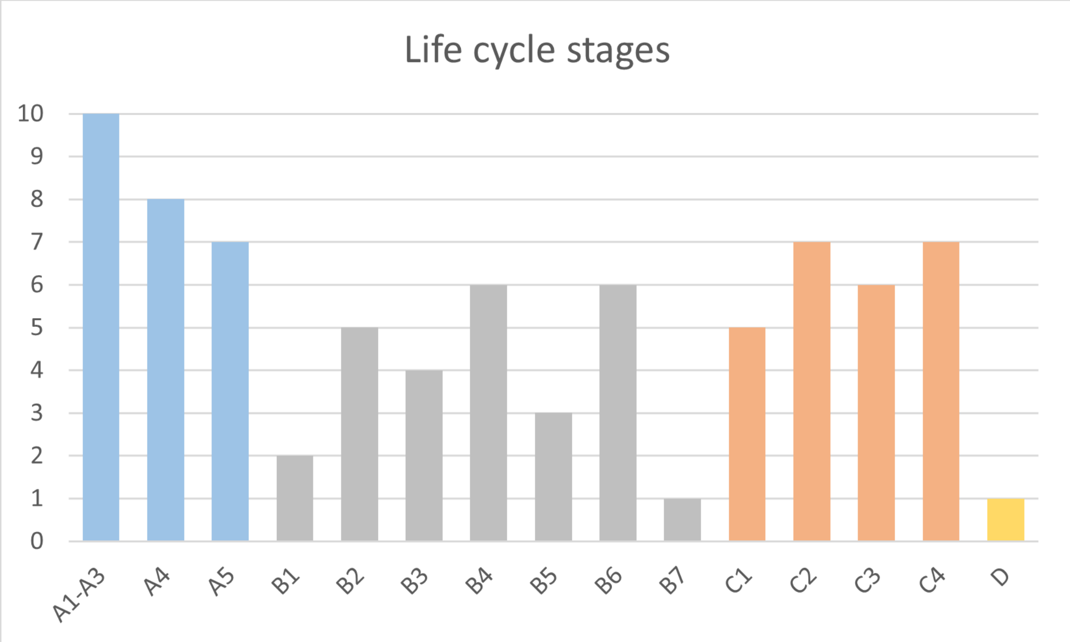

Figure 2.1. life cycle stages include in the LCA from the literature review, based on the stages presented at DS/EN 15978 [Dansk Standard, 2012].

Although there exists prior research on using a wood structure as an alternative to reduce the environmental impact of the construction sector, the topic is still interesting and relevant to analyse especially when it comes to the benefits after the EoL and the impact of the carbon store of the wood. As mentioned in Chapter 1, LCA analysis can be conducted using different approaches that can lead to divergent results for the same element or building which can create doubts about the impact [Andersen et al., 2021]. Assessing the environmental impact of a bio-based element such as wood can lead to this scepticism because not all LCA analyses include biogenic carbon calculations in their analysis [Andersen et al., 2021].

From the literature review 5 out of 10 analysed articles included the biogenic carbon in the results: Lukić et al. [2021]; Liang et al. [2021]; Vanova et al. [2021]; Dabaieh et al. [2020]; Chen et al. [2020]. Two different approaches were reported in the literature review, however, none of the articles described which type of approach was used to calculate the results.

The first approach described is commonly known as the 0/0 approach under the assumption that bio-based elements are carbon-neutral when the CO_2 absorbed during the growing phase is equivalent to the amount released in the EoL, in addition, in this approach biogenic carbon is excluded from the LCA analyses [Hoxha et al., 2020]. On the other hand, the second approach the -1/+1, accounts for biogenic carbon as neutral during the life cycle of the material [Hoxha et al., 2020]. The uptake of CO_2 is accounted in the production stage phase as -1 and at the EOL is released as +1 [Hoxha et al., 2020] which should provide the same results, if analysed correctly [Andersen et al., 2021]. The -1/+1 approach increases the transparency of the use of biogenic carbon in an LCA throughout the life cycle of the element. Further, the biogenic carbon of bio-based wood should only be included when the wood is from sustainable forests [Andersen et al., 2021]. For this reason, the use of wood to reduce carbon footprint can lead to a mistrust of the real impact of wood construction

on the environment.
The use of wood as a construction element in Denmark is not spread as it is in other Nordic countries as most buildings in Denmark are made of concrete structure [Lendager and Pedersen, 2020]. The use of wood is mainly for energy purposes such as heating, however, the type of wood used for incineration is wood pellets that come from countries such as Latvia, Slovenia, Sweden and Russia [Liang et al., 2021], which increases the CO_2 emission, related with the transportation of wood [Liang et al., 2021]. A challenge that can be faced in the use of wood for heating consumption is directly related to the Russian invasion of Ukraine, taking place now in 2022, since according to Birgisdóttir [2019] 11% of the wood for incineration used in Denmark comes from Russia. Construction wood waste is added to pallet wood in the incineration process to produce heat and energy [Danish Ministry of Climate and Utilities, 2019], with Russian wood being banned in the EU [European-Comission, 2022], the use of waste wood from the construction sector will increase, emitting more CO_2, since this type of wood is denser and will not be reused or recycled in the EoL, releasing the biogenic carbon at the incineration process.

2.2 LCA of bio-based insulation

For the LCA of bio-based insulation material, the same process was made in the AUB with the keywords shown in figure 2.2.

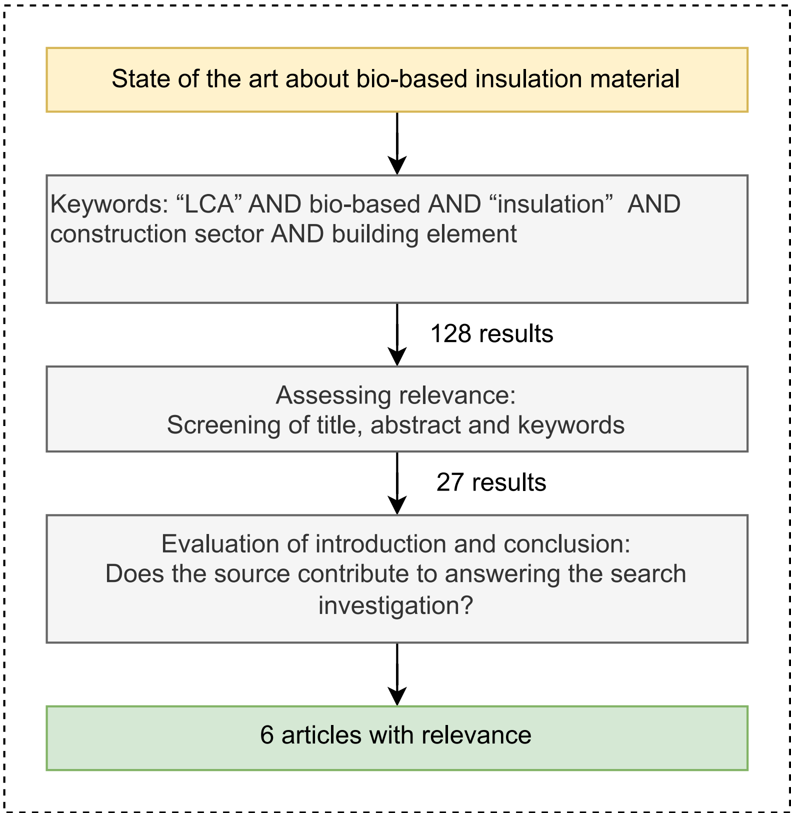

Figure 2.2. literature review-insulation bio-based material

The literature review showed different choices of bio-based materials using LCA. Pittau et al. [2019] compared the use of different types of insulation with Expanded polystyrene

(EPS), the selected materials were: straw, injected hempcrete, hempcrete block and glass wool. Using the same line of thoughts, Carcassi et al. [2022] compared bamboo, cork, straw, cotton, kenaf and lime plaster insulation with the same market option, EPS. In both cases, the analysis showed the bio-based materials as the best option to reduce CO_2 emissions, however, straw had the best results by Pittau et al. [2019] with 27% of reduction, while Carcassi et al. [2022] presented bamboo as the option with 52% less environmental impact. In addition Sattler and Österreicher [2019] showed that paper insulation emits 46% less than EPS.
On the other hand, Göswein et al. [2020] argued that not only the material choice is important to reduce GWP emissions. The article analysed different types of EoL for straw insulation and showed that energy recovery can emit 98% less in comparison to landfill EoL, and when compared to the material recovery scenario the emissions represent -2%. Moreover, the use of bio-based material can be used to achieve a reduction in the GWP emission, but on the other hand, it can increase other environmental impacts such as presented by Barrio et al. [2021], with the use of bark insulation, for instance, it had a reduction in GWP of 12% although eutrophication freshwater increased 75%. Heidari et al. [2019] also reported the increase of other environmental impacts not related to CO_2 emission with the use of bio-based materials, according to Heidari et al. [2019] land use which includes land transformation, land occupation and permanent impact of land use had an increase of 60% to produce hemp shiv for insulation.
Even though different materials were analysed in different articles no relevant articles about seaweed insulation were found in the research. Seaweed was used as roofs on the island of Læsø (figure 2.3), located in the North Jutland region of Denmark [Miljøstyrelsen, 2018], because natural resources such as straw and wood were scarce on the island in the 1600s; therefore the use of seaweed roof has an important cultural heritage for the country [Visit Læsø]. However, the use of seaweed as an alternative material is not exclusive to Denmark, seaweed has been used in other countries as well, for instance, on the island of Formentera in Spain, seaweed was used as thermal insulation in roofs achieving the same thermal conductivity as EPS, a synthetic insulation material [Carmona et al., 2018]. The use of seaweed as fibre reinforcement in lime mortars is being studied in Greece by Stefanidou et al. [2021] showing good results such as the avoidance of the thermal degradation of fibre´s components.

Figure 2.3. Image of a roof made of seaweed in the Island of Læsø, Denmark. (https://www.visitnordjylland.com/north-jutland/destinations/seaweed-roofs-laeso)

Nowadays, the construction sector seeks for sustainable materials and solutions [Miljøstyrelsen, 2018] to avoid the natural resource scarcity hits the sector. According to Møller and Pedersen [2018] by 2056, Denmark will run out of gravel one of the most used material in the construction sector. Seaweed is a bio-based material commonly found all over the Danish coast [Seghetta et al., 2016b; Thomas et al., 2021; Miljøstyrelsen, 2018]. Every year, many municipalities spend public resources on cleaning the beaches of seaweed, and getting rid of tonnes of seaweed is a cost of several hundred kroner per tonne, for example, Odsherred reports DKK 200 per tonne and some municipalities can achieve the amount of 22.000 tons per year, that is the case of Solrød and Køge municipality [Miljøstyrelsen, 2018]. Therefore, many municipalities are very interested in finding alternative applications for this resource [Miljøstyrelsen, 2018]. Companies have been working on developing new sustainable materials from natural and recycled fibres over the past years and have received a significant number of inquiries not only from the largest architectural companies in Denmark but middle and small size companies too with interest in seaweed as a bio-based alternative material [Miljøstyrelsen, 2018].
To gain knowledge about the state-of-the-art of seaweed as insulation material in Denmark the danish word *ålegræs isolering* was used in a Google search for grey literature. As a result, the report Miljøstyrelsen [2018] was found presenting seaweed as an acoustic panel insulation product. Even though this report will analyse seaweed as heating insulation

in walls, Miljøstyrelsen [2018] will be used as one of the baseline data about the seaweed production and life cycle of the element together with Aveiro et al. [2019]. which shows the production of seaweed in a lab, going through the implementation in water and different EoL for the material.
Furthermore, to understand the properties of seaweed as a algae data from Thomas et al. [2021]; Seghetta et al. [2016a,b]; Dias et al. [2021b] will be used. Seghetta et al. [2016a] shows the potential of algae in bioeconomy using as bioethanol, liquid fertilizer and protein-rich ingredient for fish feed; therefore it will be used to support the reuse scenario as EoL in the LCA when incineration will be avoided.
In addition, Thomas et al. [2021] presented the environmental impacts of the cultivation of seaweed while analysing the nutrient uptake potential of seven types of algae, while Seghetta et al. [2016b] analyse the algae type *Saccharina latissima* in the coast of Denmark. The same type of algae was analysed by Dias et al. [2021b] from the cultivation, going through the production until the EoL as extraction to be used in the pharmacy industry; plus other two types of algae were analysed by Dias et al. [2021b], however, this report will only use the data collected from the type *Saccharina latissima*. The collected studies will be used to help build the LCA analysis since the type of algae found on the coast of Denmark is a mixture of *Zostera marina*, commonly known as *Eelgrass*; and macro and/or microalgae, such as bladder wrench, leaf tongs and sugar seaweed (*Saccharina latissima*) [Miljøstyrelsen, 2018], [Seghetta et al., 2016b]. In this study, the word seaweed will be used to express the use of the mixture of algae found on the Danish coasts.

Research question and research design 3

Based on the literature review shown in chapter 2 the analysed articles showed that bio-based materials have been assessed to reduce the environmental impact of the construction sector. The literature also showed that LCA can be built in different ways, with or without counting biogenic carbon which can affect the transparency of the results. Further research in this study will concern to analyse the environmental impact of a building with load-bearing reused wood structure and seaweed insulation, two bio-based elements to understand the impact of material selection to reduce the environmental impact compared to a conventional structure type with the aim to assist the construction sector. This concern leads to the following main research question:

What is the environmental impact of using a load-bearing structure made of reused wood and seaweed insulation when compared to conventional structural systems?

To answer the main research question, sub-questions were made to support and structure the research question.

- What would be the environmental impact of increasing the use of wood?
- What are the impacts of using an innovative bio-based element such as seaweed as wall insulation?
- What are the biogenic CO_2 emissions related to increased use of bio-based materials such as wood and seaweed and how do these emissions contribute to climate change?
- How can bio-based elements assist the Danish construction sector to elaborate environmental policy-making to reduce CO_2 emissions?

A research design was elaborated to support the following research question and the sub-questions. The flowchart diagram is illustrated in figure 3.1 and explains how the sub-questions will lead to answering the main research question.

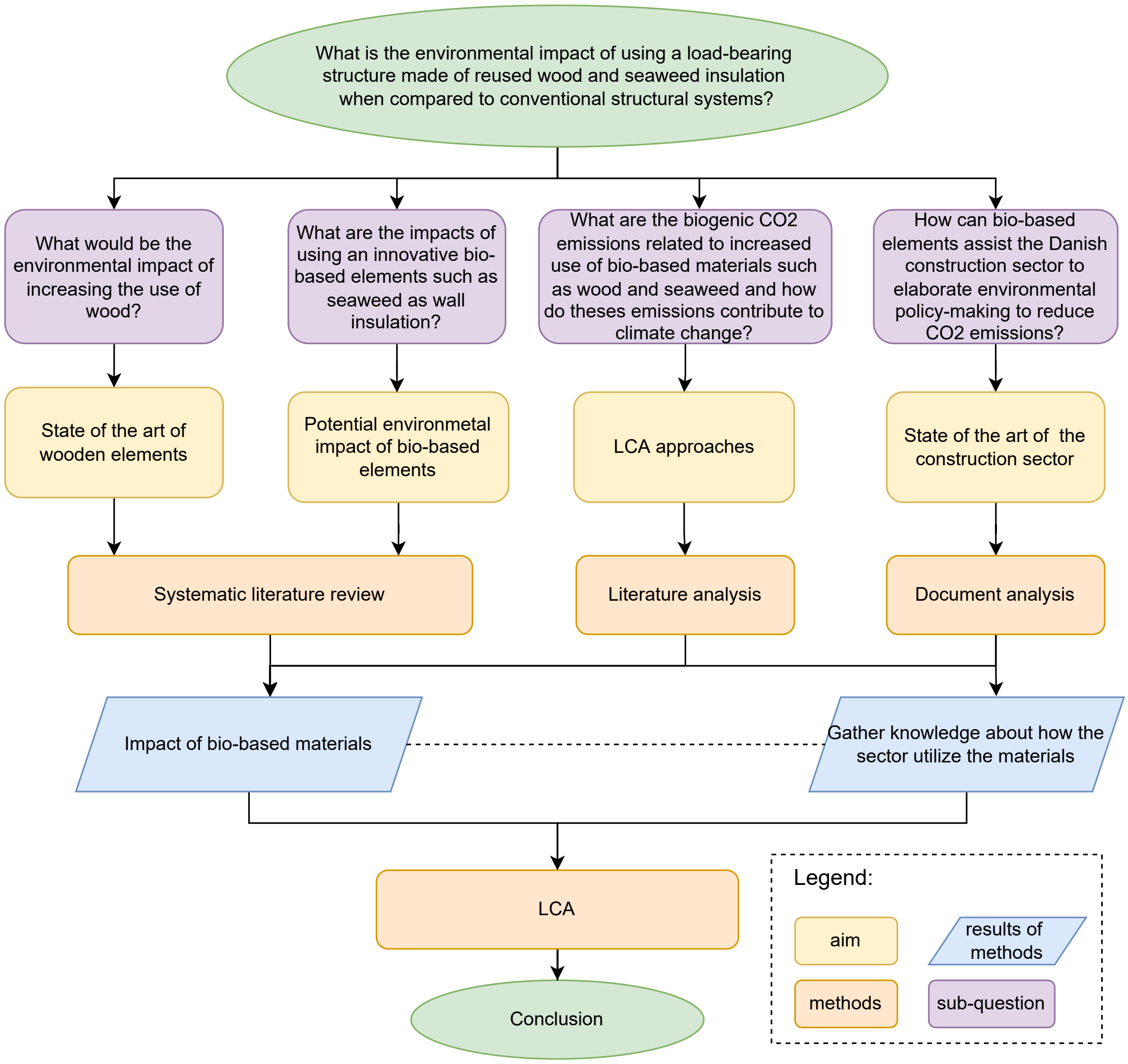

Figure 3.1. Research design illustration

3.1 Document analysis

To answer the last sub-question and gather knowledge about the state-of-the-art of the Danish construction sector goals, document analysis was performed. This method requires searching and selecting specific documents about the topic for review followed by a synthesis of the collected data [Bowen, 2009]. The focus of this research was to find documents with data; targets and goals; and environmental conditions/requirements for the building and construction sector in Denmark. The following documents were selected for analysis:

- National Strategy for Construction Sector[Housing and Authority, 2021]
- Build Report 2021:12 - Whole life carbon assessment of 60 buildings possibilities to develop benchmark values for LCA of buildings [Zimmermann et al., 2021].
- Recommendations to the Danish Government from the Climate Partnership of the construction industry [Klima-, Energi- og Forsyningsminisertiet, 2019].
- A sustainable bioeconomy for Europe: strengthening the connection between economy, society and the environment [Commission, 2018]

3.2 Motivation

To comprehend the impact of environmental choices in a more real-life context this project can be explained through the lens of Actor-Network Theory (ANT), a socio-technical theory where the design process is responsible to explain the network to new ones that will support the design and spread it [Callon, 1998]. ANT can help explain changes that happen in the innovation process where human and non-human actors are interconnected [Frank et al., 2022]. The process occurs within the innovation gaining support and interest from the actors, that saturate the market wanting the product. To diffuse the innovation non-human elements, such as LCA can help to involve actors [Frank et al., 2022].
In order to be part of the sustainable market, bio-based elements need to have relevant actors who see the value and potential of using the element on their project [Frank et al., 2022]. An important actor in this process is the architecture firms that are in charge of convincing the end-consumer about the use of the product and at the same time have to convince the building companies to think out of the box.
In Denmark the top 3-4 building companies (in danish: *typehusproducenter*) are responsible for three-quarters of the demand of users [Licitationen, 2019] therefore, the enrollment of these companies in the network will increase the access to more user base [Frank et al., 2022]. In addition, the use of sustainability between building companies and architects could be a competitive quality type of business model [Akrich et al., 2002].
When the end-user now includes the homeowner, who has no professional knowledge about the construction field, it is important to make them understand the value and impact of the choosing a sustainable material not only the environmental aspect but the social aspect as well when it is connected to the increase of health, comfort, and general well-being for themselves and their family [Frank et al., 2022].
Another important aspect for the homeowner would be economical, for instance, less energy consumption [Frank et al., 2022]; higher total sale, easier and faster to sell [Lendager and Pedersen, 2020]. According to Rambøll [2019], about 20% of Danes are willing to pay 1400 DKK more monthly to live in a sustainable house. However, Videnscenteret-bolius [2021] shows that one of the barriers faced by Danes to live in a sustainable house is *missing knowledge* about sustainable options.
In this *missing knowledge* aspect this research will lay down to communicate the impacts related to the use of sustainable elements (bio-based materials) in the building construction. Using a bio-based material such as seaweed in new construction can face resistance from the end-user (homeowner), the use of networks to spread the benefits and show results is important to create material acceptance.

Methodology 4

In this chapter will be presented a description of the different methods that were used to answer the main research question and the sub-questions presented in chapter 3. In addition, the chapter will also include uncertainties and challenges faced during the build-up of the report and the impact of the chosen methodology.

4.1 Case study

According to Ruuska et al. [2018], in the construction scenario, case studies are used as a method to address the environmental performance of the building through their site-specific nature and dynamic behaviour. This project will present two scenarios to be analysed according to their material impact differences. This case study can be classified as an "*extreme case*", which has the objective of achieving the biggest amount of information on given scenarios, which will provide a stronger scientific basis and validate the results in a broader context [Flyvbjerg, 2006]. Flyvbjerg [2006] developed a table with types of strategies for a selection of samples and cases which can be seen on figure 4.1.

Table 1
Strategies for the Selection of Samples and Cases

Type of Selection	Purpose
A. Random selection	To avoid systematic biases in the sample. The sample's size is decisive for generalization.
1. Random sample	To achieve a representative sample that allows for generalization for the entire population.
2. Stratified sample	To generalize for specially selected subgroups within the population.
B. Information-oriented selection	To maximize the utility of information from small samples and single cases. Cases are selected on the basis of expectations about their information content.
1. Extreme/deviant cases	To obtain information on unusual cases, which can be especially problematic or especially good in a more closely defined sense.
2. Maximum variation cases	To obtain information about the significance of various circumstances for case process and outcome (e.g., three to four cases that are very different on one dimension: size, form of organization, location, budget).
3. Critical cases	To achieve information that permits logical deductions of the type, "If this is (not) valid for this case, then it applies to all (no) cases."
4. Paradigmatic cases	To develop a metaphor or establish a school for the domain that the case concerns.

Figure 4.1. Strategies for the selection of samples and cases [Flyvbjerg, 2006].

An *extreme case*, clarifies the causes behind the problem and its consequences, instead of describing the problem itself, as it can be seen in a typical or average case [Flyvbjerg, 2006]. Since this study aims to analyse the environmental impact of two different load-bearing structures, it is more relevant to point out which element can contribute to reducing the environmental impact and the consequences of choosing this element than to describe the problem itself.
The analysed scenarios for this project are described as WSW element and CRW element as show below:

- **Wood + seaweed insulation (WSW):** this scenario will be the main focus of the research, where the wood will play as the load-bearing structure and the seaweed will be used as insulation (figure: 4.2)

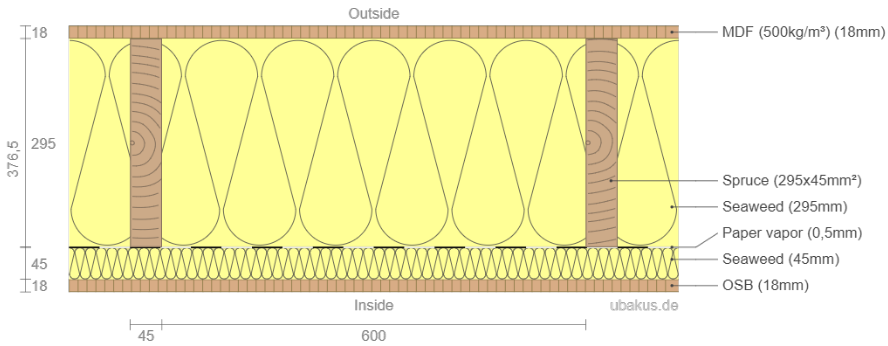

Figure 4.2. WSW - schematic floor plan of the WSW element

- **Concrete + rock wool insulation (CRW):** in this scenario the building structure will be made with a concrete wall and rock wool as the insulation material (figure: 4.3)

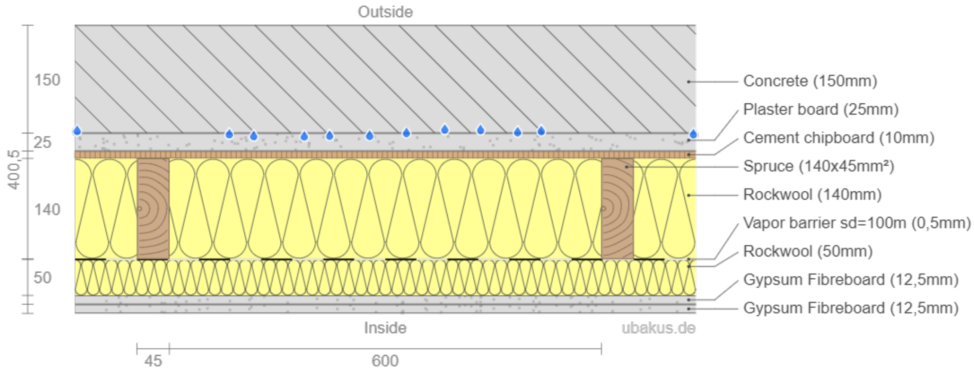

Figure 4.3. CRW - schematic floor plan of the CRW element

The case study aims is to assess the environmental impact of a load-bearing structure of a new building construction made of two different structures materials and two different insulation options as described before. It will not be included the impact of foundations, flooring, internal wall, ceiling, roof, windows, doors and technical installations (drains, water, heating, ventilation and cooling) in this case study. The concrete wall scenario was chosen as the baseline scenario since concrete buildings are the most conventional type of construction nowadays in Denmark [Rinne et al., 2022].

4.2 Dynamic Life Cycle Assessment (DLCA)

An LCA will be conducted as the environmental assessment tool used in this report since can address, in a systematic way, the environmental impact of a building or material throughout its life cycle [Dansk Standard, 2008].
Due to the complexity of bio-based materials regarding the timing of the biogenic carbon uptake and release, Levasseur et al. [2010] developed the Dynamic LCA (DLCA) approach to overcome this issue, where a characterization factor is used to determine a moment in time where the emissions occur [Levasseur et al., 2010]. For this reason, a DLCA will be conducted in this report to assess the impact of the bio-based elements in the different scenarios.

4.2.1 Goal and scope

This study will examine the environmental impacts of a $1m^2$ of a bio-based load-bearing structure made of wood structure and seaweed insulation (WSW) in comparison to a conventional structure made of concrete and rock wool (CRW) with EoL after 50 years as shown in table 4.1. The thermal conductivity of the wall will not be included in the analysis furthermore the analysis will not take into account the energy consumption.

Table 4.1. The defined function, functional unit and reference flow.

Term	Description
Function	Serve as a facade and the bearing structure of the building
Function Unit (FU)	$1m^2$ of a load-bearing structure wall with 25MPa of strength for 50 years.
Reference flow (RF)	WSW scenario: $1m^2$ of a wood structure wall with seaweed insulation with 376,5 mm width for 50 years.
	CRW scenario: $1m^2$ of concrete structure wall with rock wool insulation with 400,5 mm width for 50 years

System boundaries

According to the Dansk Standard [2012] system boundaries define the processes that are included in an assessment. The DS/EN 15978 standard presents five different life cycles stages to assess the environmental performance of a whole building, taking into account the material production and consumption, the operation process, which includes water and energy use, the EoL of the building parts and the benefits beyond system boundary [Zimmermann et al., 2021], as shown in figure 4.4.
Following the DS/EN 15978, the system boundary for this project was defined as cradle to grave including module D as presented in figure 4.4, the included stages are represented by the colours blue, orange and yellow. The production stage (A1-A4) is responsible for the raw materials extraction, transport and manufacture of the material used to produce an element; the end-of-life stage (C1-C4) is where the demolition and waste processing are counted. In addition, the disposal phase (C4) is responsible to address the end-of-life of the element to be recycled, reused, landfilled or incinerated. Further, the benefits beyond boundaries phase (D) show the benefits and impacts of the disposal of the element at the end of life [Lukić et al., 2021].

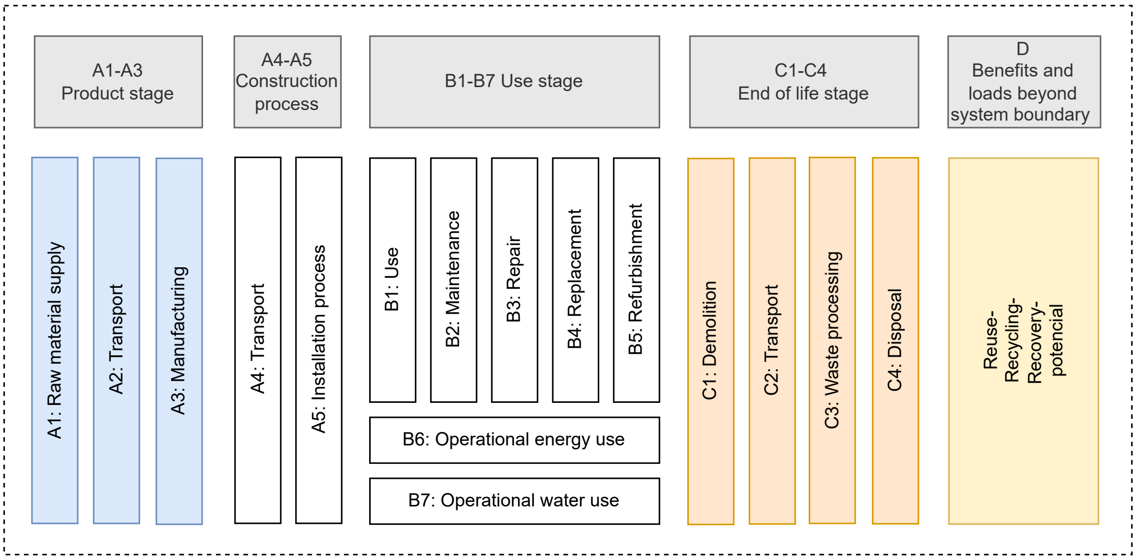

Figure 4.4. Illustration of life cycle stages with inspiration from [Dansk Standard, 2012]. The life cycle stages included in this LCA report are marked in blue (A1-A3), orange (C1-C4) and yellow (D).

For this project, the use phase (B1-B7) is not included, because the analysis is focused on a load-bearing structure and the B phase is responsible for providing the operational impact of the building, which includes energy and water consumption, replacement, repair and refurbishment of elements.
The inputs and outputs from the production of the elements CRW and WSW are presented in the flow diagram in figure 4.5 to figure 4.7. The green arrows are the inputs to the production of the elements while the green dotted arrows are material substitution . The outputs are presented by the red arrows, where the red dotted arrows show the avoided products from the EoL of the elements used into the production of new material and the full red arrows show the materials that cannot be reused/recycle and goes to landfill.

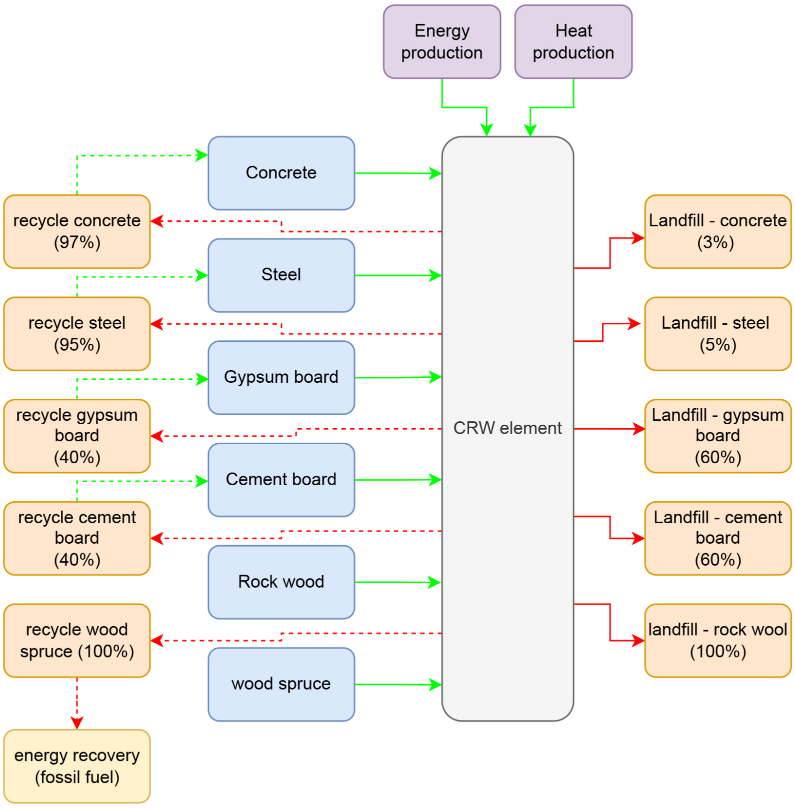

Figure 4.5. CRW current EoL scenario.

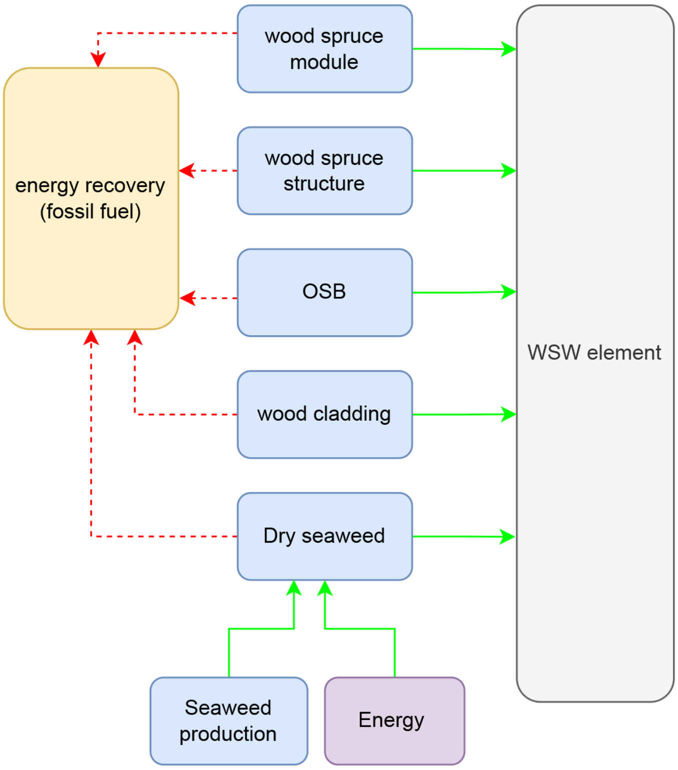

Figure 4.6. WSW reuse EoL scenario.

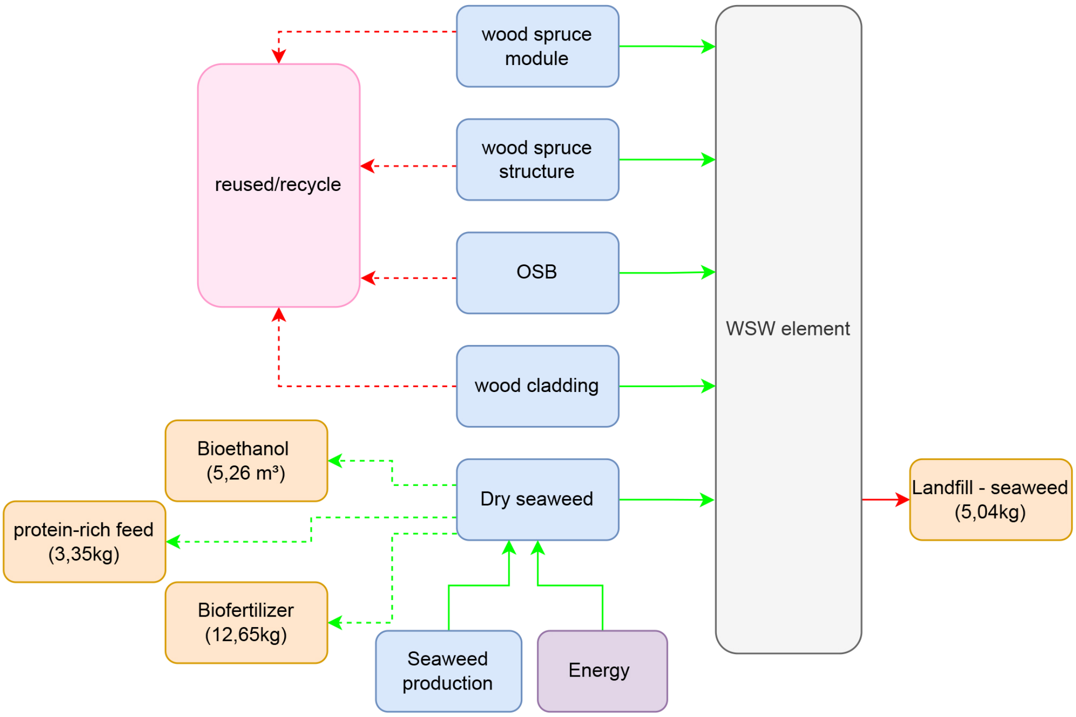

Figure 4.7. WSW incineration EoL scenario

The software SimaPro 9.3.0.3, developed by the Dutch company PRé Consultants, will be used to conduct the LCA using a consequential framework and with a focus on the selected environmental impact: Global Warming Potential (GWP), Land use, Fossil resource scarcity, Freshwater eutrophication, Marine eutrophication, Freshwater ecotoxicity and Marine ecotoxicity. These impacts were chosen to better comprehend the impact of an increase in wood and seaweed production.

4.2.2 Life Cycle Inventory

According to the Dansk Standard [2008], the Life Cycle Inventory (LCI) is where data used in the calculation is collected and quantified into inputs for the analysis. The data used in the LCA calculations for the CRW scenario were based on the structural calculations for the original project for the concrete production, and for other products such as gypsum, cement board and rock wool insulation an Environmental Product Declaration (EPD) was used as a baseline of the product production and EoL scenarios [EPD Danmark, 2022, 2021; EPD Knauf, 2021a,b] respectively. The amounts used for the FU are described in table 4.2.

Table 4.2. Materials used to produce the CRW element.

Materials used	Amount
CRW element	
Reinforced concrete	359 kg
Gypsum board (2x)	13,4 kg
Cement board	8,0 kg
Rock wool 50mm	8,0 kg
Rock wool 140mm	9,8 kg
wood spruce	0,0063 m^3

In addition, for the WSW scenario data from Miljøstyrelsen [2018]; Aveiro et al. [2019] were used for the seaweed production and De Rosa et al. [2018] was used in the calculation of the dynamic LCA of the wood elements. The material amounts used to provide the FU are described in table 4.3.

Table 4.3. Materials used to produce the WSW element.

Materials used	Amount
WSW element	
Seaweed (dry matter)	26,3 kg
OSB	0,018 m^3
Wood cladding	0,018 m^3
Wood structure	0,027 m^3
Wood module	0,009 m^3

The explanatory calculation used to build the LCA and the chosen process from the Ecoivent V3 3.6 database are shown in external Appendix I of this project. Architects from the office responsible for the project verified the analysis to validate the numbers used in the LCA.

A consequential LCA approach was chosen to look into the marginal values of the elements instead of the average effects [Finnveden et al., 2009], this is due to the fact that this approach can determine the differences that can occur if changes are made in the product system [Matthews et al., 2015]. This approach can help choose the material that fits better

in the construction type and goals, assisting the construction sector to elaborate policy-making according to the material's impact.
To build the LCA analysis some assumptions were made to built the production phase and the EoL. For the wood production, the by-product sawn chips and slabs were identified by De Rosa et al. [2018] as coming from the marginal supplier from the Eucalyptus production in Brazil. For the concrete production, according to the Danish Environmental Protection Agency in 2013, 97% of the concrete waste were recycled in Denmark, however, this number accounts for backfilling and recycling process together, and only 3% went to landfill [Miljøstyrelsen, 2015]. According to Miljøstyrelsen [2015], the common reuse scenario of concrete is to be crushed and used on roads as backfilling, if the concrete is reused for another purpose, another material will have to replace it. Brick are the second most common material used in backfilling [Miljøstyrelsen, 2015], moreover to produce a single brick 0,5kg of CO_2 are emitted [Lendager and Pedersen, 2020].
Gypsum and cement board showed with the recycle ratio of 40% [EPD Danmark, 2022, 2021] and 60% going to landfill. Although the EPD for rock wool mentions that the material is partly recycled, the end of life is presented as landfill since *"an established collection system does not yet exist"* [EPD Knauf, 2021a,b], for this reason, 100% of the material was modelled as landfilled. For the seaweed EoL, 3 outputs were identified by Seghetta et al. [2016a]:20% in bioethanol, 12,73% in protein-rich feed and 48,09 in biofertilizer, however, no information about the rest of the 19,18% of the material were presented in the article, therefore it was assumed that the amount was landfilled.

4.2.3 Life Cycle Impact Assessment

The aim of the Life Cycle Impact Assessment (LCIA) is to evaluate the relevance of the potential environmental impacts of the analysed elements, which have been calculated in the LCA. This is done by associating the selected inventory data with the chosen environmental impact categories and the category indicators to comprehend in a better way the outcome of the LCA results [Dansk Standard, 2008].
The method ReCiPe2016 will be used for the LCIA because it provides characterisation factors related to climate changes, land and water use. It includes the impacts of climate changes on freshwater ecosystems and characterisation factors referring to a specific land use type [Huijbregts et al., 2017], which will help in the understanding of the impact of seaweed and wood production.
The midpoint categories *GWP* and *Fossil resource scarcity* were chosen together with the impact of biogenic carbon and fossil fuel because they were more relatable for the goals stabilised by the Housing and Authority [2021] to reduce CO_2 emissions. In addition, the literature review presented in section 2.1, showed GWP as the impact category analysed in all reviewed articles, in 7 out of the 10. Furthermore, the impact of biogenic carbon was mentioned as a category to look at to improve LCA results. The use of bio-based elements can mitigate the need of burning fossil fuel since wood is the most used element in incineration plans in Denmark Birgisdóttir [2019], which can be analysed in the fossil resource scarcity impact. However, the use of bio-based materials can point out additional impact categories related to these materials. According to Heidari et al. [2019], the land use for wood elements shows a significant impact related to the production of the material. Also, the direct and indirect impacts of land use in the wood production were analysed by

De Rosa et al. [2018].
In opposition to using land in the production phase, seaweed is produced in water. For this reason, the impacts categories: *fresh water eutrophication* and *marine eutrophication*, were chosen to be included in the analysis for this project. As presented by Seghetta et al. [2016b,a] the amount of phosphorus and nitrogen equivalent, measured in the above-mentioned impact categories respectively, shows a reduction where seaweed is produced. On the other hand, the saturated amount of 1,4-dichlorobenzene, measured by the categories *fresh water ecotoxicity* and *marine ecotoxicity*, leads to an inhibition of seaweed to photosynthesis [Zhang et al., 2016], reducing the ability to storage biogenic carbon [Thomas et al., 2021].
In conclusion, the categories with more relevance to answering the research question and sub-questions of this project were selected to be analysed: *GWP, land use, fossil resource scarcity, freshwater eutrophication, marine eutrophication, freshwater ecotoxicity* and *marine ecotoxicity*. With the use of bio-based material *biogenic carbon* and *fossil fuel* emissions will be analysed too.

Life cycle assessment 5

In this chapter, the DLCA results will be discussed from the comparison between the CRW and WSW elements, as presented in section 4.1, with two different EoL scenarios for the WSW element. For the scenarios, the amount used in the production of the elements are shown in table 4.2 and 4.3, and the external Appendix I presents the explanatory calculations.

5.1 Dynamic LCA

A dynamic LCA (DLCA) was conducted to analyse the environmental impact of the elements from the case study. In a static LCA, the timing of carbon emission is not taken into account, it is considered the annual average amount of the forest stock, being absorbed in the production and released at the EoL [De Rosa et al., 2018]. Opposing this approach, a dynamic LCA uses a time-dependent factor to account for the emissions of wood, providing the real climate change related to the emission [Levasseur et al., 2010]. According to Breton et al. [2018], the use of DLCA in bio-based case studies provides more comprehensive and consistent results of the impact. For this reason, a DLCA was built for this project to understand the impact of wood production. For the wood production data from De Rosa et al. [2018] was used as the main wood activity, and updates in the activities were made when it was showing in SimaPro9.3.0.3 that it was no longer available. Furthermore, for seaweed the carbon release was based on the Seghetta et al. [2016a].

5.2 End-of-life scenarios

In Denmark, the current EoL scenario for bio-based materials is considered as incineration with energy recovery, used mainly for residential heating [Lendager and Pedersen, 2020]. To convert the amount of energy recovered from bio-based materials data from Hansen [2017] was used as the baseline.
The WSW element is composed by two bio-based materials; seaweed and wood (OSB; wood cladding, structure and module). Because seaweed is classified as bio-based material this research will assume the EoL as the same as other bio-based elements, as the EoL is not well elaborated yet. However, studies show seaweed with potential to be transformed after the EoL into 3 new products: protein-rich fish feed ingredient, bioethanol and liquid fertilizer [Aveiro et al., 2019; Seghetta et al., 2016a], therefore, the impact of these benefits will be included in the analysis.
The current EoL for the CRW elements is assumed as 97% of the element is recycled and 3% is landfilled [Miljøstyrelsen, 2015], the same occurs with reinforced steel when 95% is recyclable and 5% landfilled. For gypsum, cement board and rock wool the EoL are based

on each product's EPD [EPD Danmark, 2022, 2021; EPD Knauf, 2021a,b], respectively. For wood spruce used in the CRW element, the same principle for bio-based material was applied. Figures 4.5 to 4.7 illustrates the flow diagram of the CRW element, WSW + incineration and WSW + reuse element, respectively. For calculations amounts see Appendix I.

5.3 Results

The analysis of the environmental impact between CRW element and WSW element showed a difference in the GWP emissions of 74kg of CO_2-eq being emitted when elements are compared, on the other hand, a difference of 162,8 kg of CO_2 was presented when analysing the category CO_2, fossil when compare both elements, as shown in figure 5.1

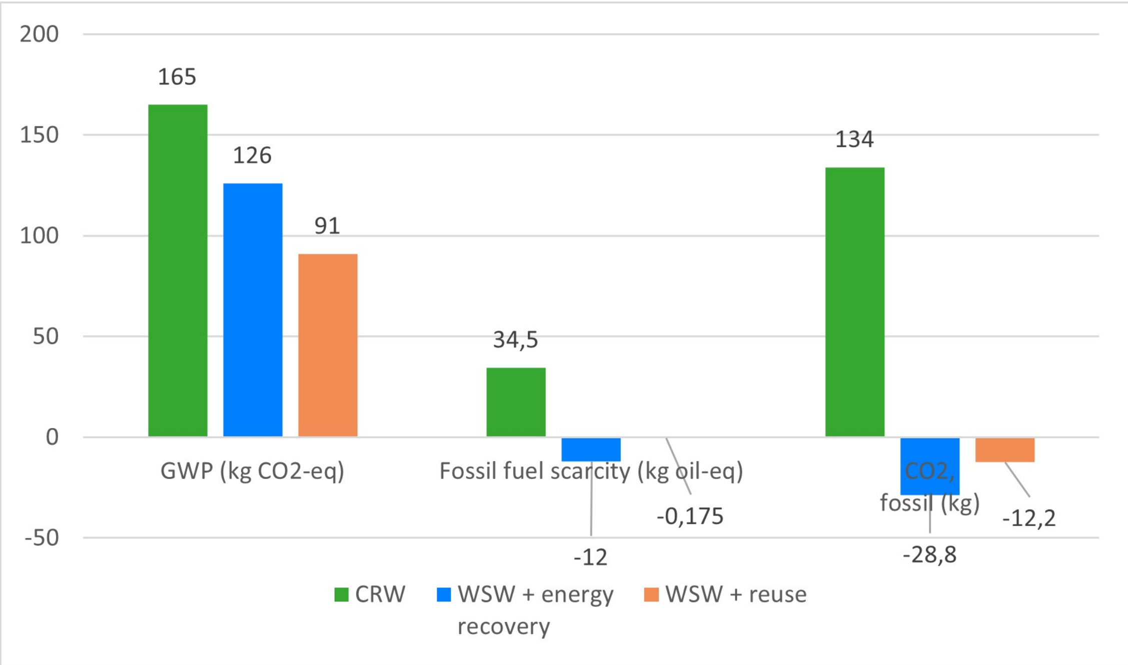

Figure 5.1. Environmental impact assessment - GWP; fossil fuel scarcity and CO_2,fossil. Method:ReCiPe 2016 Midpoint (H).

WSW+energy shows 23,64% less CO_2-eq emissions in comparison to the CRW element, furthermore, the WSW+reuse presented a reduction of 44,85% in GWP emissions in comparison to the CRW element. Furthermore, the avoidance in the burning of fossil fuel results in the lowest impact from the WSW+energy in comparison to the others when accounting for fossil fuel scarcity with -12kg oil-eq while CRW element will emit 34,5kg oil-eq. Moreover, the both scenarios of WSW element show negative amount of CO_2,fossil emissions and CRW presented 134kg of CO_2,fossil emissions.
On the other hand, figure 5.2 shows the biogenic carbon emission, where the WSW element shows in both scenario higher emission in comparison to CRW.

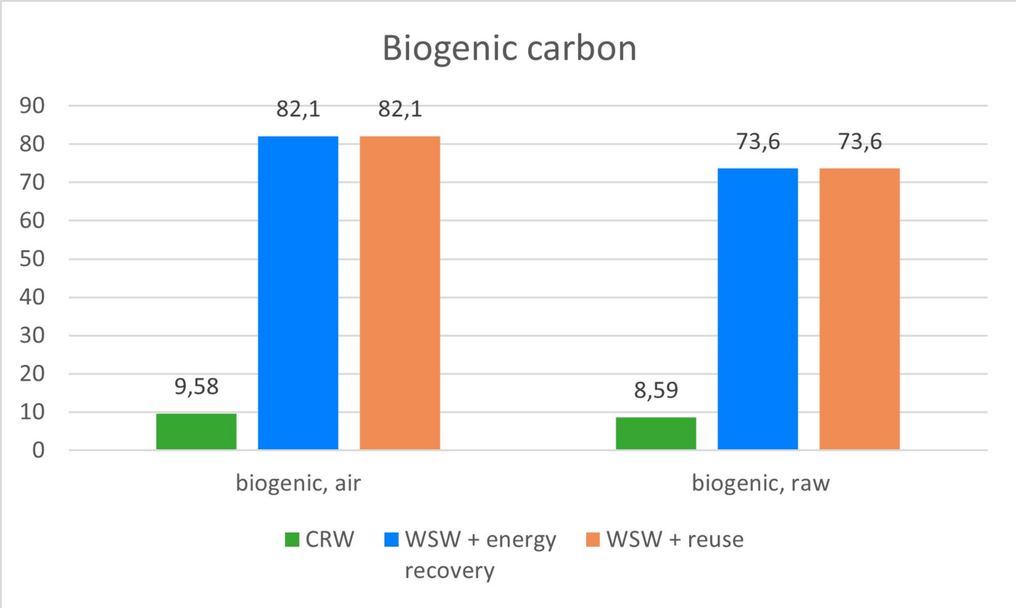

Figure 5.2. Environmental impact assessment graphic for biogenic carbon air and raw emissions. Method:ReCiPe 2016 Midpoint (H).

Because the WSW element is composed by bio-based materials, CO_2 is absorbed during its life cycle which explains the higher amount of CO_2, biogenic; shown in figure 5.2. The WSW element will absorb during the life cycle of it 73,6kg of biogenic CO_2 and release 82,1 kg and the CRW element will emit back to the atmosphere 9,58kg of biogenic CO_2. The release of biogenic carbon is not as harmful as the release of CO_2 fossil, because the carbon absorbed was part of the atmosphere cycle, differently from the fossil that was locked up in the ground.
As it can be seen in figure 5.1, WSW+energy emits 46,5kg oil-eq less and 162,8kg CO_2,fossil less in comparison to CRW element. Even with the difference between CRW and WSW+energy being 39kg GWP, the last scenario demonstrate having the lower environmental impact among others, since the burning of fossil fuel will be avoided, preventing the release of underground carbon that was not part of the environmental cycle, increasing in this way the concentration of CO_2 in the air.
Although both scenario of the WSW element present lower GWP emissions than the CRW element, when the land use impact is analysed the WSW+reuse scenario demonstrate to have 7m^{2}a crop-eq more impact than the CRW element, as shown figure 5.3.

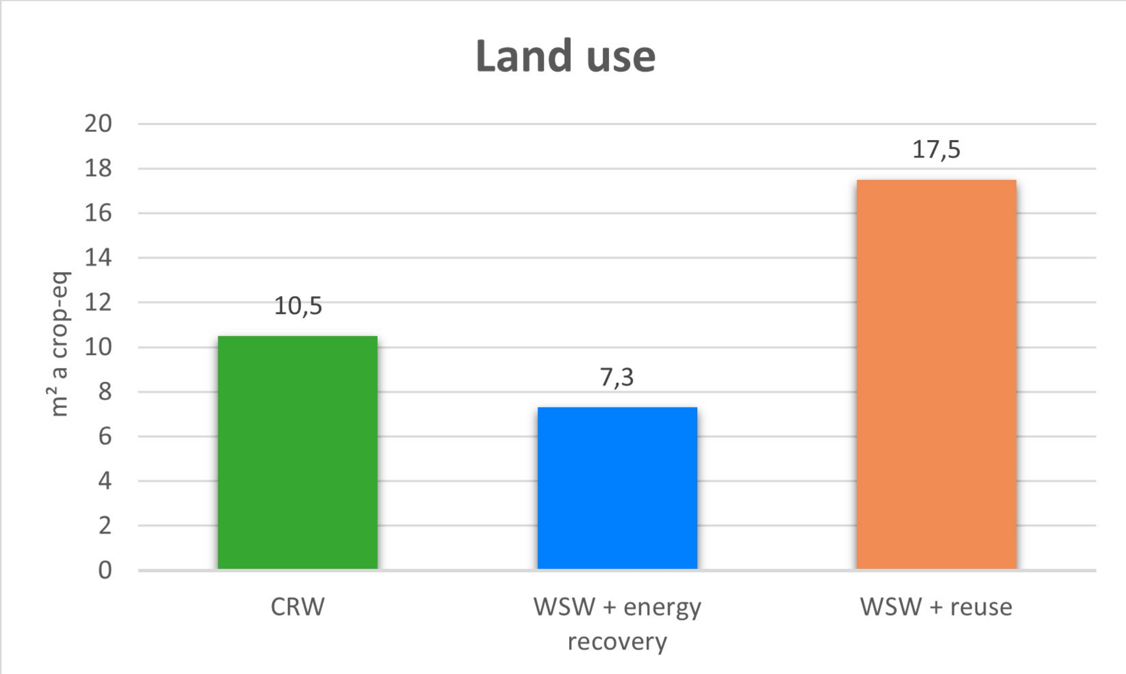

Figure 5.3. Environmental impact assessment graphic for land use. Method:ReCiPe 2016 Midpoint (H).

This is due to the fact that the WSW+reuse will need to produce more wood to replace the ones that will be reused at the EoL of this scenario. Even with the CRW element presenting only 1,0% of wood to be built, which comes from the wood spruce used to hold the insulation, another material has wood in the composition, and that is the case of cement board. As presented in the product's EPD EPD Danmark [2021], up to 7% of the product is cellulose/fibres which is responsible for increasing the land impact of the CRW element. On the contrary, the WSW+energy presents the lowest impact among all, as a consequence of the incineration process of the scenario, instead of producing more wood to be used in the power plan incineration, the wood from the WSW+energy scenario substitute it, which will require less land to plant more trees.

Another relevant analysis made in this project is focusing on the impact of seaweed production, since land is not needed to produce it, other environmental impacts categories were chosen to be investigated related to water impact: *freshwater eutrophication*, *marine eutrophication*, *freshwater ecotoxicity* and *marine ecotoxicity*.

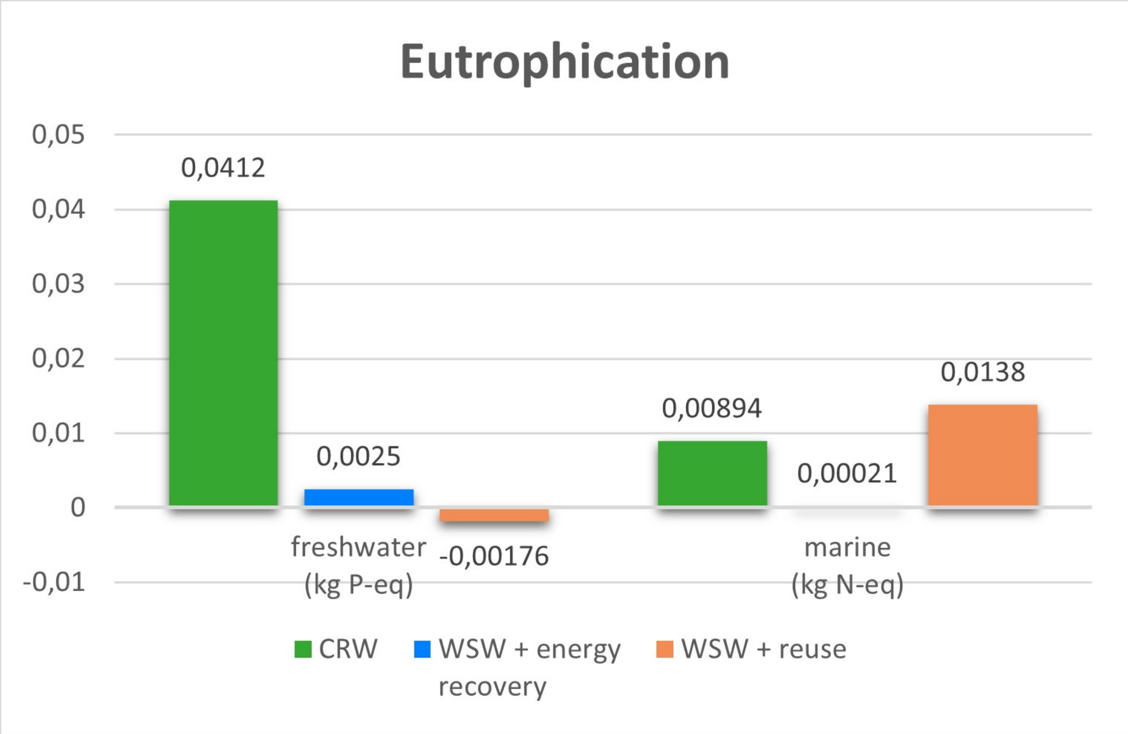

Figure 5.4. Environmental impact categories related to water impact. Method:ReCiPe 2016 Midpoint (H).

Figure 5.4 shows the environmental impact of *freshwater and marine eutrophication.* It can be seen that in the first impact category the CRW element demonstrate a higher impact related to water among others. Seaweed is responsible to captures phosphate from the water which can be seen from the small impact produced by the WSW element in both scenarios. Even though seaweed absorbs nitrate from water the WSW+reuse scenario shows a higher impact in comparison to the CRW element, this impact comes from the assumption of the EoL of seaweed as producing protein-rich fish feed ingredient, which is demonstrated in figure 5.13.

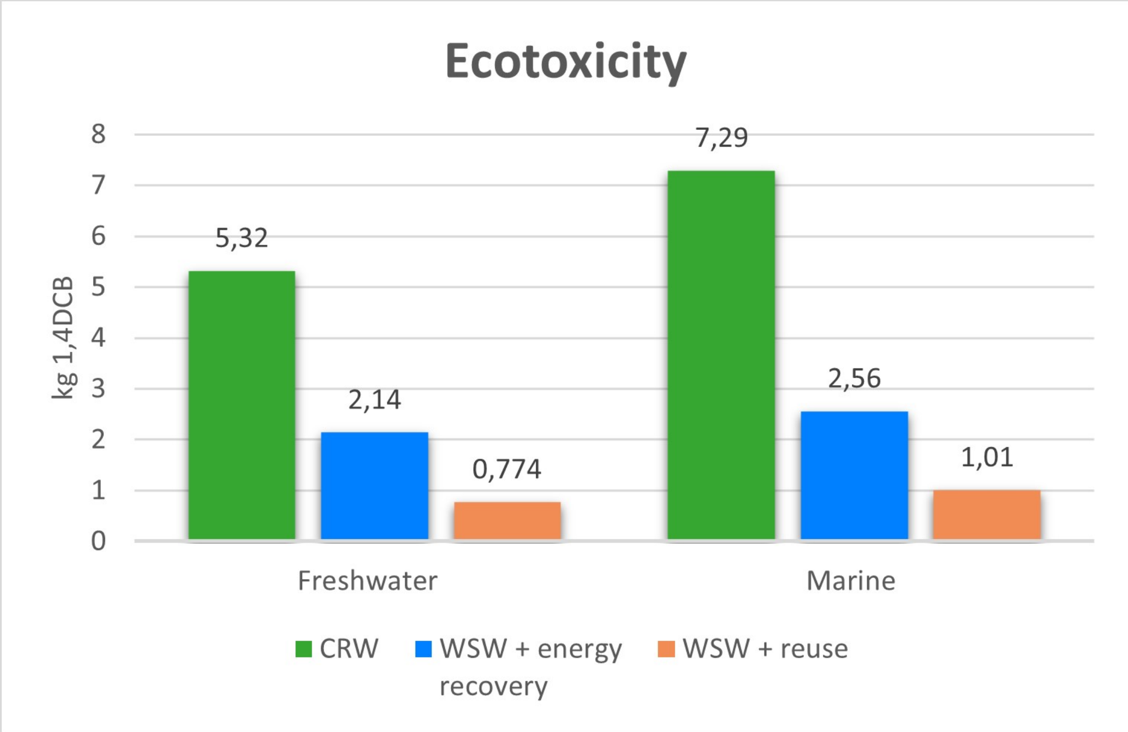

Figure 5.5. Environmental impact categories related to water impact. Method:ReCiPe 2016 Midpoint (H).

In the category *fresh water ecotoxicity*, shown in figure 5.5 the CRW element emit 59,77% and 85,45% more related to energy and reuse scenario of the WSW element respectively. Cement and steel production are behind 42,9% and 41,3% of the emission from CRW element, respectively. For *marine ecotoxicity* category, CRW emits 64,88% more compare to the energy recovery scenario and 85,15% more to the reuse scenario of the WSW element as demonstrated in figure 5.5. Ana once again, cement and steel are behind the emission from this category with 40,4% and 43,3% of the emissions, respectively.

5.3.1 Environmental impact of seaweed production

The production of seaweed was modelled using data from the off-shore farm from Aveiro et al. [2019]. After that, data from Miljøstyrelsen [2018] was added to the analysis creating a drying process, making seaweed able to be used as an insulation material, this process is illustrated in figure 5.6.

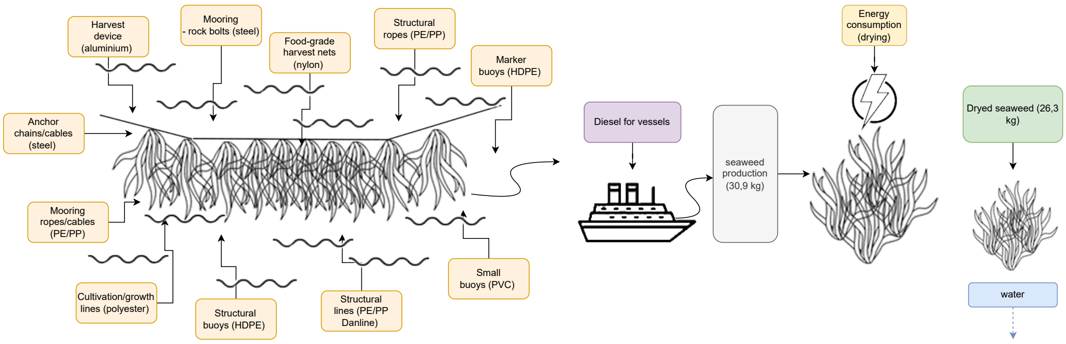

Figure 5.6. Illustration of seaweed production and drying process.

Figure 5.7 shows the negative amount of GWP from the production of seaweed, which represents a positive environmental impact, absorbing CO_2 from the atmosphere. The land use impact in the production of seaweed comes from a secondary activity, the steel production. Steel is used to produce the anchor that hocks seaweed into a rope in water, steel production is responsible for 83,3% of the emissions, however the whole activity have the impact of 0,00402 m^2a crop-eq in seaweed production. The same occurs with the 0,0748kg oil-eq impact related to fossil fuel scarcity, which comes from the diesel used in vessels to harvest the seaweed and from the electricity used in the drying process.

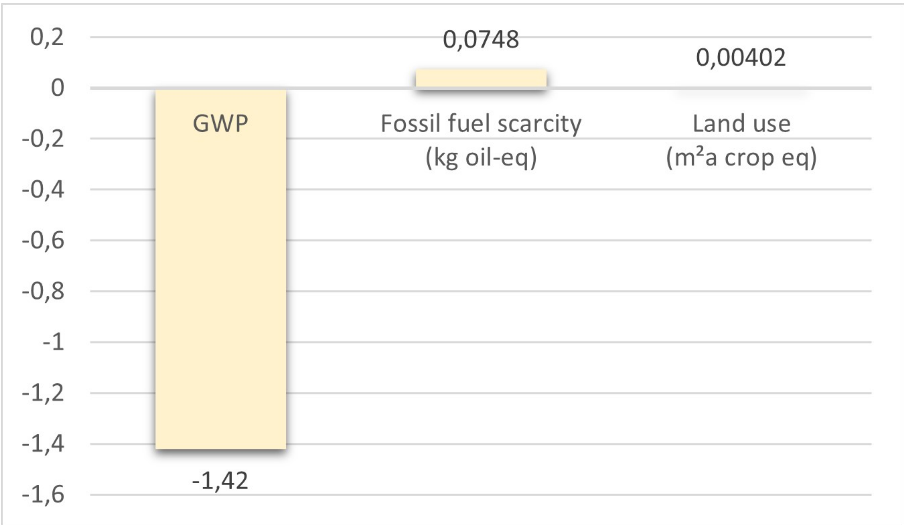

Figure 5.7. Impact categories of seaweed production. Method:ReCiPe 2016 Midpoint (H).

As bio-based material seaweed captures CO_2 during its life cycle as presented in figure 5.8 with the biogenic carbon amount of 0,00721kg, however, the CO_2, fossil emissions come from the steel and diesel production, being responsible for most of the 0,0712 kg; 26,7g and 21,6g, respectively, as figure 5.11 shows.

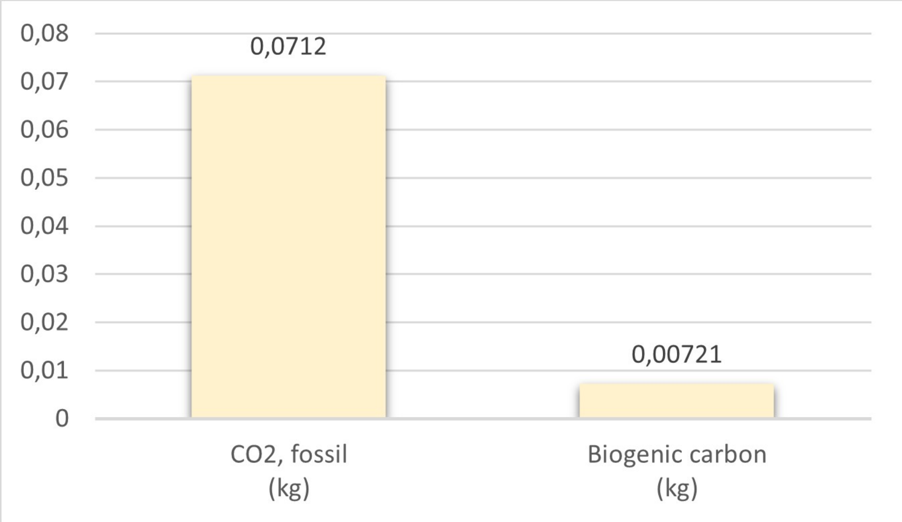

Figure 5.8. Impact categories of seaweed production. Method:ReCiPe 2016 Midpoint (H).

The water-related impacts appear in small amounts as shown in figure 5.9 with 0,00366 and 0,00257 kg 1,4 DCB impact in freshwater ecotoxicity and marine ecotoxicity. Showing that producing seaweed will not harm existing marine life.

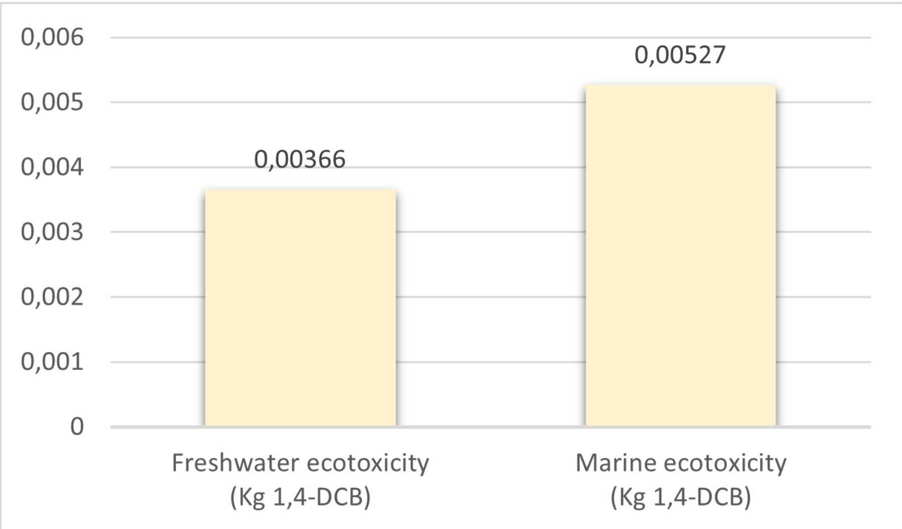

Figure 5.9. Impact categories of seaweed production. Method:ReCiPe 2016 Midpoint (H).

The same occurs with freshwater and marine eutrophication in figure 5.10, a small amount of Phosphate(P) and Nitrate(N) are emitted to water, as presented by Seghetta et al. [2016a]; Aveiro et al. [2019]; World-Economic-Forum [2022] the introduction of seaweed in water with a high concentration of P and N, seaweed will absorb theses ion providing more balanced water.

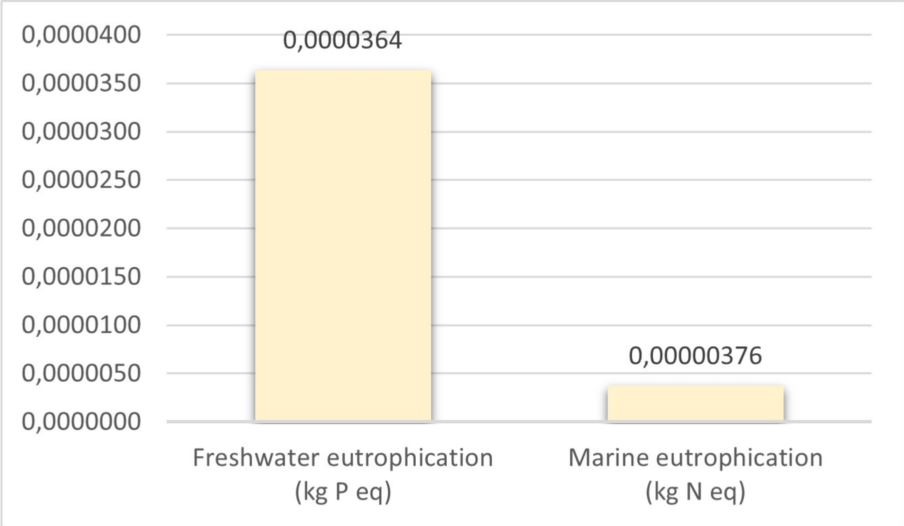

Figure 5.10. Impact categories of seaweed production. Method:ReCiPe 2016 Midpoint (H).

To comprehend better the emission to the water in the production phase, figure 5.11 analysed the product with the most impact related to the select environmental categories. It went out that steel is responsible for the bigger impact in the selected categories, showing significant impact in 11 out of the 18 impact categories shown in SimaPro. The use of steel in seaweed production comes from the anchor chain/cables and mooring system. Ferronickel from the stainless steel used in the anchor and mooring is the metal behind the increase of the impact in the water. The impact that aluminium produce comes from the harvesting device and the diesel is coming from the use of diesel from vessels. Another impact related to the seaweed production is the use of nylon to attach the seaweed to the production rope, this rope is left in the open sea and the deterioration of the nylon is responsible for 32,6% of the marine eutrophication in the seaweed production. To reduce this impacts a change in the use of the presented materials should be considered.

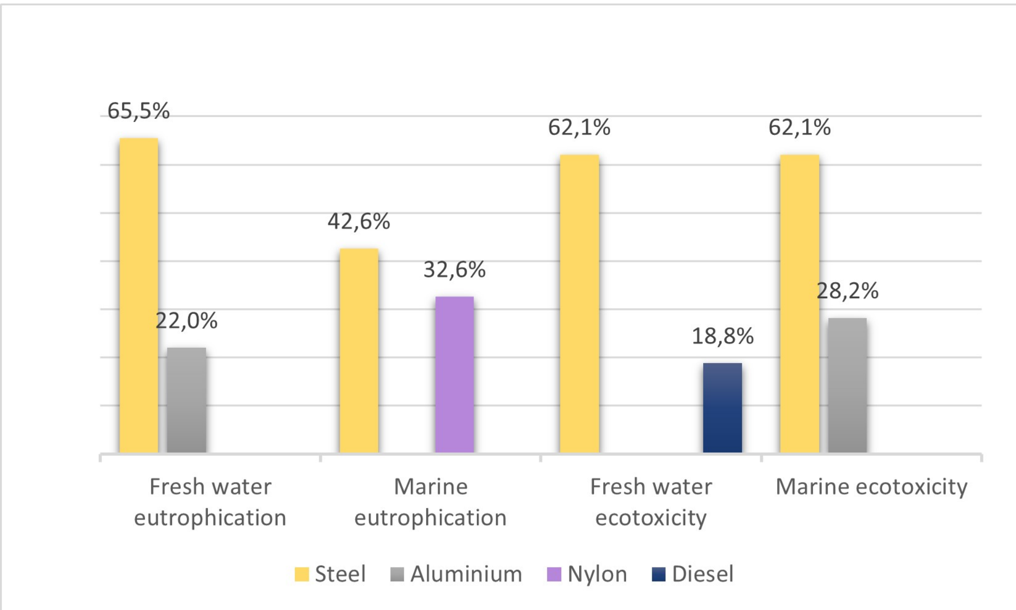

Figure 5.11. Impact categories of seaweed production. Method:ReCiPe 2016 Midpoint (H).

In the analysis of the WSW+reuse scenario, the D phase (benefits beyond boundary) was included, however, some of the activities from the SimaPro database were not the specific one related to the seaweed production, in this case, the closest activities were chosen. According to Seghetta et al. [2016a], the D phase from seaweed have 3 potential benefits beyond boundaries; protein-rich fish feed ingredient, bioethanol and liquid fertilizer. The analysed impacts are seen in figure 5.12

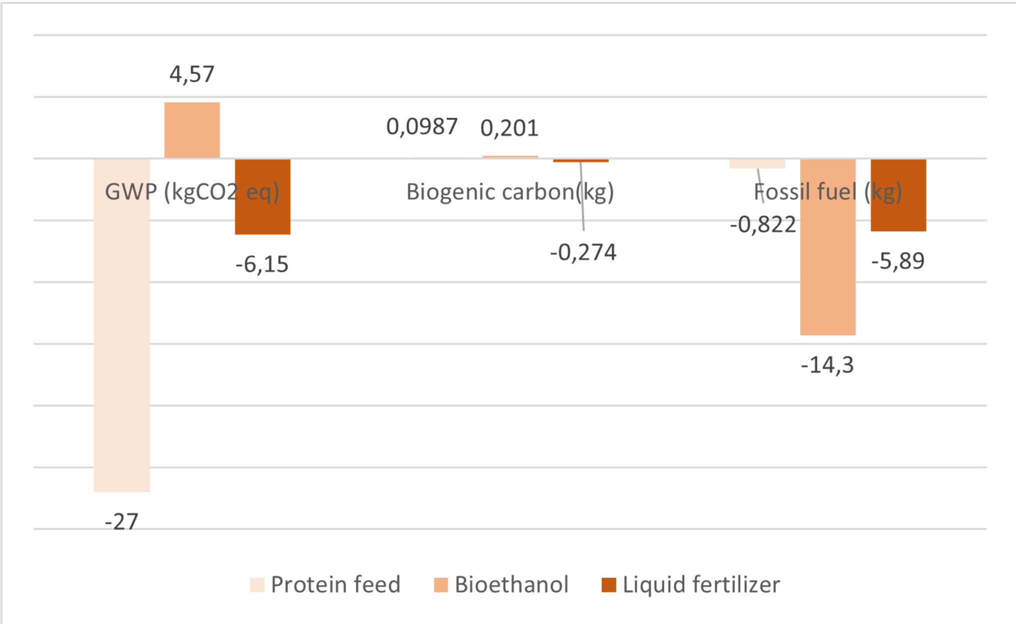

Figure 5.12. Impact categories from D phase of seaweed production. Method:ReCiPe 2016 Midpoint (H).

The transformation of seaweed in liquid fertilizer in the EoL of the material show as being the most popular scenario option as it is discussed in Seghetta et al. [2016a], Seghetta et al. [2016b], Thomas et al. [2021] and Miljøstyrelsen [2018]. In the analysis made in this project, liquid fertilizer reduced the environmental impact with a negative amount in all 18 categories analyzed in SimaPro. On the other hand, seaweed transformation as protein feed in the EoL shows a bigger impact in 4 out of the 7 categories analysed in figure 5.12 and figure 5.13, however, is the EoL scenario behind of smaller GWP emissions amount.

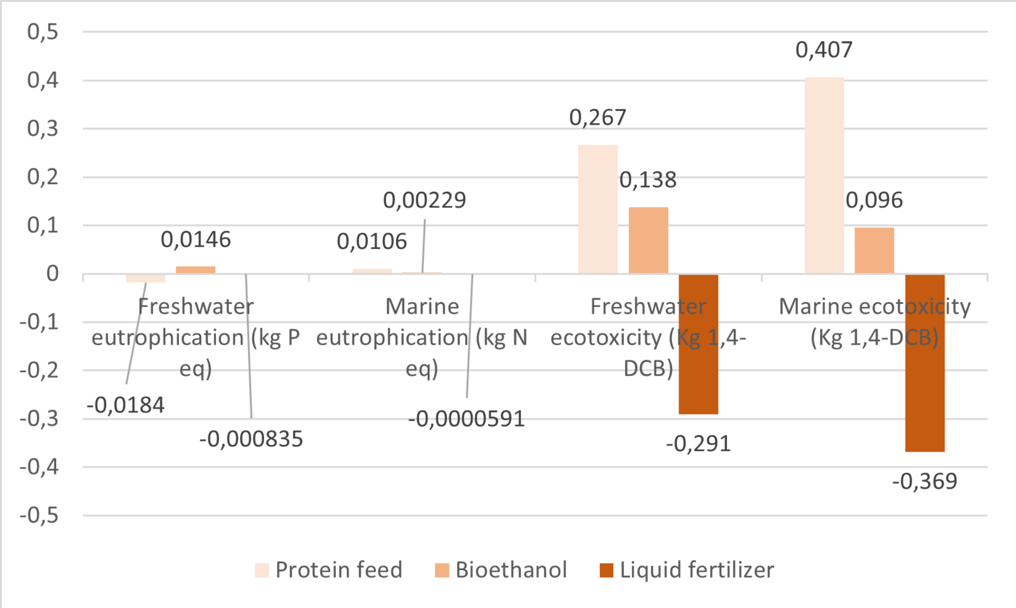

Figure 5.13. Impact categories of seaweed production. Method:ReCiPe 2016 Midpoint (H).

5.3.2 Sensitivity Analysis

The sensitivity analysis aims to show the impact of different variations in the data collected amount to build the LCA and how these variations can affect the results of the defined FU: 1 m^2 of a load-bearing structure made with wood and seaweed insulation (WSW) and 1 m^2 of a load-bearing structure made with concrete and rock wool insulation(CRW). Due to the use of a DLCA, the sensitivity analysis will be performed by changing the land use of the wood. According to De Rosa et al. [2018] the release of carbon biomass changes according to the different types of Land Use Changes (LUC). The direct LUC (dLUCs) is when land receives a different use as it was previously designated, for instance turning a forest into arable land, in opposition an indirect LUC (iLUCs) is when it can be seen a land-use intensification in another land caused by product demand [De Rosa et al., 2018]. For the sensitivity analysis, the iLCU approach will be replaced by a dLUC in order to comprehend the impact of land use of bio-based materials.

As present in figure 5.14, the sensitivity analysis showed a significant change in the impact category of land-use when land is used as arable instead of land with intensive use. The change showed an increase of 3890% in the CRW element and for the WSW element, the change demonstrated an increase of 47982% in WSW+energy and 20014% for WSW+reuse in comparison with the impact from iLUCs approach. The WSW+energy appears with the highest impact among others due to the fact of in this scenario the EoL is modelled as incineration purpose as described in section 5.3.

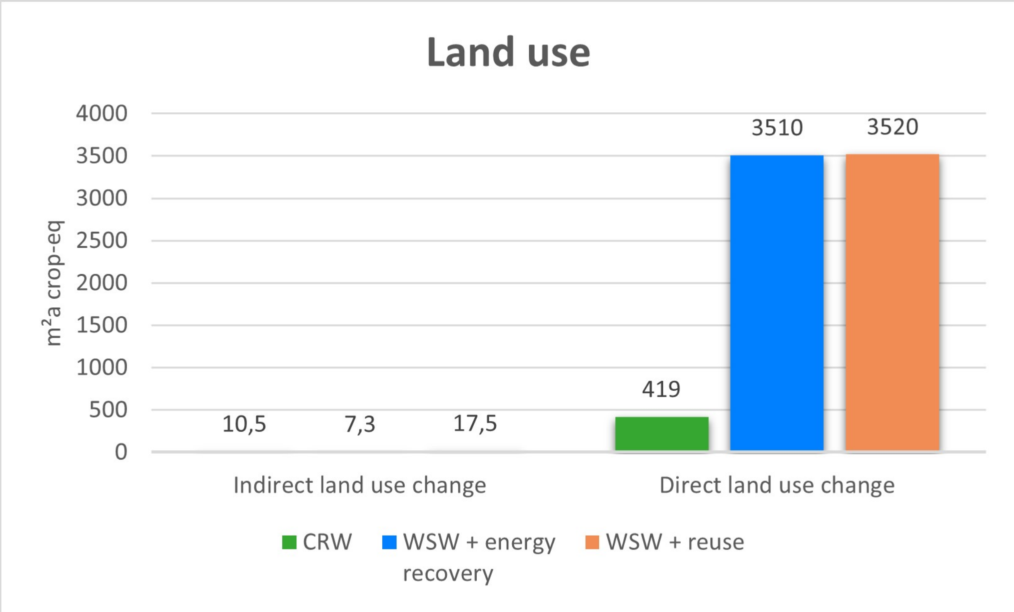

Figure 5.14. Sensitivity analysis using dLUC, land use impact category. Method:ReCiPe 2016 Midpoint (H).

The EoL scenario of WSW+energy represented an increase of 15%, while the WSW+reuse showed 1065,71% increase in the fossil fuel scarcity category, as shown in figure 5.15. This is due to the fact that the WSW+reuse scenario, will produce new materials to replace the reused ones from the reuse EoL. The CRW presented the smaller increase among other with 0,58%, due to the fact that the concrete production, is not sensitive to land-use changes.

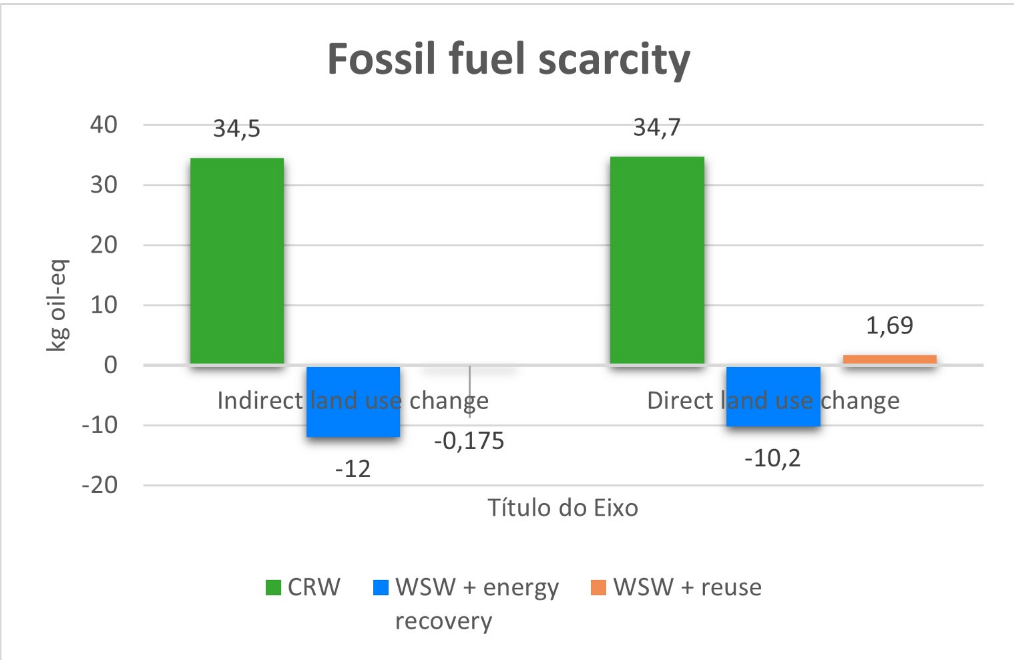

Figure 5.15. Sensitivity analysis using dLUC, fossil fuel scarcity impact category. Method:ReCiPe 2016 Midpoint (H).

However, when counting GWP emissions CRW showed an increase of 44,85%, of which

64,7% comes from the wood spruce used in this scenario. As GWP measures the Earth's temperature, turning forest land into arable land would represent a significant impact in this category as can be seen with the increase of 503,17% from the WSW+energy and 696,70% from WSW+reuse, as figure 5.16 shows.

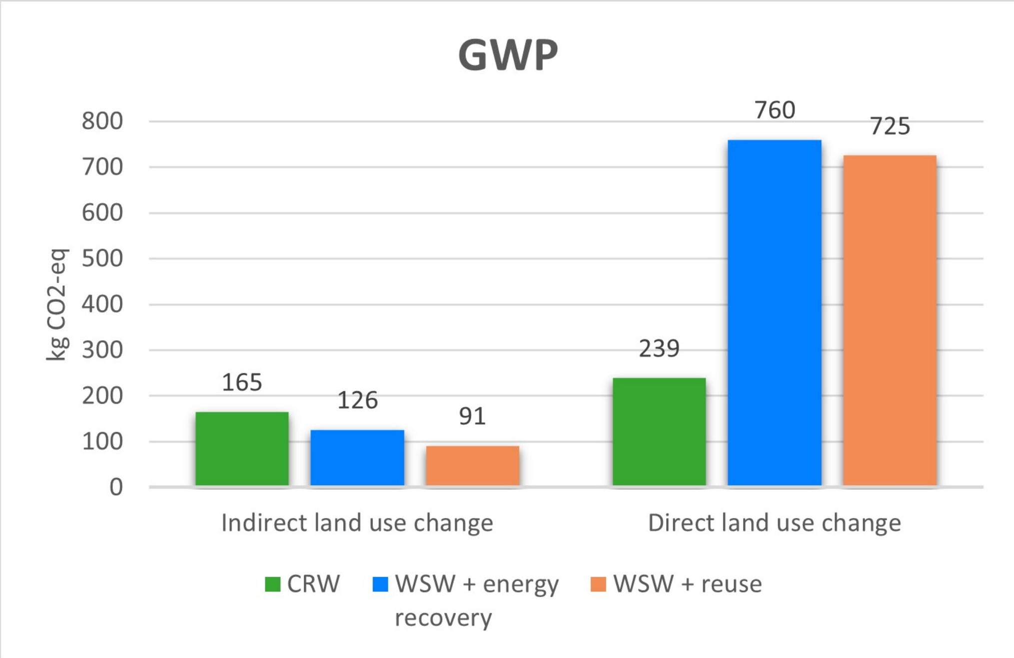

Figure 5.16. Sensitivity analysis using dLUC, GWP impact category. Method:ReCiPe 2016 Midpoint (H).

Furthermore, the dLUC showed an increase in the CO_2, fossil impact category, with CRW presenting the smaller change with 0,75%, followed by WSW+energy with 19,44% and WSW+reuse with the highest increase with 46,23%. In comparison to the CRW element both WSW scenarios still present a negative amount of emissions, however, the change in the land-use affects more the WSW+reuse due to the fact that more wood will need to be produced to substitute the wood for this scenario.

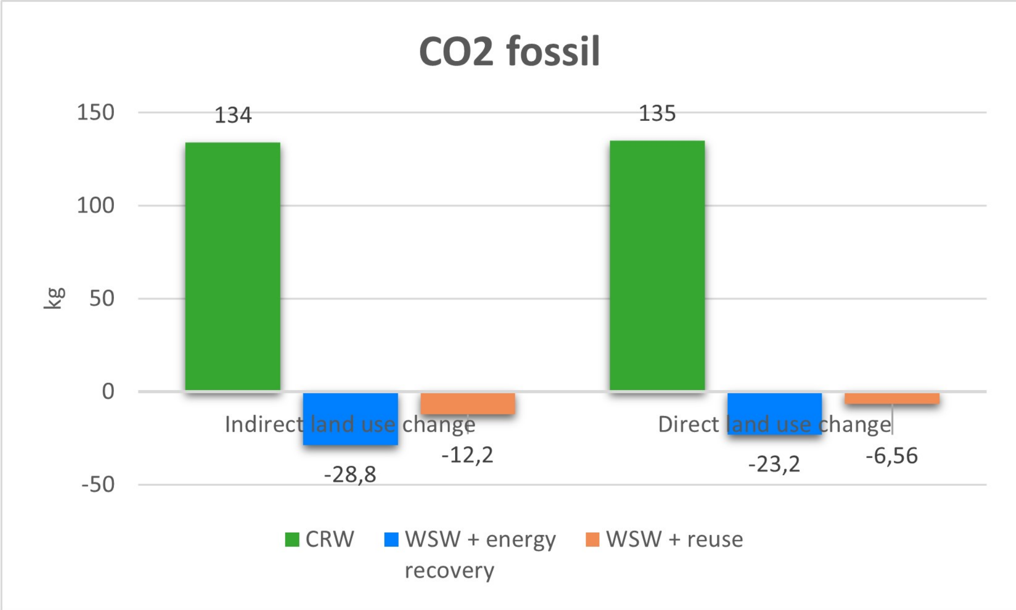

Figure 5.17. Sensitivity analysis using dLUC, CO_2, fossil impact category. Method:ReCiPe 2016 Midpoint (H).

Figure 5.18 shows the impacts from freshwater eutrophication for both elements. The impacts from the CRW element come mostly from the steel production, though the increase showed with dLUC is 0,24%. WSW element showed an increase of 22% in the energy scenario and 31,82% in the reuse scenario. The first one demonstrates the incineration process responsible for freshwater eutrophication, while the second one, indicates the production of biogas that made the increase in the scenario. The WSW+reuse is not affected in the category of marine eutrophication, while CRW and WSW+energy showed steel as the material with more impact related to dLUC.

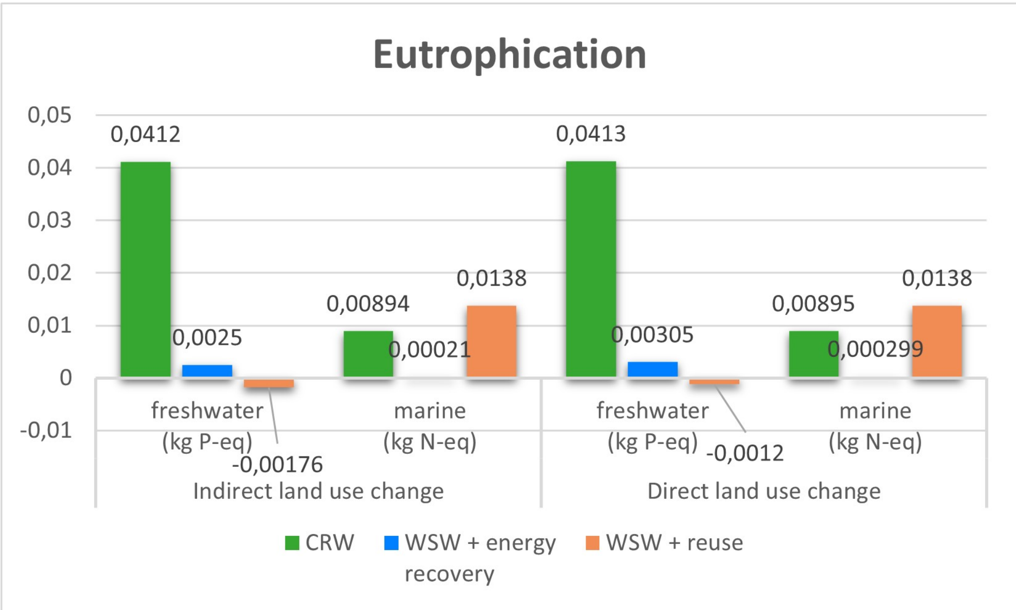

Figure 5.18. Sensitivity analysis using dLUC, eutrophication impact categories. Method:ReCiPe 2016 Midpoint (H).

The ecotoxicity impacts are presented in figure 5.19. For the WSW+energy in both categories, freshwater and marine, the incineration process is behind the increase in the emission, 1,40% and 5,08% respectively. For the CRW and WSW+reuse, the increase in the emissions is from steel, with 0,19% more emission in freshwater and 0,27% more in marine from the CRW element, while WSW+reuse presents 4,91% and 12,87% more emissions, respectively.

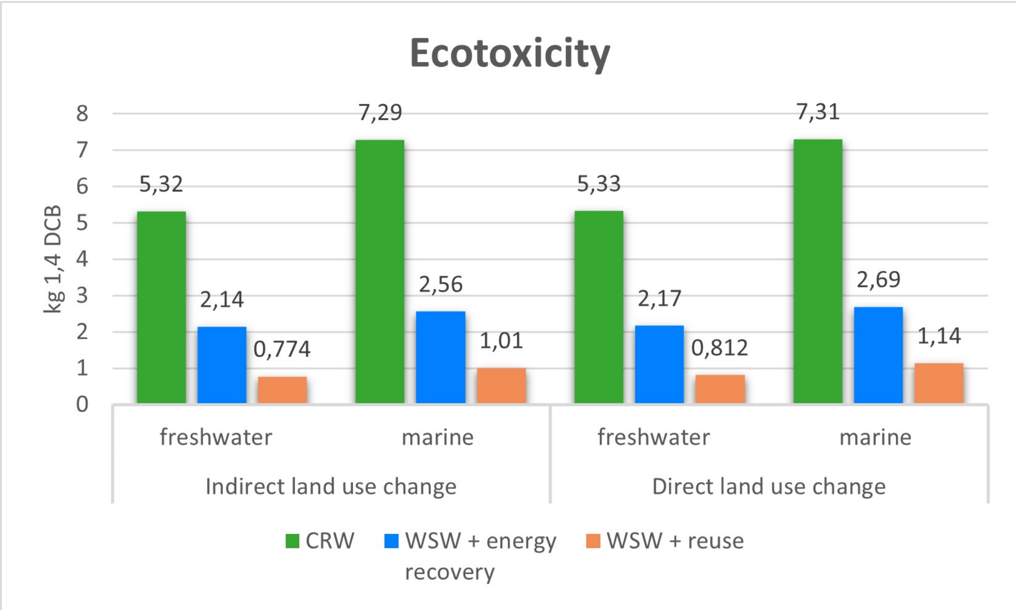

Figure 5.19. Sensitivity analysis using dLUC, ecotoxicity impact categories. Method:ReCiPe 2016 Midpoint (H).

Despite what have being demonstrated in the other categories, the biogenic carbon does not show any change as presented in figure 5.1. Moreover, a GWP (time-dependent) was calculated according to De Rosa et al. [2018] using 100 years for the emission. As figure 5.20 shows the CWR element will absorb 8,59kg of CO_2 and release 9,58kg, while the WSW element absorb 73,6kg of CO_2 and release 82,1 kg. Even with the difference between the CO_2 emission of the elements, the WSW shows an environmental benefit storing 65,01 kg more in comparison to the CRW.

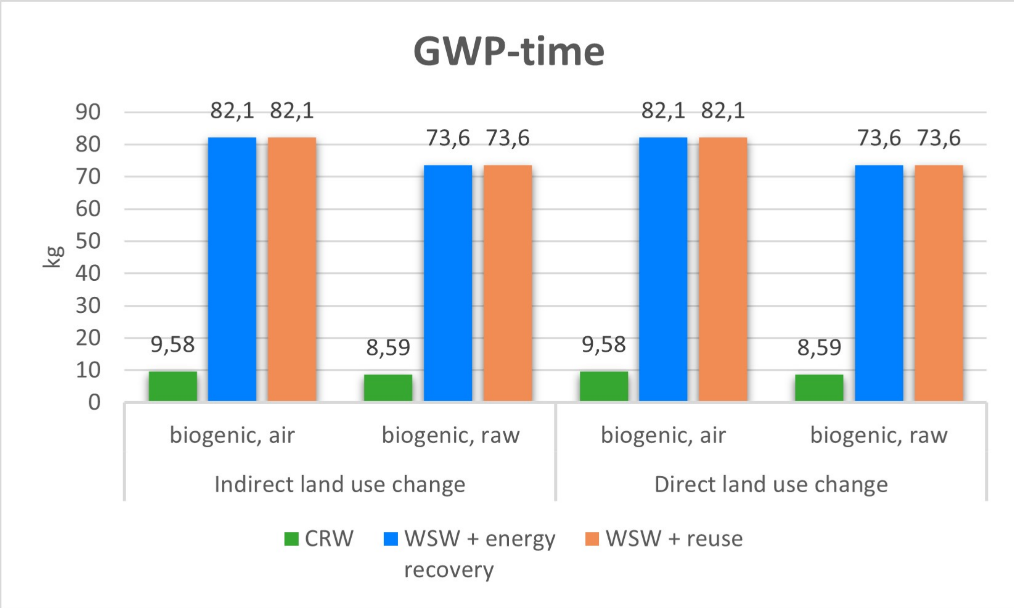

Figure 5.20. Sensitivity analysis using dLUC, GWP-time impact categories. Method:ReCiPe 2016 Midpoint (H).

It can be inferred from the sensitivity analysis that the change in iLUC to dLUC will have more impact in the categories of land use, GWP and fossil fuel scarcity, with the last two directly related to CO_2 emissions.

6 Discussions

Based on the LCA results, shown in chapter 5 it can be inferred that the WSW element has a significantly lower impact than the CRW element when the focus is on GWP emissions. However, the analysis showed that different land use approaches and EoL can provide different results for the WSW element.
In comparison to the CRW element, the WSW+energy recovery has 23,64% less GPW impact, and the WSW+reuse element show 44,85% less; having the WSW+reuse as the best scenario of the analysed options when analysing CO_2-eq emission. However, to produce the WSW element more land will be needed to produce wood, since 61,6% of this element is wood-based. The results presented in figure 5.3 shows the WSW+reuse using 66,67% more land than the CRW element while WSW+reuse show 30,48% less land use. CRW presented a higher impact due to the use of wood spruces and the need for wood fibre for the cement board. These results answer the first sub-question (figure 3.1) "*What would be the environmental impact of increasing the use of wood?*". The use of wood as a load-bearing element will decrease the CO_2-eq emission by 44,85% in comparison to the conventional use of concrete and rockwool, although the use of wood show an increase in land use of 66,67%. However, as presented in the sensitivity analysis the use of land is sensible to the land-use choice, having a direct impact on the calculations as presented in figure 5.16 and 5.14, where a dLUC will present CRW element with a GWP impact of 32,96% less than the WSW and with 88,07% less of land use.
In opposition to wood production, no land use is needed to produce seaweed, as demonstrated in section 5.3.1 and reported by Seghetta et al. [2016a,b]; Thomas et al. [2021]; Aveiro et al. [2019]; Miljøstyrelsen [2018] which can be seen as a potential matching insulation type to use in a wood load-bearing structure since wood request more land use as demonstrated above. To answer the second sub-question "*What are the impacts of using an innovative bio-based element such as seaweed as wall insulation?*" the analyses showed that seaweed demonstrates a GWP impact of -1,42 CO_2-eq in the production phase and can achieve -27kg CO_2-eq with the EoL as protein feed. At the production phase, 0,0748 kg oil-eis emitted in the category of fossil fuel scarcity, however, the EoL as liquid fertilizer can achieve -5,89 kg oil-eq. The land-use impact shows a small amount of 0,00402 m^2a crop-eq, the same can be seen in the impacts related to water as demonstrated in section 5.3.1, the impact are smaller and come from the secondary production of steel, nylon and aluminium mainly to attach the seaweed to the ropes and from diesel used in the vessels for harvesting.
As reported by the World-Economic-Forum [2022] industrial production of seaweed helps to clean polluted waters and create a safe place for small creatures to reproduce in open waters. Although the production of seaweed is beneficial for the water, the wild seaweed is found in unbalanced water, where the concentration of nitrate and phosphate are high

Thomas et al. [2021]; Miljøstyrelsen [2018]. The production of seaweed and its introduction to water re-establish the balance of the water because seaweed captures the nitrate and phosphate of it [Seghetta et al., 2016a]. Therefore, it can be concluded that the production of seaweed reduces the GWP impact, re-balancing the water nutrients, and produce a clean and safe place for marine species to live.

Even though seaweed production reduces environmental impact, the use of it in the construction sector can face some barriers, such as fire legislation. As a bio-based material, seaweed has a fire classification of class E, which means it will only be approved by authorities to be used when completely covered by material class K1, for instance, gypsum board, and its use is only approve in buildings with the maximum height of 5.1 meters [Kapitel 4 - Bygningsreglement, 2018].

As presented in chapter 2 the impact of bio-based elements have being discussed since different LCA approaches can lead to different results [Lukić et al., 2021]. As presented in section 5.3.2 the choice of the land-use approach shows substantial differences in the results according to how LUC are modelled. This differences can lead to a scepticism of the benefits of using bio-based materials as reported by Lukić et al. [2021]; Vanova et al. [2021]; De Rosa et al. [2018]; Andersen et al. [2021]. The increase in the use of bio-based materials can mislead the results of the environmental impact, for instance, it can show a small GWP impact while not presenting a higher impact on land use. Moreover, the use of bio-based element does not mean any climate change impact, for instance, the decomposition of wood in landfill capture CO_2, but on the other hand, it will emit biogenic methane, where methane emissions have a bigger impact on the GWP impact than carbon emissions have [Liang et al., 2021]. In Denmark, all bio-based materials are assumed to be incinerated at the EoL [Birgisdóttir, 2019] which will release a substantial amount of CO_2 into the atmosphere when having buildings constructed mainly with bio-based elements [Vanova et al., 2021]. As shown in figure 5.2 the WSW element will emit more biogenic carbon than the CRW element , on the other hand more carbon will be sequestrated in the WSW element. Because the time to lower the Earth's temperature is getting closer [IPCC, 2018], the use of bio-based materials can assist the construction sector to reduce their emissions, since a bigger amount of carbon will be stored for more time in bio-based materials, and less CO_2, fossil will be released into the atmosphere, as presented by Bionergy [2022], the release of biogenic carbon is less harmful in comparison to the release of CO_2, fossil. At the same time, the sector has to be aware that the increase in the demand of wood can affect others environmental impact as presented previously. The increase in the demand has to be carefully cared for, not putting down a forest to produce more wood, which will increase land use impact and directly affect the GWP results. This conclusion answers the third sub-question of the project: "*What are the biogenic CO_2 emissions related to increased use of bio-based materials such as wood and seaweed and how do these emissions contribute to climate change*".

The three sub-question answered previously will help to answer the fourth sub-question "*How can bio-based elements assist the Danish construction sector to elaborate environmental policy-making to reduce CO2 emissions?*". For the construction sector to develop poly-making a more standardised approach to assess the impact of bio-based material has to be used for the entire sector. For instance, the software LCAbyg was developed to assist the Danish construction sector in LCA calculation [Birgisdottir and Rasmussen, 2019] and it follows the EN 15978 standard [Jørgensen et al., 2020]. Therefore,

LCAbyg does not include all life cycle phases of the standard (4.4),for instance, C1 - C2 phases are excluded from the analysis. Furthermore, as discussed by Lukić et al. [2021]; Vanova et al. [2021]; Liang et al. [2021]; Dabaieh et al. [2020]; Chen et al. [2020], different approaches lead to different results, the accounting of biogenic carbon in an LCA can present different results, using a 0/0 approach or the -1/+1 approach, the results of the impact will depend on how it was modelled. The construction sector should elaborate a guide on how bio-based materials should be calculated, assuring the comparability of results. Therefore, as discussed, bio-based elements have low fire resistance, which can be a barrier faced by the construction sector to use this material combination in buildings on bigger scale, as it was faced with wood elements decades ago Lukić et al. [2021]. However, the use of fire impregnates in wood, and in the case of seaweed, keeping the material closed by clay or gypsum board are solutions already approved in the fire legislation [Kapitel 4 - Bygningsreglement, 2018].
Even with the ability to store CO_2 and reduce the GWP, to assist the Danish construction sector, a standardisation in LCA calculation of bio-based elements can reduce the scepticism about the material and spread its use. Furthermore, fire legislation can be updated to include the safety in the use of bio-based materials in combination with already approved elements, which can reduce the mistrust of this type of material. In this way, poly-making can be elaborated by encouraging the use of bio-based to reduce the CO_2 emissions from the sector. As presented bio-based materials have less GWP impact, reduction in fossil fuel scarcity, and even with more biogenic carbon emission it shows less carbon, fossil emissions, reducing the climate change.
With the analysis made in chapter 5 and the sub-question answer in this chapter, it can be concluded that the use of wood and seaweed will minimize the environmental impact related to GWP emissions and fossil fuel scarcity in comparison to the conventional load-bearing structural system (CRW element), however, the use of reused wood is a constraint, since is not available in industrial scale, to supply the need of it more wood will be required from forestry which will cycle to more land-use increasing this environmental impact. On the other hand, the production of seaweed reduces the environmental impact related to water, reducing P and N concentrations in polluted water and creating a clean and safe environment for marine life. Also, the EoL related to seaweed showed potential climate change reduction.
Answering the research question: "*What is the environmental impact of using a load-bearing structure made of reused wood and seaweed insulation in comparison to conventional structural systems?*" It can be inferred that the WSW element demonstrated an environmental impact reduction in comparison to the CRW element, in 6 out 7 of mid-point impact categories analysed: *GWP, Fossil fuel scarcity, freshwater and marine ecotoxicity, freshwater and marine eutrophication*, the last one show a higher impact in comparison to CRW only in WSW+reuse scenario, due to the assumption of protein-rich feed EoL, CRW only presents less impact in *land use* impact category when considering an iLUC in a DLCA approach.

7 Conclusion

This report investigates how the use of bio-based materials can assist the construction sector to reduce its environmental impact by analysing a load-bearing wood wall with seaweed insulation in comparison to the conventional concrete wall with rock wool insulation.

The study shows a reduction of 44,85% in the GWP emission from the WSW element when compare to CRW, for the FU of $1m^2$ of a load-bearing wall. On the other hand, the land-use impact demonstrates an increase of 66,67% for the same comparison. The production of seaweed reveals a reduction in GWP impact, absorbing -1,42kg of CO_2-eq in $1m^2$ of wall and a small impact related to water. The increase in the use of seaweed will help to clean polluted water and keep marine life safe, as presented by Miljøstyrelsen [2018] the use of seaweed on an industrial scale will have to be supplied by an off-shore seaweed farming, where seaweed will be introduced in water and will absorb P and N presented in it, restoring the water balance, in contrary, wild seaweed appears in unbalanced waters and in more seasonal scale, which will be a barrier to use it in industrial scale.

As presented in section 5.3.2, LCA results varied significantly according to the modelling assumptions. For this reason, this study could be improved by a better understanding of seaweed production and EoL, to minimise assumptions, which could lead to a more precise environmental impact of this material. However, with the worldwide focus on reducing the GWP effects, the results presented in this study showed that the use of bio-based elements can reduce the GWP potential which can assist the construction sector to reduce its environmental impact related to CO_2 emissions and help Denmark to achieve the Climate act target of reducing by 70% the CO_2 emission by 2030 [Klima-, Energi- og Forsyningsminisertiet, 2019] and the European goal to achieve carbon neutrality by 2050.

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