University College Ghent
Campus Mercator
Henleykaai 84
9000 Ghent

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A comparison of the environmental impact of vertical farming, greenhouses and food import

A case study for the Norwegian vegetable market

Student:	Klaus De Geyter
Education:	Business management
Specialisation:	Environmental Management
Company:	BySpire
Thesis supervisor:	Katrijn Cierkens

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Foreword and Acknowledgement

As a last year student Business management: Environmental Management at University College Ghent, I was assigned to write a bachelor thesis to conclude my education. Since I wanted to work on an international topic, that would challenge me, I looked for a Life cycle assessment case I could work on.

This bachelor thesis was made for BySpire, a vertical farm in Oslo (Norway). The goal of this thesis is twofold: The main research goal is to make an honest, objective comparison between the three selected food production methods and to analyse the environmental impact of three different production cycles on the selected impact categories. The second goal was to gain insight in the sustainability of the vertical farm, BySpire. The aim hereby is to find the phases with the highest impact on the environment and to find the most effective improvements regarding the future development of the site.

I would like to express my gratitude to the following persons who helped me during the writing of this bachelor thesis as without them it would have been much more difficult to finish this bachelor thesis in the same successful way.

I would like to start with thanking Christian Drabløs, who was my mentor at BySpire, and who gave me the opportunity to work on an LCA and helped me get to know the agricultural methods and technologies. I want to thank also Veerle Van Linden, an LCA expert at the Research Institute for Agriculture, Fisheries and Food in Flanders, Belgium. Without her guidance and help, I would probably still try to figure out how to conduct an LCA study. Also, her feedback on my results was very appreciated. I would like to thank my thesis supervisor, Katrijn Cierkens, who invested lots of time guiding me through the research project first with preparing me in Belgium and then during the writing stages. I want to thank all the other people I had contact with and who made time for me to answer questions or offered useful input, and especially Stig Jakob Hanasand, the owner of the greenhouse site studied in this thesis, who showed me that there are also helpful greenhouse owners in Norway. Finally, I want to thank my grandparents who always believed in me, for my father and mother who were always there for me with guidance and a helping hand in life, and last but not least my girlfriend Sabrina Dietz who finds, even when times are hard, the energy to be there for me with all her support.

Abstract

In this Bachelor thesis, a Life Cycle Assessment (LCA) of lettuce production for the Norwegian market was carried out. In particular, environmental impact of each life-cycle step of three different food production methods (BySpire, vertical farming site in Norway; greenhouse in Norway; food import from the Mediterranean region) was assessed. The life cycle includes the nursery phase, cultivation phase, diesel production phase, electricity grid mix phase, natural gas production phase, the irrigation phase and the transportation phase. For each phase, the thesis will look at its environmental impact on the categories climate change, fresh and marine eutrophication, particulate matter formation, terrestrial acidification and water depletion. Analyses were performed after the setting up of a database containing all inflows and outflows of the whole lettuce production line, data about the means of transportation and transportation distances, representing, hence, a cradle to gate approach including the transportation of the lettuce from the growing facility to the city centre of Oslo, Norway. Results indicate that the vertical farming site has the lowest environmental impacts, with the exception of the impact on water depletion and freshwater eutrophication where the greenhouse site has the lowest impact. However, when looking at certain phases, it is visible that the greenhouse site is in general performing better than the two other methods. Only because of the natural gas phase and the cultivation phase which are contributing a significant amount of environmentally harmful emission the greenhouse has an overall worse impact than the vertical farming site. The import of lettuce from the Mediterranean region has compared to the two other food production methods the highest environmental impact. To get a full cradle to grave picture of the three different food production methods, further phases such as e.g. the packaging phase or the waste (water) management should be included in a next LCA. To reduce the environmental impact of the vertical farming site to an even greater extent, research on for example the switch to an electric transport mean, the use of a CO_2 enrichment or a rainwater collector can be conducted.

In deze bachelorproef, werd een Levens Cyclus Analyse (LCA) van sla productie voor de Noorse markt uitgevoerd. In het bijzonder werd de milieu-impact van elke levenscyclusstap van drie verschillende voedselproductiemethodes (BySpire, een bedrijf met verticale landbouw in Noorwegen, glastuinbouw in Noorwegen, voedselimport uit het Middellandse zeegebied) beoordeeld. De levenscyclus bevat de kwekerijfase, teeltfase, diesel productiefase, elektriciteitsnetwerkfase, aardgasproductiefase, de irrigatiefase en de transportfase. Voor elke fase, zal in deze bachelorproef, gekeken worden naar de impact op het milieu op vlak van de volgende categorieën : klimaatverandering, zoet- en zoutwater eutrofiëring, fijnstofvorming, bodemverzuring en wateronttrekking. Analyses werden uitgevoerd na het genereren van een databank met daarin alle in- en uitstromen van de gehele slaproductielijn, gegevens over het transportmiddel en de transportafstand, wat aldus een “cradle to gate”-benadering vertegenwoordigt, inclusief het transport van de sla uit de teeltfaciliteit naar het centrum van Oslo (Noorwegen). Uit de resultaten blijkt dat de verticale landbouwsite de laagste milieu-impact heeft, met uitzondering van de gevolgen voor de wateronttrekking en de eutrofiëring van zoetwater. De glastuinbouwfaciliteit heeft hier de laagste impact. Wanneer men echter naar bepaalde fasen kijkt, is het duidelijk dat de glastuinbouwfaciliteit over het algemeen beter presteert dan de twee andere voedselproductiemethoden. Alleen vanwege de aardgasproductiefase en de teeltfase die een aanzienlijke hoeveelheid uitstoot van schadelijke stoffen met zich meebrengen, heeft de glastuinbouwfaciliteit uiteindelijk een slechter effect dan het verticale landbouwbedrijf. De invoer van

sla uit het Middellandse zeegebied heeft, vergeleken met de twee andere voedselproductiemethoden de grootste milieu-impact. Om een volledig beeld van de cradle to gate van de drie verschillende voedselproductiemethoden te krijgen, moeten andere fasen zoals bijvoorbeeld de verpakkingsfase of afval(water)beheersfase worden opgenomen in een volgende LCA. Om de milieu-impact van de verticale landbouwsite nog meer te verminderen, kan verder onderzoek worden gedaan naar bijvoorbeeld het overschakelen naar een elektrisch transportmiddel, het gebruik van een CO_2-verrijking of een regenwaterverzamelaar.

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1 Introduction

By 2050, 66% of the world population will live in urban areas while in 2016 this was just 54.5%. The coming years will bring an estimated rise of 2,5 billion of the urban population by 2050, with the biggest increase up to 90% predicted in Africa and Asia (DESA, 2010).

A larger population will require a larger demand for food. At this present stage, however, our conventional agricultural methods are not prepared for such an increased large-scale production and will not be able to satisfy this demand for food. Therefore, the Food and Agriculture Organization of the United Nations determined a major goal for the coming years: eliminating hunger while making agriculture at the same time more sustainable. Yet, this goal is facing a lot of challenges. Next to the increase in the global population, also social conflicts and problems such as wars, unequal food distribution, wasting of food, and also natural disasters and climate change, are threatening the food security which will need to increase in coming decades (FAO, 2017).

Thus, agricultural methods and food production systems need to adapt to a changing world. Nowadays, agriculture claims around 34% of the land surface (Roser & Ritchie, 2018) while the water consumption for agricultural purposes accounts for 72% of all the water used by humans. Especially in semi-arid and arid regions, food production consumes an enormous extra supply of water through irrigation which consequently drains a lot of fresh water reservoirs (Graff, 2011). This is the case for example in the south of Spain where most of the Spanish food for export is produced. Here, like in many other areas of the world, agriculture currently uses around 80% of the water resources (Martinez-Mate, Martin-Gorriz, Martínez-Alvarez, Soto-García, & Maestre-Valero, 2018). However, intensive agriculture is not only threatening the global water resources, but it is also influencing other parts of the ecosystems. Worldwide you can find a lot of signs and evidences that natural resources are declining or losing their quality. Soil nutrient depletion, erosion, desertification, loss of tropical forest and biodiversity are just a few of these visible signs (FAO, 2009).

A country that tries to preserve the quality of its resources and thus its agricultural land is the Kingdom of Norway (Snellingen Bye, Amund Aarstad, Ingun Løvberget, & Høie 2017). Despite the high yields in the field of fisheries and aquaculture, the agricultural sector is not very big in Norway. Because of the cold climate, thin soils, and mountainous terrain only 3,4% of the country is currently used for agricultural purposes (Statistics Norway, 2017). However, the demand for fresh vegetables is high while at the same time the Norwegian conventional farming methods are not capable of fulfilling this demand. This causes a big need for importing food products and leads to the fact that only 29,8% of the consumed vegetables and fruits are produced in Norway (OFG, 2017).

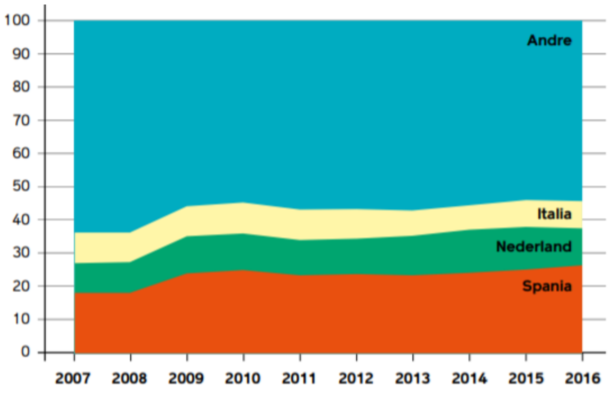

Figure 1: The strongest countries which import vegetables into Norway over the last 10 years. The strongest country, Spain, increased his percentage from 18,2% in 2007 to 26,7% in 2016 (OFG, 2017).

Of the 69,2% of the imported vegetables and fruits in 2016, 26,7% originates from Spain, 11,2% comes from the Netherlands and 8,2% from Italy as visualized in figure 1. The other countries have individual percentages under 5%. In the coming future, the percentages of imported fruits and vegetables are expected to increase even more (OFG, 2017). Most of the vegetables destined for northern countries like Norway, Sweden, UK, or Germany are produced in south-eastern Spain, where for instance Murcia is a big production location. In this region and throughout all Spain most of the vegetables are grown in open field circumstances and not in greenhouses thanks to the good weather conditions throughout the year (Martinez-Mate et al., 2018).

Considering the expected increase of the population in urban regions, the current dependence on import from other countries and the limited area of arable land in Norway, give motives for the rise of another farming method: urban farming. Urban farming is a way of growing, handling and distributing food in an urban area like villages, towns, or cities. Well known examples of urban farming sites are city gardens, like L*osæter in* Oslo, where citizens have small patches of ground that can be farmed collectively inside the city. Another example that is getting increased attention is vertical farming, where vegetables are grown indoors. Also, greenhouses are often considered as an urban farming method, but are because of the high real estate prices not yet often placed inside a city, but more at the edges of urban areas. Although these farming methods also work outside urban areas, their advantages are often bigger inside urban areas, mainly because of the shorter distance between producer and consumer(Nguyen Berg, 2018).

Greenhouses are buildings made of transparent material, like glass, in which plants are grown under controlled conditions. The main principle behind a greenhouse is to keep the incoming solar radiation inside. By reducing the amount of escaping radiation, the heat inside will be preserved. This principle with natural lighting in combination with semi-controlled circumstances, like humidity, additional CO_2, heat, provides a way of producing plants which are much better protected from external factors such as weather, predators and diseases while they also growing in an ideal microenvironment. Greenhouses can vary in size, from small houses to gigantic buildings, but offer a flexible way of growing vegetables all year round in most climate regions in an efficient way (Shamshiri et al., 2018).

Instead of growing food on a horizontal surface like in conventional farming or greenhouses, vertical farming uses - as the name indicates - vertically stacked layers to grow food. By growing plants in a vertical but not a horizontal way, the need for arable surfaces is drastically decreased. Most vertical farms are using Controlled Environment Agriculture (CEA) technologies, that controls all the different environmental factors like humidity, temperature, CO_2 and water. Vertical farms are best known for their use of artificial light, since they work unlike greenhouses independent from natural light. By controlling everything and working sealed off from the outside world, vertical farms are even more independent from the outside world than greenhouses (Association for Vertical Farming, 2017b).

Generally speaking, the international and main trend is to move towards more sustainable food production methods. The Addis Ababa Action Agenda, the Paris Agreement on climate change, the World Humanitarian Summit are just a few of the examples that implemented food security in their agenda (FAO, 2017). In 2015, the United Nations established goals to end poverty, protect the planet and ensure prosperity for everyone. These 17 sustainable development goals must be realised by 2030. 8 of these goals are represented in figure 2. Hereby, new farming methods, like vertical farming, can bring humanity towards a more sustainable and fairer world. It is obvious that indoor farming will contribute to eliminate hunger (SDG2). Especially, in a world where the climate change will increase extreme weather incidents and rising global temperatures, outdoor conventional agriculture will be more vulnerable and the need for greenhouses and vertical farming facilities will increase to safeguard food security and a stable supply of food, without interference of weather patterns. By providing fresh and pesticide-free food, agriculture can help establishing healthier eating habits (SDG3) and cope with

Figure 2: 8 Sustainable Development Goals from the United Nations that are relevant for agriculture (Nino, 2015).

malnutrition issues. Some modern vertical fam sites can help clean water and sanitation (SDG6) and are capable of cleaning municipal and industrial wastewater by using biofilters like mushrooms and plants. Affordable and clean energy (SDG7) plays also an important role since agriculture, in particular greenhouses and vertical farming, is very energy intensive. Solar power, mini wind turbines and anaerobic digesters are just a few examples of clean energy used to produce plants at vertical farming sites. Since cities are the biggest importers of food, but don't produce so much themselves sustainable cities and communities (SDG11) are an obvious goal to meet. By increasing the food supply from inside the city, urban farming methods, like vertical farming, can help cities to become more self-sufficient and lower their food miles. Climate action (SDG13) is also an urgent topic. Intense agriculture contributes in many ways to climate change. The use of fossil fuels for machineries, fertilizers production and greenhouse gas emissions are just a few examples. Life below water (SDG14) is also affected by the emissions of agricultural processes such as the use of pesticides and fertilizers. These chemicals can accumulate and cause eutrophication and interfere with the aquatic fauna and flora. Vertical farming can support achieving this goal since they use in general a closed circular system that does not contaminate water with any pesticides or fertilizers. Finally, there is the effect on life on land (SDG15), where many animal species and ecosystems are under pressure because of habitat loss through an increased need for arable land and the use of monoculture. By using the land surface more efficiently and promote more eco-friendly agriculture, e.g. agroforestry or vertical farming, it is possible to increase the biodiversity on this globe (De Mauro, 2017; Game & Primus, 2015; Nino, 2015).

When looking at these sustainable development goals it seems that conventional agriculture will not contribute to achieve these goals but rather increase the pressure on arable land and resource depletion. Thus, a shift is needed, which could possibly be initiated by the switch to urban farming technologies. Vertical farms can help to meet the United Nation sustainability goals and the increased food demand by supplying an additional food production method that is not sharing the same vulnerabilities and risks as conventional agriculture. However, the goal of vertical farming is not to fully replace conventional farming, but to be a complement to the conventional agriculture methods, particularly in urban areas. If implemented in a right way, vertical farming can help human society move towards a fairer and more sustainable world (De Mauro, 2017). Vertical farming is increasing in popularity, but when looked at the vertical farming market in Norway, the potential is not yet realised. When focusing on the Norwegian retail market, there is a market value of 1700 Million NOK for vegetables that are suitable for going in vertical farming sites. Today 50% of this particular market is supplied by imported food to Norway (BySpire, 2017). One of the main processes in the vertical farming technology is the hydroponic system which also can be found in the conventional greenhouse farming. Hydroponics is a method of growing plants without soil using nutrient solutions in water only the routes are exposed to the nutrient solution (Association for Vertical Farming, 2017a). One of the vertical farming sites in Norway is BySpire. BySpire is founded in 2016 and by now the biggest vertical farming site in Norway with a yearly maximum production of 50000 plants.

Based on this background, this bachelor thesis will investigate the challenges and future aspects of the food production and food security of Norway. Three different ways of exploiting resources for the food production need to be analysed, since the Norwegian fruit and vegetable market is supplied by the import of food, greenhouses as well as vertical farms. It is therefore necessary to evaluate the environmental impact of the three food production methods and the resources they use.

Life cycle assessment (LCA) is a method for evaluating environmental impact of a single product or a whole process throughout its complete life cycle or lifespan, which is also known as a ‘cradle to grave’ analysis. In this thesis the ´cradle to gate` approach including the transportation from the lettuce growing facility to the city centre of Oslo is used. This will include the nursery phase, cultivation phase, diesel mix at refinery phase, electricity grid mix phase, natural gas mix phase, the irrigation phase and the transportation phase.

For each phase, the thesis will look at its environmental impact on the categories climate change, fresh and marine eutrophication, particulate matter formation, terrestrial acidification and water depletion. The main goal is to make an honest, objective comparison between the three selected food production methods and to analyse the environmental impact of three different production cycles on the selected impact categories. A sub goal of the thesis is gaining insight in the sustainability of the vertical farm, BySpire. The aim is hereby to with find the phases with the highest impact on the environment and to find most effective improvements regarding the future development of the site.

Thus, the research questions of this study are:

- What are the environmental impacts of locally cultivated vegetables by vertical farms and greenhouses in Norway, and the imported vegetables and how well do these food production methods preform when compared to each other?
- Which phases of the vertical farming production have the highest impact on the environment and which phases have the biggest improvement potentials?

2 Methodology

2.1 Research methodology

The research questions of this study are the following “What are the environmental impacts of locally cultivated vegetables by vertical farms and greenhouses in Norway, and of the imported vegetables and how well do these food production methods perform when compared to each other?” and “Which phases of the vertical farming production have the highest impact on the environment and which phases have the biggest improvement potentials?”.

To answer these questions first a literature study was conducted. Based on this, the focus was laid on the lettuce production. Lettuce is a vegetable that can be produced and supplied with all three food production methods for the Norwegian food market and for which enough data of the whole lettuce production cycle are available. Different information sources were used to generate a database containing all inflows and outflows of the whole lettuce production line, data about the means of transportation and about the transportation distance of all three food production methods. The information from the vertical farming site (BySpire) was gathered from personal contact with the employees of the farm and their available databases regarding the used systems, methodologies and materials.

For the greenhouse site, different greenhouses in the Oslo area were contacted. There are lots of greenhouses in the Oslo area (ISHS, 2018), but unfortunately none of these greenhouses were willing to participate in the study. The greenhouse, Hanasand Gård, on the other hand, was willing to share their methods and data. In this study, the goal is to compare food production methods in the area of the city of Oslo. Hanasand Gård is located near Stavanger, however similar working methods, systems and data can be expected for Hanasand Gård and other greenhouses and since the climate is more or less the same most of the year, the environmental impact can also be expected to be very similar. Data was gathered through mail and telephone.

For the import, data from literature on lettuce production in Southern Spain and Italy was used. Further, data about the food transportation between the Mediterranean regions and Norway was collected. For this purpose, Intertermo AS, a logistic company coordinating the food transport between Spain and Norway, was contacted.

After the data inventory and the construction of the data base was made for all three food production methods, corresponding process plans were designed in the LCA software, GaBi Education. GaBi software is a modelling program for life-cycle assessments produced by the German company “thinkstep AG”. The background processes for the modelling used by the GaBi software are in accordance with the databases of SETAC Global Guidance Principles for Life Cycle Assessment (UNEP SETAC, 2011).

During the design of the LCA, all production steps were identified and created into production phases, the available data were then linked to these different phases and six impact categories were selected. Finally, the environmental impact of the nursery phase, cultivation phase, diesel mix at refinery phase, electricity grid mix phase, natural gas mix phase, the irrigation phase and the transportation phase were analysed in relation to the following categories: climate change, fresh and marine eutrophication, particulate matter formation, terrestrial acidification and water depletion. These categories are commonly used in most previous LCA studies conducted on food products (Roy et al., 2009).

The LCA was conducted according to the ISO standard ISO 14040-14044. The focus of the LCA was on the energy and water consumption since it was impossible to conduct a whole cradle to grave assessment due to the lack of necessary data and the time frame of this thesis.

2.2 Selected food production methods

Three different food production methods were selected for this research:

- a vertical farming facility in Oslo named BySpire (figure 3)
- a greenhouse in Rennesøy named Hanasand Gård (figure 4), but assumed to be located around Oslo
- the import of lettuce from the Mediterranean area (figure 5)

Norwegian conventional farming methods such as open field agriculture were excluded from this study since the lettuce production from these methods is negligible

Figure 3: Location of BySpire (vertical farm site) in Oslo

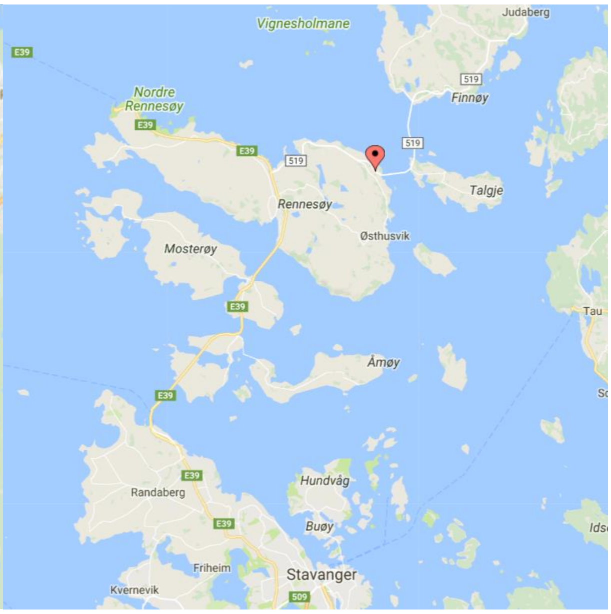

Figure 4: Original location of Hanasand Gård (greenhouse site) in Rennesøy, near Stavanger.

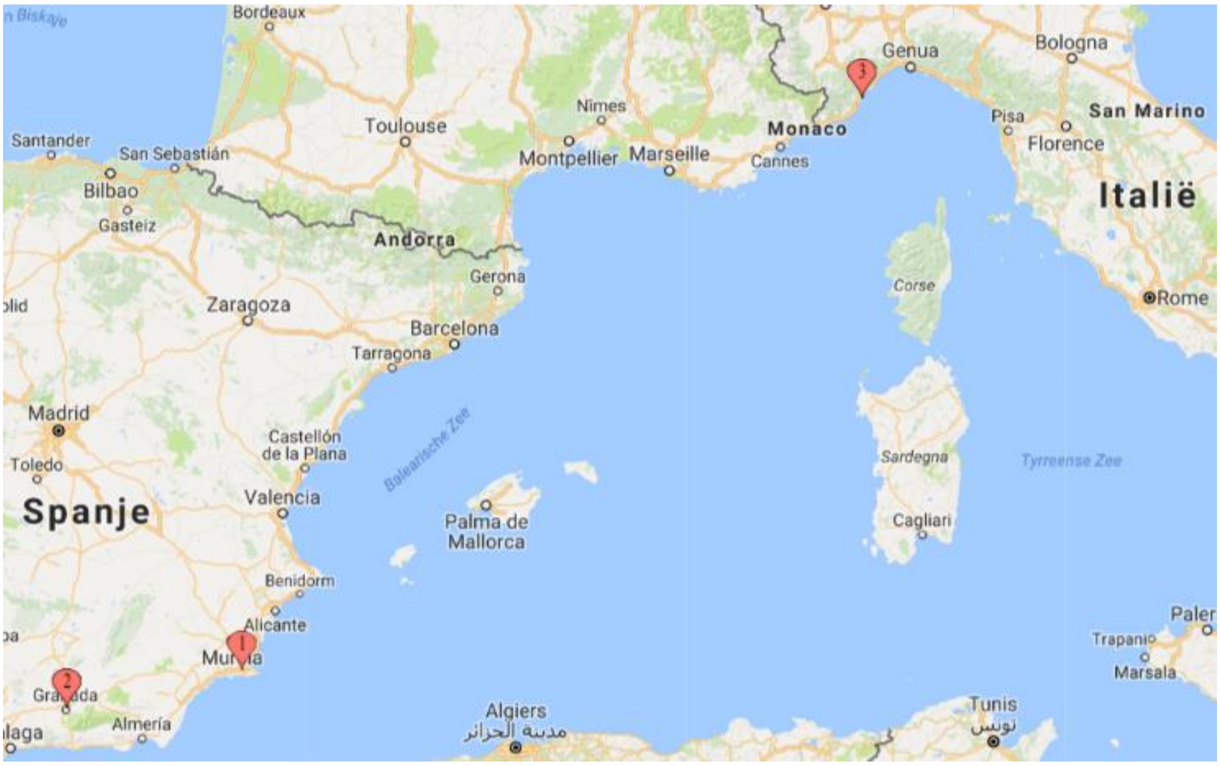

Figure 5: Location of the three open field sites in the Mediterranean area: Cartagena site (1) and Granada site (2) in Spain, and Albenga site (3) in Italy.

2.2.1 Vertical farming

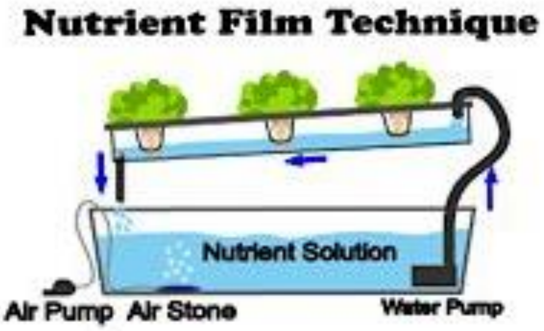

Figure 6: Simplified representation of hydroponics technology in the BySpire facility, the Nutrient Film Technique: at the top a plant production system with irrigation pipes is shown, the drained water is collected in the bottom reservoir, and is recirculated to the plant production system which the necessary nutrients and oxygen (NoSoilSolutions, 2018).

BySpire is a vertical farming facility located in an office building in Oslo as shown in figure 7, which produces mug parsley, coriander, basil, mint and lettuce. The whole production, from the germination to the harvest, takes place in a closed environmental agriculture (CEA) system. CEA is an umbrella term applied for a wide range of indoor plant production system. Generally speaking, CEA can be defined as a system of growing plants in an enclosed environment, using tools and technology to guarantee optimised growing conditions and to prevent emissions to enter the outside atmosphere (Fogg, Rauhala, Satterfield, & Scott, 1979). Hereby, parameters like temperature, CO_2 content, light intensity or humidity can be controlled. Within the CEA, BySpire is using a hydroponic system in combination with LED lights. The hydroponic type used is the nutrient film technique (NFT) as displayed in figure 6. This means that the plants are constantly in direct contact with circulating water, oxygen and nutrition. BySpire is adding nitrogen (N), phosphorus (P) and potassium (K) fertilizers to the circulating water. In this set-up there is no need for soil and the nutrients are directly available for the plants. The LED-lights are optimised for plant growth and consume very little energy compared to traditional growth lights (Lin et al., 2013). The lights only emit the needed wavelengths, while emitting heat at the same time (Ahn, Jang, Leigh, Yoo, & Jeong,

Figure 7: BySpire site with stacked layers.

2014). This heat is not considered to be wasted energy, since this is increasing the temperature in the facility without the need for extra heating systems. Moreover, because most energy in Norway comes from hydropower, which is a clean energy source, the usage of electricity for the lights and heat, is a good choice (IEA, 2017). By cooling the room with air-conditioning and ventilators, the temperature is kept under control. Next to these technics, BySpire is also experimenting with fogponics, where water and nutrients are transformed into a very fine fog using ultrasound. This mist will be circulated passed the roots and consists of small particles of nutrients attached to water molecules that then are absorbed by the pores of the roots. The latter is not yet included in the further LCA analysis.

2.2.2 Greenhouse

Figure 9: Greenhouse facility of Hanasand Gard. This is a large scale hydroponic site.

Hanasand Gård in Rennesøy, near Stavanger is a farm with a greenhouse facility (see figure 8). The greenhouse is their main activity and they grow 18 different varieties of tomatoes, in addition to chili, peppers, lettuce, cucumbers, raspberries and strawberries. Besides this, sheep are kept in the fields around the greenhouse. The production takes place in two different rooms: One for the germination of the seeds (nursery phase), and the other one for the actual cultivation of the vegetables (cultivation phase). The greenhouse site uses a different hydroponics system than the vertical farming facility. The greenhouse uses a Drip system as shown in Figure 8., which is one of the irrigation technologies recommended for greenhouses by multiple organizations (National Institute for Food and Agriculture, 2018). The nutrient solution runs through individual tubes to each vegetable, dripping over the roots and circulates back into a reservoir. The vegetables are placed in an absorbent grow medium because the solution drips slowly. Like the vertical farming site, the greenhouse is using N, P and K fertilizers. For the cultivation of these vegetables different factors like heat, humidity, water, etc. are regulated in a semi-closed environment. Water is circulating through the irrigation system and is recollected. However, through the evaporation of plants and open windows that are used to cool the greenhouse site, emissions can enter the environment. For heating purposes, the greenhouse is using natural gas. In Norway, the government recommends for greenhouses to burn fossil fuels like natural gas or propane for heating and CO_2 enrichment purposes (Norsk Gartnerforbunds, 2014).

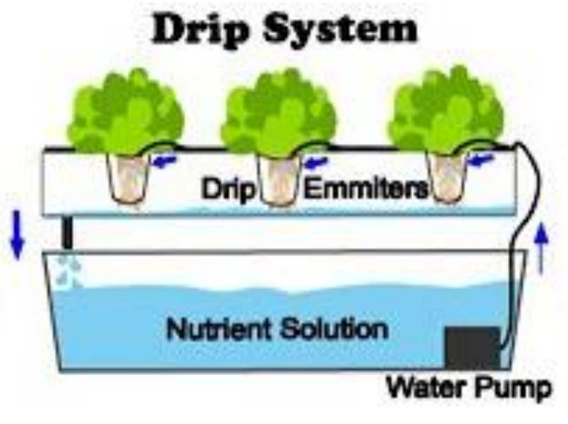

Figure 8: Simplified representation of hydroponics technology in the Greenhouse facility, the Drip System: The nutrient solution runs through individual tubes to each vegetable, dripping over the roots and circulates back into the reservoir. The vegetables are placed in an absorbent grow medium because the solution drips slowly (NoSoilSolutions, 2018).

To transport their food products to the customer, the vegetables are divided over truck (50%) and train (50%) (Hanasand Gård og Gartneri, 2017). Since the greenhouse location can be find at the west coast of Norway, a new ‘fictive’ location for Hanasand Gård is determined based on the averaged distance, see table 1, between the different greenhouses in the Oslo area and the city centre for the LCA-analysis. Because no data are available on how the greenhouses around Oslo are transporting their goods to the customers in Oslo, the assumption was made that a fictive greenhouse in the Oslo area operating the same way than Hanasand Gård is also dividing their vegetables over truck and train.

Table 1: Different greenhouse facilities in the Oslo area, with their addresses and the distance by road (for trucks) and by rail (for train) for that greenhouse. The distance by train is in some cases longer than by truck because of the lack of direct train connection to Oslo.

Name	Location	Km to Oslo centre	
		Truck	Train
Bjørkely Gartneri ENK	Myragutua, 2022 Gjerdrum	32,5	29,1
Elvenhøy Gartneri AS	Baneveien 34, 3400 Lier	38,7	48,0
Frantz Hegg Gartneri AS	Heggalleen 12, 3400 Lier	41,2	48,6
Hesleberg Gartneri ANS	Heslebergveien 16, 1390 Vollen	27,6	26,4
Sjøstrand Gartneri ENK	Sjøstrandveien 23, 1391 Vollen	28,9	30,2
Snarum Gartneri AS	Vestsideveien 88, 3400 Lier	38,1	46,1
Søren Helmen Haskoll Gartneri DA	Ringeriksveien 165, 3403 Lier	37,5	43,9
Sørum Brødrene Gartneri DA	Vikerveien 8, 3425 Reistad	36,8	42,2
Average distances:		**35,16**	**39,31**

2.2.3 Food import from Spain

The data from the lettuce import are collected from previous LCA studies conducted in Spain and Italy, the main import countries for vegetables in Norway. They represent 34,9% of the imports in Norway. Data from the Albenga site (Bartzas, Zaharaki, & Komnitsas, 2015) in Italy, and the Granada site (Romero-Gámez, Audsley, & Suárez-Rey, 2014) and Cartagena site (Martinez-Mate et al., 2018) in south east Spain are used. All three sites in these studies are open field agriculture systems, controlled by agricultural research facilities and are being extensively monitored. Due to the similar key growing conditions at these locations, see appendix 10.1, the data is combined and averaged. Big parts of the sites (up to 50%) are also used for the cultivation of other vegetables and fruits, like fruit orchards, olive groves, horticultural crops, vineyards, maize and wheat fields, but the LCA studies selected for this thesis from literature focused on the production of lettuces. Moreover, the selected locations have climate characteristics in common. In the past there was more water in the area available, but due to increased human activity, e.g. urbanization, infrastructure and intensive agriculture, the level of the groundwater dropped, and water scarcity increased. Next to this, the use of fertilizers has affected the groundwater quality. Thus, the water needs to be pumped up, filtered to prevent contamination and desalination or deionizing processes are often needed. With 89%, reverse osmosis is the main method to produce desalinated water in Spain. Reverse osmosis is a process where water flows across a semipermeable membrane that blocks saline ions to bypass. The external pressure applied on the brackish water to push the water through the membrane is hereby very energy costly. The desalinated water needs then to be transported to the agricultural sites (Bartzas et al., 2015; Cuenca, 2012; Martinez-Mate et al., 2018). All the sites are using N, P and K fertilizers as well as chemical pesticides to protect the lettuce plants from pests.

After the harvest, the vegetables are transported from Murcia with Diesel Euro 6 trucks with a maximum load of 22,000 kg to Lierskogen (Gjellebekkstubben 9, 3420 Lierskogen) in Norway after which a smaller truck transports the vegetables to Oslo (Risø, 2018).

2.3 Life cycle assessment

Life cycle assessment (LCA) or life-cycle analysis is a way of determining the potential environmental impacts of all the stages of a product´s life or process. A complete LCA starts at the raw material extraction and goes all the way to the disposal of the final product. Designers, managers and companies can use this methodology to have a critical look at the total impact of their product. Like this, an LCA can bring new and broad views upon the environmental impacts of a product (GDRC, 2018). This study will determine the impacts caused by the consumption of raw materials (use of pesticides, fertilizers, and water) and consumed energy of the three different food production methods.

This thesis and the research was conducted according the guidelines and framework of the ISO 14040-14044 series of the International Organization for Standardization (ISO) (ISO, 2006).

According to the ISO-standard, there are four phases to an LCA as shown in figure 10:

- Goal definition and scoping (mentioned in 2.3.1): identifying the LCA's purpose and the expected products of the study, and determining the boundaries (what is and is not included in the study) and assumptions based upon the goal definition;
- Life-cycle inventory (mentioned in 2.3.2): quantifying the energy and raw material inputs and environmental releases associated with each stage of production;
- Life-cycle Impact assessment (mentioned in 3): assessing the impacts on human health and the environment associated with energy and raw material inputs and environmental releases quantified by the inventory;
- Life-cycle interpretation (mentioned in part 3): evaluating opportunities to reduce energy, material inputs, or environmental impacts at each stage of the product life-cycle.

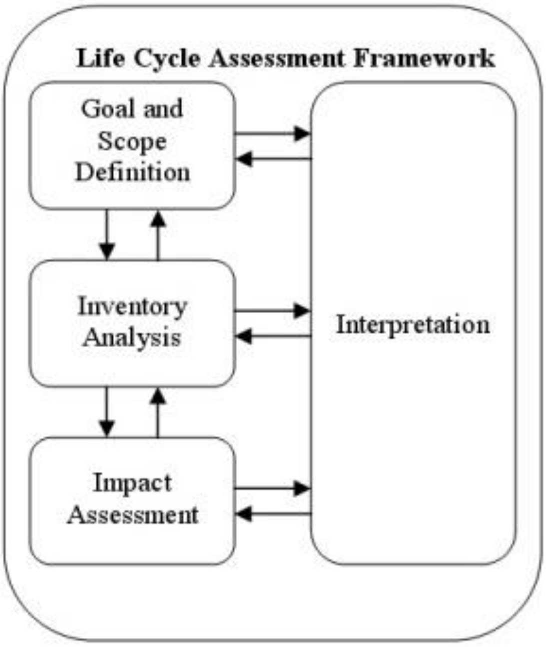

Figure 10: The four phases of an LCA according to the ISO 14040-2006 Life cycle assessment framework (ISO, 2006).

2.3.1 Goal and scope definition

The main **goal** of this research is to make an honest comparison of the environmental impact of locally cultivated vegetables (lettuce) by vertical farms and greenhouses in Norway on the one hand and imported vegetables on the other hand. The vegetable lettuce was selected since there is a large amount of data for this crop available in the literature. Besides the large amount of data available, characteristics of lettuce plants simplify the process of making accurate predictions of yields, operating costs, inputs, and outputs which is useful and needed for an LCA study (Graff, 2011).

Moreover, a sub goal is defined: for BySpire, the vertical farming site it is very important to gain an insight in the sustainability of the processes of the whole production cycle. The aim is to find the phases with the highest impact on the environment and to find the most effective improvements regarding the future development of the site. The main target audience of this study is the management team of the vertical farm. They want to get an overview on how sustainable their production is at the current stage of the company´s existence. It should become obvious how they perform compared to their competitors regarding the environmental impact of their product and which phases in their production line have the biggest environmental impact. This information will be used to improve the system and also - in case the research establishes this - to show their clients and investors that BySpire has a sustainable way of farming. Next to BySpire, the larger audience group for this study consists of policymakers, like the Norwegian department of agriculture, and interested citizens.

The three case studies, described in 2.2, involved in this study are:

- Case 1: Cultivation of lettuce in vertical farming facility of BySpire in Oslo, Norway (VF).
- Case 2: Cultivation of lettuce in greenhouse in Rennesøy, Norway, but assumed to be located around Oslo (GH).
- Case 3: Cultivation of lettuce in open field coming from the import sites in the Mediterranean area (IM).

Since it is important for this study to take transport to Oslo into consideration too, the selected functional unit is one head of fresh lettuce (0,250 kg) transported to Oslo. This means that only a produced product that is being transported to the customers in Oslo, will be considered and that the reference flow is defined as one head of cultivated lettuce. This functional unit will be used throughout all the production systems and case studies and will hereby normalise the flows in between the production processes.

2.3.1.1 System boundaries.

In this study, the ‘‘cradle-to-gate” approach was used and extended, considering all the production processes involved from raw materials extraction (i.e. the cradle) to the point where the final product (lettuce) is ready to leave the farming facilities (i.e. the gate). The gate is here extended to the centre of Oslo since transport is included in the definition of the functional unit.

When looking at the system boundaries, different main phases are taken into account: nursery, cultivation and transport to Oslo. Figure 11 shows the different phases, the processes and the inputs and outputs of a system for all the three food production methods. If a method doesn’t need certain processes, inputs or outputs, they are considered to be zero. For example, only the vertical farming site and the greenhouse site will use artificial lighting and cooling thus the energy consumed due to artificial lightening is zero for the greenhouse and import sites. Screenshots of the specific process structure of the three food production methods in the LCA software can be found in appendix 0.

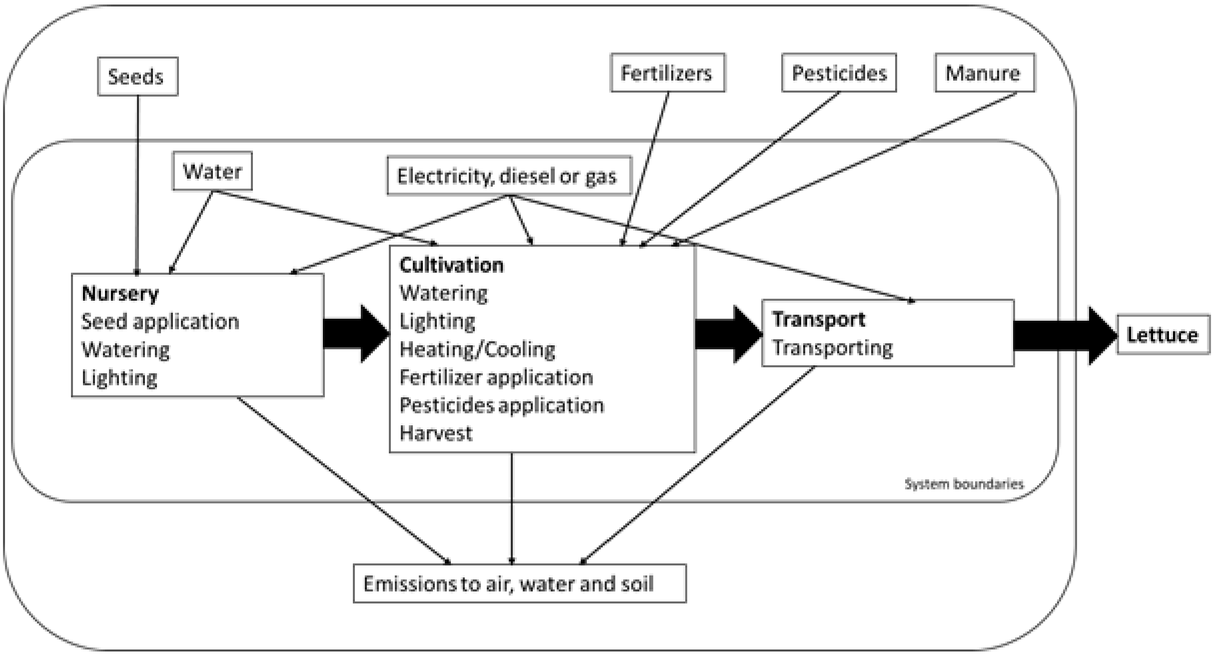

Figure 11: Generic scheme of the system boundaries, production phases, inputs and outputs of the three cases. If a case doesn't need certain processes, inputs or outputs, they are considered to be zero.

2.3.1.2 Impact categories.

During the design of the LCA, all production steps were identified and created into production phases, the available data were then linked to these different phases and six impact categories were selected. The impact categories were selected according to their relevance for the agricultural sector and based on previous LCA studies. Thus, this study will focus on following impact categories: climate chance without biogenic carbon, eutrophication (marine and fresh water), terrestrial acidification, particle matter, and water depletion. In appendix 10.3, these categories are briefly explained. The methods that are used are recommended by the European Commission (European Commission, 2012) and represented in table 2.

Table 2: Recommended Life Cycle Impact analysis methods by the European commission in the ILCD2001 with their corresponding flow properties.

Impact	Recommended LCIA method according to ILCD2011	Flow property
Climate change (GWP100)	IPPC2007	Mass CO_2 -equivalents
Freshwater eutrophication	ReCiPe2008	Mass P-equivalents
Marine eutrophication	ReCiPe2008	Mass N-equivalents
Particulate matters/Respiratory inorganics	RiskPoll model	Mass PM2.5-equivalents
Terrestrial acidification	(Posch et al., 2008; Seppälä, Posch, Johansson, & Hettelingh, 2006)	Mole H+ -equivalents
Resource depletion - water	Swiss Ecoscarcity2006	Water consumption m3 equivalent

To reduce the complexity of this study, to stay in the scope of this thesis and to only focus on the most relevant impacts caused by agricultural processes (defined in accordance with a Belgian expert on LCA studies), the following impact categories were excluded: ozone depletion potential, photochemical ozone creation potential, terrestrial eutrophication and cumulative energy demand. Even though they are excluded for this present study, they might be relevant for a future, more complex LCA analysis.

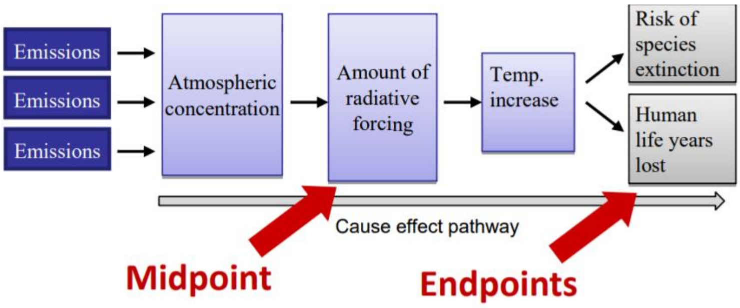

Figure 12: Example of the midpoint and endpoint determination for the climate change impact cathegory (Huijbregts et al., 2016).

After defining the impact categories that will be included in this study, it was important to decide until which point in the cause effect pathway the impact will be followed. As displayed in Figure 12, there are two ways of looking at these impact categories, either focused on the midpoint or the endpoint of the cause effect pathway. By using characterization factors, it is possible to determine the level of impact on the environment is caused by a certain emission or resource depletion and how high it is. Characterization factors are quantitative representations of the importance of a specific pollutant measured in a unit or emission. For instance, the characterization factor of the climate change impact category (or global warming potential (GWP)) is measured in Mass CO_2-equivalents. Characterization factors at the midpoint level are situated along the impact pathway, preferably right after the point where the environmental mechanism is the same for all the different environmental flows connected to a specific impact category. The second approach is to look at the characterization factors at the endpoint level. This level is linked to three areas of protection: human health, ecosystem quality and resource scarcity. Since the endpoint level approach builds usually on many necessary assumptions and is therefore a very complex simulation, looking at the end point is more uncertain than the midpoint characterization. At the same time, the midpoint characterization has a stronger correlation to the environmental flows and impacts, which makes that all the impact categories will be followed until the midpoint of the cause effect pathway (Huijbregts et al., 2016).

2.3.2 Life cycle inventory

The main LCA processes of all agricultural cultivation practices are described in detail in this part. They are also generally visualized in Figure 11. Since the production line of lettuce is very complex and consists of several phases, it is necessary to clarify which phases are included and which ones are left out from this LCA-study and the reasoning behind this decision. This is addressed in Table 3. Some phases, like packaging, waste water management and pesticide production, are not included into the current LCA, but do still provide with some data to be addressed and discussed separately in this study.

Table 3: Included and excluded phases in the LCA with the corresponding reason. If there is a "X" in the last column, the phase is not integrated in the LCA, but is addressed separately.

Included	Cultivation phase	This is the main process in an agricultural industry and has enough validated input data available from the three assessed food production methods.	

	Diesel production (Diesel mix at refinery) phase	The fuel needed for the transportation is part of the impact of the transport and should not be left out. The output diesel impacts its supply chain which consists of well drilling, crude oil production and processing, but also the transportation of crude oil via pipelines, vessels and trucks to the refinery.	
	Electricity grid mix phase	Energy needed for lights, cooling, heating, and other production conditions is generated in different ways in Spain than in Norway. See Table 17. This needs to be taken into account. This phase also assesses the impact of the grid itself.	
	Irrigation system phase	There is sufficient data regarding the water amount and electricity used is available for the three methods. Water used for this system is divided in tap water (vertical farming facility), rain water (greenhouse) and Deionised water (Import)	
	Natural gas production (natural gas mix) phase	Natural gas is used for heating purposes, but the production is different in Spain and Norway. Norway has big supplies of its own and they will need to travel less distance to the end of the supply chain than this is the case for Spain. The supply chain consists of exploration, production, processing (e.g. desulphurisation), liquification and regasification (for transport purposes, the long-distance transport.	
	Nursery phase	Included since this is the cradle of the growing process. The greenhouse and vertical farming sites are first letting the plants grow in a separate place before transporting them to the actual cultivation facility. The nursery phase of the vegetables in Spain is at the same location as the cultivation phase.	
	Transportation phase	There is sufficient validated data for the transport (trucks and train) to Oslo from the different cultivation sites. For the greenhouse, the transport is considered as if the greenhouse was located in the Oslo area, in other words the average distances for truck and train to the Oslo centre.	
Excluded	Packaging phase	There is not enough data available about the import from Spain and the packaging from the vertical farm is not included in the GaBi database. Since the packaging boxes from BySpire are also reused, the outflow would remain under 1% of the impact. According to the guidelines, this means that the impact is small enough to leave it out of the LCA.	X
	Waste management phase	The greenhouse as well as BySpire are treating their waste as if this would be household waste. By doing so there is no validated data available about the quantity and kind of waste that leaves the facilities.	
	Waste water management phase	There is not enough data available to be included in the LCA study. The greenhouse and BySpire are both not measuring the output water (for cleaning purposes), the runoff in Spain is also not measured and thus unknown.	X
	Fertilizer production and	The production of fertilizers cannot be included since the procedures related to that are kept secret for products (patented) the greenhouse	

	transportation phase	and the vertical farm are using. Not enough data about the transport of the fertilizers is available and since these are products that are imported for the greenhouse and the vertical farm, it can’t be used.	
	Pesticide production and transportation phase	Not enough validated data available for the sites in the Mediterranean area. The production processes are unknown (patented) and the transportation is also not registered. So, this phase is left out, out of the LCA.	X
	Buildings and installations phase	A very important phase, since it describes the impact of the manufacturing of equipment and installation, or the construction of buildings for the different methods. But due to time related issues and since the data from the Mediterranean region is inaccurate and the vertical farming and greenhouse sites are not open about their constructions, this could not be included in the LCA.	

The included phases are described in detail in the following part.

The first phase is the **Nursery** phase where the planting and germination of the seeds takes place. This phase needs the following inputs: water, energy and seeds, and has the seedlings as output.

The second phase is the **Cultivation** phase. The main inputs of the cultivation process are fertilizers, pesticides, water, lighting, heating, cooling and ventilation. The output is cultivated lettuce and emissions to air, water and soil. Pre-farm cultivation is not included. At the same time, only on-site cultivation is included in the analysis. The cultivation phase is different for the three different food production methods.

BySpire operates indoors with hydroponics, this way the facility does not need soil or pesticides. The closed environmental agriculture system prevents contamination by unwanted substances from the outside and emissions to leave the system to the atmosphere. This is including emissions from fertilizers to the air and water to the outside world. No pesticides are necessary in a closed facility. In order to prevent fungi and other infections, the systems are cleaned by hand with cleaning alcohol when the water is not flowing at a certain level in the facility. At the vertical farming site, artificial lighting (LED) is used to provide the plants with extra light and heat so they can grow all year long under optimal conditions. Increased temperature in the summer is regulated by using cooling technology like air-conditioning and ventilators. The greenhouse is a semi-closed system and has only emissions to the air. They don’t use chemical pesticides, only natural pesticides, like ladybugs. The greenhouse site also uses artificial lights, so the plants are provided with extra light to grow also in the dark winter months under optimal conditions. The cooling and heating are also regulated at this site. For the cultivation of the import, the same circumstances and assumptions as for the study of Martinez-Mate were selected. Thus, cultivation procedures of an open field agriculture were chosen. The weather conditions are in Mediterranean regions throughout the year good enough for open field agriculture, so greenhouse structures are often not considered for a large-scale production of crops (Martinez-Mate et al., 2018). Consequently, the cultivation phase of open field agriculture does not require extra lighting, heating, cooling and ventilation.

Cultivation operations are part of the cultivation phase. They include fertilizer use, pesticide use and harvesting. These processes generate emissions from fuel consumption, electricity consumption and machinery operation. Pest management in the Mediterranean region is accomplished through a combination of treatment strategies such as crop rotation, interplanting and field spraying of pesticides. In the previous studies they assumed the use of small diesel-powered tractors for the application of compost, pesticides and fertilizers.

The **Irrigation system** has also a significant impact since this is consuming a large amount of water and energy. The three different food production methods are using three different sources of water for irrigating their lettuce. The open agriculture sites have water supply coming from groundwater from nearby wells for drip and overhead irrigation systems. The greenhouse uses rainwater collected in rainwater collector. The vertical faming site pumps tap water in a loop through the hydroponic system. Both greenhouse and vertical farming sites will, in case of pollution or contamination, clean their systems by hand and refill with new water.

The last phase of the process is the **Transport** to Oslo. The vertical farming site uses a small truck powered by fossil fuels to deliver all their vegetables to their clients in Oslo centre, while the greenhouse site uses a small truck powered by fossil fuels for 50% of their vegetables. The other 50% is transported by train. The trainlines around Oslo are electrified, which means it is not powered by fossil fuels (Cargonet AS, 2016). The logistics behind the transportation of food items from the Mediterranean regions to Oslo is undertaken by Intertermo AS, a Norwegian transport firm. They transport broccoli, lettuce, cauliflower and celery from the Murcia region in Spain to Lierskogen in Norway. In total, the transport of lettuce from Spain to Oslo is split up in two parts. First, the lettuce is transported directly from Murcia to Lierskogen which adds up to 3427 km. The trucks have a maximum load of 22000 kg and are running on diesel with a Euro 6 engine. The second part is from Lierskogen to Oslo, to the end consumer which is a trip of 34,4 km. (Risø, 2018).

Throughout all the phases, the used energy is coming from different sources and has different applications. Therefore, the **production of diesel**, the **production of energy**, and the **production of natural gas** are taken into account. Diesel is used as fuel for the transportation phase, but also for the application of fertilizers and pesticides in the Mediterranean. Electricity has different sources in Norway than in Spain as seen in Table 17 in appendix 10.8 and this is also how the they are implemented in this LCA study. Natural gas is used to heat the greenhouse facility.

Since the sub goal was to find the phases with the largest contribution and in order to make the analysis less complex for the target audience, the management team of BySpire, the decision was made to only analyse phases that have a contribution over 5% on the impact categories.

2.3.2.1 Data collection and data quality.

In this study, all the useful inputs and outputs related to cultivation of lettuce in the different cases are identified and measured when possible and can be found in appendices 10.5 and 10.6. To complete the life cycle inventory for these cases, a combination of first hand data from the sites, previous literary studies and the available databases on the GaBi software were used. The data sources concerning the processes from the life cycle inventory, mentioned in title 2.3.23.2, are listed in appendix 0.

2.3.3 Uncertainty analysis

Within this life cycle inventory, the inputs and yields of the three different food production methods are described with absolute values, which are displayed in appendix 10.5. The input data from the Mediterranean food method are mean values and are based on the data in appendix 10.6. According to Frischknecht´s report on methodology in LCA, this kind of measurable description brings along some uncertainty that can be caused by the following reasons:

- Variability and stochastic error due to measurement uncertainties, process-specific variations, temporal variations, etc.
- Appropriateness of the data: For instance, using the European diesel mix at the refinery to approximate the Norwegian and Spanish refineries.
- Neglecting flows: Not all relevant information is available in the available databank, to properly describe a full process (Frischknecht et al., 2004).

In this study:

- Variability and stochastic errors have been considered by changing the measurements values to high and low values in the LCA and predicting the effect in the LCA results.
- The uncertainty due to the appropriateness of the data has not been included, since the available GaBi databases are not always providing more specific data. By using the most accurate data this uncertainty was minimalized but did not give a specific outcome on how uncertain the result could be.
- Uncertainty due to neglecting flows is not been included since the available GaBi databases here also are coming short in providing enough information. By excluding certain flows, it is uncertain to know what their impact would be, but the uncertainty is minimized by consulting LCA-experts. Some of these flows are separately described in part 4

Finally, the results of the study were, as recommended in the ISO 14040-44 norm, reviewed by an expert in this research field. Veerle Van Linden, an LCA-expert of the Institute for Agricultural and Fisheries Research in Belgium, analysed the set-up of the study and the general results and they were considered to be a valid outcome for this study.

3 LCA results and discussion

3.1 General impacts of the three food production methods

3.1.1 Results of the Life Cycle Impact Assessment

By implementing the input data from appendix 10.5, in the process models from appendices 10.2.1 to 10.2.3, and using the recommended LCIA methods in the GaBi software, the following general results were generated.

Table 4: Impact category in absolute values of the three food production methods.

Impact category	BySpire	Greenhouse	Import
Climate change excl. biogenic carbon (kg CO_2-Equiv.)	7,78E-01	1,59E+00	2,23E+00
Eutrophication freshwater (kg P-Equiv.)	5,30E-06	8,14E-07	7,38E-05
Eutrophication marine (kg N-Equiv.)	1,07E-03	1,64E-03	3,86E-03
Particulate matter/Respiratory inorganics (kg PM2.5-Equiv.)	6,31E-05	1,99E-04	2,81E-04
Terrestrial acidification (Mole of H+ Equiv.)	2,39E-03	6,01E-03	8,49E-03
Resource depletion: water (m^3 Equiv.)	1,33E-02	5,85E-04	1,08E-01

The impact categories in absolute values of the import case study are the highest of the three compared food production methods, while the vertical farm almost always has the lowest impact. The exception for this it the impact category “Water depletion” and “Freshwater eutrophication”, were the greenhouse has the lowest impact followed by the vertical farming site and the import case. Moreover, it is worth noting that BySpire has 88% less impact on the water depletion than the import case, while the greenhouse site has even an 99% lower impact than the import case (see figure 18).

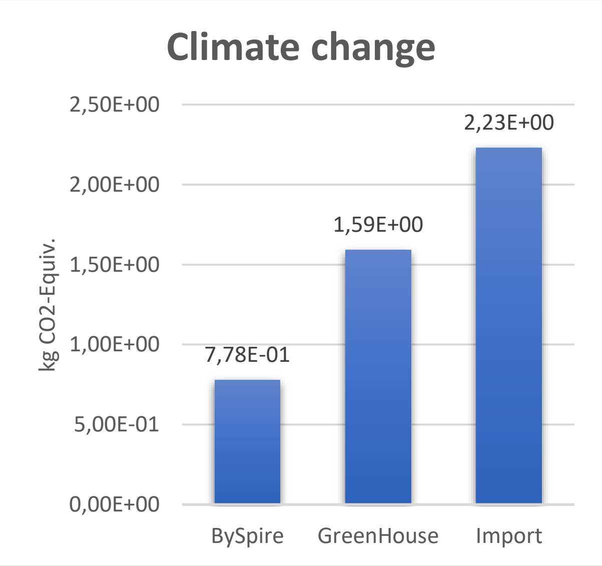

Figure 13: Climate change, exclusive the biogenic carbon, in kg CO_2-equivalents for the three food production methods.

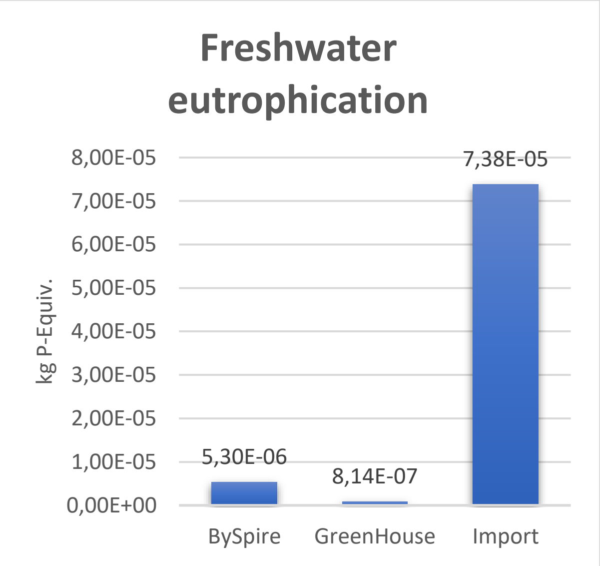

Figure 14: Freshwater eutrophication in kg P-equivalents for the three food production methods.

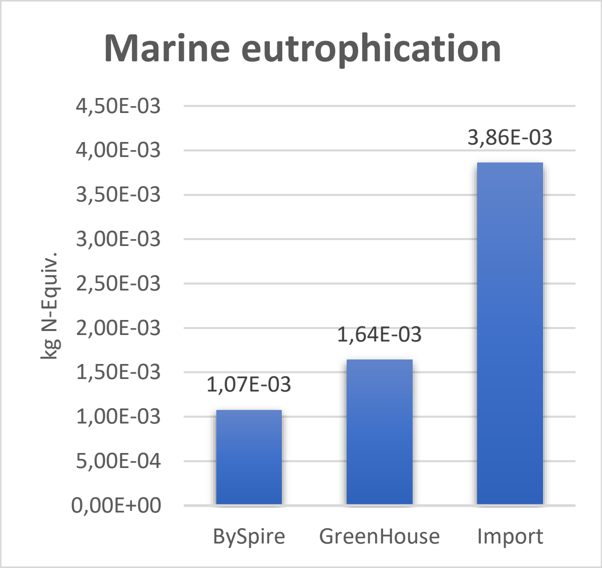

Figure 15: Marine eutrophication in kg N-equivalents for the three production methods

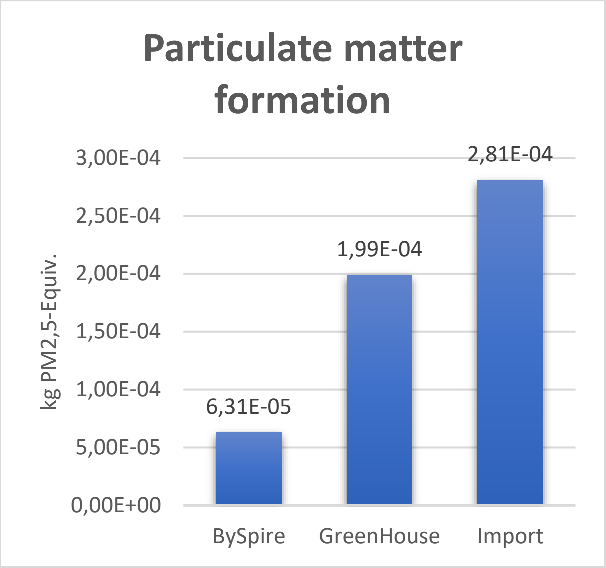

Figure 16: Particulate matter formation in kg PM2.5-equivalents for the three production methods

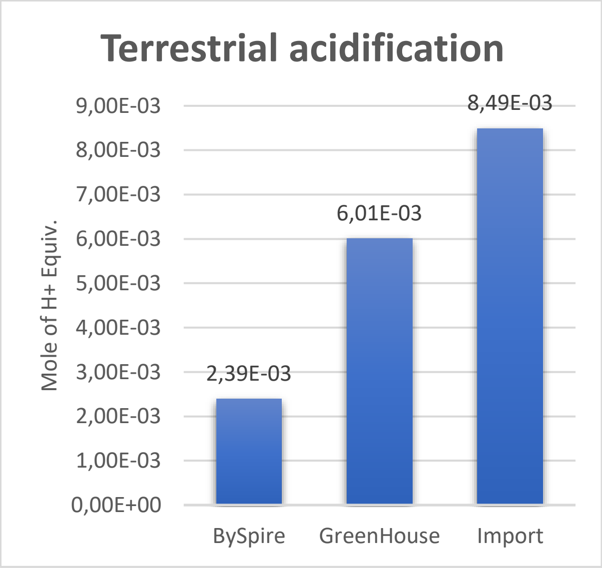

Figure 17: Terrestrial acidification in mole of H+ equivalents for the three production methods

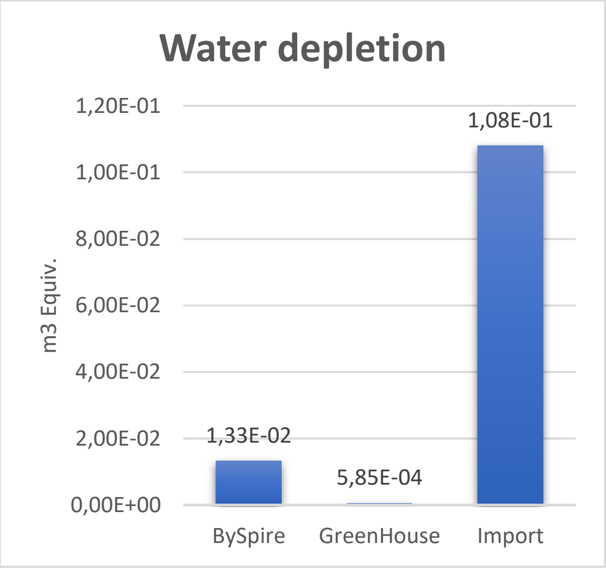

Figure 18: Water depletion in m³ equivalents for the three production methods

3.1.2 Interpretation of the Life Cycle Impact Assessment

3.1.2.1 Impact analysis of the Vertical Farming case

As shown in Figures 13 to 18, BySpire has a lower impact on all assessed impact categories, except for the impact category water depletion and freshwater eutrophication. The low impact results from the fact that By Spire's vertical farming facility can be considered as a controlled environment agriculture (CEA). The aim of this agriculture type is to cultivate plants throughout all their life stages under optimised conditions (Nelkin & Caplow 2008). Operating inside buildings or other enclosed facilities enables the regulation of all parameters in the closed environment and keeps the interactions with outside influences at a minimum. This also leads to the exclusion of natural services like sunlight and water. The technology behind CEAs is controlling and optimizing inflows like energy, water, air and nutrients and reducing outflows by recycling and reusing the resources. Hereby it focuses on parameters such as temperature, humidity, carbon dioxide (CO_2), light, nutrient concentration and the pH (Shamshiri et al., 2018). According to the technical and design department of BySpire, the vertical farm is operating according to the newest standards of CEAs by monitoring and controlling exactly the parameters that are mentioned above. Just the CO_2 level in the closed environment is currently only monitored but not controlled (Van Lubek & Bøgeberg, 2018). The CEA is also the cause of the 0% contribution of the cultivation and nursery phases in figure 19. Due to the provision of artificial light, plant production becomes a year-round business for BySpire. Moreover, there is no weather-related plant failure due to floods or droughts as temperature, irrigation and photo-intensity is artificial and optimally controlled. Although processes like the artificial lighting, the cooling, and the pumping require energy use, vertical farming dramatically reduces the use of fossil fuels since BySpire is not using any agricultural machinery or pesticides. Even if the manufacturing of the installations, like the nutrient and water delivery system, the platforms for plant production, the LED construction and artificial growing media, was included, the production will be generating additional energy consumptions, environmental impact and costs. This could be a disadvantage compared to conventional agriculture like the ones from the Mediterranean area, where as the greenhouse agriculture in Norway has similar requirements (Banerjee & Adenaeuer, 2014). However, the energy needed to operate them would have less impact on the environment because of the greener energy in Norway compared to Spain as seen in table 17 in appendix 10.8. Furthermore, since the herbs and vegetables are grown close to points of consumption, the transportation of goods to the costumer is reduced, thus saving energy and material resources.

To analyse the exact origins of BySpire's impact on the environment and to connect them with the specific phases of the vertical farming facility, the different impact categories are broken down and discussed in section 3.2.2.

3.1.2.2 *Impact analysis of the Greenhouse case*

The level of the impact of the greenhouse lies for every category in the medium range between the impact level of the BySpire site and the import as shown in figures 13 to 18. The only exception for this is the water depletion and freshwater eutrophication which will be explained in 3.3.2.2 and 3.3.2.6. A possible reason for this is that Hanasand Gård greenhouse is a semi closed facility is. A semi closed facility has the big advantage of being more energy and yield efficient compared to the conventional open greenhouse system, where not much is controlled (Qian et al., 2009). A high concentration of CO_2 which is possible through the semi closed environment of the greenhouse is one of the typical climate characteristics which leads to reported savings of up to 30% in fossil fuel and an increase of production by up to 20% compared to an open field production (Marcelis, Raaphorst, Heuvelink, & Bakker, 2007).

However, under North European climate conditions with long and cold winter, intensive heating in the cold season is required since the thermal isolation capacity of greenhouses is rather limited (Sanyé-Mengual, Cerón-Palma, Oliver-Solà, Montero, & Rieradevall, 2013). Moreover, during winter time with a low amount of natural daylight, artificial lighting is needed to a greater extent. Thus, the annual energy use for keeping up the preferred conditions for plant growth in greenhouses in Northern regions is 50% higher than for greenhouses in Mediterranean areas (Baytorun & Zaimoglu, 2018). Nevertheless, in most places in Scandinavia the electricity is very cheap to come by compared to other European countries (Norges vassdrags- og energidirektorat, 2016).

Another fact to consider is the availability of food products coming from greenhouses in Norway. Vegetables that are produced in Norwegian semi closed greenhouses are only available from mid-May and typically sold out in the stores by the beginning of November. Thus, a year-round availability of this product without import is not guaranteed. This is the case for lettuce, tomatoes and other vegetables grown in Norwegian semi closed greenhouse, which are also imported in large numbers from the Mediterranean throughout the year (Nordenström, Guest, & Fröling, 2010).

To clarify the origin of environmental impacts and to connect them with the specific phases of the greenhouse facility, the different contributions of the phases on the impact categories are presented in 3.3.2.

3.1.2.3 Impact analysis of the import case

As tables 9 and 10 and figures 13 to 18 indicate, the impact of the import of lettuce from the Mediterranean region has, compared to the other two food production methods in Norway, the largest impact on the environment. Spain produces every year around 22 million tons of fresh fruit and vegetables. Approximately 60% of these food items are exported, while the remainder is for domestic consumption. The market value of the exported chilled or fresh vegetables was estimated at approximately 1.8 billion euros in 2017 (Fepex, 2016).

Most of the imported vegetables are cultivated on open fields since this is the main practice in the Mediterranean regions (Martinez-Mate et al., 2018). However, open field agriculture is one of the main drivers of climate change, especially when also all indirect emission sources, like for example emissions from pesticide production (which are not included here) are taken into consideration (Aguilera, Guzmán, & Alonso, 2015). Chemical pollutants can freely transfer directly to the air, water and soil by processes such as for example leaching. The main influences on these transfers are the amounts of these products farmers add on their fields, the timing, soil conditions, application methods, etc (Birkved & Hauschild, 2006).

Another important factor to consider in the discussion about food imports from Spain and its impact on the environment is the transportation distance of food items. The carbon emission per unit of product over the whole transport chain including systems of cold storage, packing, transport to the receiving country and the transport to local retailers is an important factor in all LCA studies assessing the environmental impact of food import (Coley, Howard, & Winter, 2009). Already the transport from Spain to Oslo adds up to 3500 km. This long distance and the associated emissions of GHG and PMF put pressure on different impact categories like climate chance, marine eutrophication, particle matter formation and terrestrial acidification.

Besides the cultivation, the nursery phase and the use of trucks for transport, the irrigation system provides a significant impact on the assessed categories. It plays a big roll in 5 of the 6 impact categories, namely climate chance, freshwater eutrophication, marine eutrophication, particle matter formation and terrestrial acidification. Since the areas are dealing with brackish groundwater and water scarcity (e.g. due to competition with industry, tourism and intensive agriculture in the past years), the water must be pumped up, filtered to prevent contamination but mainly prevent salinization on the fields, and transported to the agricultural sites, etc. (Bartzas et al., 2015; Martinez-Mate et al., 2018). These processes will increase the energy consumption and resource depletion.

A more detailed analysis of the different phases of the food import and their influences on the impact categories is represented in 3.4.2.

3.2 Impact analysis of the contributions of the different production phases of the Vertical Farming Site

3.2.1 Results of the Life Cycle Impact Assessment

The transportation and the diesel that fuels the transportation are the biggest contributors to climate change, marine eutrophication, Particulate Matter Formation and Terrestrial Acidification. In the Particulate Matter Formation impact category, the water from the tap plays also an important part too. For the impact category freshwater eutrophication, the diesel and tap water have the biggest contribution.

The values and percentages for the cultivation and nursery phases are 0, except for the water depletion.

Table 5: Contributions in absolute values and percentages of the different phases at the BySpire site for Climate change, Freshwater eutrophication and Marine eutrophication.

	Climate change excl. biogenic carbon		**Freshwater eutrophication**		**Marine eutrophication**	
	kg CO_2-Equiv.	%	kg P-Equiv.	%	kg N-Equiv.	%
Cultivation	0	0%	0	0%	0	0%
Diesel mix at refinery	1,09E-01	14%	3,33E-06	63%	1,41E-04	13%
Electricity grid mix	3,58E-02	5%	9,45E-08	2%	1,37E-05	1%
Nursery	0	0%	0	0%	0	0%
Tap water	2,47E-02	3%	1,88E-06	35%	2,61E-05	2%
Truck	6,09E-01	78%	0	0%	8,93E-04	83%

Table 6: Contributions in absolute values and percentages of the different phases at the BySpire site for Particulate matter/Respiratory inorganics, Terrestrial acidification, Resource depletion water

	Particulate matter/Respiratory inorganics		**Terrestrial acidification**		**Resource depletion water**	
	kg PM2.5-Equiv.	%	Mole of H+ Equiv.	%	m^3 Equiv.	%
Cultivation	0	0%	0	0%	1,04E-02	78%
Diesel mix at refinery	2,36E-05	37%	5,64E-04	24%	8,42E-04	6%
Electricity grid mix	2,10E-06	3%	4,18E-05	2%	3,26E-04	2%
Nursery	0	0%	0	0%	1,83E-03	14%
Tap water	5,02E-06	8%	7,34E-05	3%	0	0%
Truck	3,23E-05	51%	1,71E-03	72%	0	0%

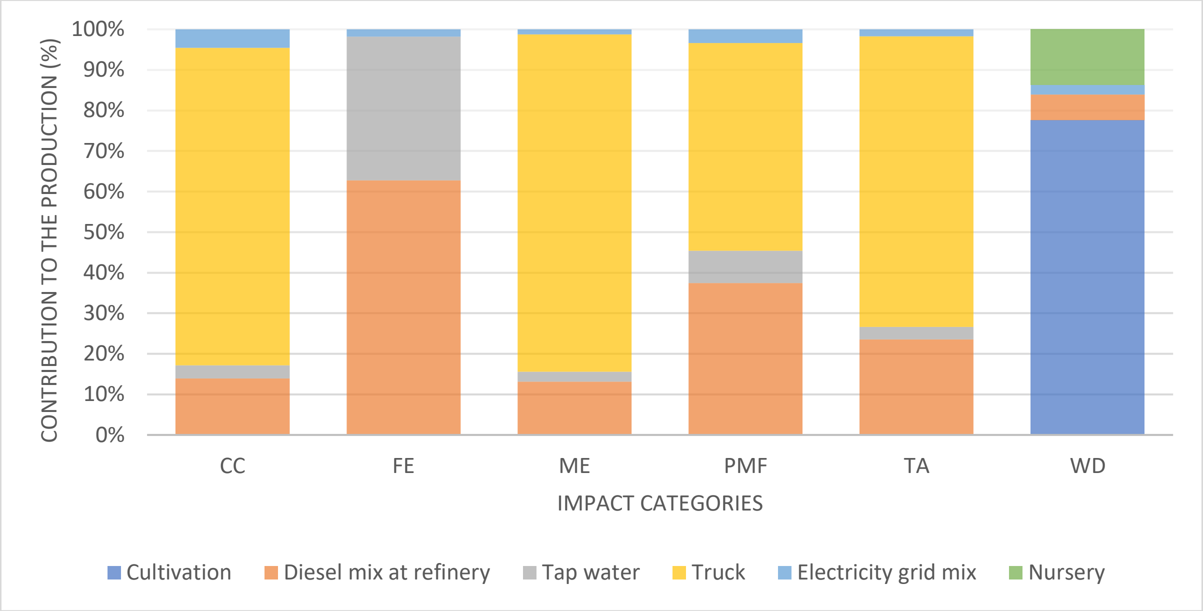

Figure 19: Contribution of each production phase to each impact category for the vertical farming cultivation of lettuce (CC: climate chance; FE: freshwater eutrophication; ME: marine eutrophication; PMF: particle matter formation; TA: terrestrial acidification and WD: water depletion).

3.2.2 Interpretation of the Life Cycle Impact Assessment

3.2.2.1 Climate change

Figure 19 shows the contribution of the different phases of the lettuce production in the vertical farming facility to the assessed impact categories. For climate change impact category, the truck use and the diesel mix refinery have the biggest impact (78% and 14% respectively). While burning the fuel, the truck is emitting greenhouse gasses (CO_2, CH_4, N_2O), which will lead to an increase in the atmospheric concentration of greenhouse gasses. This increases the radiative forcing capacity, which captures more heat on earth (greenhouse effect) and leads to an even higher increase in the global mean temperature (Stocker et al., 2013).The second largest impact is caused by the diesel production. The diesel production emits during its entire supply chain greenhouse gases. The supply chain consists of well drilling, crude oil production and processing, but also the transportation of crude oil via pipelines, vessels and trucks to the refinery as defined in the corresponding GaBi database. Especially, the transportation of the refinery products emits greenhouse gasses, but also the processing and flaring of these products causes a significant amount of greenhouse gasses (Eriksson & Ahlgren, 2013; European Commission, 2015). Although the truck use represents a big part of the contribution, it has to be taken into account that the climate change impact in absolute numbers is quite low compared to the other cases. This is mainly because of the short distance from the cultivation site to the Oslo city centre. It is important to note that not all products are brought to the city centre, but some deliveries are picked up by the clients. Although these emissions can be defined as indirect emissions they are included in the transportation of the vertical farm.

3.2.2.2 Freshwater eutrophication

The biggest contribution is related to the production of the diesel mix as shown in figure 19. Throughout the whole production line of diesel wastewater is produced. This water contains a small but demonstrable amount of phosphorous (around 0.8 mg/l). This amount of phosphorus ends up in the surrounding waters if the refinery does not have its owns wastewater treatment plant (European

Commission, 2003). The production of diesel will also cause small NO_X emissions which contain a bit of phosphor in the organic material.

Moreover, during the production of tab water phosphorous is emitted. Hence the use of tab water is contributing with 35% to the eutrophication of freshwaters. This is mainly related to the application of certain filters. But also, the application of certain filters in the treatment process contributes to fresh water eutrophication. Mainly the activated carbon filters are responsible for the emissions to water. To produce the activated carbon for the filter phosphate is emitted to the environment due to leakages from the mining of hard coal. These filters are used in wastewater treatment plants to produce drinkable tap water (Vanderheyden & Aerts, 2014). The composition of these mixes in Oslo is patented and cannot be made public (Lund, 2018). The contribution of the tap water is also related to fuel consumption in the treatment process (Sauer, Schivley, Molen, Dettore, & Keoleian, 2009).

3.2.2.3 Marine eutrophication

Whilst freshwater eutrophication is mainly caused by phosphate emissions, marine eutrophication is caused by nitrate emissions connected to ammonia, ammonium ion, nitrite, nitrogen dioxide, and nitrogen monoxide (European Commission, 2012). When fossil fuels, like diesel, are burned, nitrogen oxides (NO_X) are released into the air. This will form smog and acid rain, which will redeposit on land and water either through wet deposition like rain and snow or in the form of dry deposition on days with stable weather circumstances. Moreover, power plants, refineries and exhaustion from cars and trucks are the main sources of NO_X (Nixon, 2012).With an 83% contribution to marine eutrophication, the transport truck of BySpire has by far the strongest impact. The second highest impact is connected to the diesel refinery with 13%, which also emits NO_X (Eriksson & Ahlgren, 2013).

3.2.2.4 Particulate matter formation

The use of trucks for transportation purposes (51%) and the production of diesel needed for fuelling these trucks (37%), have the biggest contributions to the formation of particulate matter. Vehicles are releasing particulate matter in from of engine exhaust, brake linings, tire friction and the use of the clutch. This kind of particulate matter is deposited onto the road, which will be suspended with dust particles and road wear materials by the passing traffic (Belis, Karagulian, Larsen, & Hopke, 2013 ; Karagulian et al., 2015). Mechanically generated particles (e.g. through tire friction) and carbonaceous particles created from combustion of fossil fuels are called primary particle emissions. Secondary particulate matter formations are formed when these primary emissions undergo reactions in the atmosphere with gaseous pollutants like for instance nitrogen dioxide (NO_2) and ammonia (NH_3) (Seinfeld & Pandis, 2016). Thus, the use of trucks and the production of diesel are the two main phases in the vertical farming production where primary particles are emitted.

The production of tap water is contributing with 8% to the particulate matter formation. Norway uses surface water to generate tap water. Within in this water purification process, where surface water is transformed into tap water, filters that are used to eliminate suspended particles out of the surface water are getting regularly cleaned with the backflush method. During the backflush the filters are exposed to a counter current where either air or water is used. Within this process, fine particles can enter the atmosphere (Sharaai, Mahmood, & Sulaiman, 2010).

3.2.2.5 Terrestrial acidification

Acidifying pollutants like nitrogen oxides (NO_X), sulphur dioxide (SO_2) and ammonia (NH_3) enter the environment via various pathways and have a wide range of impacts on groundwater, surface waters, soils, organisms, whole ecosystems and man-made structures (e.g. buildings) (Bouwman, Van Vuuren, Derwent, & Posch, 2002). Inputs of acidifying pollutants may lead in the long term to losses of soil buffer capacity, a lower pH level, increased leaching of nitrate accompanied by base cations, and increased concentrations of toxic metals (e.g. aluminium) (Reuss & Johnson, 2012). In case of the vertical farming site, the terrestrial acidification is dominated by the contribution of the truck transportation (72%) and the diesel mix refinery (24%). The main reason for this is the emission of airborne acidifying chemicals that are formed by the combustion of fuel caused by the transportation of deliveries. Also, the production of diesel emits NO_X and SO_2 and is therefore contributing to the terrestrial acidification (Eriksson & Ahlgren, 2013).

3.2.2.6 Water depletion

Norway's big lakes and rivers (surface waters) provide a rich freshwater system which is in general under less pressure from human impacts than a lot of other countries in Europe. Due to this abundance of accessible surface water, only 15% of the Norwegian water consumption is supplied by groundwater (Norwegian Environment Agency, 2018). However, the use of blue water (groundwater and surface water) is also contributing to the impact category water depletion.

The percentages for the water depletion in figure 19 indicate that the cultivation and nursery phase are contributing the most to the depletion of water with 78% and 14% respectively. Although these are high percentages, it should be kept in mind that only 0,012m3 water is used for these two phases. Compared to the amount of used water in the nursery and cultivation phase of the import case, the vertical farm is saving 88% of the water use. The reason for this low amount lies in the use of the hydroponic system where a great amount of the water inflow is recycled. The only water escaping the production cycle is the water the vegetables are investing in growth and evaporating through the leaves in to the air inside the controlled room (Van Lubek & Bøgeberg, 2018).

Moreover, the diesel mix refinery is contributing with 6% to the water depletion. The diesel refinery is depleting most of its water through the evaporation from the cooling systems, e.g. cooling towers, the steam vents and through open topped cookers (Henderson, 2016).

3.3 Impact analysis of the contributions of the different production phases of the greenhouse site

3.3.1 Results of the Life Cycle Impact Assessment

Cultivation phase, natural gas production and the truck are in general the biggest contributors for the impact categories. The natural gas production is contributing the most to the climate change impact, Marine eutrophication, Particulate Matter Formation and Terrestrial Acidification. The cultivation and truck phases provide also big contributions to the impact categories of Marine eutrophication, Particulate Matter Formation and Terrestrial Acidification. Moreover, it is notable that the cultivation phase is almost the only contributor to freshwater eutrophication. In contrast with the vertical farming site, the cultivation and nursery phase are not contributing at all to the water depletion. Instead, the electricity grid mix, the natural gas mix and the diesel mix refinery phase are causing the depletion of water.

Table 7: Contributions in absolute values and percentages of the different phases at the greenhouse site for climate change, freshwater eutrophication and marine eutrophication.

	Climate change excl. biogenic carbon		Freshwater eutrophication		Marine eutrophication	
	kg CO_2 -Equiv.	%	kg P-Equiv.	%	kg N-Equiv.	%
Cultivation	6,58E-02	4%	0	0%	4,15E-04	25%
Diesel mix at refinery	1,55E-02	1%	4,76E-07	58%	2,02E-05	1%
Electricity grid mix	3,56E-02	2%	9,39E-08	12%	1,36E-05	1%
Natural gas mix	1,38E+00	87%	2,44E-07	30%	7,87E-04	48%
Nursery	0	0%	0	0%	0	0%
Rail transport	0	0%	0	0%	0	0%
Truck	8,72E-02	6%	0	0%	4,02E-04	25%

Table 8: Contributions in absolute values and percentages of the different phases at the greenhouse site for Particulate matter/Respiratory inorganics, Terrestrial acidification, Resource depletion water.

	Particulate matter/Respiratory inorganics		Terrestrial acidification		Resource depletion water	
	kg PM2.5-Equiv.	%	Mole of H+ Equiv.	%	m³ Equiv.	%
Cultivation	3,13E-05	16%	1,82E-03	30%	0	0%
Diesel mix at refinery	3,38E-06	2%	8,08E-05	1%	1,21E-04	21%
Electricity grid mix	2,08E-06	1%	4,16E-05	1%	3,18E-04	54%
Natural gas mix	1,41E-04	71%	3,30E-03	55%	1,46E-04	25%
Nursery	0	0%	0	0%	0	0%
Rail transport	0	0%	0	0%	0	0%
Truck	2,13E-05	11%	7,65E-04	13%	0	0%

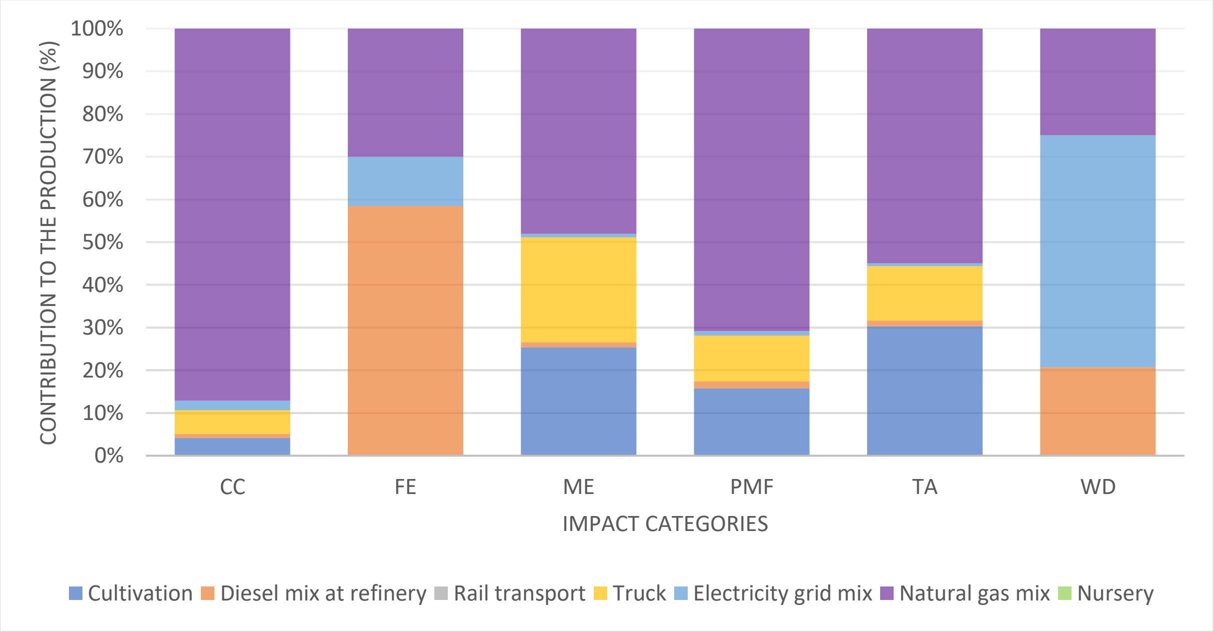

Figure 20: Contribution of each production phase to each impact category for the greenhouse cultivation of lettuce (CC: climate chance; FE: freshwater eutrophication; ME: marine eutrophication; PMF: particle matter formation; TA: terrestrial acidification and WD: water depletion).

3.3.2 Interpretation of the Life Cycle Impact Assessment

3.3.2.1 Climate change

Table 7 shows that the production of the natural gas mix has the highest impact with 87 % (the actual burning of this gas brings the cultivation phase only to a 4% contribution here) on the climate change potential followed by the use of trucks (6%). Natural gas is for the most part composed of methane. Literature shows that within the lifetime of a well, 3.6% to 7.9% of the methane diffuses from shale-gas production to the environment through venting and leaks (Howarth, Santoro, & Ingraffea, 2011). Another work reports direct measurements of methane emissions of 190 onshore natural gas production sites in United States of America. These measurements lead to an estimate of 2300 kilograms of methane emissions per site during the lifetime of a well. Methane is a very powerful greenhouse gas, giving the fact that it has a far greater global warming potential (GWP: 28) than carbon dioxide (GWP: 1), especially over the time span of the first decades following the emission (Howarth et al., 2011; IPCC, 2014). These studies and numbers explain the high impact of natural gas on the climate change category of the greenhouse. The reasons for the contribution of the truck use to the climate change are already explained in 3.2.2.1.

3.3.2.2 Freshwater eutrophication

The biggest and almost only contributor to the freshwater eutrophication is represented by the diesel production with 58%. The explanation of this can be found in 3.2.2.2.

Electricity grid mix 12% causes phosphate emissions by installation and maintenance of the grid (Gibon & Hertwich, 2014; Jorge, 2013).

The second biggest contribution is related to the production of the natural gas mix with 30%. Throughout the whole production line wastewater is produced. This water contains a small amount of phosphorus. This amount of phosphorus ends up in the surrounding waters if the production site does not have its owns wastewater treatment plant (European Commission, 2003). The production of natural gas will also cause NO_X emissions which contain a bit of phosphorus in the organic material.

3.3.2.3 Marine eutrophication

The natural gas mix contributed with 48% the most to marine eutrophication followed by the truck, which is in the second position with a contribution of 25%. These contributions were dominated by the emissions of nitrogen oxides from the natural gas production and the combustion by the truck use.

The cultivation phase was another main contributor to marine eutrophication, with 25% of the impact. This was primarily due to the burning of the natural gas for heating purposes, during which process NOx are emitted. Moreover, nitrogen emission can diffuse to the environment using nitrogen fertilisers. Even though the greenhouse is using a semi-closed agricultural system, nitrogen particles in the air of the facility can escape through open windows into the environment.

3.3.2.4 Particulate matter formation

Particulate matters emissions were mainly found during the natural gas production (71%), the cultivation (16%) and the truck use (11%). The natural gas production is by far the largest contributor to the particulate matter formation. Through extracting, processing, transmitting, storing, and distribution of natural gas, particles are emitted to the atmosphere. Engine exhaust is a big source of these emissions due to incomplete combustion in reciprocating engines and turbines used to transport the natural gas through pipelines and vessels (Spath & Mann, 2000). In combination with this process, the formation of secondary particulate matter plays also a big role (Alanen et al., 2017).

Since natural gas is burned for heating the cultivation area, particulate matter is formed through the combustion of fossil fuels. Thus, also the cultivation phase is contributing to the particulate matter formation.

The correlation between the truck use and the formation of particulate matter is already explained for the vertical farming site since BySpire is also using trucks as a mean of transportation (see 3.2.2.4 for more information).

3.3.2.5 Terrestrial acidification

The natural gas mix was the main contributor to terrestrial acidification, with 55% of the impact, followed by the cultivation phase (30%) and the truck (13%). Impact was dominated by the NO_X and SO_X emissions occurring in the process of natural gas and the combustion of fossil fuels and the burning of natural gas during the cultivation phase.

3.3.2.6 Water depletion

Contrary to the vertical farming process, the cultivation and nursery phase of the greenhouse have hardly any impact on water depletion due to the fact that the greenhouse site is using collected rainwater (green water) for irrigation purposes. For the impact category water depletion in LCA studies, only the use of groundwater and surface water is considered (Jolliet et al., 2003). The use of rainwater has therefore no impact on this category. The biggest contributors to the water depletion impact category are therefore the Electricity grid mix (54%), the Natural gas mix (25%) and the Diesel mix at refinery (21%).

The electricity mix has with over 50% the highest level of impact on the water depletion. In Norway, hydroelectricity generates at least 96% of the national electricity demand (IEA, 2017). This electricity is transported through 11,097 km of electricity lines and cables, 121 substations and 345 transformers, plus hundreds of kilometres of interconnectors connecting Norway to the electricity grid of Denmark and the Netherlands (Jorge, 2013). Even though the water used to produce hydropower is not escaping the production cycle, the manufacturing processes and the maintenance of the electricity transportation equipment use up a lot of groundwater and surface water (Jorge, 2013). This might explain the high impact of the electricity grid on the water depletion for the greenhouse.

Also, the production of natural gas consumes a lot of water. Water is by far the largest by-product in volume of the production of natural gas. Water is trapped in underground formations, brought up to the surface along with the gas and finally separated from the natural gas during the manufacturing process (Veil, Puder, Elcock, & Redweik Jr, 2004). Moreover, studies indicate that water discharge from gas productions is highly toxic and about 10 times more polluted than produced water coming from oil platforms (Jacobs, Grant, Kwant, Marquenie, & Mentzer, 1992). Thus, around one quarter of the water depletion of the greenhouse site is caused by the production of natural gas.

As already mentioned in 3.2.2.6, the water consumption for diesel refinery is high. Water consumption adds up to 0,20, 0,30 and 0,40 litre water/litre diesel for the cracking, the light coking and the heavy coking process within the diesel production and leads therefore also to an increased water depletion (Sun, Elgowainy, Wang, Han, & Henderson, 2018).

3.4 Impact analysis of the contributions of the different production phases of the import of food to Norway

3.4.1 Results of the Life Cycle Impact Assessment

The production of irrigation water (deionised water) and the transport to Lierskogen in Norway (truck 1) are the biggest contributors to climate change. For freshwater eutrophication, Particulate Matter Formation and Terrestrial Acidification, the cultivation, diesel for transportation and water are the most important contributors. Truck 1 also plays a big role in Particulate Matter Formation and Terrestrial Acidification. In marine eutrophication, the cultivation, diesel, water and the transport to Lierskogen (truck 1), have the biggest influence. The biggest impact on water depletion comes from the cultivation and nursery. The transport from Lierskogen to Oslo (truck 2) has almost no contribution to all the different impact categories.

Table 9: Contributions in absolute values and percentages of the different phases for the importation to Norway for climate change, freshwater eutrophication and marine eutrophication.

	Climate change excl. biogenic carbon		**Freshwater eutrophication**		**Marine eutrophication**	
	kg CO_2-Equiv.	%	kg P-Equiv.	%	kg N-Equiv.	%
Cultivation	6,58E-02	3%	2,74E-05	37%	1,15E-03	30%
Deionised water	9,31E-01	42%	3,90E-05	53%	9,47E-04	25%
Diesel mix at refinery	1,86E-01	8%	5,69E-06	8%	2,42E-04	6%
Electricity grid mix	6,65E-02	3%	8,20E-08	0%	4,99E-05	1%
Nursery	3,87E-03	0%	1,62E-06	2%	6,79E-05	2%
Truck 1	9,64E-01	43%	0,00E+00	0%	1,38E-03	36%
Truck 2	1,16E-02	1%	0,00E+00	0%	1,69E-05	0%

Table 10: Contributions in absolute values and percentages of the different phases for the importation to Norway for Particulate matter/Respiratory inorganics, Terrestrial acidification, Resource depletion water.

	Particulate matter/Respiratory inorganics		**Terrestrial acidification**		**Resource depletion water**	
	kg PM2.5-Equiv.	%	Mole of H+ Equiv.	%	m^3 Equiv.	%
Cultivation	3,13E-05	11%	1,82E-03	21%	7,84E-02	73%
Deionised water	1,43E-04	51%	2,71E-03	32%	0	0%
Diesel mix at refinery	4,04E-05	14%	9,66E-04	11%	1,44E-03	1%
Electricity grid mix	1,02E-05	4%	2,15E-04	3%	8,42E-03	8%
Nursery	1,84E-06	1%	1,07E-04	1%	1,96E-02	18%
Truck 1	5,37E-05	19%	2,64E-03	31%	0	0%
Truck 2	6,13E-07	0%	3,25E-05	0%	0	0%

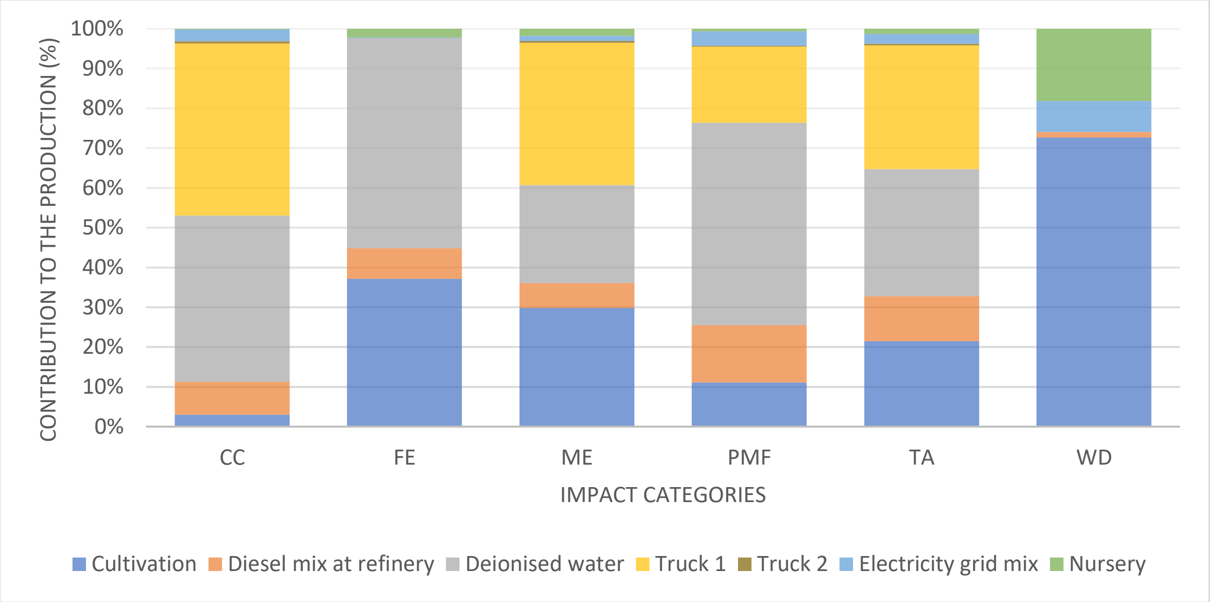

Figure 21: Contribution of each production phase to each impact category for the import of lettuce to Norway (CC: climate chance; FE: freshwater eutrophication; ME: marine eutrophication; PMF: particle matter formation; TA: terrestrial acidification and WD: water depletion).

3.4.2 Interpretation of the Life Cycle Impact Assessment

3.4.2.1 Climate change

Figure 21 shows that the truck use for the transportation of goods from Murcia to Lierskogen (truck 1) represents almost half of the contribution (43%) to the emission of CO_2 -equivalents. As earlier explained, the reason behind this are the greenhouse gas emissions connected to the burning of fuel. The very small contribution of the transport from Lierskogen to Oslo (truck2) is caused by the short distance and the truck load.

The deionised water used for irrigation purposes has the second highest impact on the climate change category with 42%. The irrigation of vegetable cropping systems in Mediterranean areas implies a high consumption of energy and large GHG emissions associated with water pumps, infrastructure to distribute the water and used machinery (Aguilera et al., 2015). Particularly, the desalination process through reverse osmosis is very energy consuming (see 2.2.3). Since there is a constant demand of water, processes like the desalination or the transportation of water have to work on a reliable basis. Thus, these processes are often based on fossil fuels which are unlike the renewable energy sources independent of weather conditions (Aguilera, Guzmán, & Alonso, 2015) (Daccache, Ciurana, Rodriguez Diaz, & Knox, 2014). Nuclear energy is available in Spain and contributes with 20,01% to the entire electricity grid as seen in table 17. The other main energy sources are natural gas (20,13%) and coal (13,6%), which are well known sources for greenhouse gas emissions (Ministerio de Industria, 2015).

The diesel mix refinery is discussed in Climate change3.2.2.1 and is used not only for the transportation with diesel, but also for the other machinery on site that are used for ploughing, planting, soil management and harvesting, but also the application of fertilizers and pesticides.

3.4.2.2 Freshwater eutrophication

The biggest contribution (53%) is related to the deionised water. The biggest impact is the energy needed for the filtering and pumping of the water, since installation and maintenance of the electricity grid causes phosphate emissions. Besides this will during the handling of the concentrated waste water, resulting from the reverse osmoses process, in e.g. sewage systems, phosphorous emissions can escape to the environment through air and water (Kumar, Badruzzaman, Adham, & Oppenheimer, 2007).

The other major contribution is the cultivation phase with 37%. This can be explained by the runoff of fertilizers and pesticides to close rivers and lakes. Emissions from fertilisers' application like NO_X, NH_3, NO_3, PO_4 are relevant to eutrophication. PO_4 especially for freshwater eutrophication (Schmidt Rivera, Bacenetti, Fusi, & Niero, 2017).

The impact that the production of diesel has on freshwater eutrophication is explained in 3.2.2.2.

3.4.2.3 Marine eutrophication

The NO_X that is emitted by the transportation has the highest impact (36%) in this impact category. As discussed earlier in 3.2.2.3, this is caused by the combustion of fuel. The same applies to the production of diesel (6%) as mentioned in 3.2.2.3.

The other contributions are the cultivation phase. This can be explained by the runoff of fertilizers and pesticides to close rivers and lakes. The emissions from the fertilisers' application like NO_X, NH_3 and NO_3, have and influence on the Marine eutrophication (Schmidt Rivera, Bacenetti, Fusi, & Niero, 2017)

The water used for the irrigation has a contribution of 25%. This is caused partly by the nitrates in the concentrated stream that are given off and can find their way to coastal areas where they will lead to marine eutrophication (Ersever & Pirbazari, 2002). Moreover, since the desalination technologies in Spain are run with fossil fuels NO_X emissions emitted during the desalination process are impacting the environment (Raluy, Serra, Uche, & Valero, 2004).

3.4.2.4 Particulate matter formation

The use of transportation (19%) and the production of diesel (14%) needed for the transportation, are just as in the case of the vertical farm important for the formation of particulate matter. See 3.2.2.4 for more information regarding the impact of transportation and the diesel refinery on particulate matter formation.

For deionised water (51%) purposes, as explained in 3.4.2.1, fossil fuels are used to produce energy for the desalination technology. As a result of the combustion of these fuels, particulate matter will be formed and released into the environment. Another pathway is the accumulation of particles on the reverse osmose membranes, which will most likely lead to PM entering the environment when these membranes are cleaned. Next to the filtration of the water, the transportation to the agricultural site will use fuel, which emits more particulate matter.

Cultivation 11% due to management of the soil through processes like ploughing and harvesting, primary particulate matter, like dust and other particulate matter, is brought into the atmosphere. Secondary particulate matter is formed as a reaction with the fertilizers application that releases emissions in the air. An example is NH_3 that will lead to the formation of NH_4^+ which is a PM2.5 (Fu et al., 2015).

3.4.2.5 Terrestrial acidification

The terrestrial acidification is clearly again dominated by the transportation (31%) and the diesel refinery (11%). This is already explained in 3.2.2.5.

In the cultivation phase (21%), the use of fertilizers will contribute to the emission of compounds like NOx and NH_3 and will have because of this also an impact on the acidification of the soil, since they are lowering the pH of the soil (Schmidt Rivera, Bacenetti, Fusi, & Niero, 2017).

During the production of deionised water (32%) fossil fuels are burned, which is emitting NO_X.

3.4.2.6 Water depletion

While water is quite an abundant resource in Norway, it is more precious and limited in Spain as mentioned in 2.2.3.

With 73%, the cultivation phase has obviously the biggest impact on the water resources, together with the nursery which contributes with 18% to the water depletion. The reason for this is that it takes a lot of water to keep the vegetables hydrated in the warm Mediterranean climate.

Just as in the case of the vertical farm facility, the electricity grid (8%) is a consumer of water. And again, is the amount of electricity needed, not enough to make them very high in contribution. As mentioned before and in table 17, the electricity is mainly coming from natural gas (20,13%) and nuclear sources (20,01%) which consume water resources.

4 Neglected processes

As mentioned in Chapter 2, it was not possible to include all life cycle phases of the three discussed farming methods. However, it is expected that these phases could deliver a significant contribution to the environmental impact of the farming methods. Three of the excluded phases are briefly mentioned in this thesis. Available data and data of previous studies are gathered to have a view on the possible impact of these three phases in a future LCA study.

4.1 Packaging

The main goals of food packaging are the protection of food products from chemical, biological and physical influences and the provision of information for the consumer regarding ingredients and nutrients (Coles, 2003). Packaging technology must balance the protection of food with other aspects such as energy and material costs, heightened social and environmental consciousness, and strict regulations on pollutants and disposal of municipal solid waste. To prevent waste, three main principles are recommended: the light weighting of the package, the reuse and the refilling of the packaging and its sustainable recycling (Marsh & Bugusu, 2007).

BySpire uses reusable boxes for large deliveries at restaurants and recycled paper bags for the smaller deliveries. Especially for short transport ways and a fast consumption by the consumer, paper packaging is commonly used. Statistics on the use of packaging materials and recycling packaging waste of the EU-27 market in 2010 shows that paper packaging has the highest recovery rate (84% of all used paper packaging is recycled) amongst all used packaging material (EUROPEN, 2013). Studies show that packaging from recycled paper has in general a lower impact on the environment than other types of packaging (Finnvedenab & Ekvallc, 1998; Zabaniotou & Kassidi, 2003). The greenhouse uses large wooden boxes for deliveries over 5kg, and plastic packaging for smaller quantities. The client must dispose of these packaging materials themselves (Hanasand, 2018). The import uses the biggest amount of packaging. They pack the vegetables multiple times to make sure they survive the long transportation. Because of the durability, plastic is often chosen for this purpose. In general, it is known that the longer the transport- both in distance and time – the more packaging, like wooden packaging is required on top of the plastic (Wakeland, Cholette, & Venkat, 2012).

4.2 Waste water management

80% of the global fresh water is used for agricultural purposes (Martinez-Mate et al., 2018). The production of one kilogram of cereal grains for example requires around 1000 litres of water (Pimentel et al., 2004). This water will usually be contaminated during agricultural processes by e.g. fertilizers and pesticides and will leaves the agricultural system as waste water. Waste water management is therefore needed to minimize the environmental impact.

BySpire as well as the greenhouse site are using fertilizers in their cultivation process but have almost no water escaping from their farming systems due to the closed loop of the hydroponics. Because of alarm systems and a software controlling the water level, possible leakages are quickly detected, and additional water losses are therefore very small. Real waste water is produced when the systems are cleaned once per month. Despite the water used for this purpose, a whole clean-up of the plant production systems of both sites is conducted on average on a monthly basis. Throughout the year this represents a small contribution to the waste water outflow. Water used for these cleaning purposes is currently not recorded for both sites. Cleaning water will be treated in the municipality waste water treatment plant.

In contrast to the BySpire and the greenhouse site, waste water in the form of runoff water can be found at the Mediterranean sites. Due to the open field cultivation the water which is not absorbed by the plants is entering the environment untreated. This runoff water will be contaminated with pesticides and fertilizers. Thus, it is very important to reduce the amount of runoff waters to safe fresh water and to reduce the discharge of pesticides and fertilisers in the environment (Wauchope, 1978).

4.3 Pesticide production

According to the study of Audsley et al., the pesticide manufacturing represents about 9% of the energy use of arable crops – depending on the crop type this percentage can vary slightly. Moreover, the manufacturing of pesticides is contributing with about 3% to the 100-year Global Warming Potential from crops (Audsley, Stacey, Parsons, & Williams, 2009). Based on this data, an LCA on lettuce growth in Spain shows that pesticides production together with the auxiliary equipment and fertilisers were the main contributors for all used impact categories (primary energy, global warming potential, eutrophication potential, acidification potential, abiotic resources) for the lettuce production in Spain. The transportation of the pesticides to the farmland was not even included in this LCA (Romero-Gámez et al., 2014).

BySpire uses neither chemical, nor natural pesticides as it is not required. Since the site of BySpire is a type of closed environmental agriculture the contact with influences from the outside environment is limited. The entrance of parasites, insects or fungi is therefore prevented. The greenhouse uses natural pesticides such as ladybugs against Ichneumon wasps (*Ichneumonidae*), plant bugs (*Macrolophus sp.)*, and red spider mites (*Tetranychus urticae*) since through open windows pest species can occasionally enter the system. Only the Mediterranean sites are using chemical pesticides and are therefore the only of the three methods which need to include a pesticide production phase in an LCA. The choice made by BySpire's and the greenhouse of not using any chemical pesticides is leading therefore to a zero-impact on the environment concerning the use and production of pesticides.

5 Comparison between the vertical farming, greenhouse and import cases

5.1 LCA

When starting to compare the three food production methods, it is important to note that the exclusion of certain phases (and especially the manufacturing of buildings, installations and used machinery), can lead to an underestimate of the actual impact of all three food production methods. When looking at table 4, it is possible to compare the impact of the three different production methods on the six assessed impact categories in absolute numbers. The results show that the vertical farming site has the smallest environmental impacts in absolute numbers (except freshwater eutrophication and water depletion), the greenhouse has the middle values, while the import case has the biggest impact in absolute values. However, when looking deeper into the life cycle of the cases and focusing on the level of the underlying phases, it is clear that this trend is not followed in general. The percentages of tables 5 to 10 are useful information for looking separately into the different cases. However they should not be used to compare the three different food production methods since they do not share exactly the same phases in their life cycle. Absolute numbers nevertheless show the level of impact in the unit of the emission of each phase. The units for each phase stay the same throughout the production methods and can be therefore used to make a comparison between the sites. Thus, when the absolute values from tables 5 to 10 are combined, as presented in appendix 10.7, it is possible to compare the three different food production methods and to observe which phases have the biggest impact.

Cultivation phase: the cultivation phase of the vertical farming facility has the lowest impact on all the categories except freshwater eutrophication and water depletion. The low values of the vertical farm are explained by the used CEA technology, where the whole production process is cut off from the environment. The cultivation phase of the greenhouse has a medium impact and the cultivation phase of the import case has the biggest impact on all impact categories. The slightly higher values produced by the greenhouse´s cultivation phase are explained by the fact that some emissions can escape through to the atmosphere the open windows for ventilation. Moreover, the burning of natural gas for heating purposes during the cultivation phase emits CO_2, NO_X and particulates which leads to a contribution to all impact categories apart from the water depletion category. The cultivation phase of the Mediterranean sites has the biggest impact on all the categories due to the open field agriculture. The open field agriculture allows the free dispersal of emissions into the environment. Since the greenhouse has no phosphorus emissions during its cultivation phase in the air it does not contribute to fresh water eutrophication. And since it is using collected rainwater in the cultivation phase, it is not contributing to water depletion (explained more in detail under the irrigation phase). Thus, the cultivation phase of the vertical farming site as well as of the import sites is using up more water resources.

Diesel mix at refinery phase: For the diesel production phase, the greenhouse has the lowest values, followed by the vertical farm and the import which has the biggest impact. The greenhouse needs less fuel for transport since it is dividing their vegetables over truck and train while the vertical farm only uses a truck. A lower consumption of fuel also means less water depletion in order to produce this fuel, so this impact category also has the lowest value for the greenhouse, while higher values for the vertical farm and the import case are visible.

Electricity grid mix phase: For the electricity production phase, the greenhouse has the lowest values, followed by the vertical farm and the import is again having the highest. The vertical farm needs more electricity than the greenhouse, which means that they do not have the lowest impact here. When looking at the freshwater eutrophication category it can be noticed that the electricity mix phase of the import site has the lowest emissions of phosphorus. Phosphorous emissions are mainly caused by the installation and maintenance of the electricity grid. Due to the geographical and climatic circumstances, large distances need to be covered in Norway and more replacements need to be done, which maybe lead to an increased maintenance of the electricity grid and thus higher phosphorous emissions compared to the situation in Spain.

Transportation phases (Truck, Truck 1 + 2, Railroad transport): The analysis of the transportation phase shows that the greenhouse has the most environmental friendly way of transporting, since they are dividing their products half part over a full truck and half part over an electric train. According to the LCA approach of GaBi, the use of electric trains produces no emissions and has therefore no impact on the environment. The vertical farming facility follows in second place because of the transportation of smaller deliveries over a shorter distance. Due to its long distances, the transportation from the Mediterranean region has the highest impact.

Nursery phase: Since the nurseries of the vertical farm and the greenhouse are closed off from the outside world, no emissions can enter the environment. Thus, the impact is zero, which makes the import automatically the highest for all categories. Because of the water depletion, the vertical farm has more impact than the greenhouse in that category.

Irrigation phases (Tap water, Rain water and Deionised water): The greenhouse site uses green water (water resources supported from rainfall) whereas the vertical farming site as well as the Mediterranean production sites predominantly use blue water (irrigation water from surface and ground water). Within the LCA approach, green water is not considered as a contributor to the impact categories. Thus, the greenhouse has automatically the lowest impact for the irrigation phase. The vertical farming site has through the use of tap water the second highest influence on the impact categories, while the import case which needs to clean the ground water through reverse osmose has the highest influence on the environment. The rainwater collectors of the greenhouse facility could however have an impact on the land use. Since greenhouses can’t use their roofs to place the rainwater collectors on them, surrounding areas need to be used.

Natural gas mix phase: The greenhouse site is the only site which is using natural gas during its production process. Since the production of the natural gas is a process with a very high impact (e.g. through its high energy consumption, emission of environmentally harmful substances, resource depletion), it represents a large contributor to the following categories: climate change, marine eutrophication, particulate matter formation, terrestrial acidification and water depletion. This increases therefore the whole general impact of the greenhouse on the environment.

5.2 Packaging, waste water management and pesticides production

Although further research is recommended, in order to make a well-founded statement on the impact of packaging, waste water management and pesticides production, a brief qualitative comparison is made in order to have an indicator about the impact of these phases on a future extended LCA study.

As discussed in 4.1, due to the use of multiple packaging and primary use of plastic for the import case, it can be assumed that this case will be having the biggest impact on the environment. The greenhouse uses less packaging since the distance is shorter, but after considering the current state of knowledge on food packaging and its recycling methods, it seems that By Spire's choice for a paper packaging is an appropriate and sustainable way of transporting their products.

A founded comparison for waste water management is not possible yet, since the amounts of waste water and the exact mix of pollutants they contain are currently not being measured by all three cases. But based on what is currently known about the production ways, it can be asserted that the open field site for the import emits more polluted waste water. It contains pesticide and fertilizer run off. Thus, their impact will be probably the highest. The waste water for the greenhouse site and the vertical farming site contains probably more or less the same contaminations. And since they have a similar cleaning routine, the outflow could also be the same and is treated in the same way, a municipality waste water treatment plant. According to that, their impact will most likely be the similar.

Since in this study, only the Mediterranean sites are using chemical pesticides, they are the only farming method with a need to include the production of pesticide in an LCA study. This will lead to a significant impact that will be similar as described in 4.3. The production of pesticides should definitely be taken into account when possible data are available. Due to the fact that the greenhouse site uses natural pesticides and the vertical farming site uses no pesticides, their impact concerning the use and production of pesticides on the environment will be zero.

6 Possible improvements for the vertical farming site

Since it is the sub goal of this thesis to gain insight in the sustainability of the vertical farming site, and to determine the phases which have the highest impact on the environment and so find most the effective improvements regarding the future development of the site, several suggestions will be given here. Although the vertical farming site of BySpire has in absolute values already the lowest general impact has on all impact categories except freshwater eutrophication and water depletion, it doesn't mean they do not have room for improvements.

BySpire should start with measuring more parameters. Measurements are already collected for quantity of water and fertilizers, water and air temperature, humidity level, CO_2 level, pH-values, EC-values, etc. It is recommended to take exact **Measurements** for yield, seeds, seedlings, solid waste and waste water (cleaning water). This information will prove itself helpful and necessary for future research, but also for daily operational purposes. The more information is being monitored and accurately collected in an easy reachable file in the company, the better and faster this information can be used for the benefit of the company.

Moreover, BySpire should continue maintaining the good relationship with its clients and build out the flourishing collaboration with local retailers and restaurants. Reliable local customers could have a direct influence on the production so that BySpire could make specific products for local needs. This would represent a unique and valuable situation on the Norwegian food market. The reliability of BySpire to harvest the needed products at precise times could be very valuable for their customers. An example of these specific, client tailored could be edible flowers, or special herbs for restaurants.

An important improvement in the current LCA would be to change from the delivery truck on diesel to electric powered **transportation**. Since Norway has a large supply of renewable energy in the form of hydropower, and the main negative impact from the electric transportation would be the energy production, this would be a perfect solution to eliminate the current large impact of the diesel fuelled truck. Emissions of the truck and of the correlated diesel production would be hereby eliminated. Since the electric transportation itself will not have any negative emissions and the energy used will be mainly hydropower, the emissions in that situation will also be low (The Guardian, 2018; Wilson, 2013). It is important to keep in mind that the manufacturing of the trucks is not considered in this LCA study.

To show the improvements of the switch to an electric truck, the BySpire LCA plan is redesigned to suit electrical transportation and added in appendix 10.2.4.10.2.4 This leads to the following new results10.2.4 for the vertical farming site, as shown in table 11 and figure 22. They show large reductions in the general impact of the vertical farming facility.

Table 11: The Impact categories of the vertical farming facility in absolute values in two different scenarios. Transportation powered by diesel fuel or powered by electricity. The reduction is also given in percentages.

Impact category	BySpire with diesel powered transportation	BySpire with electric powered transportation	Reduction
Climate change excl. biogenic carbon (kg CO_2 - Equiv.)	7,78E-01	6,11E-02	92%
Eutrophication freshwater (kg P-Equiv.)	5,30E-06	1,98E-06	63%
Eutrophication marine (kg N-Equiv.)	1,07E-03	4,00E-05	96%

Particulate matter/Respiratory inorganics (kg PM2.5-Equiv.)	6,31E-05	7,15E-06	89%
Terrestrial acidification (Mole of H+ Equiv.)	2,39E-03	1,16E-04	95%
Resource depletion water (m^3 Equiv.)	1,33E-02	1,25E-02	6%

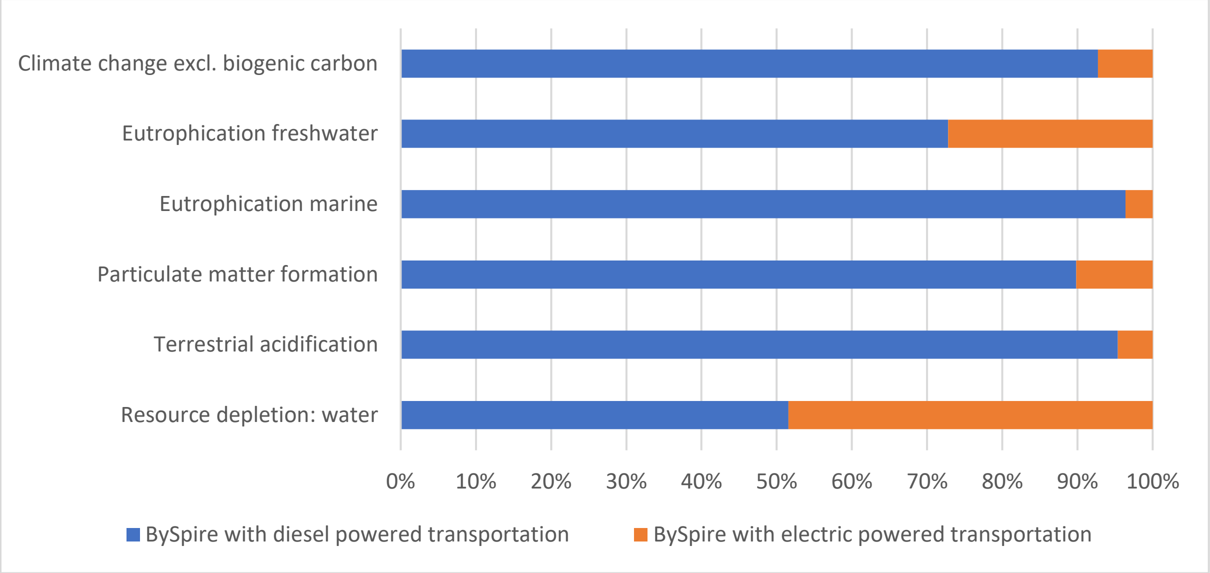

Figure 22: The impact of the vertical farming site in percentage with transportation powered by diesel vs powered by electricity.

In order to reduce the water usage and the impact from the tap water, especially on freshwater eutrophication, **rain water** could be used as an alternative water source, lowering the impact they have. Rainwater could be harvested and collected in rainwater collection tanks on the building and could replace the consumed water in the nursery and cultivation phase at BySpire site. However, if the rainwater collectors cannot be located on top of the building but needs to be placed on the ground, the possible impacts on the land use must be considered. The vertical farm “Maison Productive” in Montréal (Canada) uses successfully rainwater to supplement building’s greywater (wastewater produced in households or office buildings from streams without faecal contamination) in its production line for irrigation purposes (Thomaier et al., 2014). When rain water is used, the water should go through a filter to keep anything biological from entering the facility. Next to the use of a local resource and the replacement of the tap water, the harvest of rainwater has also the potential to delay and reduce the run-off of heavy rainfalls or storms which can be especially important in an urban setting like Oslo. Before this water source can be used research is needed concerning the water needed during the different seasons and how much rain water is available during these seasons. A combination where mainly rain water is used during the year, and in case of a long period without rain fall, tap water could help bridging the dry periods.

Another water source, although smaller than the rain water, is water retrieval through **dehumidification**. One of the biggest benefits of growing plants in a controlled environment is the potential of recovering water (Möller Voss, 2013). In the nursery and cultivation phases, water with all its nutrients enters the plants through the roots. Solutes get absorbed and the unused water is evaporated through the leaves in the air. This evaporated water can be gathered and reused. By placing dehumidification devices in the controlled environment room, vapor in the air can be effectively collected and all the water in circulation can be used (Despommier, 2010). Moreover, the water that evaporates is without any pollutants and has the quality of drinking water (Kalantari, Tahir, Lahijani, & Kalantari, 2017). A working example is the vapour heat pump in the EXE-kas of the Research Station for Vegetable Production in Belgium. In this heat pump air is dried through contact with a salt solution due to a heat mass exchanger, it also contains a mechanical vapour compression which will concentrates the salt solution This technology allows the humidity of a room to be controlled and returns water back into the system, while also heating the room. This prototype is currently still being tested but is showing very promising results towards the future (Van Linden, 2018; Wittemans & Bronchart, 2018). Using a dehumidification device creates a complete closed loop of the hydroponic system. In some cases, this creates the possibility of a becoming a more self-dependent company and saves financial as well as environmental sources (Möller Voss, 2013).

As mentioned before, **CO_2 enrichment** could lead to a more efficient production. The most recent studies are recommending a concentration of 1,000–2,000 ppm in the controlled environment room under light (Kozai , Niu, & Takagaki, 2015). Studies show that an enriched concentration of atmospheric CO_2 has a positive effect on growth and photosynthetic performance (McLeod & Long, 1999). Given that CO_2 enrichment is a proven method in CEA controlled facilities to increase the yields of the cultivated crop with 30% (Becker & Kläring, 2016), it is strange that BySpire does not use this yet. There are two possible reasons for its current choice. The first one is that BySpire does not have access to a CO_2 source. A good CO_2 source would be in close proximity and should not cost too much in terms of investment and transportation. In Norway, the government recommends greenhouses to burn fossil fuels like natural gas or propane for heating and CO_2 purposes (Norsk Gartnerforbunds, 2014), but more creative solutions are also invented. By building the CEA facility next to a CO_2 emitting factory, the CO_2 flue gas can be transported into the cultivation rooms without large expenses or losses. This provides benefits for both companies, lowering the CO_2 emissions to the atmosphere and increasing the yields (Miljogartneriet, 2018). But since the vertical farm is located inside an office building which is surrounded by other office buildings and warehouses, there is not an easy accessible CO_2 source close by. The burning of natural gas is not an option since the heating is already sufficient enough. The second reason is that the yield of the site is already stable and large enough and there is no need to increase this yield at the current facility, since there is no need to sell more vegetables than they currently produce. For the next vertical farming facility of BySpire, which will probably be bigger and more technologic advanced, tanks of CO_2 could be purchased from nearby companies producing CO_2 as a side effect. This would reduce the global warming potential of these companies and increase the yield of BySpire while other factors stay the same as now. To calculate the most effective CO_2 concentration for the plants of the vertical farm of BySpire further research is recommended.

7 Future research

More research will be needed in the future. A new LCA study should also include phases that were left out in this study for reasons listed in table 3. These phases include waste management, waste water management, fertilizer production and transportation, pesticide production and transportation and buildings and installations. Too less information could be gathered in this study due to of time and data constraints. An improved LCA with up to date databases is recommended. Since the used GaBi databases could occasionally not provide all necessary data needed for this LCA study, and recommendations and reviews are more in favour of using SimaPro or OpenLCA, it could be interesting to use another software and different databases in the future.

Regarding this new LCA study, other impact categories, like ozone depletion potential (ODP), photochemical ozone creation potential (POCP), and terrestrial eutrophication (TA), could and should be assessed when the excluded phases are included. They will give a more clarifying image of how BySpire is influencing the world. When BySpire wants to make a comparison with another food production method, or wants to install a new technology, it could be interesting to include the impact category: Cumulative energy demand. This category will show the energy needed in the different productions phases and is a handy tool in determining and comparing the energy efficiency. This can be calculated in an LCA following the method described by Hischier et al . New technologies and problems, like the fogponics BySpire is currently already trying out, or new cooling systems since the current one is not sufficient enough, could be addressed in a sustainable way.

In combination with a new LCA, a cost and benefit analysis could be used to determine also the financial part of new investments or parts of the LCA, like growing material, other transportation means or different cultivated vegetables.

Furthermore, the suggested improvements in 6 should be investigated:

- Shift from delivery truck on diesel to electric powered transportation;
- Rain water as an alternative water source for tap water;
- Water retrieval through dehumidification;
- More efficient production and higher yield, through CO_2 enrichment.

8 Conclusion

The intent of this study was to make an honest comparison of the environmental impact of locally cultivated vegetables (lettuce) by vertical farms and greenhouses in Norway, and the imported vegetables. Through the analysis of the LCA potential environmental impacts of the lettuce production cycle on the impact categories climate change, freshwater and marine eutrophication, particulate matter formation, terrestrial acidification and water depletion of the three different food production methods were identified. The included phases in the life cycle inventory were the nursery phase, cultivation phase, diesel mix at refinery phase, electricity grid mix phase, natural gas mix phase, transportation phase and the irrigation phase. The results indicate that the lowest impacts on the environment are related to the production of lettuce in the vertical farming site, while the largest impact is connected with the food import. In absolute values, BySpire has far lower emissions than the greenhouse and the food import. The low values of the vertical farm are explained by the use of closed environment agriculture technology, where the whole production process is cut off from the environment and working on optimal growing conditions due to the control of all relevant parameters (e.g. light, humidity, temperature). Only for the freshwater eutrophication and the water depletion categories the greenhouse has the lowest impact since it does not release phosphate emissions to the atmosphere and is using rainwater for irrigation purposes instead of ground water and surface water. In general, considering the environmental impact and sustainability of the food production methods, a significant factor was whether the system was closed, semi-closed or open since this determines the amount of emissions entering the environment. For the greenhouse site, however, the use and corresponding production of natural gas was a significant contributor to environmentally harmful emissions.

When looking at the different phases, it can be noticed that not for every phase in the life cycle of lettuce production, the vertical farm has the lowest impact it is and that consequently the phases of greenhouse site are in general performing better than the two other methods. For instance, the transportation phase of the greenhouse has a lower impact on all the impact categories than the transportation phase of the vertical farm and the food import since the greenhouse is using party electric powered trains while BySpire only uses trucks with lower load and empty space (leading to a higher environmental impact per lettuce); and the import case has the longest transportation way. Only because of the natural gas phase and the cultivation phase which are contributing a significant amount of environmentally harmful emissions, the greenhouse has an overall worse impact on the assessed impact categories than the vertical farming site.

Conclusively, life cycle assessment was a useful approach to assess the environmental performance of the three food production methods. However, the results were obtained with the presently available data and methodology, that didn’t allow a full cradle to grave analysis. Therefore, some further phases should be included in future LCA studies to have a more complete picture of the production cycle. This should include the packaging phase, the waste water management phase, fertilizer production and transportation phase, Pesticide production and transportation phase and Buildings and installations phase. However, to exploit the full environmental advantages of the vertical farming technology, extensive research is required to optimise the production process of BySpire in the most sustainable way. Future human resources can therefore be invested in the following research questions:

- What is the most efficient way to collect all needed measurements for an improved LCA?
- How can BySpire expand its network of local customers in Oslo?

- What are the costs and benefits of a rainwater collector, a dehumidification device and a CO_2 enrichment?

Generally speaking, the Nordic countries represent a good market for vertical farming technology, since they don’t have suitable conditions for agriculture in terms of climate and space, and on the other hand enjoy a high abundance of renewable and cheap energy, mainly in the form of hydroelectric power. Oslo is therefore definitely a good location. As a final reflection one can say that vertical farming as conducted by BySpire is at that this current stage not a replacement for conventional farming methods, but a promising complement for the local food market of Oslo.

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10 Appendices

10.1 Growing conditions lettuce in the Mediterranean region

The ideal growing conditions are coming from Starke Ayres lettuce production guideline (Starke Ayres, 2014). The conditions of the Albenga site (Bartzas, Zaharaki, & Komnitsas, 2015) in Italy, and the Granada site (Romero-Gámez, Audsley, & Suárez-Rey, 2014) and Cartagena site (Martinez-Mate et al., 2018) in Spain, are from different sources. The information about growth periods are extracted from the corresponding studies; the pH and rooting depth from interviews with responsible contact of the research facilities (Komnitsas, 2018; Martin-Gorriz, 2018; Romero-Gámez, 2018). They gave their estimates on what the soil conditions were during the studies. The temperatures are averages for the last 6 years for the areas that are collected from World Weather Online (World Weather Online, 2018).

Table 12: Key growing conditions for the Mediterranean open field cultivation for lettuce compared to the ideal conditions.

Indicators	Ideal conditions	Albenga site	Granada site	Cartagena site
Grow period	Annual	Annual	Annual	Annual
Soil structure	nitrogen-rich, loose soils	loamy soils	nitrogen-rich, loose soils	loamy soils
pH range	6.0 and 6.8.	6.2 – 6,9	6,6	6,4
Rooting depth	450 – 600mm.	500mm	550mm	550mm
Temperatures	Max = 25 °C; Ideal = 15 to 20 °C; Min = 7 °C	7 - 26	9 - 29	15 - 28

10.2 LCA models

10.2.1 Vertical farming site

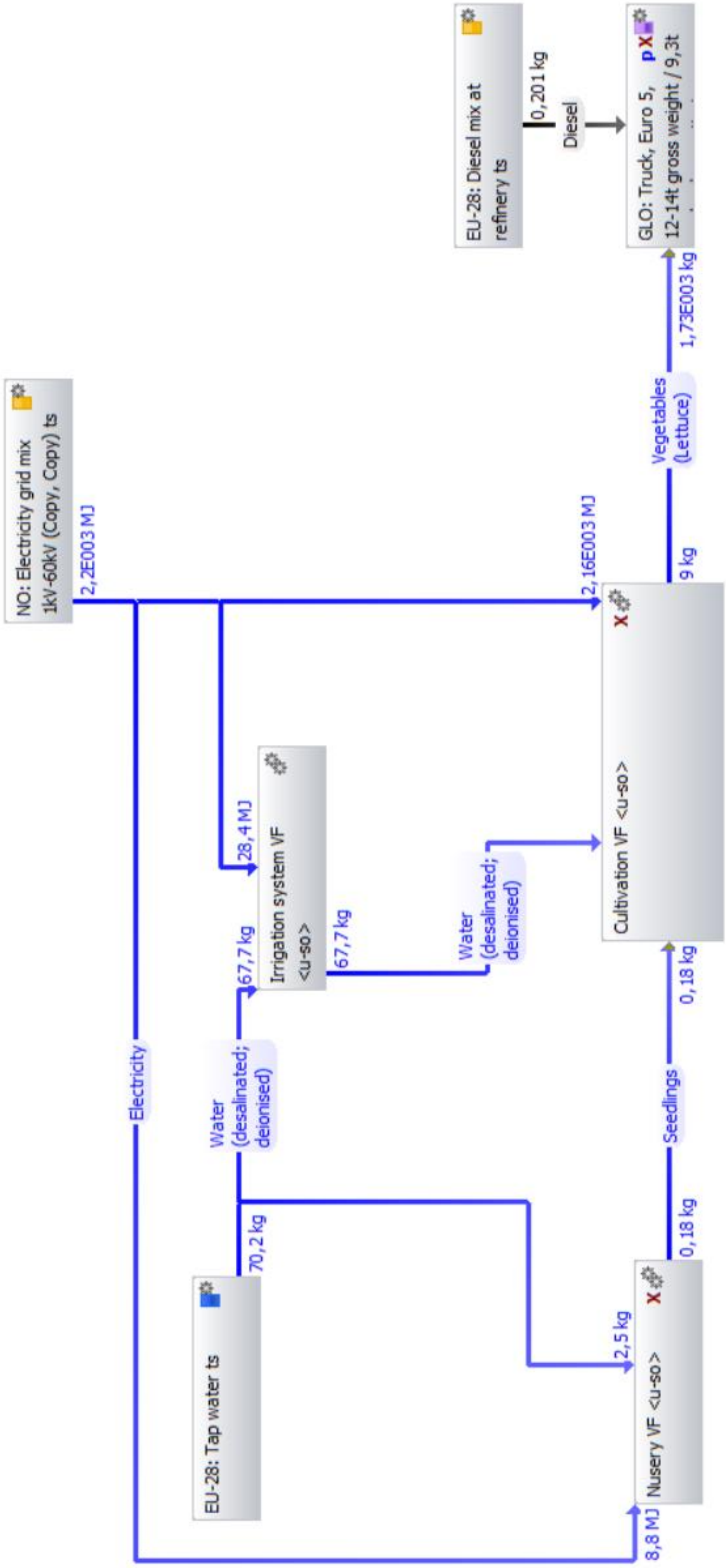

Figure 23: Screenshot of the plan of the processes of the vertical farming site. Not all flows are visible since some have an origin outside the system boundaries, like e.g. the production of fertilizers, but the reference and elementary flows are visible.

10.2.2 Greenhouse site

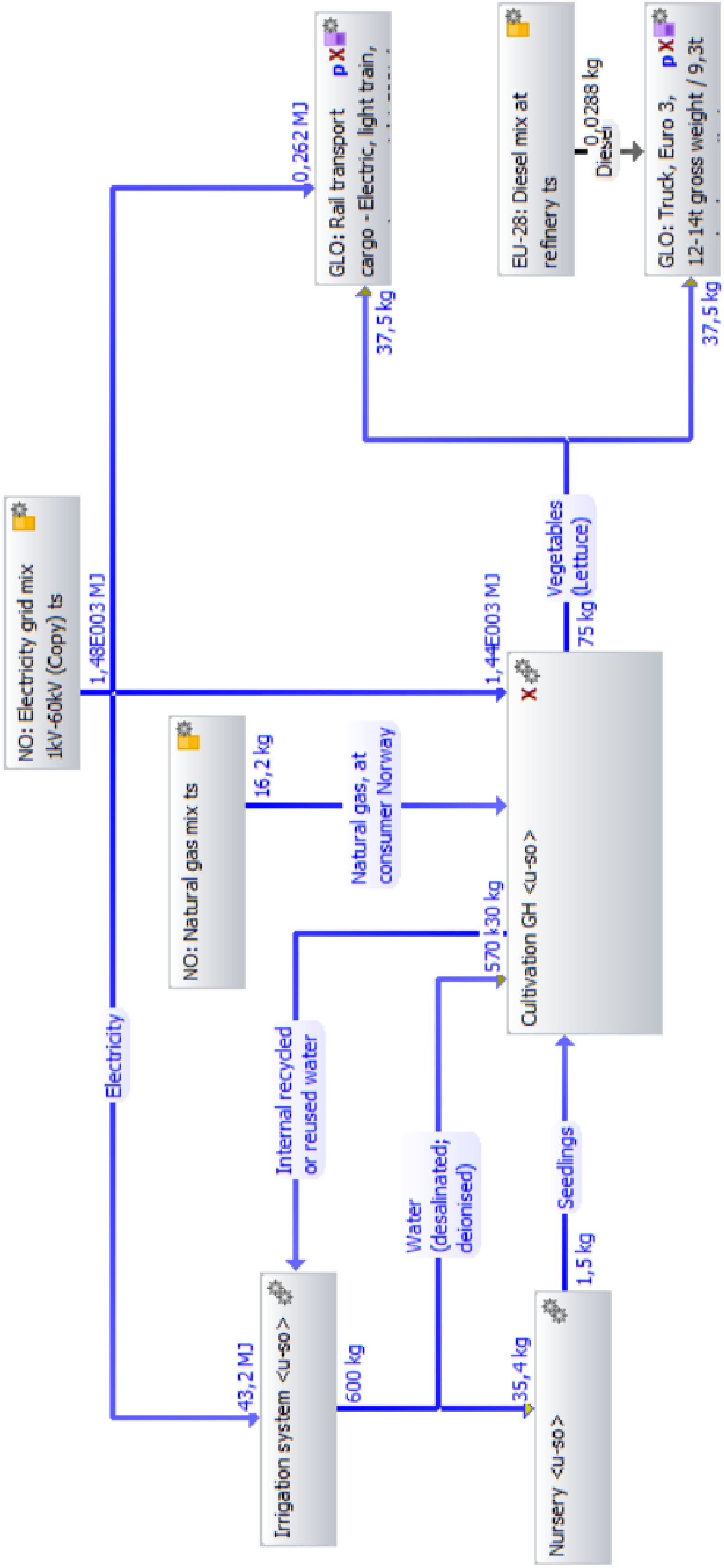

Figure 24: Screenshot of the plan of the processes of the greenhouse site. Not all flows are visible since some have an origin outside the system boundaries, like e.g. the production of fertilizers, but the reference and elementary flows are visible.

10.2.3 Import case

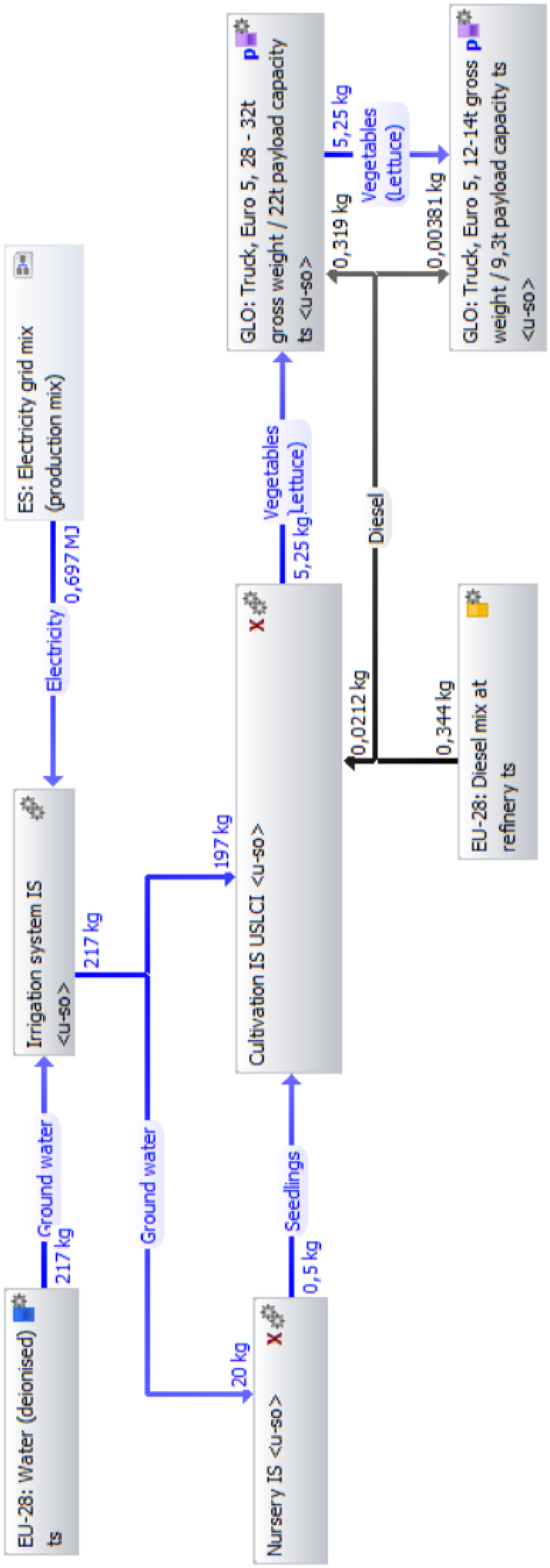

Figure 25: Screenshot of the plan of the processes of import case. Not all flows are visible since some have an origin outside the system boundaries, like e.g. the production of fertilizers, but the reference and elementary flows are visible.

10.2.4 Vertical farming site with electrical transportation

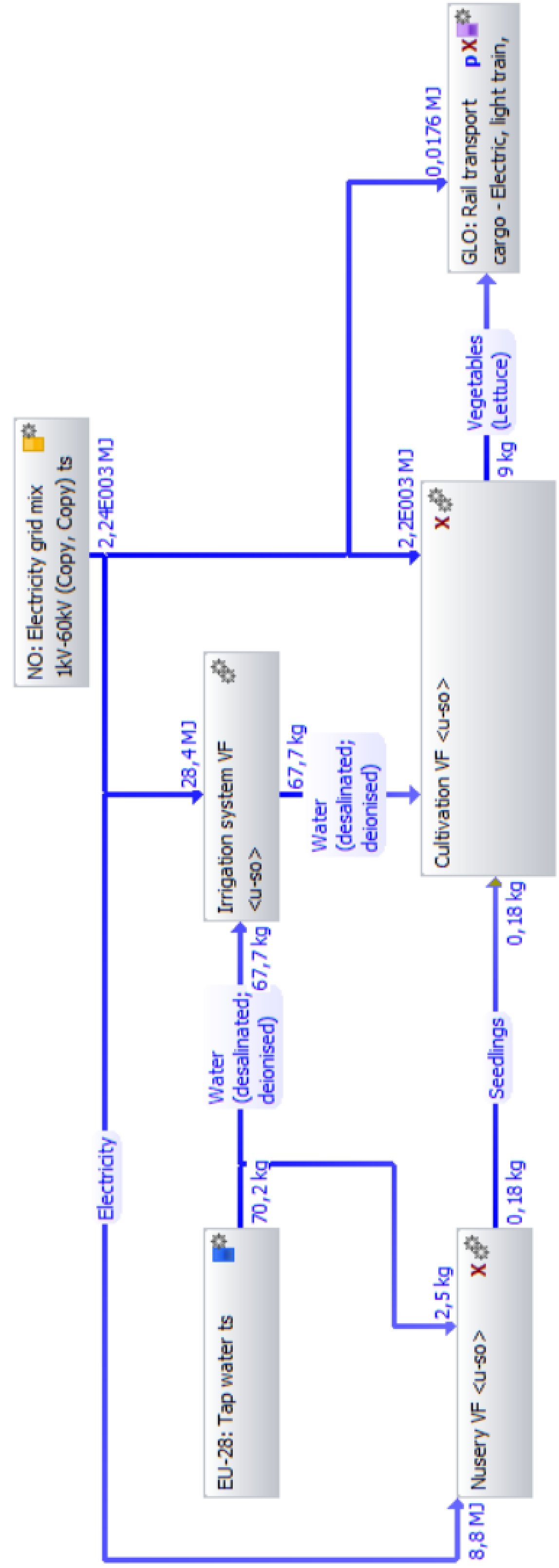

Figure 26: Screenshot of the plan of the processes of vertical farming site when the transport is powered by electricity (truck or very light train have the same impact according to GaBi, only the power input can change in different cases). Not all flows are visible since some have an origin outside the system boundaries, like e.g. the production of fertilizers, but the reference and elementary flows are visible.

10.3 Clarification of the impact categories

10.3.1 Climate change without biogenic carbon (CC)

This climate change impact category is here the same as the global warming potential on 100 years. Just like inside a greenhouse there is a small-scale greenhouse effect. This mechanism occurs also on a global scale. The shortwave radiation from the sun will be partly absorbed by the earth's surface, which leads to direct warming, and partly reflected as infrared radiation. In the troposphere, this reflected part will be absorbed by greenhouse gasses and will radiate in all directions. Since this also radiate back to the earth, this will result in a warming effect at the surface. Biogenic carbon emissions are CO_2 emissions connected to the natural carbon cycle.

Next to this natural mechanism, the greenhouse effect will be enhanced by human activities. Examples of greenhouse gasses that are increased by human activities are among others carbon dioxide (CO_2), methane (CH_4) and CFCs. The main processes of the natural and human greenhouse effect are presented in figure 27. The analysis of the greenhouse effect is considering the possible long term global effects with the global warming potential.

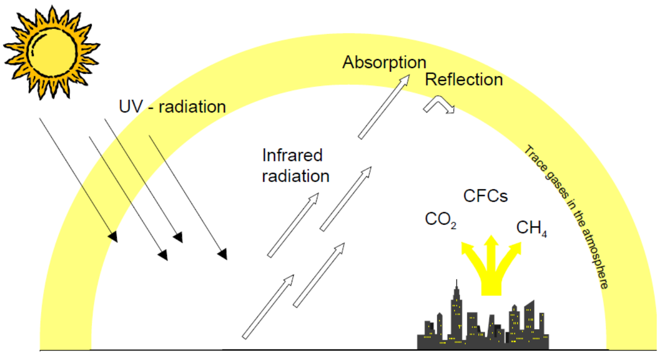

Figure 27: The working of the natural greenhouse effect and the main emissions of the anthropogenic greenhouse effect (PE International, 2010).

The climate change without biogenic carbon is calculated in carbon dioxide equivalents (CO_2-Equiv.). This means that the global warming potential of an emission is in relation to an emission CO_2 (PE International, 2010).

10.3.2 Freshwater eutrophication (FE)

Eutrophication is the enrichment of nutrients in a certain place. Freshwater eutrophication takes place in lakes, rivers, streams, etc. Air pollutants, wastewater and fertilization in agriculture all contribute to freshwater eutrophication.

The result of these emissions in the freshwater ecosystems is an augmented algae growth, which can block the sun and prevent it from reaching the lower levels of the waterbody. This will lead to a decrease in photosynthesis. On top of this, dead algae will need oxygen in order to decompose. The combination of these effects is causing a serious decrease in the oxygen concentration, which can lead to the dying of fauna and flora, and even to further decomposition without the presence of oxygen. This last decomposition produces hydrogen sulphide and methane. This could possibly lead to the destruction of the ecosystem.

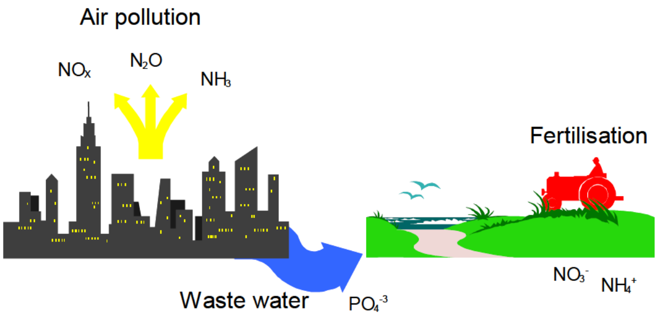

Figure 29: The main causes of nutrients responsible for freshwater (P) and marine (N) eutrophication. Industrial, domestic and agriculture runoff are the dominant contributors to eutrophication (PE International, 2010)

Phosphates are the primary limiting factors for freshwater eutrophication. Figure 29: The main causes of nutrients responsible for freshwater (P) and marine (N) eutrophication. Industrial, domestic and agriculture runoff are the dominant contributors to eutrophication shows the main causes of nutrients responsible for freshwater (P) and marine (N) eutrophication. Industrial, domestic and agriculture runoff are the dominant contributors to eutrophication. The freshwater eutrophication is calculated in phosphate equivalents (P-Equiv.) When looking at eutrophication, it is important to keep in mind that this is a problem with different effects in different regions (PE International, 2010).

10.3.3 Marine eutrophication (ME)

Eutrophication is the enrichment of nutrients in a certain place. Unlike freshwater eutrophication, marine eutrophication will take place in coastal areas. Air pollutants, wastewater and fertilization in agriculture all contribute to marine eutrophication.

The result of these emissions in coastal ecosystems is an augmented algae growth, which can block the sun and prevent it from reaching the lower levels of the waterbody. This will lead to a decrease in photosynthesis. On top of this, dead algae will need oxygen in order to decompose. The combination of these effects is causing a serious decrease in the oxygen concentration, which can lead to the dying of fauna and flora, and even to further decomposition without the presence of oxygen. This last decomposition produces hydrogen sulphide and methane. This could possibly lead to so called hypoxia or dead zones, which refers to a reduced level of oxygen in the water and what destroys whole ecosystems (National Ocean Service, 2018).

Nitrates are the primary limiting factors for marine eutrophication. Figure 29: The main causes of nutrients responsible for freshwater (P) and marine (N) eutrophication. Industrial, domestic and agriculture runoff are the dominant contributors to eutrophication shows the main causes of nutrients responsible for freshwater (P) and marine (N) eutrophication. Industrial, domestic and agriculture runoff are the dominant contributors to eutrophication. The marine eutrophication is calculated in nitrate equivalents (N-Equiv.) When looking at eutrophication, it is important to keep in mind that this is a problem with different effects in different regions (PE International, 2010).

10.3.4 Particulate matter formation (PMF)

Particulate matter or respiratory inorganics are made up of a heterogeneous mix and are distinguished by their size. PM10 are particles smaller than 10 µm in diameter (coarse particles), PM2.5 are particles smaller than 2.5 µm in diameter (fine particles) and PM1.0 are particles less than 1 µm in diameter (ultra-fine particles).

As seen in figure 29, particulate matter originates from different sources. The main human sources of these particles are connected to mechanical processes and operation conditions like crushing, transport of non-cohesive materials, ploughing, and construction sites. These are the biggest anthropogenic particles. Also, from human origin are chemical or thermal processes and operation conditions, where particles are formed and the state of a material is changed due to chemical reactions or high-temperature that are followed by evaporation and condensation like the combustion of fuels and biomass. These are normally the smaller anthropogenic particles. Particulate matter emissions from natural origin are often related to natural circumstances like for example forest fires, pollen, volcanic eruptions, fungi and bacteria. The formation of particulate matter can be divided also into three types: primary particulate matter that is released directly into the atmosphere by many human and natural sources; secondary particulate matter which is formed by physical and chemical reactions from other pollutants; resuspended particulate matter is particulate matter that is returned into the air through wind action or road traffic after it has been deposited.

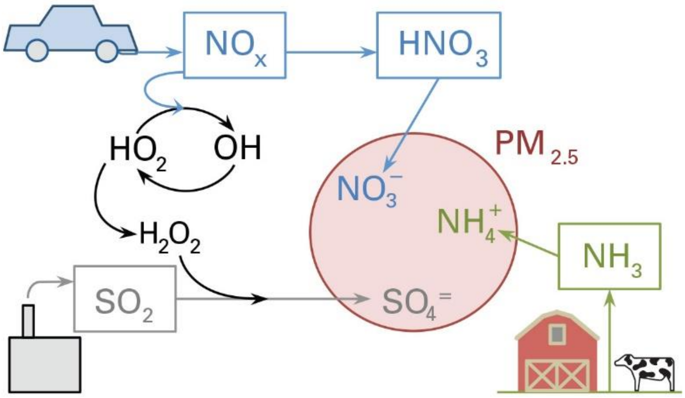

Figure 30: It shows the three major emissions that form fine primary particulate matter: nitrogen oxides (NO_X) largely from vehicles, sulphur dioxide (SO_2) from power plants and industrial facilities, and ammonia (NH_3) from agricultural activities. Sunlight and chemical reactions in the atmosphere convert the emissions to new chemical species that can combine to form tiny secondary particles with a diameter of PM2.5 (Stauffer, 2016).

Particles often exist out of salts (nitrates, sulphates, carbonates, chlorides), organic carbon compounds (PAHs, oxides), heavy metals and black carbon. Black carbon is the product of an incomplete combustion of fossil fuels and biomass.

By absorbing and diffusing light, suspended particulate matter can reduce the visibility and affect the climate. When they deposit on the soil, they will contribute to the physical and chemical degradation of materials. When they deposit on vegetation, they can suffocate the plants and prevent further photosynthesis. From the point of view of heat, particulate matter has already been linked to certain breading disorders, asthma attacks and an increasing number of deaths from cardiovascular or respiratory diseases. The particulate matter formation is calculated in PM2.5-equivalents. It must be taken into account that these emissions can be carried far from the place they are emitted, and effecting regions without emitters of particulate matter (Citepa, 2018).

10.3.5 Terrestrial acidification (TA)

The main reason behind the acidification of soils and waters is the transformation of air pollutants into acids. This will lead to a decrease in the pH value of rainwater from 5,6 to 4 or even lower. The primary pollutants are sulphur dioxide, nitrogen oxide and their corresponding acids (H_2SO_4 und HNO_3) are responsible for this effect. These lower pH values are damaging ecosystems, whereby the most well know impact is forest dieback.

There are direct and indirect effects of acidification. Direct examples are that

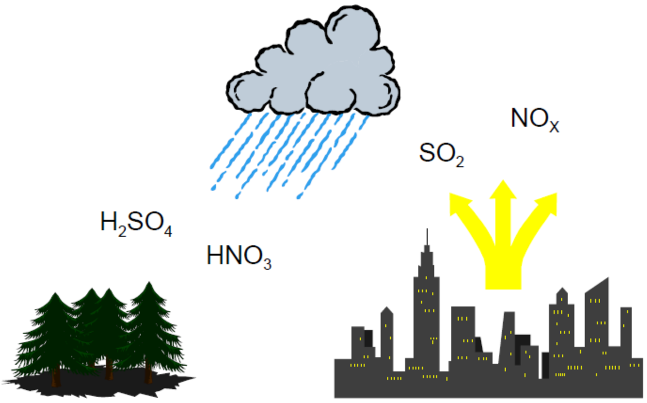

Figure 31: A simplistic representation of the most important ways of impact that are causing acidification (PE International, 2010).

nutrients can wash out of the soil, an increased solubility of metals into the soil, etc. An indirect example is building materials that are damaged due to corrosion. When looking at acidification, it is important to keep in mind that this is a global problem, with different regional effects. Figure 31: A simplistic representation of the most important ways of impact that are causing acidification (PE International, 2010). shows the most important impact acidification has. The terrestrial acidification is given in mole H$^+$ -equivalents. This can be described as the ability of certain pollutants to release H$^+$ -ions (PE International, 2010).

10.3.6 Water depletion (WD)

The (blue) water depletion can be divided into freshwater depletion and marine or coastal water depletion. The impact of water depletion is addressed in terms of quality and quantity, this means the decrease in water availability of a certain quality. This impact category focusses on the freshwater depletion since the depletion of marine or coastal water systems has a small impact. Only in the case of extreme water extraction this could result in the transformation of the quality, like for example an increase in the salinity.

The freshwater (blue water) depletion can be divided into depletion out of groundwater and surface water sources. Figure 32: A scetch of the different ground and surface sources used by industry and agriculture. Artesian Aquifer is under pressure, with flowing well (when pressure is high) and not flowing well (when pressure is low), a spring where the water table is higher than groundwater, can cause surface waters like stream and pond (U.S. Geological Survey, 2014). shows the different aquifers of the ground water and a stream for surface water. These sources are often controlled at a local level for the depletion amount. The water that is extracted from these sources has to be available for agricultural, industrial and urban drinking purposes. Besides this the natural environment should be preserved by keeping defined quality levels for the aquatic and terrestrial species. Natural and human interventions will determine the water source quality in a specific area like for example the acidity, salinity and toxicity. It is important to notice that rain water (green water) does not fall under the categories freshwater in this case and is therefore not taken into account for the LCA calculations. The water depletion is calculated in water consumption (m^3 equivalents). Water depletion is an impact category that has a direct local impact but can have indirect impacts on a larger scale (PE International, 2010).

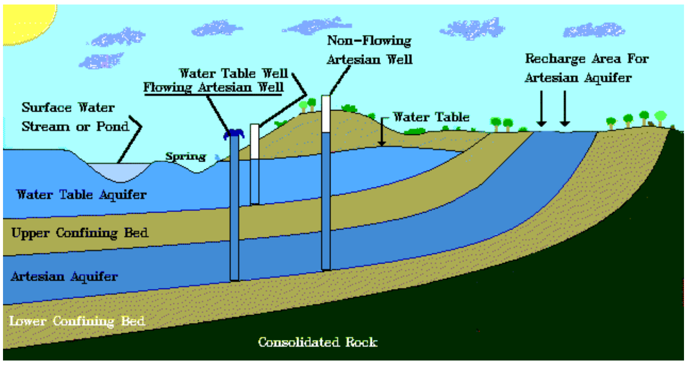

Figure 32: A scetch of the different ground and surface sources used by industry and agriculture. Artesian Aquifer is under pressure, with flowing well (when pressure is high) and not flowing well (when pressure is low), a spring where the water table is higher than groundwater, can cause surface waters like stream and pond (U.S. Geological Survey, 2014).

10.4 Data sources

Table 13: LCA phases of the three different food production methods with their corresponding type of source, data source and additional information.

Process phase	Type	Data source	Additional information
Vertical farming			
Cultivation	ED	Own data collection and measurements at BySpire site	From older data collection and measurement equipment. Quantity water and fertilizers; number of watts for the electrical devices; yield; production surface; time
Diesel mix at refinery	GD	GaBi education database 2017	General information for European Union
Tap water	GD	GaBi education database 2017	General information for European Union
Truck	GD	GaBi education database 2017	General information for a global scale, for a Euro 5 engine with 12-14t gross weight and 9,3t payload capacity
Irrigation system	ED	Own data collection and measurements at BySpire site	From older data collection and measurement equipment. Quantity water; number of watts for the electrical devices.
Electricity grid mix 1kV-60kV	GD	GaBi education database 2017	Information from the Norwegian electricity grid
Nursery	ED	Own data collection and measurements at BySpire site	From older data collection and measurement equipment. Quantity water and fertilizers; number of watts for the electrical devices; seedlings; production surface; time
Greenhouse			
Cultivation	ED, SD	Data measurements provided by Hanasand Gård; Agribalyse database v.1.2	Quantity water, natural gas, electricity, yield; kinds of pesticides and fertilizers and almonds; production surface; emissions to air
Diesel mix at refinery	GD	GaBi education database 2017	General information for European Union
Rail transport	GD	GaBi education database 2017	General information for a global scale, for an electric light train with total weight 500 ton and a 363-ton payload capacity
Truck	GD	GaBi education database 2017	General information for a global scale, for a Euro 3 engine with 12-14t gross weight and 9,3t payload capacity
Irrigation system	ED	Data measurements provided by Hanasand Gård	Quantity water; number of watts for the electrical devices.

Electricity grid mix 1kV-60kV	GD	GaBi education database 2017	Information from the Norwegian electricity grid
Natural gas mix	GD	GaBi education database 2017	Information for the Norwegian natural gas production.
Nursery	ED, SD	Data measurements provided by Hanasand Gård;	Quantity water and fertilizers; number of watts for the electrical devices; seedlings; production surface; time;
Import			
Cultivation	LD, SD	(Bartzas et al., 2015; Martinez-Mate et al., 2018; Romero-Gámez et al., 2014), Agribalyse database v.1.2	Information regarding water use, fertilizer use, pesticide use, electricity use and diesel use; emissions to air, water and soil
Diesel mix at refinery	GD	GaBi education database 2017	General information for European Union
Water (deionised)	GD	GaBi education database 2017	General information for European Union
Truck	GD	GaBi education database 2017	General information for a global scale, for a Euro 5 engine with 12-14t gross weight and 9,3t payload capacity
Truck	GD	GaBi education database 2017	General information for a global scale, for a Euro 5 engine with 28-32t gross weight and 22t payload capacity
Irrigation system	LD	(Bartzas et al., 2015; Martinez-Mate et al., 2018; Romero-Gámez et al., 2014)	Information regarding water use, electricity use
Electricity grid mix	GD	GaBi education database 2017	Information from the Norwegian electricity grid
Nursery	LD, SD	(Bartzas et al., 2015; Martinez-Mate et al., 2018; Romero-Gámez et al., 2014), Agribalyse database v.1.2	Information regarding water use, fertilizer use, pesticide use, electricity use and diesel use; emissions to air, water and soil
ED: experimental raw data, SD: specified database, GD: generic database, LD: literature data.			

10.5 Data concerning the three food production methods

Table 14: Table with all the inflows, outflows and transportation distances of the different food production methods in an average year. The data is corresponding with 1 functional unit.

Parameter		**Averages Import**		**Greenhouse**		**Vertical farming**	
		Amount	Unit	Amount	Unit	Amount	Unit
Inflow							
Nursery	Water	20	L/m^2	35,4	L/m^2	2,5	L/m^2
	Electricity	0	kWh/m^2			2,446	kWh/m^2
Fertiliser	N fertilizer (as N)	0,01180	kg/m^2	0,88	kg/m^2		
	P fertilizer (as P_2O_5)	0,01173	kg/m^2	0,13	kg/m^2		
	K fertilizer (as K_2O)	0,02840	kg/m^2	0,25	kg/m^2		
	NPK	0	kg/m^2	0	kg/m^2	1,039	kg/m^2
Irrigation water	Use	217,27	L/m^2	600	L/m^2	67,683	L/m^2
	Reuse water	0	L/m^2	30	L/m^2	Unknown	L/m^2
Electricity	Irrigation (Pumps, air)	0,133	kWh/m^2	12	kWh/m^2	3,942	kWh/m^2
	Grow lights	0	kWh/m^2	400	kWh/m^2	591,3	kWh/m^2
	Heating/cooling	0	kWh/m^2	0	kWh/m^2	19,71	kWh/m^2
	Others	0	kWh/m^2	0	kWh/m^2		kWh/m^2
Natural gas		0	kWh/m^2	235	kWh/m^2	0	kWh/m^2
Diesel	Machinery	0,02526	L/m^2	0	L/m^2	0	L/m^2
Compost		2,01576	kg/m^2	0	kg/m^2	0	kg/m^2
Pesticides	Herbicides	0,00096	kg/m^2	0	kg/m^2	0	kg/m^2
	Fungicides	0,00046	kg/m^2	0	kg/m^2	0	kg/m^2
	Insecticides	0,00064	kg/m^2	0	kg/m^2	0	kg/m^2
Surface		17333	m^2	24000	m^2	120	m^2
Outflow							
Seedlings		0,5	kg/m^2	1,5	kg/m^2	0,18	km/m^2
Yield		5,34	kg/m^2	75	kg/m^2	99	km/m^2

Waste water		Unknown		Unknown		Unknown	
Transportation		3427	km (truck)	35,16	km (truck)	5,5	km (truck)
		34,4	km (truck)	39,31	km (train)		

10.6 Data concerning the Mediterranean import

Table 15: Table with all the inflow and outflows for the Mediterranean sites in an average year in the corresponding location, that was used as a basis for the averages used in the overall LCA study. The data is corresponding to 1 functional unit.

		Granada site		**Albenga site**		**Cartagena site**		**Average data**	
		Amount	Unit	Amount	Unit	Amount	Unit	Amount	Unit
Inflows									
Fertiliser	N fertilizer (as N)	84	kg/ha	150	kg/ha	120	kg/ha	118	kg/ha
	P fertilizer (as P_2O_5)	92	kg/ha	160	kg/ha	100	kg/ha	117	kg/ha
	K fertilizer (as K_2O)	220	kg/ha	400	kg/ha	232	kg/ha	284	kg/ha
Irrigation water		1218	m^3/ha	1600	m3/ha	3700	m3 ha	2 173	m3/ha
Electricity	Pumps (1) /irrigation (3)	99,303	kWh/ha	130,45	kWh/ha	3774	kWh/ha	1 335	kWh/ha
Diesel	Machinery	45,09	L/ha	70,82533	L/ha	642	L/ha1	253	L/ha1
Compost		20000	kg/ha	25472,943	kg/ha	15000	kg/ha	20 158	kg/ha
Pesticides	Herbicides	7,93462	kg/ha	8	kg/ha	13	kg/ha	10	kg/ha
	Fungicides	3,76008	kg/ha	4	kg/ha	6	kg/ha	5	kg/ha
	Insecticides	5,22565	kg/ha	6	kg/ha	8	kg/ha	6	kg/ha
Outflows									
yield		42400	kg/ha	66600	kg/ha	51150	kg/ha	53 383	kg/ha
Surface		12	ha	22	ha	18	ha	17,333	ha

10.7 Comparison between food production methods

Table 16: List of the impact of the different phases per food production method. Next to the corresponding absolute value is the percentage that indicates how much the absolute value contributes to the total emission for a specific impact category. (CC: climate chance; FE: freshwater eutrophication; ME: marine eutrophication; PMF: particle matter formation; TA: terrestrial acidification and WD: water depletion). A colour code was added to show clearly which phase has the no or lowest (green), middle (orange) or biggest (red) impact. The different transports of one food production method are looked at as one whole.

	CC	FE	ME	PMF	TA	WD
Cultivation VF	0	0	0	0	0	1,04E-02
Cultivation GH	6,58E-02	0	4,15E-04	3,13E-05	1,82E-03	0
Cultivation IM	6,58E-02	2,74E-05	1,15E-03	3,13E-05	1,82E-03	7,84E-02
Diesel mix at refinery VF	1,09E-01	3,33E-06	1,41E-04	2,36E-05	5,64E-04	8,42E-04
Diesel mix at refinery GH	1,55E-02	4,76E-07	2,02E-05	3,38E-06	8,08E-05	1,21E-04
Diesel mix at refinery IM	1,86E-01	5,69E-06	2,42E-04	4,04E-05	9,66E-04	1,44E-03
Electricity grid mix VF	3,58E-02	9,45E-08	1,37E-05	2,14E-06	4,18E-05	3,26E-04
Electricity grid mix GH	3,56E-02	9,39E-08	1,36E-05	2,08E-06	4,16E-05	3,18E-04
Electricity grid mix IM	6,65E-02	8,20E-08	4,99E-05	1,02E-05	2,15E-04	8,42E-03
Truck VF	6,09E-01	0	8,93E-04	3,23E-05	1,71E-03	0
Truck GH	8,72E-02	0	4,02E-04	2,13E-05	7,65E-04	0
Rail transport GH	0	0	0	0	0	0
Truck 1 IM	9,64E-01	0	1,38E-03	5,37E-05	2,64E-03	0
Truck 2 IM	1,16E-02	0	1,69E-05	6,13E-07	3,25E-05	0
Nursery VF	0	0	0	0	0	1,83E-03
Nursery GH	0	0	0	0	0	0
Nursery IM	3,87E-03	1,62E-06	6,79E-05	1,84E-06	1,07E-04	1,96E-02
Tap water VF	2,47E-02	1,88E-06	2,61E-05	5,02E-06	7,34E-05	0
Rain water GH	0	0	0	0	0	0
Deionised water IM	9,31E-01	3,90E-05	9,47E-04	1,43E-04	2,71E-03	0
Natural gas mix GH	1,38E+00	2,44E-07	7,87E-04	1,41E-04	3,30E-03	1,46E-04
Total impact	**4,59E+00**	**7,99E-05**	**6,57E-03**	**5,43E-04**	**1,69E-02**	**1,22E-01**

10.8 Electricity grid in Spain and Norway

Table 17: The sources of the Spanish and Norwegian electricity grid as used in the GaBi education database. Other studies are stating similar numbers.

Energy source	Spanish electricity grid	Norwegian electricity grid
Geothermal	0	0
Biogas	0,32	0,01
Biomass solid	1,34	0,15
Coal gases	0,49	0,07
Hard coal	13,6	0,03
Heavy fuel oil	4,85	0,02
Hydro	14,48	96,22
Lignite	0,87	0
Natural gas	20,13	1,83
Nuclear	20,01	0
Peat	0	0
Photovoltaics	4,48	0
Solar thermal	0	0
Wind	19,01	1,41
Waste-to-energy	0,42	0,26