Vertical Farming: A future perspective or a mere conceptual idea?

A Comprehensive Life Cycle Analysis on the environmental impact of a vertical farm compared to rural agriculture in the US

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Preface

In front of you lies the last report that I will write in my college days, the closing statement of a very joyful and expressive period in my life in which I have learned a lot. This report is a product of the research that was carried out to complete the master's degree in Water Management and Engineering at the University of Twente in Enschede. As the title suggests, the report is based on research in vertical farming. More specific, the environmental impacts of vertical farming compared to rural agriculture through a Life Cycle Analysis (LCA), based on a fictive case study in Oklahoma.

Despite the Civil Engineering knowledge obtained in my bachelor studies, bachelor thesis and master studies, writing this master thesis was a proper challenge. Even though this subject (belonging more to environmental studies) diverted from my original interests in water engineering, the most challenging factor was the lack of data and other research on the subject. Being a relatively new farming technique and a possible solution to modern day food problems, spoke to me and during this study I gained a lot of knowledge, not only on this subject, but on being a researcher in general. For this I am thankful and even though I will not become a full time researcher, I hope to eventually use these skills in the work field.

First of all, I would like to show my gratitude towards my daily thesis supervisor, Karina Vink, for the guidance and encouragement you have given throughout this thesis. If I had any questions I could always ask and your support, feedback and interesting ideas on the subject has given me clear directions and more joy writing this thesis. I would also like to thank my main thesis supervisor, Maarten Krol, for guiding me in both my bachelor and master thesis. Even though, this is not your main subject, you helped me to keep a clear structure and keep in mind the red thread throughout the thesis.

Secondly, I would like to thank Marten Toxopeus, Strahinja Jokic and Silu Bhochhibhoya for helping me with the program GaBi and my computer model. I would like to thank you for the quick response on all my questions and for the conversations and discussions we had that shed light on some of the improvements I could make as well as giving me new ideas on the subject at hand.

Last but not least, I would like to give my appreciation to my parents, my brother, my friends and my girlfriend for all the discussions, support and feedback on the thesis. With my injuries in early 2020, following a global pandemic (COVID-19) in march and still going, I would like to thank my parents for helping me and giving me a place to stay when I was immobilized and I would like to thank my friends and my girlfriend for distracting me once in a while with video calls or one on one visits, while writing this thesis at home in a pandemic lock down.

I have written this report in honor of Arjen Hoekstra. Arjen Hoekstra was a pioneer in water, environment and sustainability studies, the founder of this master thesis subject and a very driven professor. Sadly, shortly after the first conversation on this master thesis subject, Arjen Hoekstra passed away. Therefore, I would like to dedicate this thesis to him and I hope I have taken this thesis subject in a direction that he would have wanted.

I hope you enjoy reading this report!

Zwolle, 10/09/2020
Rob Wildeman

Summary

It is expected that the population of the earth will keep rising in the coming decades, surpassing 9 billion in 2050. This rise in population causes pressure on agricultural land and food production, as well as global warming and resource depletion. In order to mitigate all these problems, food production per unit area has to be maximized and be as efficient and non-polluting as possible. Revolutionary techniques such as technological advancements in rural agriculture, greenhouses and urban agriculture are being studied to find possible solutions to the major problems at hand. One of these techniques in urban agriculture is called Vertical Farming (VF) - the urban farming of eatable crops inside a building with an ideal climate regulated by (semi) closed loop systems – and is believed to be the perfect solution to both the agricultural food problems and the climate change and resource depletion problems. To test this theory, this study creates and analyzes a fictive vertical farm in the state of Oklahoma USA, based on the local climate characteristics and peer-reviewed sources on vertical farming systems. With the use of a Life Cycle Analysis (LCA), the environmental impacts of the lettuce production in this farm are calculated and the results are compared to the rural agriculture of the same crop (located in California USA).

This study shows that most of the claims made on the technique of vertical farming are in fact true. A vertical farm has a higher yield than rural agriculture, with more than 80 times the yield of open field agriculture, due to multiple harvests a year and a higher plant density, has a lower water footprint, with 18 times less water used, due to the semi-closed loop water system, has a lower freshwater pollution rate, with a eutrophication reduction of 70-90%, due to minor use of excessive fertilizers and has a major decrease in transport distance and thus a decrease CO_2 emissions during transport. However, due to the large electricity demand to keep all high-end systems running in a VF, the CO_2 emissions of a vertical farm are actually higher than that of rural agriculture. In fact, this high electricity use causes a lot of spikes in the graphs of almost all impact category, especially in the Terrestrial Acidification and the Land Footprint. Contrary to many beliefs, stating that the Land Footprint is only linked to the surface area in relation to plant density ratio, the Vertical Farm actually has a massive Land Footprint, due to the fact that electricity production and other production steps in the LCA also require a lot of land use. The results demonstrate that a Vertical Farm, just like any other agriculture technique, has its positives and negatives. Even though, it can help solve problems such as large food shortages and minimal water use, it has negative impacts elsewhere, in this case on land footprint, acidification of the ground and climate change.

This study highlights the whole framework of a vertical farm and its characteristics, the positives and negatives of vertical farming and the importance of analyzing every step in a life cycle of a product or system. The thesis concludes by addressing the possibility of more efficient crop lay-outs and sustainable systems as well as the vertical farm's potential in other fields of study such as extreme climates and aerospace.

Keywords Vertical Farming, Life Cycle Analysis, LCA, lettuce, agriculture, environmental impact, indoor cultivation, climate change, water footprint, land use

Samenvatting

Het wordt verwacht dat de groei van de wereldbevolking aankomende decennia zal blijven toenemen tot meer dan 9 miljard in 2050. Deze bevolkingsgroei veroorzaakt druk op de landbouw en de voedselproductie, evenals opwarming van de aarde en uitputting van grondstoffen. Om al deze problemen te verminderen, moet de voedselproductie per oppervlakte-eenheid worden gemaximaliseerd en zo efficiënt en niet-vervuilend mogelijk gemaakt worden. Revolutionaire technieken zoals technologische vooruitgang in standaard landbouw, kassen en 'urban farming' worden bestudeerd om mogelijke oplossingen te vinden voor deze grote problemen. Een van deze technieken in 'urban farming; wordt Vertical Farming (VF) genoemd – het verbouwen van eetbare gewassen in een gebouw met een ideaal klimaat gereguleerd door (semi-) gesloten systemen - en wordt beschouwd als de perfecte oplossing voor zowel voedsel problemen, klimaatverandering en uitputting van grondstoffen. Om deze theorie te testen, creëert en analyseert deze studie een fictieve Vertical Farm in de staat Oklahoma, VS, gebaseerd op de lokale klimaatkenmerken en peer-reviewed bronnen over Vertical Farming. Met behulp van een Life Cycle Analysis (LCA) worden de milieueffecten van de slaproductie in de Vertical Farm berekend en worden de resultaten vergeleken met de standaard landbouw van hetzelfde gewas (gevestigd in Californië, VS).

Deze studie laat zien dat de meeste beweringen die over de techniek van vertical farming worden gedaan, inderdaad waar zijn. Een Vertical Farm heeft een hogere opbrengst dan gewas verbouwing op het platteland, met meer dan 80 keer de opbrengst van normale gewasverbouwing, dankzij meerdere oogsten per jaar en een hogere plantdichtheid, heeft een lagere watervoetafdruk, met 18 keer minder waterverbruik, dankzij het semi- gesloten watersysteem, heeft een lager zoetwaterverontreinigingspercentage, met een vermindering van eutrofiëring van 70-90% door een gering gebruik van overtollige meststoffen en heeft een grote afname in transportafstand en daarmee een lagere CO_2-uitstoot. Echter, vanwege de grote elektriciteitsvraag om alle high-end systemen in een Vertical Farm draaiende te houden, is de CO_2-uitstoot van een vertical farm hoger dan die van standaard andbouw. In feite veroorzaakt dit hoge elektriciteitsverbruik veel pieken in de grafieken van bijna alle impactcategorieën, vooral in de Terrestrial Acidification (verzuring) en de Land Footprint (landgebruik). In tegenstelling tot wat vaak wordt beweerd, heeft de Vertical Farm een enorme Land Footprint in vergelijking met standaard landbouw. Veel studies over vertical farming suggereren vaak dat de Land Footprint alleen gekoppeld is aan het oppervlak van het gebouw in relatie tot de plantdichtheid, echter vanwege elektriciteitsproductie en andere productiestappen in de LCA neemt de Land Footprint hard toe. De resultaten tonen aan dat een Vertical Farm, net als elke andere landbouwtechniek, zijn voor- en nadelen heeft. Hoewel het kan helpen bij het oplossen van problemen zoals grote voedseltekorten en minimaal watergebruik, heeft het elders negatieve gevolgen, in dit geval op het landgebruik, verzuring van de grond en klimaatverandering.

Deze studie belicht de volledige structuur van een Vertical Farm en zijn kenmerken, de voor- en nadelen van Vertical Farming en het belang van het analyseren van elke stap in een levenscyclus van een product of systeem. Het proefschrift sluit af met de mogelijkheid voor een efficiëntere gewasindelingen en duurzame systemen, evenals het potentieel van de Vertical Farm in andere studiegebieden, zoals extreme klimaten en in de ruimte.

Keywords Vertical Farming, Life Cycle Analysis, LCA, sla, landbouw, milieu-impact, binnenteelt, klimaat verandering, Water Footprint, landgebruik

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Glossary

VF	Vertical Farming – the act of cultivating crops inside a building with an ideal growing climate regulated by systems.
Plant Factory (PF)	A different terminology for vertical farming, often used in Asian countries, usually lower rise buildings.
Urban Agriculture	The act of growing crops in an urban area, techniques that fall under this term are for example green walls, rooftop gardens and vertical farming.
Life Cycle Analysis / Life Cycle Assessment (LCA)	An analysis based on the materials and resources needed for a product, that takes into account multiple steps in the life cycle of a product or system and that calculates the product's impact on the local and global environment.
Closed loop system	A system that uses no outside resources, besides the initial input, and produces no waste, as it recycles all its own components in the process.
Environmental impact	Any change to the environment, whether adverse or beneficial. The effect that people's actions have on the environment.
GHG emissions	Green house gas emissions – emissions such as CO_2 and methane that retain heat and therefore increase the greenhouse effect and thus global warming
rural agriculture	Standard agriculture in a rural area, consisting of open field and greenhouse agriculture
Hydroponics	An irrigation method that consists of a water tank, gutters and a cycling water system
pathogens	A bacterium, virus, or other micro-organism that can cause disease
Footprint	A measure how fast we consume resources and generate waste
Gray Water Footprint	Indicator of freshwater pollution that can be associated with the production of a product over its full supply chain
hinterland	The remote areas of a country away from the city (in this instance)
urbanization	An increased number of people moving from rural land to urban areas
leafy greens	Plant leaves eaten as a vegetable, often short-lived plants
precipitation	Any kind of weather condition where water in any form falls from the sky
aquifer	A large underground layer of water-bearing permeable rock, rock fractures or unconsolidated materials
Highrise	A high building with many stories
life expectancy / longevity	The average period that a building material is expected to 'live'
ArcGIS	A geospatial mapping and analytics program
R-value	A measure of how well a two-dimensional barrier resists conductive flow of heat (insulation value)
germination	Growing stage in which seeds are put in saturated mats and grow to seedlings (small plants)
nursery	Growing stage in which seedlings grow into larger plants
dry weight	The weight of a product without any water content
nutrient solution	A carefully proportioned liquid fertilizer used in a hydroponic system
NFT	Nutrient Flow Technique – A hydroponic technique in which a very shallow stream of water containing all the dissolved nutrients required for plant growth is re-circulated past the bare roots of the plants in a watertight gully.
PPFD	Photosynthetic Photon Flux Density – It measures the amount of PAR that actually arrives at the plant
PAR	Photosynthetic Active Radiation – It defines the type of light needed to support photosynthesis

DLI	Daily Light Integral – describes the number of photosynthetically active photons that are delivered to a specific area over a 24 hour period
HVAC	Heating, ventilation and air conditioning system
COP	Coefficient Of Performance - The ratio of the cooling load of the culture room to the electricity consumption of the air conditioners
VPD	Vapor Pressure Deficit – The difference between the amount of moisture in the air and how much moisture the air can hold when it is saturated
BMS	Building management system
ISO	An International Standard published by the International Organization for Standardization
LCIA	Life Cycle Inventory Analysis – The compilation and quantification of inputs and outputs for a given product system through outs its Life Cycle.
GaBi	A program that is created to design, model and calculate Life Cycle Analyses
FU	Functional Unit – A consistent unit to use throughout the whole analysis
Cradle-to-gate	Assessment type where the life cycle is partially calculated from start to the factory gate
Cradle-to-grave	Assessment type where the whole life cycle is calculated from start to finish
Cradle-to-cradle	Assessment type where the whole life cycle is calculated and the materials are circulated
GWP	Global Warming Potential – An impact category that measures the heat absorbed by any greenhouse gas in the atmosphere, as a multiple of heat that would be absorbed by the same mass of carbon dioxide
TA	Terrestrial Acidification – An impact category that measures the changes in soil chemical properties based on a deposition of acidic materials
FE	Freshwater Eutrophication – An impact category that measures the level of nutrients in freshwater ecosystems, which causes excessive growth of aquatic plants or algal blooms.
WF	Water Footprint – An impact category that measures the combined amount of water consumed during every step in the life cycle analysis
LF	Land Footprint – An impact category that measures the real amount of land, wherever it is in the world, that is needed to produce a product, or used by an organization or by a nation.
plan (model)	A scheme/diagram of elemental flows representing the calculation model
Point (Land Use)	A unit used for the Land Footprint impact category, similar to 40.47 m^2
Evapotranspiration	The process by which water is transferred from the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants
prefab	Prefabrication, often used in concrete building materials
extrapolation	Extending data to an unknown situation by assuming that existing trends will continue.
interpolation	A type of estimation of constructing new data points within the range of a discrete set of known data points
recycle rate	Percentage of material that is recycled

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1. Introduction

1.1. Background

At the start of the 19th century a total of 1 billion people walked on the earth. Since then the population of the world has massively increased to 7.7 billion in April 2019 and is ever so increasing. The population growth rate has passed its maximum in the 1960's in which it was larger than exponential growth. Since then it has decreased to a more linear trend going into the year 2020 (Roser, Ritchie, & Ortiz-Ospina, 2019). Although the United Nations show a varying set of scenarios on world population changes from increasing greatly to decreasing or even going negative, shown in Figure 1 World Population Prospects 2019 , the largest possibility of change is still set on an increasing world population (United Nations, 2019). The ever so increasing population causes large issues in many world aspects, from poverty (currently 10% (living under $1.90 a day)) and other human related effects, to the exhaustion and depletion of many of the worlds resources (highly dependent on the resource). A few of these issues are discussed in this report, with the main one being a combination of world resource depletion and human related effects, namely the never ending demand for food for the enormous amount of people and the available land on which to produce this vast amount of food. Other impacts of this increasing population are for example the emissions of greenhouse gasses, increasing the rate of climate change and the change of land classification from the continued decreasing natural land and biodiversity to an increasing urban or agricultural land. These other impacts are described further on in the report. It is even described as a 'trilemma' in Kozai's book on indoor agriculture. "We are facing a trilemma in which there are three almost equally undesirable alternatives: (1) shortage and/or unstable supply of food, (2) shortage of resources, and (3) degradation of the environment. This trilemma is occurring at the global as well as local and national level amid an increasing urban population and a decreasing and/or aging agricultural population." (Kozai, Smart Plant Factory, 2018)

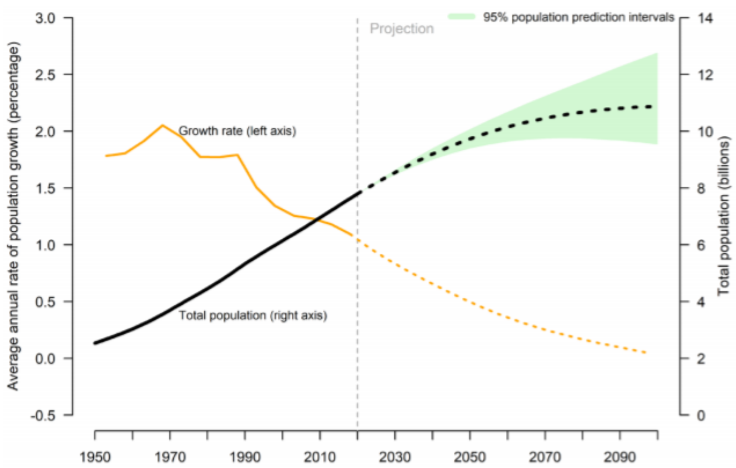

Figure 1 World Population Prospects 2019 (United Nations, 2019)

This was also observed by writer Essarts in 1974, looking over Tuscan countryside, seeing the city slowly consuming the land towards his small community of farmhouses: "One would have trouble imagining that there are sources capable of meeting the needs of this vast pit." (Des Essarts, 1974)

This quote represents the problems we are facing with food supply in the past, today and in the future. To feed all these people living in urban and rural areas an enormous agricultural landmass is needed. As Despommier explained in an interview "The size of South America in landmass is used just to grow our crops that we plant and harvest today. The amount of food consumed by only cities is around half of this amount and thus needs a landmass of half the size of South America" (Despommier, Feeding the World in the 21st Century, 2014). These farmlands, scattered around the world are not keeping up with the demand and certainly not with the even higher demand expected in the future. "Much of the land on which the world's food is grown has become exhausted or no longer usable. Likewise, there is not an endless supply of areas that can be converted to agricultural use." (Kretschmer &

Kollenberg, Can Urban Agriculture Feed a Hungry World?, 2011). At this moment a third of the plant's land is severely degraded (mostly due to agriculture) and the United Nations calls for a shift away from this destructive intensive agriculture. (Intergovernmental Pannel on Climate Change, 2019)

To cope with these problems, a change in agricultural practices has to happen. "For thousands of years, right up to modern times, agriculture was essentially practiced in the same way as the original farmers derived it: dig a hole, plant a seed, fertilize it, irrigate it, pick out the weeds, harvest the crop, ship/store/sell it." (Despommier, Farming up the city: the rise of urban vertical farms, 2013) After the introduction of modern mechanically advanced techniques (pesticides, herbicides, modern irrigation systems, domesticated and cultured plants) agriculture has become more and more efficient. As time progressed yields increased even more and have now reached a point where yields cannot significantly increase anymore with the current techniques on the same piece of land in a flat perspective. To increase the yield of food for an ever growing population we therefore have to expand the agricultural territory or explore the possibilities of the third dimension: height. Taking this dimension in perspective means that plants will be stacked on top of each other to "achieve a much higher yield with a higher quality of plants compared to the current situation" (Kozai, Smart Plant Factory, 2018) on the same surface area as traditional agriculture. If this idea is expanded multiple stories a tower arises which is called a "Vertical Farm".

1.2. Definition

A Vertical Farm belongs to the wide term of urban agriculture. Urban agriculture is the practice of harvesting produce in an urban area in various ways while "contributing to resilience by providing locally produced food and diversifying existing food supply, creating alternative earning opportunities for residents." (Aragon, Stuhlmacher, Smith, Clinton, & Georgescu, 2019) Most of the urban farming methods such as rooftop and forest gardens, green walls, community greenhouses and street landscaping, are quite small scaled and managed by one person or a small group of people. The vertical farm however, is often made on a larger scale and is managed by a company with several employees, as shown in the study of (Allegaert, 2020). Despommier, a spokesman of modern day vertical farming, states the definition of a vertical farm as: "Any building that is designated to grow food inside of it, which is taller than one story" (Despommier, Farming up the city: the rise of urban vertical farms, 2013). Even though this definition contains all vertical farms, it is still very broad. Within this definition vertical farms can be characterized as towers with a significant amount of stories for crop cultivation and a small land surface area. Vertical farms in this definition can also be characterized as so called 'vertical indoor greenhouses' or 'Plant Factories', which are often horizontally stretched out buildings which are just over one or two stories high with a single floor and plants stacked in growing racks (shown in Figure 1).

Figure 2 Vertical farming in an old industrial building.

For research purposes and performing a literature study, a broad definition is used to include as many reports and papers as possible to gain sufficient knowledge on the dimensions, techniques, systems and general structure of these farms. Throughout this report the initial definition is modified to make the concept of a vertical farm understandable and analyzable. A set of characteristics has been added to the main definition which fit most modern and future planned vertical farms. A vertical farm is defined as: "Any building that is designated to grow food inside of it with a controlled and monitored growing environment and climate, which is taller than one story and contains at least a semi-closed loop system of resource use."

1.3. Controversy

The vertical farming concept, with its roots in Francis Bacon's book of growing terrestrial plants without soil in 1627 and in Life Magazine its 'modern' sketch of an open-air layered vertically stacked farming landscape in 1909 (Crumpacker, 2018; Vago, 2018), has had a lot of controversy on the possibility to function in society. Most authors in the past have drawn the conclusion that the technology not advanced enough to make a stable climate for the plants of which not enough is known, whereas most authors nowadays draw the conclusion that vertical farms are not economically feasible or profitable enough to stay alive without any large initial investments or funds during its user phase. (Beacham, Vickers, & Monaghan, 2019; Pinstrup-Anderson, 2018; Al-Chalabi, 2015; Banerjee & Adenaeuer, 2013) Aside from the larger picture of implementing of vertical farms there are also still a lot of conflicting claims on the techniques and the (dis)advantages of vertical farms. Examples include that vertical farms are said to improve the yield of agricultural crops on a comparably sized surface area of cultivation as rural agriculture, have a significant reduction in land use due to the vertical perspective, have a significantly reduced water use due to closed-loop technological growing systems and would reduce many problems with external uncontrollable factors (such as weather) and emissions. These claims and more are discussed in further detail in Chapter 2.

1.4. Current Research

If these claims are completely valid or have proper argumentation is difficult to say as some rely on the general public's opinion, conceptual ideas, old studies and/or case studies with scarce data and are therefore not tested or researched enough. This lack of data in many fields of study within the concept of Vertical Farming and the influence of their parameters on each other, gives a very complex problem in the vertical farming community. "One of the major issues is a paucity of the yield potential, crop quality, energy efficiency and other parameters of VF systems in order to properly assess their potential" (Beacham, Vickers, & Monaghan, 2019) More importantly, besides input parameters and the design variables for a vertical farm, the impacts on the environment, the food chain, health, etc. are barely researched. For example "studies of the energy use, GHG production, yield and water use of VF (Vertical Farming) systems are scarce." (Beacham, Vickers, & Monaghan, 2019)

Even with the significant amount of vertical farms already existing around the world, around 55 registered and more expected in coming years (Roobeek, White paper on Vertical Horticulture, 2018; Brin, et al., 2016), most of them with the characteristics of the vertical farm shown in Figure 1, there is a notable knowledge gap present due to the function of most of these vertical farms. These large scale farms are rarely research institutes with study cases but rather commercial plant factories which sell to a niche market, mostly to specialized restaurants that use it as an advert to increase their customer amount (Brin, et al., 2016). As this is a good way of starting off with vertical farms and keeping them running with the money earned, signed agreements decline the publishing of data or used techniques which decreases the amount of studies that can be achieved on this topic. "It appears that such analyses are done by the producers themselves and not made available in open access." (Pinstrup-Anderson, 2018)

1.5. Aim of the Study

With the aforementioned world problems as well as claims on the advantages gained from constructing/operating vertical farms, a hypotheses can be stated. Is this modern farming technique called vertical farming a better alternative than traditional rural agriculture, based on their respective environmental impacts? This study sets out to analyze this hypothesis and contribute to the vertical farming concept. This study sets up a Life Cycle Analysis in order to gain insight on the environmental impacts of a vertical farm compared to rural agriculture, inevitably also checking some of the environmental claims given in other articles, studies and documents. The environmental impacts that result from the Life Cycle Analysis are partly converted into footprints such as carbon footprint, water footprint and land footprint.

Although some studies have been executed, not a lot is known on how an actual vertical farm would compare to traditional agriculture on these aspects. Therefore, this study strives to contribute to the literature on vertical farming and enhance the qualitative and quantitative knowledge and data on this concept.

This thesis analyzes a fictive vertical farm in Oklahoma City in the United States, harvesting lettuce, that would otherwise be transported over a large distance. The fictive vertical farm will be adapted to the climate and location and will therefore be applicable in a comparison with rural agricultural data related to this location. More on these subjects will be explained in further chapters.

2. Claims

In this chapter the different kind of statements on vertical farming are given. These are claims being made on the advantages of this concept and future prospects of vertical farming as well as the allegations on the disadvantages and drawbacks of vertical farming. There are still great insecurities with these statements as research on this topic is in a beginning stage and data and test cases are scarce. These statements give an interesting view on the way people tend to think of vertical farming and its place in solving food insecurity problems. The statements are divided into four categories: Environmental, Economical, Social and Political. The most interesting category for this report and therefore the most detailed is the Environmental category.

2.1. Environmental

2.1.1. Food security

The largest contributing factor in the existence and ongoing research on the concept of vertical farming is food security and sources claim that the vertical farm is the best solution to solve this problem. “Indoor farming offers many advantages over traditional soil-based agriculture; the most important one being total control of conditions necessary to achieve optimal survival, growth and maturation of any given crop, thereby ensuring maximum yield per square foot of growing space.” (Despommier, Farming up the city: the rise of urban vertical farms, 2013) This maximum yield consists of factors such as ‘more plants per surface area due to stacking up plants in racks’ (Graff, 2011; Banerjee & Adenaeuer, 2013), ‘using technologically advanced growing systems (hydroponic and spectral lighting)’ (Aldrich & Bartok, 1994; Burrage, 2014; Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016), ‘optimal growing conditions (climate control, HVAC)’ (Kozai, Smart Plant Factory, 2018) and ‘multiple harvests a year’. (stated from 8-14 yields a year depending on the crop) (Thorpe, 2016; Cheng, 2018; Burrage, 2014)

The specific maximum yield of a vertical farm is very variable depending on the farms characteristics, type of crop and many other factors playing a role. Therefore every report, journal article, book and other source states a different comparison: “Green Spirit Farms near New Buffalo has a stacked indoor growing area that yields 12 harvests per year compared to 45-50 days in California, or traditional farming in Michigan.” (Thorpe, 2016). “In vertical farms as many as eight crops per year are typically harvested, compared with just three from most outdoor farms.” (Despommier, Farming up the city: the rise of urban vertical farms, 2013). “It should be noted that soil-free cultivation in efficiency maximized vertical farm systems, can potentially increase yields up to 10 times compared to soil-based systems.” (Burrage, 2014) Some sources even state that “crops grow quicker, larger, and with many more harvests per year than external conditions permit” (Graff, 2011) and that there is “strong evidence indicating the nutritive value of S/CEA crops is equal or surpasses that of the most successful field grown crops” (Graff, 2011) While there are a lot of supporters on this theory, the opposition makes opposing claims that the concept of vertical farming “has little relevance for feeding the population” and is only suitable for architectural and industrial challenges rather than actually existing (Rundgren, 2017).

Besides the yield improving with modern technology and controlled environments, there are many more advantages to Vertical farming increasing the security of food. (Despommier, Farming up the city: the rise of urban vertical farms, 2013)

The production of vegetables in open fields is associated with large risks and uncertainties from biotic and abiotic stresses, such as pest attacks, insufficient available land, droughts, floods and strong winds. Climate change and associated irregular weather patterns and extreme weather events add to these uncertainties. (Pinstrup-Anderson, 2018; Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016; Graff, 2011) This often results in significant loss of many types of annual harvest. Many of these problems can be solved using indoor growing facilities, shielded of from the outside weather and climate changes. “If properly designed, a vertical farm’s contained growing environment would greatly reduce the risk of invasive pathogens and insects impeding crop growth” (Graamans, Baeza, van den Dobbelsteen, Tsafaras, & Stanghellini, 2018) Therefore, well-engineered indoor growing facilities such as vertical farms can “minimize or even eliminate the possibility of agricultural losses, and without the use of toxic pesticides” (Despommier, Farming up the city: the rise of urban vertical farms, 2013)

2.1.2. Land Use

A characteristic of vertical farms is the third dimension of agriculture: height. Vertical farms use this dimension to cultivate multiple crops on the same piece of land in square meters. (Banerjee & Adenaeuer, 2013; Al-Chalabi, 2015). In almost all sources this topic is addressed, however often very shallow as they only take into account the actual building footprint and not the land use of the components of the vertical farm.

With the same amount of crops cultivated, the land footprint of conventional agriculture is very large. Thus placing this conventional agriculture into a vertical farming tower would create new opportunities for the rural land. In an environmental perspective this would be very beneficial as abandoned agricultural land can be reclaimed to its original ecological function. Thus returning this land to vegetation growth gives potential to rejuvenate the national ecosystem. (Benke & Tomkins, Future food-production systems: vertical farming and controlled-environment agriculture, 2017; Despommier, Farming up the city: the rise of urban vertical farms, 2013)

2.1.3. Water use

The agricultural industry is one of the largest sector, using water to grow and cultivate crops for food production and animal feed. While it is the largest sector, its water use is for a large portion quite inefficient. (United Nations, 2011). With this problem in mind, vertical farms are said to be a solution using an almost fully closed loop system (retaining the water within the system instead of releasing it in any form). (Benke & Tomkins, Future food-production systems: vertical farming and controlled-environment agriculture, 2017) When crop growth occurs within the contained environment of a vertical farm, all evaporated water can be collected by dehumidifiers and recycled back into the system. Thus eliminating the gray water footprint and keeping all waste water contained. (Kozai, Smart Plant Factory, 2018) With the waste water contained the CO_2 emission associated with the production of nitrogen fertilizers would be less as would pressures on the phosphorus and potash reservoirs. Contamination of streams and lakes by fertilizer run-off would not occur. (Pinstrup-Anderson, 2018)

As a result, the only water to leave a vertical farm’s circulation is that contained within the biomass of the saleable produce. Considering only water losses from transpiration a vertical farm would theoretically consume between 200 and 1000 times less water than a conventional farm to produce the same quantity of food. (Graff, 2011) Other figures are for example “only 5% of the water used in the production of the same quantity of vegetables in an open field” by (Pinstrup-Anderson, 2018)

2.1.4. Electricity use

Even though there are many claims praising the vertical farm as the ‘revolution in agriculture’ (Kretschmer & Kollenberg, Can Urban Agriculture Feed a Hungry World?, 2011) There are also major problems on vertical farming mentioned of which a large portion is directed to the electricity or energy usage. (Beacham, Vickers, & Monaghan, 2019) For most vertical farms the main electricity user is the lighting system supplying long hours of illumination (Kozai, Smart Plant Factory, 2018), replacing the sunlight with artificial lights, with the exception of farms in extreme cold or hot regions in which heating or cooling systems take the crown in electricity use (Graamans, Baeza, Stanghellini, Tsafaras, & van den Dobbelsteen, 2018). Furthermore, the combination of high-density crop production, limited volume and lack of natural ventilation is likely to induce a high demand for cooling and vapor removal. (Kretschmer & Kollenberg, Can Urban Agriculture Feed a Hungry World?, 2011; Graamans, Baeza, van den Dobbelsteen, Tsafaras, & Stanghellini, 2018; Rundgren, 2017) Some claims are based on the efficiency of converting sunlight to plant matter, in which it “requires eight times as much electricity as all U.S. utilities generate in an entire year for lighting alone, just to meet a year's U.S. wheat production with vertical farming would.” (Alter, 2010; Kretschmer & Kollenberg, Can Urban Agriculture Feed a Hungry World?, 2011) A possibility to release some of this stress and to decrease the emissions caused by the electricity generation is the use of renewable energy. However, “At the moment, renewable energy sources only generate about 2 percent of all power in the US. Accordingly, the sector would have to be expanded 400-fold to create enough energy to illuminate indoor wheat crops for an entire year.” (Kretschmer & Kollenberg, Can Urban Agriculture Feed a Hungry World?, 2011)

2.1.5. Urbanizing

With the increasing urbanization and people moving from the countryside to the large cities, the remaining land is left for farming or nature. As cities keep growing rapidly with its food demand following the same trend, we get our food products from further and further hinterlands. (Steel, 2013; Graff, 2011; Deelstra & Girardet, 2000) Vertical farming however, can integrate into this movement of urbanization as indoor cultivation is very flexible in their location aspect.

Placed in an urban area, a vertical farm would decrease transportation costs massively due to proximity to the consumer, as there is no requirement for long-distance transportation. Besides this, the supply chain would be very short, as well as less nutrient losses, CO_2 emissions and time from harvest to consumer purchase would be very short, assuring freshness. (Pinstrup-Anderson, 2018; Benke & Tomkins, Future food-production systems: vertical farming and controlled-environment agriculture, 2017; Despommier, Feeding the World in the 21st Century, 2014) However, it has been calculated that of the total greenhouse gas (GHG) emission of food systems, production accounts for 83%, while transport only accounts for 11% (Weber & Matthews, 2008). In contrast, transport distances will be greatly reduced through urban localization and may lead to a net reduction in transport-associated energy requirements. (Pretty, Ball, Lang, & Morison, 2005)

2.1.6. Emissions

Important elements of current environmental impacts and addition to global warming are emissions. These emissions have major impacts on the environment directly or indirectly (think of plants not surviving, acid rain, increasing global warming by containing warmth in the air). Some of the claims on these emissions have been mentioned such as the decrease in transportation emissions. However, from a life cycle perspective there are many more steps in a vertical farm that cause emissions. Construction of vertical farm facilities will also generate a lot of emissions via building construction and energy use. (Beacham, Vickers, & Monaghan, 2019) During the vertical farm user phase mostly the inner workings of the systems will create emissions indirectly by using energy. "The claim that the production is climate-smart is also questionable; T. Shiina and colleagues (2012) found that growing lettuce with artificial light causes at least 6 kg CO_2 emissions per kg, which is considerably more than for common greenhouse production and at least five times more than arable lettuce production." (Rundgren, 2017) In general it is stated that "from a life cycle perspective, the findings indicate that vertically grown produce has a carbon footprint that is much higher than conventionally grown produce." (Al-Chalabi, 2015)

2.2. Economical

In light of vertical farming's departure from conventional food production it is also important to address the economic rationale of this concept in some regard. There is a lot of concern on the economic viability of a vertical farm and an equal amount of claims praising its economic profitability. One of the issues mentioned in many research papers are the startup costs. The start-up costs of VF systems are seen as a major constraint, with quite expensive city plots compared to rural land as well as the construction (or renovation) of a multi-level enclosed building (Benke & Tomkins, Future food-production systems: vertical farming and controlled-environment agriculture, 2017; Despommier, Farming up the city: the rise of urban vertical farms, 2013; RFWireless, n.d.). Besides start up costs, the operational phase of a vertical farm is not without its own large expenses. The use of temperature and humidity control equipment, a vast hydroponic system, a lighting system for optimal growth and other systems demand a high electricity input and with this large expenses. (Graff, 2011; Benke & Tomkins, Future food-production systems: vertical farming and controlled-environment agriculture, 2017) No taking these elements in consideration can lead to one clear economic outcome: bankruptcy. "A number of vertical indoor food producing units have suffered that fate, including FarmedHere in Illinois, USA, Potponics in Georgia, USA and others." (Pinstrup-Anderson, 2018) However, others such as Urban Produce and Plenty in California, USA, Plantagon in Sweden and Aerofarm in New Jersey, USA are operating and presumably making a profit. Possibly because of advantages such as: "There is no need for heavy farm machinery such as tractors, trucks, or harvesters and no requirements for fertilizers, herbicides or pesticides" (Benke & Tomkins, Future food-production systems: vertical farming and controlled-environment agriculture, 2017). Combined with the claim that "yields of the vertical farm are so much greater on the same surface area of land, the cost could be covered." (Despommier, Farming up the city: the rise of urban vertical farms, 2013). The study of (Banerjee & Adenaeuer, 2013) concludes that extensive research is needed for the optimization of the production processing in order to reduce costs and that their use 'might be feasible', particularly in large cities with very high purchasing power. (Banerjee & Adenaeuer, 2013)

2.3. Social

On a social perspective on the rise of vertical farms, a barrier was identified by the study of (Al-Chalabi, 2015), in which "many perceived hydroponics as 'food made from chemicals' and 'not natural', which could lead to a decrease in uptake of produce grown in cities". An aspect on which other sources tend to differ in that "on a consumer perspective, it would be the option to buy vegetables on demand, ultra-fresh, pathogen-free and locally produced, characteristics preferred by many urban consumers. (Pinstrup-Anderson, 2018; Despommier, Farming up the city: the rise of urban vertical farms, 2013)

On another note some might speculate that this agricultural change would make farming communities disappear and increase the loss of agricultural jobs (RFWireless, n.d.), however it would more likely mingle a modern agrarian work force with that of more typical urban dwellers, which might prove for an interesting cultural interchange. A wide spectrum of job descriptions describe the work force in a typical large indoor growing facility, from management to growers, from HRM to IT personnel. (Bosschaert, 2008; Despommier, Farming up the city: the rise of urban vertical farms, 2013)

2.4. Political

From a political standpoint the mentioned food security is key. In America a lot of food products are for the larger part grown in only a few adjacent states and a natural occurring disaster would destroy a lot of the product. By creating a network of vertical farms distributed among for example American states, food security increases. Besides this, major shifts in food distribution networks would ensue and therefore changes in political trade balances between nations and regions. Urban farms would compete and most likely gain the upper hand in the production of the majority of food in urban regions. (Bosschaert, 2008; Benke & Tomkins, Future food-production systems: vertical farming and controlled-environment agriculture, 2017) On another note, "a key political advantage of vertical farms is that climate-change commitments are more easily satisfied and the technology supports adaptation and mitigation." (Benke & Tomkins, Future food-production systems: vertical farming and controlled-environment agriculture, 2017)

3. Methodology

The methodology chapter describes the broad philosophical and scientific underpinning of the chosen research methods, including all choices and reasoning behind these choices as well as the use of quantitative and/or qualitative methods and the explanation behind these methods. This chapter includes the choice in location, vertical farm characteristics and dimensions and LCA characteristics and choices. Besides the choices, some background information will be given on each of the subjects chosen to give more insight on the topic and as a base structure for the analysis. Choices specifically mentioned in the text are marked by a line underneath the text.

3.1. Location

3.1.1. Location choice

The location of agriculture is of great importance with both outdoor and indoor cultivation. For both indoor and outdoor cultivation the location is often largely affected by location of residence and local external factors, such as amount of water available, general climate, access to general supplies, among others. Where these forms of agriculture separate however, is the approach to external factors where indoor cultivation tends to rely on systems such as climate control. Specifically in vertical farms as the claims suggest, external factors are eliminated by system control and therefore vertical farms could be placed in any possible location in any possible climate. Claims on the urbanization state that placing vertical farms on urban ground, while being more expensive initially, would greatly improve many aspects of the food supply chain. It has been chosen to close the distance between producer, supplier and buyer and place the fictive vertical farm in an urban area for this report.

The specific location on the world map is dependent on which aspects this report tries to analyze, these can relate to different climate scenarios, food mile scenarios, automatization scenarios, food security etc.. Besides analyzing different scenarios, the location is also dependent on the type of crop and the available literature on this crop for proper comparison as well as the feasibility of a vertical farm on that location (is this concept desired, or at least not despised). While being discussed in detail in the next chapter, the crop choice will be briefly mentioned in this chapter to clarify the reasoning behind some of the location choices. The crop which this fictive vertical farm will analyze is lettuce.

The United States, while having many states, produces a lot of its crops for the largest portion only in a few states where climates are ideal (for example the cotton production in mostly Texas and the South States and Barley and Peas in the Northern States). Crops are then distributed over the United States by shipping them over canals, roads and tracks for hundreds or thousands of miles, creating a network of constantly moving transport. (USDA, 2017; Hill, 2008) This creates a perfect case study for a vertical farm, adaptable to extreme climates in the US as well as producing locally, eliminating the transporting distance.

When looking specifically at chosen crop lettuce, it is known that the group ‘leafy greens’, under which the crop lettuce is also defined, follows this same pattern, Figure 3 Harvested Vegetable Acreages . “California is not the only source of leafy greens in the U.S., Arizona is another substantial producer. It is estimated that combined, the two states produce nearly 95 percent of US leafy green crops. Of the leafy greens, the most heavily produced is lettuce, some others include spinach, kale and cabbage.” (California AG Network, 2017; Wilette, 2019).

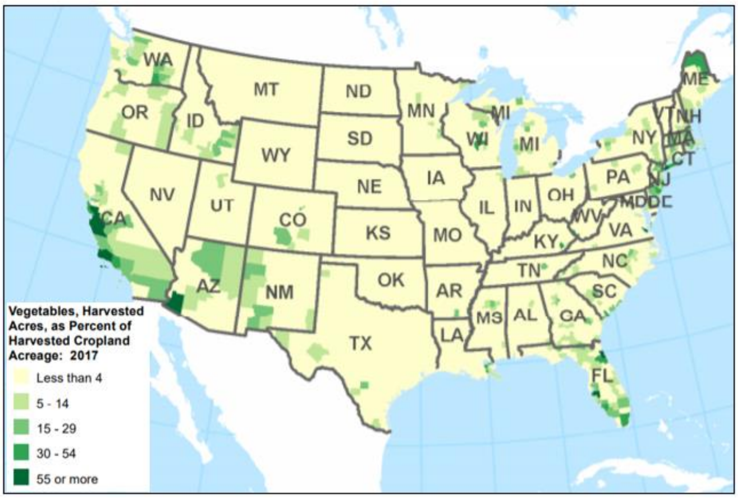

Figure 3 Harvested Vegetable Acreages (USDA, 2019)

One of the major issues as mentioned is food security. Taking a look at the map of food security of the United States, shown in Figure 4 US Food Security , shows that some states have quite a low food security, which are mostly situated in the middle and a bit to the east. These problems are, in most states, related to the amount of food available and the reliability of a constant flow of food. Food security can cause major health issues amongst many citizens of these states and should therefore be a high priority in the states agenda.

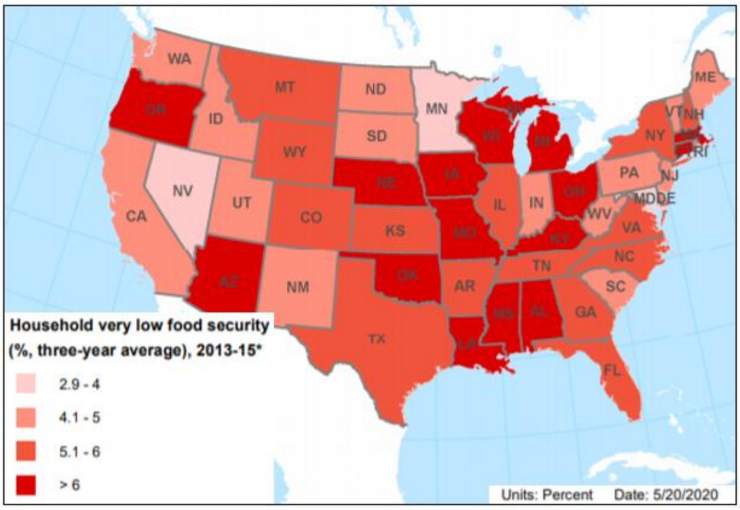

Figure 4 US Food Security (USDA, 2019)

Water available for commercial production consists of available precipitation and/or the possibility to extract it from groundwater aquifers. Looking at a map of the United States’ available precipitation shows low precipitation values in the middle and western counties and high values in the eastern and coastal counties. (U.S. Geological Survey, 2018). Underneath the US soil is a network of large aquifers which could pose as a solution, however, many of these aquifers are undergoing depletion. (Walton, 2013). Combined this results in a water stress map, shown in Figure 5 US Water Stress , in which most middle and eastern states experience the most water stress.

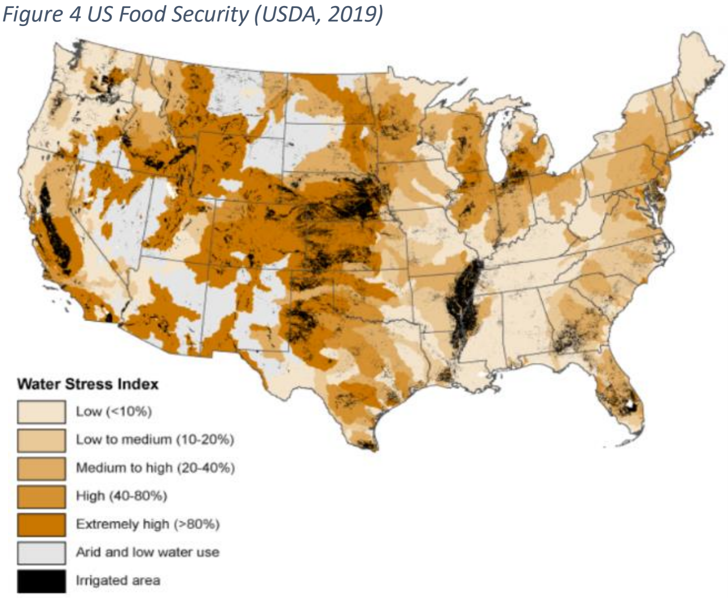

Figure 5 US Water Stress (USGAO, 2019)

Vertical farms are distinct buildings and with the minimized land use and thus a dominant vertical feature, this tower should fit into a skyline of a city. Only larger cities would be logical for a tower of this size. It would be realistic if the city would be open to the idea of urban and vertical farming, but not have an urban farm of this size already present.

Taking into account all aspects mentioned above, Oklahoma city has been chosen as the location of study, because it has low food security, quite a distance to the lettuce production area, water stress, a skyline with existing Highrise and openness towards the urban agriculture concept (CommonWealth, 2020). Elements in and aspects in which a vertical strives according to claims.

3.1.2. Oklahoma City

3.1.2.1. General

Oklahoma city is located in the state of Oklahoma in the South of the United States, shown in Figure 6 Oklahoma's place in the USA . This city has a surface area 1571 km^2 and a population of 3.956.971 citizens (density of 2.518 citizens per km^2). (United States Census Bureau, 2019) Oklahoma state has a height of 1524m above sea level in the very west and gradually decreases in height until the very lowest point of 84 meters above sea level in the very southeast. Oklahoma city in this gradual decrease is situated at 366m above sea level (Johnson K. S., 2008)

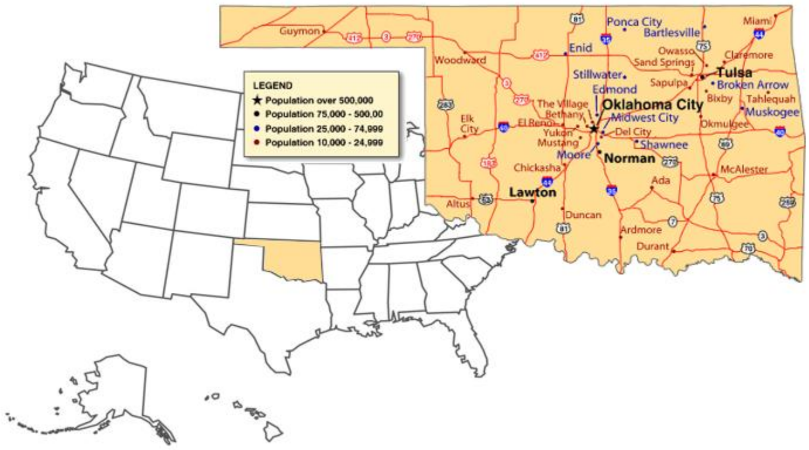

Figure 6 Oklahoma's place in the USA (Nations Online Project, n.d.)

3.1.2.2. Climate

Oklahoma state experiences a humid subtropical climate (Köppen climate classification Cfa) in the eastern part of the state, with hot, humid summers and mild to cold winters. The western portion, including the panhandle transitions to semi-arid climate (Köppen BSk), with extreme temperatures. (Weather Atlas, n.d.; U.S. Climate Data, n.d.) In future climate predictions it is expected that the western semi-arid climate (Köppen BSk) moves up more to the east, covering a larger part of the Oklahoma state. (Beck, et al., 2018) In general the more southern states are likely to have an increase in temperature and switch to a different climate that suits this temperature, according to climate predictions. (Beck, et al., 2018)

Currently the small amount of lettuce grown locally or the large amount of lettuce grown in California are experiencing high temperatures. Lettuce is considered a cool-weather crop because of its tendency to get bitter when exposed to high temperature. It is already a struggle to keep the yield of open field agriculture somewhat consistent, however with the changing climate in the southern states, the lettuce production might have to move north or indoors as temperatures rise in the future. (Baker, 2016; Beck, et al., 2018)

Oklahoma City lies in this transition and therefore does not have extreme temperatures but fluctuates between fairly normal temperatures in the mild winter and humid summer. More specific climate statistics and data is given in Table 1.

Table 1 Oklahoma city climate data and statistics (U.S. Climate Data, n.d.; Oklahoma City, Oklahoma, Climate, n.d.; ClimaTemps, 2017; Johnson H. L., 2008; OCC & USGS, 2019; USGS Natural Hazards; KOCO, 2014; Perkins, 2002; Historical Hurricane and Storm information for Oklahoma; The National Severe Storms Laboratory, 2012)

Climate Oklahoma City	
Annual high temperature	22°C
Annual low temperature	10°C
Days with temperature over 32°C	65 days
Days with temperature below freezing	73 days
Hottest month	July (34°C)
Coldest month	January (-3°C)
Average annual precipitation	90 cm
Month with lowest precipitation	June (12,5 cm)
Month with highest precipitation	January (3 cm)
Average annual snowfall	20 cm
Months with snowfall	October - April
Average relative humidity	54,5%
Average monthly relative humidity	48% (August) – 62% (January)
Average Earthquakes M3.0+ annually (mostly due to self-induced wastewater wells)	154 (changes a lot over the years due to nr. of wells)
Average Tornadoes annually	52 - 60
Tropical Storms/Hurricanes	rarely

3.1.2.3. Water

Oklahoma is underlain by 22 major groundwater basins containing approximately 390 million acre-feet of water in storage, though only one-half of that amount may be recoverable. Groundwater is the prevalent source of water in the western half of the state. According to data compiled for the 2012 Update of the Oklahoma Comprehensive Water Plan, total water use in Oklahoma in 2007 was 1,814,762 acre-feet (Oklahoma Water Resources Board, 2020):

- Approximately 56% of this use came from surface water sources and 44% from groundwater sources;
- Approximately 73% of this water was used for Crop Irrigation and Municipal/Industrial combined, Oklahoma's two largest water use sectors.

Oklahoma experiences a significant number of droughts and water scarcity is a major problem in the summer months (Figure 7 Amount of area where droughts occurred in percentage of the total area of Oklahoma county. a. Drought area percentage over a 10 year period in Oklahoma county, b. average Oklahoma county drought profile over a year (2014) b). Though droughts have been carefully monitored, the irregularities and non-correlative behavior of droughts makes them unpredictable. Even though the latest years no major droughts have occurred (Figure 7 Amount of area where droughts occurred in percentage of the total area of Oklahoma county. a. Drought area percentage over a 10 year period in Oklahoma county, b. average Oklahoma county drought profile over a year (2014) a), this does not yield a future perspective.

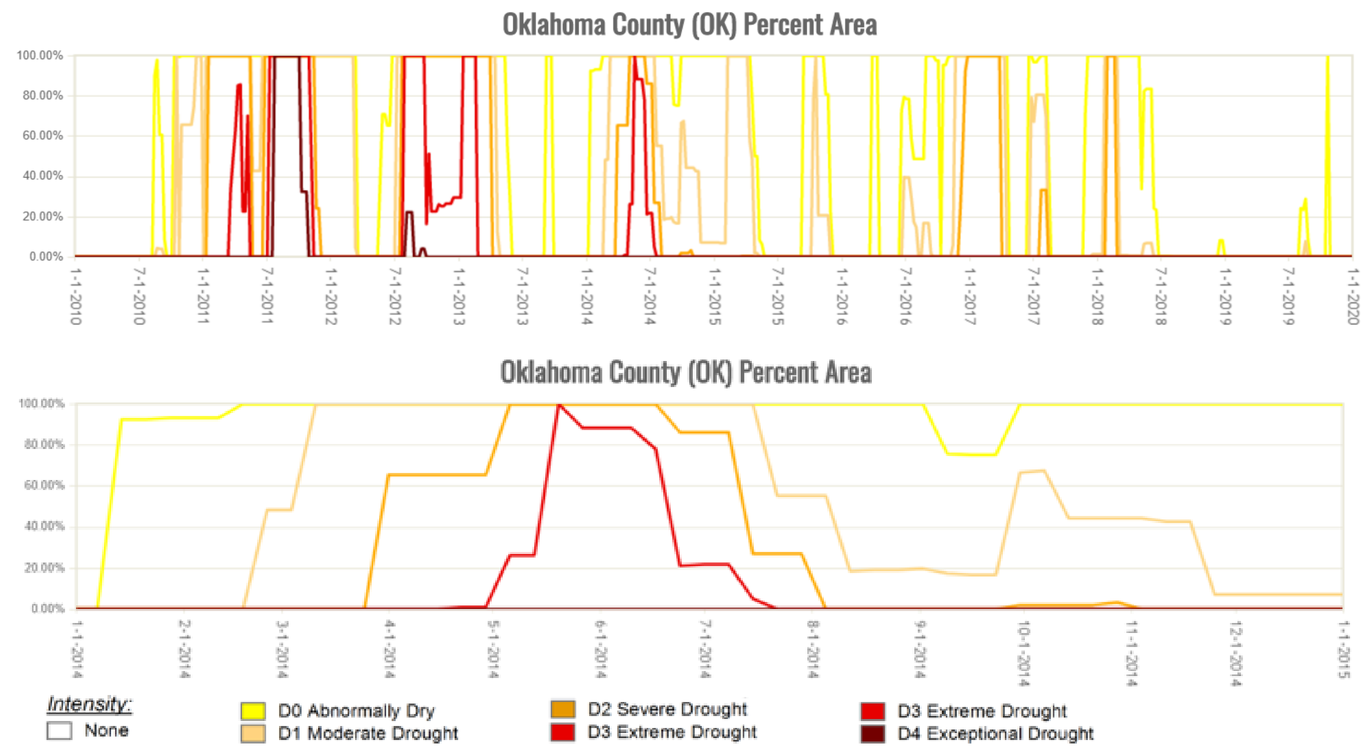

Figure 7 Amount of area where droughts occurred in percentage of the total area of Oklahoma county. a. Drought area percentage over a 10 year period in Oklahoma county, b. average Oklahoma county drought profile over a year (2014) (The National Drought Mitigation Center, 2020)

3.1.2.4. Food Security

As mentioned before and shown in Figure 4 US Food Security the food security of Oklahoma is very low. As of 2013, an estimated 654,640 Oklahomans are food-insecure, which means that they don't have consistent access to enough food, among which is lettuce (USDA, 2019), for an active, healthy lifestyle. Oklahomans are more likely to be food-insecure than most Americans, and many chronic diseases and health conditions related to food insecurity are very common in Oklahoma. More than 1 in 4 Oklahoma children rely on the Supplemental Nutrition Assistance Program (SNAP, formerly known as food stamps) to get enough to eat. It is said that "Food insecurity has a larger negative impact on Oklahoma by weakening the labor force, decreasing educational attainment, and increasing healthcare costs." (Hunger Free Oklahoma, 2017; Perry, 2019)

3.2. Crop

3.2.1. Crop choice

"With the right set-up, you can grow almost anything in a vertical farm. Just because you can, however, doesn't mean that you should." (Michael, 2017) This quote sums up the most difficult choice for commercial vertical farms, the choice of crop, as the economic viability of the crop varies greatly among all the techniques used to cultivate these crops in a vertical farm. Based on lack of demand (no profit), inappropriate technique (high production cost), climate (high heating, cooling, light costs)) and Timing and Liability (the time it takes from the seedling going into the system to the mature plant coming out and going to market). (Michael, 2017; Pando, 2015; Aragon, Stuhlmacher, Smith, Clinton, & Georgescu, 2019; Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016) "Due to the high energy intensity of vertical farming, plant factories have been applied mostly fast-growing and highly profitable vegetable crops to compensate for the high energy costs (Benke & Tomkins, Future food-production systems: vertical farming and controlled-environment agriculture, 2017). In the literature and studies discussing vertical farming, the most common crops cultivated are leafy greens and herbs (Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016; Kikuchi, Kanematsu, Yoshikawa, Okubo, & Takagaki, 2018; Graamans, Baeza, van den Dobbelsteen, Tsafaras, & Stanghellini, 2018). From these studies a list has been created with the most suitable crops for a vertical farm.

- Lettuce
- Kales
- Chard & Collard greens
- Chives and mint
- Basil
- Small woody herbs

Looking into the crop distribution across the United States it shows that potatoes, tomatoes, and the various forms of lettuce are the top three vegetables in the United States in terms of popularity (the tomato is scientifically a fruit, but functions as a vegetable for food purposes, Figure 8 U.S. per capita loss-adjusted vegetable availability in 2017

). In terms of sales and export between states, onions and carrots can be added to this list. (USDA, 2019; Essman, 2014)

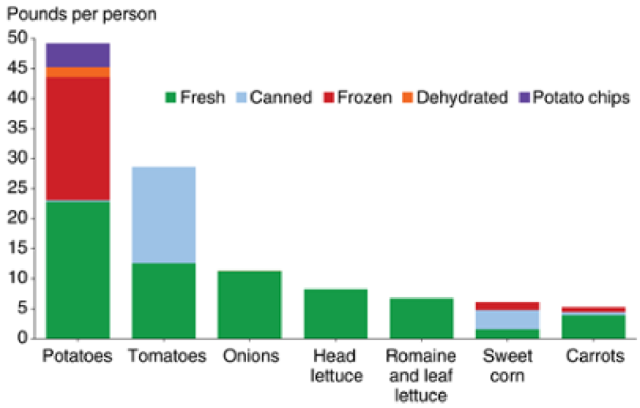

Figure 8 U.S. per capita loss-adjusted vegetable availability in 2017 (USDA, 2019)

Combining these two variables, the most logical choice of crop is lettuce. This is momentarily also the most used vegetable in existing vertical farms and studies on vertical farms as it is a low growing crop which can be easily stacked on top of each other. (Kozai, Smart Plant Factory, 2018; Beacham, Vickers, & Monaghan, 2019) This gives the opportunity to compare the results of this study with other studies on vertical farming.

3.2.2. Lettuce

The vegetable lettuce has six edible forms in the species L. sativa: crisphead (iceberg and Batavia), romaine, butterhead, leaf, Latin, and stem (Ryder, 1996). All except iceberg occur in red and green leaf forms. This thesis chooses the Iceberg lettuce (crisphead) as its type of lettuce to analyze in a vertical farm. This kind of lettuce is at this moment in time the largest portion of lettuce distributed across the US (Ryder, 1996) and also has the best comparable rural agriculture data. This lettuce has a total life cycle of 48 days from seed to harvest.

4. Vertical Farm

With the location and the crop known, the vertical farm can be designed to optimize the growing conditions for the lettuce crop in an Oklahoma City climate. The crop determines most of the system specifications, based on known technologies and data from comparable studies. The location determines some of the building characteristics and eventual specific LCA input.

4.1. Building characteristics

4.1.1. City research

The building in which a vertical farm is situated serves as a shell and has the purpose of housing all systems and protecting them from external unpredictable factors. An interesting perspective on the shell aspect from a life cycle point of view is to use an existing building which is up to building standards and which can be altered to have a vertical farm inside of it. This would save a lot of initial building materials which would weigh into the life cycle assessment as well as save initial costs, making it more attractive to build. Although, with the construction of a new building the life expectancy and recycle rate of materials would be higher. With this in mind some research has been done on the availability of buildings in the city of Oklahoma, using a public report by the Oklahoma government (OKC Goverment, 2020) on abandoned and empty buildings and an ArcGIS database with an Oklahoma postal code map, one equal to the one shown in (USNaviguide, 2019).

There are more than 50 completed high-rises in Oklahoma City, most of which stand in the central business district and 18 buildings of these fifty stand 76m and taller. (SkyscraperPage, n.d.) To create a vertical farm which has an impact on the food supply to the large city of Oklahoma City and keep the surface area relatively small, a tower is created with multiple floors, thought to reach at least 50 meters in height, embracing the vertical perspective. From the building list analysis however, it shows that almost all abandoned or neglected properties are low rise houses or commercial buildings. Therefore the idea of revising an old building into a new farm is abandoned. This research however, yielded some positive result as well. There are abandoned properties in or near the downtown district, zip codes 73103 (14) and 73106 (71), which could provide a location for a new vertical farm, fitting into the skyline and only removing old abandoned properties, increasing the viability of such a farm actually being built.

With the fictive farm having a significant height, there could be some concerns on the external factors influencing this building. Oklahoma state is the state with the most tornadoes per year (Perkins, 2002) and a significant amount of earthquakes (USGS Natural Hazards). Though, in the state of Oklahoma most tall buildings are engineered with strong enough foundations and steel framing to withstand tornado force winds and/or earthquake forces (Kennedy, Short, McDonald, McCann, & Murray, 1989; News On 6, 2008), which will also be used in this vertical farm. (Sundararajan, 1995) The building does not need a tornado shelter as it should be structurally sounds, also without any windows this building does not pose a threat in a natural hazard event. (Kennedy, Short, McDonald, McCann, & Murray, 1989)

4.1.2. Dimensions

The dimensions of the tower are dependent on the amount of lettuce it wants to produce, the type of vertical farming that is going to be applied and logical reasoning based on existing vertical farms and existing buildings in Oklahoma City.

The amount of lettuce to be produced by this vertical farm is not a number that can be calculated or determined easily. It will even change through the design process of the vertical farm and its system choices. However, a production estimation can be made to determine proper dimensions for the building. This farm does not seek to tackle all food related problems in its singularity, however it will contribute greatly to the lettuce distribution in the city of Oklahoma. Therefore, it has been chosen that this vertical farm produces around 1.000.000 lettuce in a full maturing cycle (48 days)

The technique of stacking plants on top of each other to create this vertical aspect can be achieved using a multitude of techniques explained in (Beacham, Vickers, & Monaghan, 2019), Figure 9

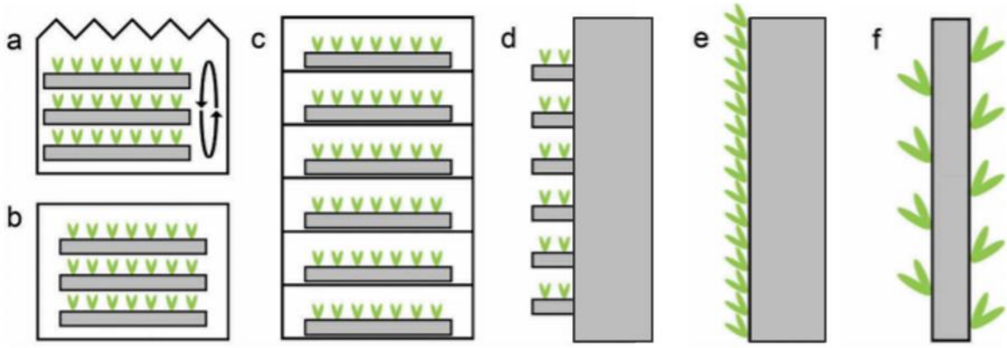

Figure 9 Representation of vertical farming (VF) types. Stacked horizontal systems (a), with level rotation/controlled environment (b), multi-floor towers (c), balcony crop production (d), green walls (e), cylindrical vertical growth units (f) , based on (Beacham, Vickers, & Monaghan, 2019)

Representation of vertical farming (VF) types. Stacked horizontal systems (a), with level rotation/controlled environment (b), multi-floor towers (c), balcony crop production (d), green walls (e), cylindrical vertical growth units (f) , based on .

This vertical farm uses two of these techniques to create separate stories with high ceilings for optimal vertical space use, as well as keeping separation of crops in different growing stadia, which require different growing climates:

"Stacked Horizontal systems", Figure 9 Representation of vertical farming (VF) types. Stacked horizontal systems (a), with level rotation/controlled environment (b), multi-floor towers (c), balcony crop production (d), green walls (e), cylindrical vertical growth units (f) , based on a. This form of Vertical Farming comprises multiple levels of traditional horizontal growing platforms, which have the potential to be stacked on top of each other within taller structures on the same floor. "This can be achieved either in glasshouses or self-contained controlled environment (CE) facilities."

"Multi-Floor Towers", Figure 9 Representation of vertical farming (VF) types. Stacked horizontal systems (a), with level rotation/controlled environment (b), multi-floor towers (c), balcony crop production (d), green walls (e), cylindrical vertical growth units (f) , based on c. "In this scenario, rather than the multiple levels of plant growth occurring in the same chamber (glasshouse of CE), the different levels of planting are located on different floors of a tower structure and so are isolated from each other." (Beacham, Vickers, & Monaghan, 2019)

Most existing vertical farms, as mentioned, use only one floor with a Stacked Horizontal system. The plants are stacked in industrial racks, of which most vertical farms use 4 to 12 stacked horizontal growing platforms per rack, resulting in 1.2 to 1.4 growing platforms per meter. (VertiCrop, 2009; Aerofarms, 2004; Sky Greens, 2011) Buildings using the Multi-Floor Towers technique are usually 3 to 6 stories tall, in which every story is as tall as a general living room in a house, creating a building that is just as tall as its Stacked Horizontal counterpart. (Levenston, 2011; Eaves & Eaves, 2018). The vertical farm in this report however, combines these techniques to create a tower that adds to the skyline of the city while keeping its land footprint very low and contributes significantly to the crop production of the city. Similarly to the economic vertical farm study of (Banerjee & Adenaeuer, 2013) the building will become quite tall and will therefore follow some of its characteristics and clever management. Firstly a proper distinction between the growing facility and the logistic side is required in which logistics are sealed of from the growing facility in the lower floors, dedicated to waste management, cleaning, packing and transporting. Secondly, within the growing facility a separation of floors can be made on the basis of different growing stages of the same crop, which require a variation on the ideal growing climate.

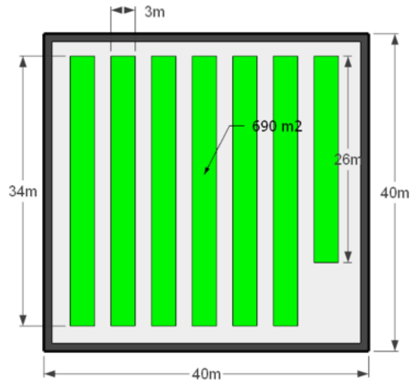

Figure 10 Dimensions main cultivation floor fictive vertical farm

Using the city research data, as well as existing buildings in the city of Oklahoma as a reference point and the estimation of production area, the length and the width of the building are chosen to be 40 meters. This 40m by 40m building therefore has a surface area of around 1500 m^2 per floor and using dimensional characteristics (such as space for walkways, equipment, dedicated rooms, etc.) from the studies of (Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016), (Kozai, Smart Plant Factory, 2018) and (Zeidler, Schubert, & Vrakking, 2017), the production area of the floor plan without any stacked plants would be 690 m^2, Figure 10 Dimensions main cultivation floor fictive vertical farm.

With the plan of using stacked horizontal systems per floor this production area will significantly increase. Based on existing vertical farms and their set-up it is chosen to stack plants 8 times. With the earlier mentioned 1.2 to 1.4 growing platforms per meter and the more precise distances from (Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016) it is chosen that the plants are stacked 8 times in 6 meter high towers. With an ideal climate controlled environment a lot of systems are needed, which also need space therefore it has been chosen to create stories of 8 meter high. The ground floor of the building will have other characteristics as this will be used for logistics and has a height of 3 meters. With the use of city research and the skyline of Oklahoma City (SkyscraperPage, n.d.) it is assumed that, to make the vertical farm part of the skyline, but not prominent part of it, it should be lower than 80 meters (top 15 highest buildings). This would result in a vertical farm with 9 floors, which is estimated to be approximately 77 meters tall (taking into account structural and system elements).

One specific feature of the building which may seem odd is the fact that no windows will be a applied in the upper stories of the building. To keep a perfect growing cycle and maximum yields using grow lights, a complete occlusion of sunlight is necessary. Also, with the absence of windows insulation will be increased and less temperature is lost throughout the day, because an insulated, concrete wall in a commercial building is recommended to at least have a R-value (insulation value) of 13 while standard double glazed windows have a R-value of 2-3. (ArchToolbox, 2020)

4.1.3. Yield

To calculate the eventual yield of this vertical farm the amount of plants must be known. In most vertical farms this is given as a density of plants per square meter. This varies majorly between producers at vertical farms and greenhouses from 21 plants/m^2 in greenhouses (Plawecki, Pirog, Montri, & Hamm, 2013; Bartzas, Zaharaki, & Komnitsas, 2015) and 22 plants/m^2 in vertical farms (Kikuchi, Kanematsu, Yoshikawa, Okubo, & Takagaki, 2018) to 36 plants/m^2 (Kozai, Smart Plant

Factory, 2018; Lomax, 2017; Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016). As this report uses a lot of the dimensions from the Plant Factory book from Kozai, Niu & Takagaki and to maximize yields on the same production surface, it is chosen to use a plant density of 36 plants/m^2.

The chosen crop of lettuce has a seed to harvest cycle of 48 days, which is divided in three or four stages within a vertical farms or greenhouse using different climate conditions to optimize growth: the germination, in which seeds are grown into seedlings (small plants), the nurseries, in which seedlings are grown into nearly mature plants and the final maturing in which the plants fully mature and get most of their texture and flavor (sometimes separated in two different phases). Each of these growing stages needs its own production area, preferably separated from each other to ensure optimal conditions. With the use of a rule of thumb from the book (created by data from studies into plant factory cultivation): "The time taken from the germination stage to the nursery stage is about 50–70% of the total cultivation period, but the space used for these two stages is only about 20–25% of the total space.", (Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016) it is calculated that from the 8 stories of cultivation, 2 stories are dedicated to germination and nurseries and 6 stories are dedicated to the last growing stage. Following the cultivation panel designs of the book, one tray holds 300 seeds in the germination and 26 seedlings in the nursery and the knowledge that germination is generally performed in a room on the side, it is calculated that nurseries will take up 90 to 95% of the 2 stories (8255 m^2 production area) and germination will be performed in a room on the side (10 by 12 meter), calculated to around 5 to 10% of the production area. (81 m^2 production area).

With 6 last growing stage stories, using plants stacked 8 times in 3*34 meter production areas results in 33.120 m^2 (or 5.520 m^2 per floor). Together with the 36 plants/m^2 this results in a total yield of 1.192.320 lettuce during one seed to harvest time period of 48 days. Given in other units for comparison this can also be seen as 24.800 lettuce per day or a total of 8.350.000 to 9.500.00 lettuce

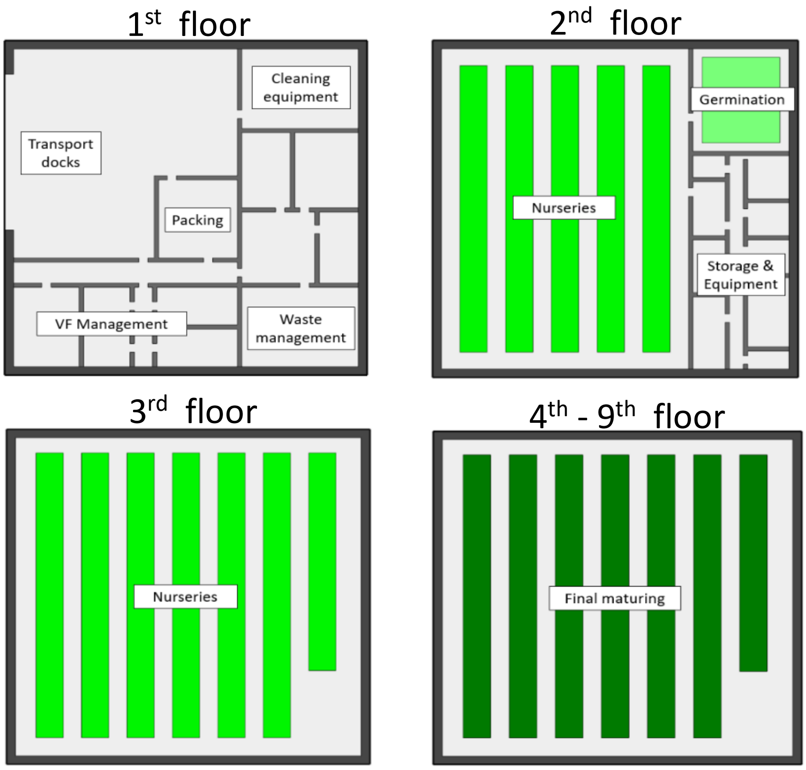

Figure 11 Chosen vertical farm floor plan design for this study

per year (7 to 8 harvests a year). These are comparable figures to the vertical farm design of (Banerjee & Adenaeuer, 2013) (if extrapolated). Fresh lettuce from this vertical has a weight of 350g, which calculates to a marketable weight of 86.800kg per day. The lettuce has a dry weight of 30g (Farag, Abdrabbo, & Abd-Elmoniem, 2013), which corresponds to the dry matter content which is usually set at 6-8% for lettuce (Graamans, Baeza, Stanghellini, Tsafaras, & van den Dobbelsteen, 2018). The dry weight is substantially lower due to the extraction of the large water content in lettuce and this unit will therefore be used in the life cycle analysis further on.

A floor plan is designed to give insight on the different floors of the building, shown in Figure 11. This design is a simplified design, as the aim of this study is not on the building physics in great detail but an environmental analysis on the building in which a few inner walls more or less, addition of specific wiring or the layout of pipelines will not affect the analysis by noticeable amounts. Though, it is worth mentioning that there are features such as staircases, bathrooms and temporary storage for daily needed equipment which are not clearly indicated on the figure, but are taken into account during the design and completion of the floor plan. A representation of the building in 3D is given in Figure 12, which is again very cubical and simplistic. The 2D and 3D figures contain different colors of green, indicating the different growing stages (as labelled in the 2D floor plan).

4.2. System Analysis

With all building characteristics known and the design of the vertical farm floor plan, a decision can be made on the interior of the vertical farm. The vertical farm is known for its ideal climate conditions, optimal growth and extensive yields. This is only possible using a fully controlled environment, which requires a set of different systems influencing different aspects of the grow needs of lettuce. “A well-designed PFAL will use high-efficiency equipment for operations, including heat pumps for cooling (and heating), variable speed motors on pumps and fans for moving water and air, and LEDs for illuminating the crop.” (Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016; Beacham, Vickers, & Monaghan, 2019)

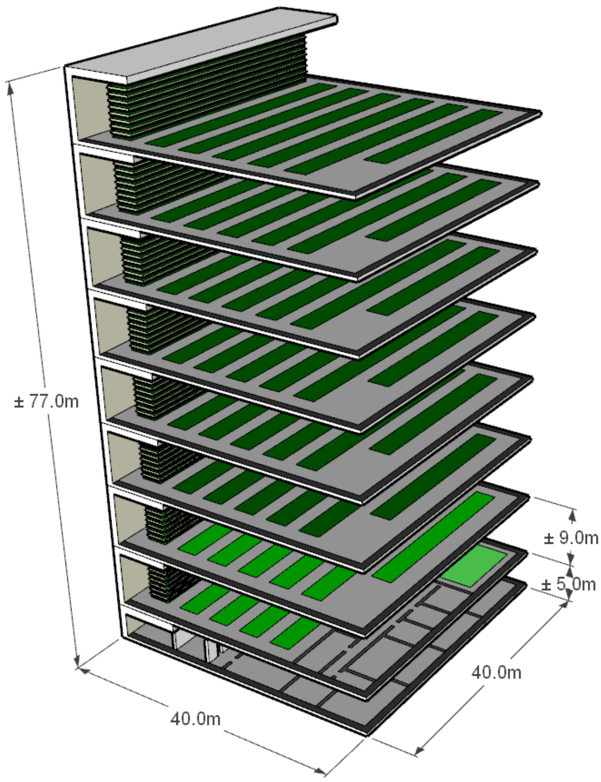

Figure 12 3D representation of the vertical farm

With the use of the book of (Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016) a list of vertical farming components has been created, shown in Table 2 Components and systems in a vertical farm . This list contains, among other things, the systems typically used in a vertical farm.

Table 2 Components and systems in a vertical farm (Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016)

Category	Equipment and Environmental Sensors
Electricity supply	Power distribution box, breakers, and relays
Air conditioning	Inner units of air conditioners with plumbing for refrigerant
	Plumbing for recycling use of drained water
	Air circulation fans
	Actual/set point temperature display unit
	Air cleaners with filters and ozone (O_3) gas generator
Nutrient solution supply	Culture beds with circulation pumps
	Plumbing with strainers and valves
	Sterilization unit (filters, UV (ultraviolet) lamp, and O_3 gas generator) (Figure 16.9)
	Tank with a floating switch, and stock solution tanks
	Plumbing for civil or clean water supply, plumbing for drainage in emergency discharge
Lighting	Light source with reflectors
	Power stabilizer, inverters, and AC-DC converters
CO_2 supply	Control unit with distribution tubes
Sanitation control	Washing/cleaning machine of culture panels (Figure 16.10)
	Cleaning tools for floor and culture beds
Stock room	Supplies for plant production, sanitation, etc.
Sensors for environmental control	Air: Temperature, relative humidity (VPD), CO_2 concentration, and CO_2 supply rate
	Nutrient solution: pH, EC (electric conductivity), temperature, water supply rate, and circulating nutrient solution flow rate
	Electrical energy: Watt meter, watt-hour meter

A lot of these systems are intertwined where "elements of one subsystem affects the components of the other. In Figure 13 Flow chart of all subsystem flows, adapted from , the system flow is represented with the details involving each subsystem" (Zeidler, Schubert, & Vrakking, 2017)

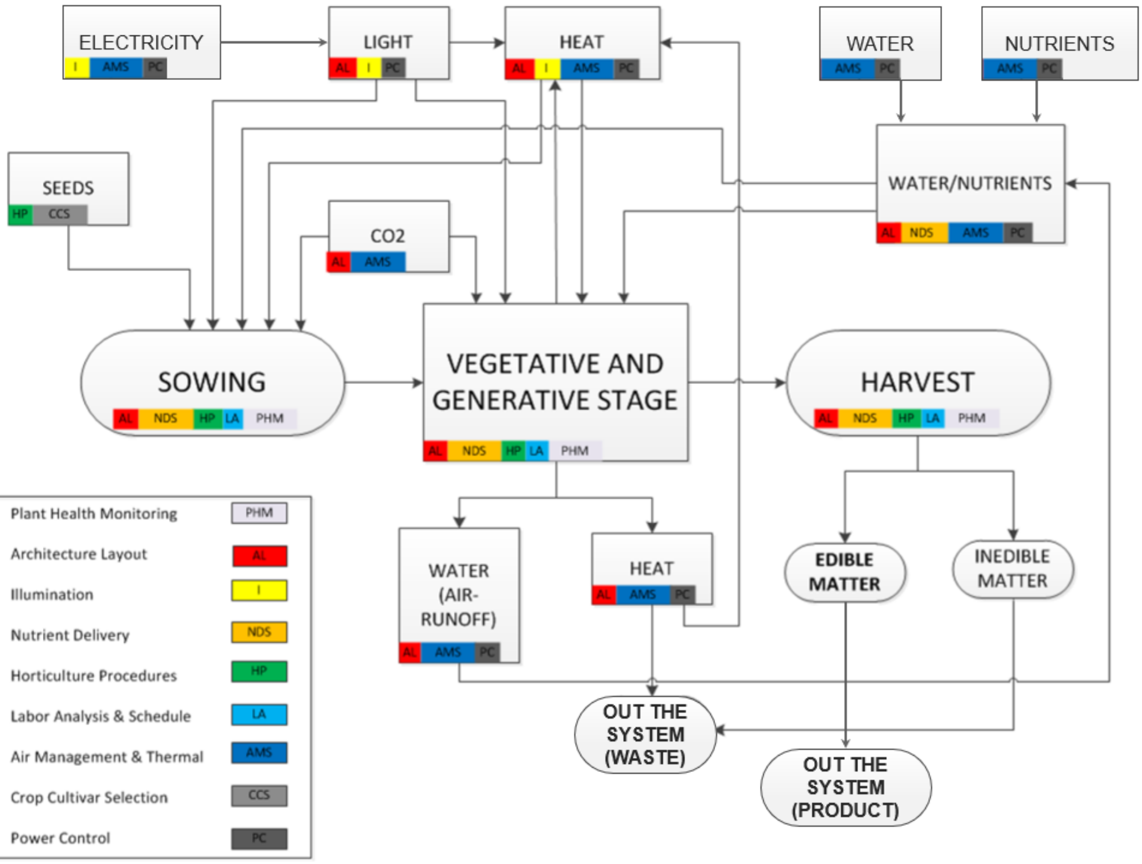

Figure 13 Flow chart of all subsystem flows, adapted from (Zeidler, Schubert, & Vrakking, 2017)

Note that in Figure 13 Flow chart of all subsystem flows, adapted from , all of the elements are flows, which are the elements being controlled by systems. The initial figure from (Zeidler, Schubert, & Vrakking, 2017) did not contain all input flows or properly named outputs flows and thus the diagram has been adapted to fit this study. In this diagram the large rectangle box in the middle shows the main section of the use phase in which the plants mature. The smaller rectangles display system components which maintain the characteristics for an ideal climate and for a closed-loop system to exist, while the larger ovale shaped boxes show an action and the smaller oval boxes show the output of the system. This figure for example shows that the water is in a semi closed loop system, because directly the water is in a constant loop, though indirectly it is removed from the system within the harvested product and therefore a small water addition is needed every time a crop leaves the system. This diagram does not contain a cooling system, as it is cools the heated air and is thus incorporated in the flow named “Heat”.

Also, as briefly mentioned, the lettuce cultivation has multiple growing stages (germination, nurseries and final maturing), within each of these stages different climates are desired, thus also different parameters and inputs are required in different parts of the building. Within this complexity of intertwined systems literary research has yielded various options, systems and input parameters which are explained further in this chapter. At the end of every subparagraph, a table is shown displaying all input and output flows as well as the system used and extra materials needed for the system to work.

4.2.1. Nutrient Solution Supply

One of the more important systems is the nutrient solution supply, which contains the required nutrients for a plant to grow. In conventional farming this is regulated by nature through rainwater and soil (which can deplete). In indoor crop cultivation, systems are used to recreate this nutrient flow, which are able to create a larger density of crops and larger yields. (Aldrich & Bartok, 1994)

The supply of nutrients is a technique that has been used for centuries, dating back to the Egyptians (Raviv, Lieth, & Bar-Tal, 2019). Over these years farmers have perfected this method and created the hydroponic and aeroponic systems. Both systems are created to be as efficient and low-cost as possible, removing the soil or aggregate from the equation. These systems are seen as (semi-)closed loop systems, meaning that after the initial water input the system can recirculate and recycle its content, without any waste flow output. With the crops absorbing water as part of its content, there is water loss through sowing and there is external water needed to refill the hydroponic system, therefore it is seen as semi-closed loop. There is no waste water flow, thus no output of water or minerals, everything is recycled within the water system loop.

As the names reveal, a hydroponic system uses a technique of flowing or stagnant water (hydro) running through the rootzone of the elevated plant (in plastic trays without soil) (Kozai, Smart Plant Factory, 2018), while the aeroponic system supplies nutrients by water vapor in air (aer) to the elevated plants (van Os, Gieling, & Lieth, 2019). In this vertical farms its chosen to use a hydroponic system. More is known about this system in terms of data, case studies and comparable data within the range of the lettuce crop and is less complex than an aeroponics system while both requiring the same resource, water. One other system is the aquaponic system, which is an adapted version of the hydroponic system, in which the stagnant water is inhabited by fish which eat waste material of the plants and convert this into nutrients for the plants. This system is relatively new, in which a lot of research has to be performed for it to be fully applicable in buildings like vertical farms.

Possible techniques of hydroponics are NFT (Nutrient Film Technique), DFT (Deep Flow Technique), spray, shallow, ebb and flow, drip irrigation and wicking systems, each of which has their own strengths and weaknesses. (Kozai, Smart Plant Factory, 2018) Wicking is the most economical and eco-friendly, however, it does not support leafy greens. Of the other systems, NFT and DFT are the most used and known systems for growing leafy vegetables. (Frost, Groves, & Charkowski, 2013; Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016)

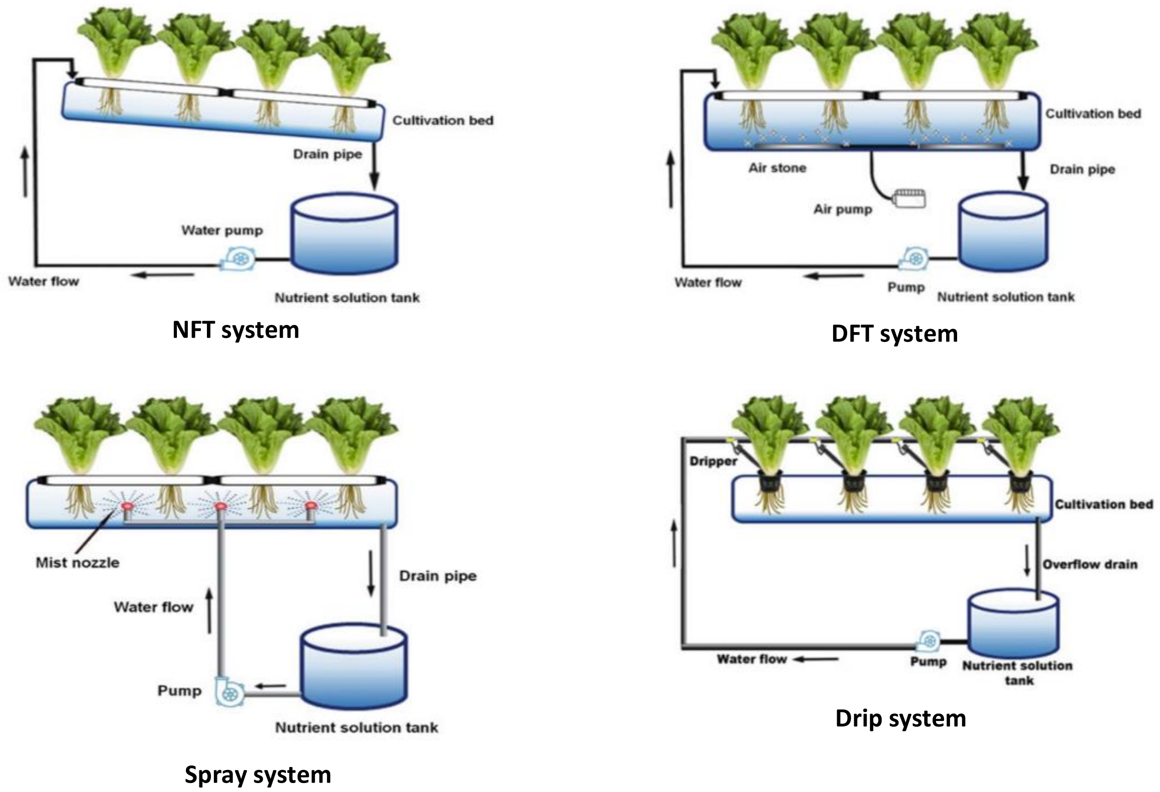

Figure 14 Often used hydroponic systems, 1. Nutrient Film Technique (NFT): constantly flowing water in an angled gutter, roots in air and tips in water, 2. Deep Flow Technique (DFT): almost stationary water in deep gutter, roots fully in water, 3. Spray system: filling the closed gutter with water vapor, roots in constant mist , 4. Drip system: water drops from above captured by gutter, waterdrops constantly flowing over roots. (Kozai, Smart Plant Factory, 2018)

Of the resulting hydroponic systems, shown in Figure 14, NFT has been chosen as the hydroponic system in this vertical farm, due to its small space requirements, low water use at any time, and simple system. It is important to mention that most NFT systems don't use an automatic timer as they run constantly throughout its lifetime. This can cause a problem in case of power shortages, outages or system failures. (Val, 2018)

A Nutrient Film Technique (NFT) system requires (Val, 2018):

- A reservoir to contain the nutrient solution
- Nutrient pump
- Tubes to distribute water from the nutrient pump to the NFT growing tubes
- Channel for the plants to grow in
- Net pots to contain plants and growing media to start seedlings in
- Return system (tubing, channel) to guide the used nutrient solution back to the reservoir
- Air pump

Table 3 Nutrient solution supply system characteristics

Input	Nutrients	Water	Electricity
System/material	Nutrient Film Technique (NFT)	Pump	Water gutter and water pipes
Output	Water vapor (through evaporation in water gutters)		

4.2.2. Lighting

"The lighting system is the heart of any indoor garden and provides plants with the energy needed for photosynthesis. Novice indoor gardeners who grasp the concept of setting up a lighting system and make the calculations will already be on the right path to creating an efficient, productive garden." (Hopper, 2017)

4.2.2.1. Type

Since the development of LED lights, a lot has improved and LED lights are being used in a lot of objects for daily use. LED lights are very energy efficient and their size can be very small compared to older lights. In plant growth in the past high pressure sodium lights (HPS) were optimal for plant growth and very efficient, however with an omnidirectional light output (360 degrees) this would result in a lot of light loss and higher energy demands. LEDs however, surpass this lamp in efficiency and lifespan, as well as being directional (180 degrees instead of 360 degrees). (Stouch Lighting) Because of these reasons vertical farms tend to use this technological advancement in lighting. (Benke & Tomkins, Future food-production systems: vertical farming and controlled-environment agriculture, 2017) It has been chosen that the vertical farm in this report will use LED lights as the means of illumination in the lighting system (Figure 15).

Figure 15 Horticulture LED growing light example (Lomax, 2017)

4.2.2.2. Color

A good lighting system is essential to ensure sufficient light and efficient energy use in an indoor farming facility. (Kozai, Smart Plant Factory, 2018) In normal circumstances plants are receiving every color of light in the light spectrum from violet to red and also other spectra rays such as Ultra violet (UV) and Infrared (IR) light. Every color taken separately has a different effect on a plants growth, development and photosynthesis process. "Generally, UV and blue light are more efficient in accumulating secondary metabolites (that affect plant characteristics such as color turning; deeper coloring; compact, hard and firm leaves; thickness and strong taste). Red light is more efficient in photosynthesis, and the far-red/red light ratio is more effective in controlling flowering, stretch of stem and leaves and other morphological characteristics (such as producing looser, soft, light-color leaves). Green light can be effective in producing a dense canopy of plants with similar color of leaves, such as iceberg lettuce or cabbage, since green light has a higher penetration rate than blue and red light." (Kozai, Smart Plant Factory, 2018). Thus every color has its own specific effects on the crop. With the desire for optimal plant growth, large yields and a crop that is rich in taste and size, combinations of different light bands is required. The study of (Han, et al., 2017) shows that with the use of RYB (Red Yellow Blue) light, these desires can be fulfilled. It has some compromises on the flowering, however the growth is optimal. Thus, it has been chosen that this vertical farm uses RYB LED lights.

4.2.2.3. Light density & active exposure hours

Lumens are a unit of measurement based on a model of human eye sensitivity in well-lit conditions, which relates to the photopic response curve (Figure 1). As you can see, the photopic response curve is bell shaped (indicated by Lumens) and shows how humans are much more sensitive to green light, than blue or red light. (Fluence Osram) Most plants however are highly efficient at using red and blue light to drive photosynthesis, indicated in Figure 16 Photopic response curve, PAR = Photosynthetic

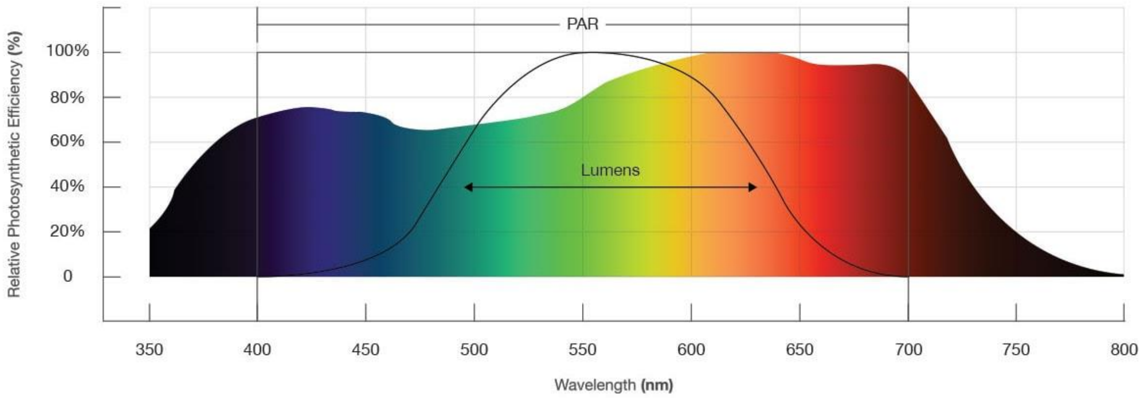

Figure 16 Photopic response curve, PAR = Photosynthetic Active Radiation (Fluence Osram)

Active Radiation with PAR (Photosynthetic Active Radiation).

The definition used for plants in the light spectrum is Photosynthetic Active Radiation or PAR, it lies in between 400 – 700 nanometers (nm). PAR itself is not the unit measurement, it defines the type of light needed. The unit measurement of PAR is Photosynthetic Photon Flux (Density) or PPF(D). With simple calculations using the Day Light Integral formula (Formula 1) the type of amount of active photons delivered to a specific area over a 24-hour time period can be calculated. (Ledtonic, 2019).

$$DLI = PPFD * \frac{T * 3600}{1000000} \qquad (1)$$

In which DLI (Daily Light Integral) is expressed in moles/m^2/day, PPFD in µmol/m^{2}s and T (photoperiod) in hours.

Using this formula and general characteristics of lettuce the specific growing light, as well as its active exposure hours can be calculated. Lettuce is said to have a Day Light Integral value of 14 – 16 (Ledtonic, 2019). With the use of the formula and Excel column calculations, a graph has been made depicting DLI at different PPFD and active exposure hours, shown in Appendix A. In this graph it is visible that a multitude of combinations of active hours and PPFD is possible resulting in the same DLI, however, very high PPFD levels over a short duration of time or very low PPFD levels over an expended period of time are rarely ideal for good growth. (Ledtonic, 2019) Several companies such as Philips create a variety of growing lights in which they often use growing lamps with a PPFD of 200 to 300 (for lettuce specific) (Lomax, 2017). Reaching the DLI of 14 of lettuce is possible with, for example, active exposure hours of 13 hours and a PPFD of 200 µmol/m^{2}s or 20 hours and 300 µmol/m^{2}s (Appendix A). Therefore, it has been chosen to use led lights with a PPFD of 250 µmol/m^{2}s and active exposure hours of 16 hours in this study.

Table 4 Lighting system characteristics

Input	Electricity	
System/material	Phillips spectrum lights	Lightracks
Output	Light	Heat

4.2.3. Climate Control

Figure 17 Modern roof HVAC system (Vanneste & Demey, n.d.)

With the previous systems Climate Control is the last of the three major systems of a vertical farm. This system creates the desirable controlled climate for a certain crop to grow as optimal and as resource efficient as possible. The Climate Control ties everything together. It uses ventilation, cooling and heating to keep conditions optimal by countering the output of the other systems and the plants. The heat from the lighting system is cooled, the humidity from the evaporation of water from the gutters and plants is lowered by dehumidifying and the CO_2 and O_2 from the plants is regulated by the fans. This creates a stabilized controlled environment. Climate Control is not a new or innovative technique, it is situated in many different machines and structures. In the United States climate control in commercial buildings is usually provided by a HVAC system (Heating, Ventilation, Air Conditioning), therefore it is <u>chosen to use a HVAC system</u> in the vertical farm in this study.

4.2.3.1. Ventilation

During photosynthesis plants assimilate a lot of CO_2 and release it during respiration. Plant are very sensitive to CO_2 levels in the air, the concentration can have a significant impact on the rate of photosynthesis. (Kitaya, Tsuruyama, Kawai, Shibuya, & Kiyota, 2000) “CO_2 concentration is probably the least controlled factor in the traditional controlled environment of greenhouses and growth chambers”, as the concentration of this gas is not only changing by plant activity, but human activity as well. (Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016) However, it can be controlled in a vertical farm by means of airflow and ventilation. “At minimum, the CO_2 concentration in PFAL should be maintained at or around atmospheric levels.” (Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016).

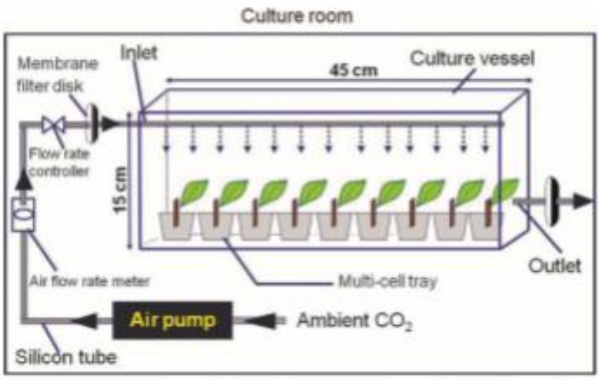

Figure 18 Mechanical ventilation in a vertical farm example (Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016)

There are two forms of ventilation possible in indoor plant factories, natural (passive) and mechanical (active) ventilation. In which natural ventilation is possible in windy locations and cost less energy. Even though Oklahoma is one of the most windy cities of the United States (Osborn, n.d.), on less windy days the CO_2 amount has to be maintained at a certain level as well to ensure optimal yield. Thus, for precise control of the airflow through the vertical farm <u>mechanical ventilation is chosen</u> as its means of airflow and CO_2 distribution, an example shown in Figure 18 Mechanical ventilation in a vertical farm example .

“We must avoid strong air current speed around the plants that may cause mechanical stress and damage. Wind-induced shaking and the resulting mechanical stress on plants reportedly reduce internode length as well as leaf size.“ (e.g., (Biddington & Dearman, 1985)). These plant responses are often observed at air current speeds greater than 1m/s.

Concentration of CO_2 can be set to 500–2000 ppm when there is an effective air circulation system continuously allowing CO_2 evenly distributed inside the plant canopy; otherwise a higher CO_2 setting is recommended. The air current speed is usually controlled between 0.3 and 1.0 m/s using air circulation fans to promote gas exchange. (Niu, Kozai, & Sabeh, 2015)

4.2.3.2. Temperature

“Considerable differences exist among lettuce varieties in heat tolerance. These differences are the primary reasons some lettuce varieties can be grown in warmer climates.” (Sanders, 2019) The lettuce used in the vertical farm has an optimum temperature for growth of 20–25 °C. At this temperature photosynthesis is found to be maximum. With higher temperatures (30 – 35°C) respiration increases. (Graamans, Baeza, van den Dobbelsteen, Tsafaras, & Stanghellini, 2018) The ideal lettuce growing temperature remains constant during one growing phase (germination, nurseries, maturing). (Seginer, Shina, Albright, & Marsh, 1991; Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016)

The plant behavior during photosynthesis, the output of the lighting system and the airflow of the ventilation all contribute to the variations in temperature within the indoor climate. To reach the optimal temperatures and continuously hold them at this position in an indoor climate requires precise cooling and heating systems.

Cooling

In a Vertical Farm, lighting contributes the greatest source of heat, followed by motors used to operate fans, pumps and automation. Because Vertical Farms are often well-insulated (Insulation value N is 0.01-0.02 h^{-1}) and designed to operate even during the cold winter nights in order to maintain a suitable internal temperature. Cooling is usually required 24/7 and year-round to remove the heat generated by the lighting system inside the space. (Sabeh, 3 challenges of growing in a vertical farm, 2019; Kozai, Smart Plant Factory, 2018; Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016; Hallikainen, 2019)

The cooling load of air conditioning is often used where the COP factor (the ratio of the cooling load of the culture room to the electricity consumption of the air conditioners) is very important. Multiple air conditioning systems are required in a large vertical farm tower, however not all of the air conditioning systems have to be running all of the time. Based on the time of day (diurnal courses) and specific season, some systems can be turned off after the temperature drops when the sun sets or in large portions of colder seasons. (Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016). More information about this is given in Appendix B.

Heating

Usually heating systems in vertical farms only contribute little to the overall climate due to the amount of heat coming from lighting, however, it is generally still needed to keep an ideal climate. The recirculation of air after being dehumidified and cooled by the air conditioning system is to cold to send back into the vertical farm (for example 7°C). Thus the air is reheated in the recirculation process.

The fictive vertical farm in this study is placed in a location where it experiences hot summers and mild winters, thus heating is only needed to reheat conditioned air.

4.2.3.3. Dehumidification

Besides the heat as a by product of the intense lighting, another by product is the evapotranspiration of plants why undergoing photosynthesis. Dehumidification is constantly required to remove the moisture added to the air via evapotranspiration (Et) from the plants and irrigation system. The rate and quantity of Et depends on several variables, including light intensity, air temperature and humidity (or vapor pressure deficit), air movement and the irrigation method. Although Et is greatest when plants are mature and the lights are on, Et does not stop when the lights go out. Plants continue to respire and give off moisture when the lights are off, and for continuously recirculating irrigation systems (e.g. NFT and aquaponics), evaporation from these systems can remain constant all day. (Katsoulas & Stanghellini, 2019; Sabeh, 3 challenges of growing in a vertical farm, 2019; Graamans, Baeza, van den Dobbelsteen, Tsafaras, & Stanghellini, 2018; Kalantari, Tahir, Lahijani, & Kalantari, 2017)

It is essential to keep the humidity level at an optimal level to avoid possible physiological disorders of plants which are usually caused by too high humidity level, such as tipburn. In the cooling panel of the air conditioner transpired water condenses and this water is recirculated into the irrigation system. Therefore, the water used in a vertical farm knows little losses, except for the water stored in crops. (Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016; Hallikainen, 2019) “The ideal range for VPD (vapour pressure deficit) is 0.8–0.95 kPa, with an optimal setting of around 0.85 kPa (Niu, Kozai, & Sabeh, 2015). This constant humidity does not significantly affect the longevity of the materials used in the vertical farm. Most of the materials are coated metal and polyvinylchloride, suitable for a humid environment as intended, or materials made with the intention of ending up in a vertical farm (hydroponic vertical farm system).

Table 5 HVAC system characteristics

Input	Electricity	Heated air	Water vapor	CO_2
System/material	HVAC	CO_2 distribution system		Ducts
Output	Cooled air	Heat (external)	CO_2	Wind

4.2.4. Information & Communication

“Controlling and monitoring the climate and status of the plants are essential elements in any agricultural production. It allows taking corrective measures in time to avoid a decrease in yield and a potential loss of marketable product.” (Zeidler, Schubert, & Vrakking, 2017) To control the ideal climate a monitoring and information system is needed. This system automatically adapts all variables to maintain a stable climate and reduce energy consumption and thus steers the other systems mentioned in the vertical farm. For the main control and communication system BMS (Building Management system) is used.

This system can not function without any knowledge of the current climate, therefore information of all the variables and measurable aspects in the vertical farm are needed. This information is gathered by monitoring equipment and sensors, for example the use of Priva E-measuring boxes (Figure 19 Priva E-measuring box). (Zeidler, Schubert, & Vrakking, 2017) Priva's climate sensors have been specially developed for the horticulture sector. They stand out in terms of accuracy, reliability and functionality and have been used by multiple studies on greenhouses and indoor growing facilities. (Maslak & Nimmermark, 2014; Bontsema, et al., 2010; Zeidler, Schubert, & Vrakking, 2017)

Figure 19 Priva E-measuring box (Priva, n.d.)

Table 6 Information & communication system characteristics

Input	Electricity	
System/material	Sensors/measuring boxes	Control computers
Output	Data	Instructions/control

4.2.5. Other Systems

Besides the four big systems keeping an ideal climate there are some smaller systems within the vertical farm which are not directly related to plant growth and maximum yields but are necessary to keep the vertical and all its systems up to standards.

Sanitation control: which is the washing and cleaning of the machines, culture beds, culture panels and tools.

Prevention control: which prevents from any diseases or insects entering the closed system. This is not possible through ventilation (membranes), hydroponics (filtering) or any other system except the human factor. Thus, airlocks, special clothing, air showers, handwashing and proper healthcare is needed.

Worker’s driven system/logistics: Which is the work done by the working staff rather than the machines in the vertical farm, which includes seeding, transplanting, harvesting (with tools), trimming, weighing, packaging, storing, shipping.

4.2.6. Cultivation System Plan

As briefly mentioned the lettuce goes through a multitude of different steps in the process of maturing. Germination is where a seed transforms in a seedling under wet conditions and is divided into two steps. The first germination phase is where the seeds are being prepared for the vertical farm and where some form of growth is visible due to opening up of the seed (budding), which takes 1 to 2 days. The second germination phase is where these seeds are transferred into the nurseries and grow into seedlings which are very small plants, which takes 14-16 days and the first grow phase, also located in the nurseries (with different conditions) where the plants are growing towards the “planting” stage, which takes 10 to 15 days. In the last growing phase also known as the maturing phase the crop is “planted” and matures to its final form and gets harvested when its completely ripe, which takes about 18 days.

With every system analyzed and discussed a cultivation system plan can be made. The cultivation system plan takes into account all systems affecting each other and combines all of the systems mentioned above to create the ideal growing conditions according to literature. Every growing stage has its own needs and the younger the plant the higher the relative humidity and the lower the light intensity and temperature. The wind speed and CO_2 levels stay the same. (Zeidler, Schubert, & Vrakking, 2017; Kozai, Smart Plant Factory, 2018) The eventual parameters for the systems are given in Table 7.

Table 7 Cultivation plan parameters in different growing stages

Stage	**Time (Days)**	**Temperature (°C)**	**Relative Humidity (%)**	**Light Intensity (µmol/m²/s)**	**CO_2 (ppm)**	**Wind Speed (m/s)**
Germination Phase 1	1-2	22	95	150	1000	0.3-0.5
Germination Phase 2	14-16	22	80	200	1000	0.3-0.5
Growth Phase 1	10-15	23	80	225	1000	0.3-0.5
Growth Phase 2	18	23	80	250	1000	0.3-0.5

Due to many sources giving different possible growing conditions and systems used, it is very farm dependent which variables will ensure the perfect climate. As this is a fictive vertical farm it can not be tested, however the conditions given in the cultivation plan will be very close to the ideal climate. If this vertical farm would ever to be tested in a model or build, fine details could be changed to ensure the maximum yield, however this is out of the scope of this study.

5. Life Cycle Analysis (LCA)

With the complete vertical farm mapped out (in the desired detail), an analysis can be executed on the building as a whole or specifically on the crop in the climate conditions given in the system analysis. This chapter covers the Life Cycle Analysis or LCA which is defined by ISO14040 series as "the compiling and evaluation of the input and outputs and the potential environmental impacts of a product system during its lifetime." (Lee & Inaba, 2004) or more comprehensive in a definition of (Ecoil, 2004): "LCA is used to provide a systematic framework that helps to identify, quantify, interpret and evaluate the environmental impacts of a product, function or service in an orderly way. It is a diagnostic tool which can be used to compare existing products or services with each other or with a standard, which may indicate promising areas for improvement in existing products and which may aid in the design of new products."

This chapter is the heart of the study and creates the basis of a Life Cycle Analysis (LCA) by discussing the various steps necessary to perform a proper LCA. The goal and scope will be left out of this chapter as they have been covered in the introduction column. In this chapter the system boundaries as well as the functional unit (on which scale the analysis is done) will be discussed. Also the impact categories, indicating the environmental impacts, are chosen and covered by this chapter. After the preparation and discussion of the various LCA steps, a Life Cycle Inventory Analysis (LCIA) can be executed together with the Life Cycle Analysis Modelling. The LCIA shows a list of materials necessary to create the vertical farm including their quantities and respective units, which are converted into the desirable functional unit in the modelling stage. In the LCA Modelling, a program called "GaBi" is used, which is specifically created to design, model and calculate Life Cycle Analyses. GaBi has 25 years of application and improvements on Life Cycle Analysis, making it a solid choice for LCA software. Databases from GaBi are used in the LCIA while also external data is used to fill in the LCIA, which itself is used as a basis for creating the model. These intertwined and interdepend tendencies of analysis steps are common in LCAs. (Liebsch, 2020)

5.1. System Boundaries

Within a product, system, function or service all activities or processes during its lifetime result in environmental impacts due to consumption of resources, usage of electricity and other necessities, emissions into the natural environment (air, land, water) and other environmental exchanges. Every stage can be analyzed and added to the overall climate impact, however this is not always necessary or possible. The life cycle of a product is given in Figure 20 Steps in the Life Cycle of a product and shows all possible steps to be analyzed. There are various different types of LCA's possible, Cradle-to-grave (analyzing the full life cycle of a product from resource extraction to end of life phase (with disposal and possible recycle stages)), Cradle-to-gate (analyzing part of the life cycle from resource extraction to the factory gate (before the transportation)), Cradle-to-cradle (similar to cradle-to-grave however, the end of life phase is a recycling process) and Gate-to-gate (analyzing one value-added process in

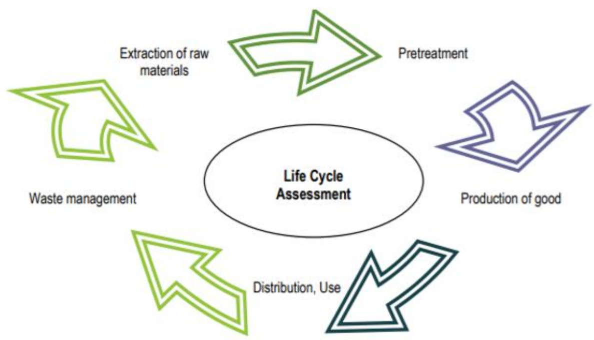

Figure 20 Steps in the Life Cycle of a product (Ecoil, 2004)

the entire production chain). Each of these analyzes a different set of the steps shown in Figure 20 Steps in the Life Cycle of a product . On top of these LCA-types there is an overshadowing classification linked to the purpose and the expected result of the LCA. This classification can be subdivided into: Ecologically based LCA (environmental impacts), Economically based LCA (Life Cycle costs) and Exergy based LCA (maximum useful work possible during a process that brings the system into equilibrium) (Rosen & Dincer, 2001; Hendrickson, Lave, & Matthews, 2005; Singh & Bakshi, 2009; Jiménez-González, Kim, & Overcash, 2000; Lee & Inaba, 2004).

Also, based on the steps of a life cycle of a product, an LCA can be modelled using a certain amount of depth and complexity to the model. In LCA terms this is given in orders. The zero (0) order is the product itself, in this case a vertical farm, The first (1^{st}) order is the direct product life cycle (production – use – end of life), The second (2^{nd}) order is the assembly of processes and products in this direct product life cycle (for example, assembly of the production phase), The third (3^{rd}) order is the assembly of the assembly (for example the energy used in the assembly of the production, phase), and so forth. The higher the phase the more detail and the more complex the model becomes. (Jokic, 2020)

This study strives to analyze the vertical farm from its raw material extraction till its end of life phase including recycling, in order to make the model as precise and in depth as possible. However, there are limitations to the depth and complexity of the model, by means of known data and time constraints on the study. Also, as mentioned in the introduction, this study focusses on the environmental impacts of the vertical farm. Because of these reasons, it is chosen to use an Ecologically based LCA that analyzes the vertical farm from Cradle-to-grave in a second (2^{nd}) order perspective.

Within the Cradle-to-grave approach a lot of processes, data and resources have to be known. Sadly, the quantitative data on vertical farms is scarce and therefore some steps in the cradle-to-grave process will contain estimated, guessed and inter- and extrapolated data. These estimations and/or even exclusions of flows will be discussed during the LCA modelling stage. Furthermore, a vertical farm contains a lot of secondary and indirect processes, which are expected to have very little effect on the eventual climate impact outcome in relation to the large systems (shown in the system analysis column as “other systems”. A simple rule of thumb used by LCA users/analysts is the 5%-rule. If an object, system or service is expected to have less than 5% impact on the eventual result and is not a majorly important section of the total product, it can be excluded from the analysis. (Meijer, Kasem, & Lewis, 2018; EebGuide Project, 2012) This results in smaller objects or elements such as sewage, wiring, general lighting (with LEDs or energy saving lamps), the toilet, etc. not being calculated or taken into account in the LCA. Exclusion of these elements will be taken into account in the final results and in the comparison to rural agricultural data. The discussion column at the end of the study sheds light on the effects of these exclusions.

5.2. Functional Unit (FU)

“The functional unit of a product system is a quantified description of the performance requirements that the product system fulfils.” (Consequential-LCA, 2015) The reason to choose a functional unit is the consistency throughout the analysis, in which every unit is comparable. This simplifies the analysis calculation, results discussion and the eventual comparison to available data. In papers, studies and books analyzing or discussing vertical farming, a functional unit of 1kg dry or fresh lettuce is often used. (Kikuchi, Kanematsu, Yoshikawa, Okubo, & Takagaki, 2018; Kozai, Smart Plant Factory, 2018;

Graamans, Baeza, Stanghellini, Tsafaras, & van den Dobbelsteen, 2018) Also, studies with rural agriculture data, on which the comparison is based, use a form of 1kg lettuce or a unit that is easily transferrable to 1kg lettuce. Therefore, this study also uses the Functional Unit of 1kg dry lettuce weight.

The Functional Unit is not used in the appendix calculations of the life cycle inventory. In this appendix (Appendix C) all of the systems and components of the vertical farm are quantified. To keep calculations simple, the units associated with the components are used. These units are converted to the Functional Unit in the large Life Cycle Inventory Analysis Table (Table 8). The conversion to the Functional Unit is based on a combination of the time of one harvest (48 days), the amount of lettuce per harvest (1.192.320) and the average dry weight of one lettuce (30g).

5.3. Life Cycle Inventory Analysis (LCIA)

In order to analyze a vertical farm, all of its components should be known. With the previous chapter on the choices and dimensions of the building and its systems this is partly displayed. As most stages in the Life Cycle of the vertical farm will be covered, "Extraction of raw materials" demands a list of the necessary raw materials and the "Pretreatment" and "Production of goods" their own lists of techniques and products. With the Life Cycle Inventory Analysis (LCIA) all of these necessities are combined into one large list showing all objects and products needed to create the vertical farm. Most of the elements of the list are taken from literature on vertical farms (extrapolated or interpolated from comparable studies), on greenhouses (and adapted to fit the vertical farm standards) and other sources (for material specific data). All of these sources, calculations and estimations are given in Appendix C, divided into sub-chapters as shown in Table 8. All of the objects in Table 8, are given with their respective quantity and unit, as well as an adapted quantity and unit which fits the functional unit. At last a life expectancy of the system components is shown which is used in LCA modelling phase further on.

Table 8 Life Cycle Inventory Analysis table (LCIA-table) based on the functional unit of "material per 1kg dry lettuce"

System components	**Material**	**Quantity / Use**	**Unit**	**Adapted quantity**	**Functional unit**	**Life Expectancy (years)**
	Building structure					
Roof	Steel sheets	12.5	ton	1.60E-05	kg/kg	30
Ceiling	Steel bars	320	ton	4.08E-04	kg/kg	60
Columns	Concrete	603	ton	7.70E-04	kg/kg	60
Inner walls	Oak wood	63	ton	8.04E-05	kg/kg	20
Outer walls	Concrete	750	ton	9.57E-04	kg/kg	60
Floor	Concrete	2404	ton	3.07E-03	kg/kg	60
Foundation	Concrete	1866	ton	2.38E-03	kg/kg	60
	Vertical Farm System structure					
	Cultivation area structure					
Warehouse racks	Steel	20.85	ton	2.66E-05	kg/kg	60
Plant seeds	Naked, shell-less untreated seeds	24840	seeds/day	3.33E+01	seeds/kg	-
Mat (germ.)	Urethane	16.93	m3	8.64E-06	kg/kg	25
Tray (germ.)	Polystyrene	10.54	m3	6.05E-07	kg/kg	60
Film (germ.)	Polyethylene	0.0143	m3	8.21E-10	kg/kg	60

Plate (germ.)	Polyethylene	7.15	m3	4.11E-07	kg/kg	60
Cultivation bed (nurseries)	Urethane	107.43	m3	4.94E-06	kg/kg	25
Cultivation bed (maturing)	Urethane	492.43	m3	2.26E-05	kg/kg	25
	Hydroponic System					
Gutters	Polyvinylchloride	470	m3	7.80E-04	kg/kg	140
Water pipes	Polyvinylchloride	11	m3	1.83E-05	kg/kg	140
Re-circulating pump	Metal machine	10190	kWh/day	1.37E+01	kWh/kg	10
Extraction pump	Metal machine	0.24	kWh/day	3.22E-04	kWh/kg	20
Water tanks	Steel	1.6	m3	1.64E-05	kg/kg	60
	Initial water	1206	m3	1.54E-03	kg/kg	-
	Water replenishment	7.936	m3/day	1.06E-02	kg/kg	-
Nutrient supply	Nitrogen (nutrients)	-	-	8.70E-02	kg/kg	-
	Phosphorus (nutrients)	-	-	9.90E-02	kg/kg	-
	Potassium (nutrients)	-	-	1.14E-01	kg/kg	-
	Lighting System					
Philips Spectrum Lamps	Lamp	97984	kWh/day	1.31E+02	kWh/kg	6.8
Light racks	Steel	43.54	m3	4.47E-04	kg/kg	60
	HVAC System					
Ventilation	Metal machine	6989	kWh/day	9.38E+00	kWh/kg	15
Air conditioning	Metal machine	9000	kWh/day	1.21E+01	kWh/kg	15
Dehumidification	Metal machine	1800	kWh/day	2.42E+00	kWh/kg	20
Heating system	Metal machine	211	kWh/day	2.83E-01	kWh/kg	20
CO_2 supply	CO_2	-	-	8.00E+00	kg/kg	-
Ducts	Steel	2056	tons	2.62E-03	kg/kg	20
Coolant	Propane	6	kg	7.66E-09	Kg/kg	-
	Monitoring System					
Priva E-measuring box	Metal machine	57.6	kWh/day	7.73E-02	kWh/kg	-
Climate computer	Electronics	12	kWh/day	1.61E-02	kWh/kg	-
Workstation PC	Electronics	4	kWh/day	5.37E-03	kWh/kg	-
Screens	Electronics	1	kWh/day	1.34E-03	kWh/kg	-

The adapted quantities are calculated with Excel using formula 2 and 3 in which the first equation is used for the conversion of a static total amount of building materials and the second equation is used for dynamic resources such as water, CO_2 or electricity per day.

$$Adapted\ static\ quantity\ (n/kg) = \frac{B(n) * SH}{(LE * 365 * R_{replacement}) * M_{totprod}} \tag{2}$$

$$Adapted\ dynamic\ quantity\ (n/kg) = \frac{RS(n/day) * SH}{M_{totprod}} \tag{3}$$

In which n is a variable unit belonging to a certain building material, B is the building material (in n), LE is the life expectancy of a building material (in years), $R_{replacement}$ is the replacement rate of the building material (-), RS is the resource (in n/day), SH is the seed to harvest time (in days (= 48)) and $M_{totprod}$ (in kg) is given in the following formula:

$$M_{totprod} = \frac{TP_1}{1/M_{dry}} = \frac{1192320}{1/0.03} = 35769.6\ kg \quad (4)$$

In which TP_1 is the total lettuce production of one harvest of the vertical farm (- (= 1192320)) and M_{dry} is the dry weight of lettuce (in kg (= 0.03kg)).

5.4. Impact Assessment

This chapter connects the study aim and goals with the available assessment methods in the software. These assessment methods in a LCA are part of the 'impact assessment' step in which the 'environmental impacts' of the vertical farm are analyzed. The term environmental impacts is very broad as it consists impacts to Global Warming, Land, Air, Water, Humans, and so on. Even though the program, with the right model input, calculates all of these impacts, not every impact is needed in this study. Some of the impact categories are not relevant to this study because neither the vertical farm or the rural agriculture causes a significant impact. Therefore, a specific set of impact categories are chosen based on the problem definition and aim of the study and the available literature for comparison to rural agriculture.

This study is assessing the vertical farm from the perspective of Climate Change (CC (or Global Warming Potential (GWP)), which is a measure of greenhouse gas emissions (GHG) based on how much heat a greenhouse gas traps in the atmosphere. This impact assessment is also known as the carbon footprint (given in kg CO_2 equivalent), the Water Footprint (WPF), which is a measure of how much blue and green water is used directly and indirectly, the Land Footprint or Land Use (LF/LU), which is a measure for the amount of land needed (in m^2) for the total life cycle (creation of the vertical farm, use phase and end of life phase), the Terrestrial Acidification (TA), which is a measure of acids emitted to the atmosphere, land or water and the Freshwater Eutrophication (FE), which is a measure of the amount of nutrients being released into freshwater sources such as rivers and lakes causing excessive algae growth, which is a hot topic among rural agriculture communities. (Huijbregts, et al., 2016; Stranddorf, Hoffman, Schmidt, & FORCE-Technology, 2005)

This set of impact categories are not all within one calculation method. Partly the method of ReCiPe 2016 v1.1 Midpoint (H) is used. This method makes use of midpoint to endpoint calculations with characterization factors. Midpoint indicators focus on single environmental problems, for example climate change or acidification. Endpoint indicators show the environmental impact on three higher aggregation levels. (Huijbregts, et al., 2016) A visualization of this method is shown in Figure 21 ReCiPe 2016 method visualization Figure 21 ReCiPe 2016 method visualization .

Even though this method covers a lot of the environmental impacts, the specific footprints mentioned earlier in the report (water footprint and land footprint) are not analyzed on their own in this method. Therefore, the method Environmental Footprint 2.0 (EF2.0) is used in the analysis to include the missing categories. (Fazio, et al., 2018)

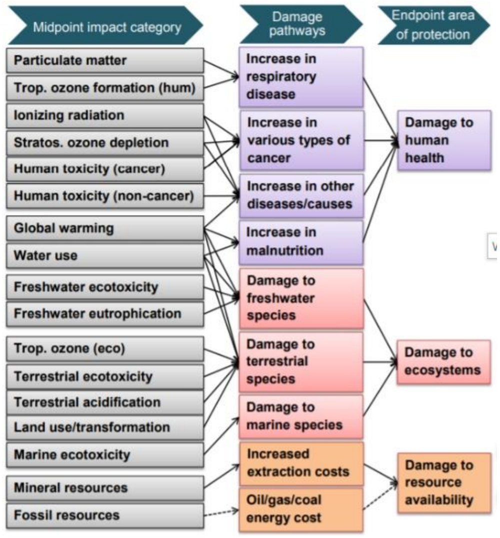

Figure 21 ReCiPe 2016 method visualization (Huijbregts, et al., 2016)

The choice of these assessment methods is mostly based on the available methods in the program GaBi, that could calculate the desired impact categories. The difference between various methods is never major (unless completely different units are used for the identically named impact category), however the small changes can affect the results and the conclusions drawn when reviewing a large object or system like a country. In the case of the vertical farm, differences between the available methods were small. The ReCiPe method is more commonly used in agricultural studies (Vázquez-Rowe, et al., 2013; Spyros, 2016), while the Environmental Footprint method is used in commercial calculations or worldwide impact calculations. (Sala, Cerutti, & Pant, 2018; Crenna, Secchi, Benini, & Sala, Global environmental impacts: data sources and methodological choices for calculating normalization factors for LCA, 2019)

5.5. LCA Modelling

In this chapter a model is created based on the vertical farm dimensions and systems mentioned in Chapter 4, the characterization of the LCA in Chapter 5.1/5.2 and the values of the Life Cycle Inventory Analysis. This model is created using the program GaBi (Sphera, 2020), which is a program designed for product sustainability with a powerful Life Cycle Assessment engine. Though this program contains a large database and many options to model a full life cycle in complete detail and with relative ease, this study did not have full access to all of these features. With a mere educational license, creative design and repeated discussions with experts in the field it has been attempted to create a Life Cycle Analysis model of a vertical farm within this license. It is important to notice that in this LCA modelling chapter every value shown in the figures is per kilogram dry lettuce (functional unit).

The model itself is divided into multiple sections, following the Life Cycle circle shown in Figure 20 Steps in the Life Cycle of a product and in multiple "plans" within these sections. "Plans" are virtual diagrams, showing the flows of materials and other resources to and from systems. Figure 22 Vertical farming GaBi model (adapted for visual aspect) shows the main plan of the vertical farm model in which the three different life cycle sections are indicated with different colors. This plan is an adapted version of the model used for calculation to give a more insightful visual representation. The three different sections are displayed in more detail and discussed in coming sub-chapters. These sections on their own consist of a multitude of other plans, shown in Figure 22 Vertical farming GaBi model (adapted for visual aspect) with the plan icon (⛼) in the top of a box. These plans are also displayed and discussed shortly in the coming sub-chapters.

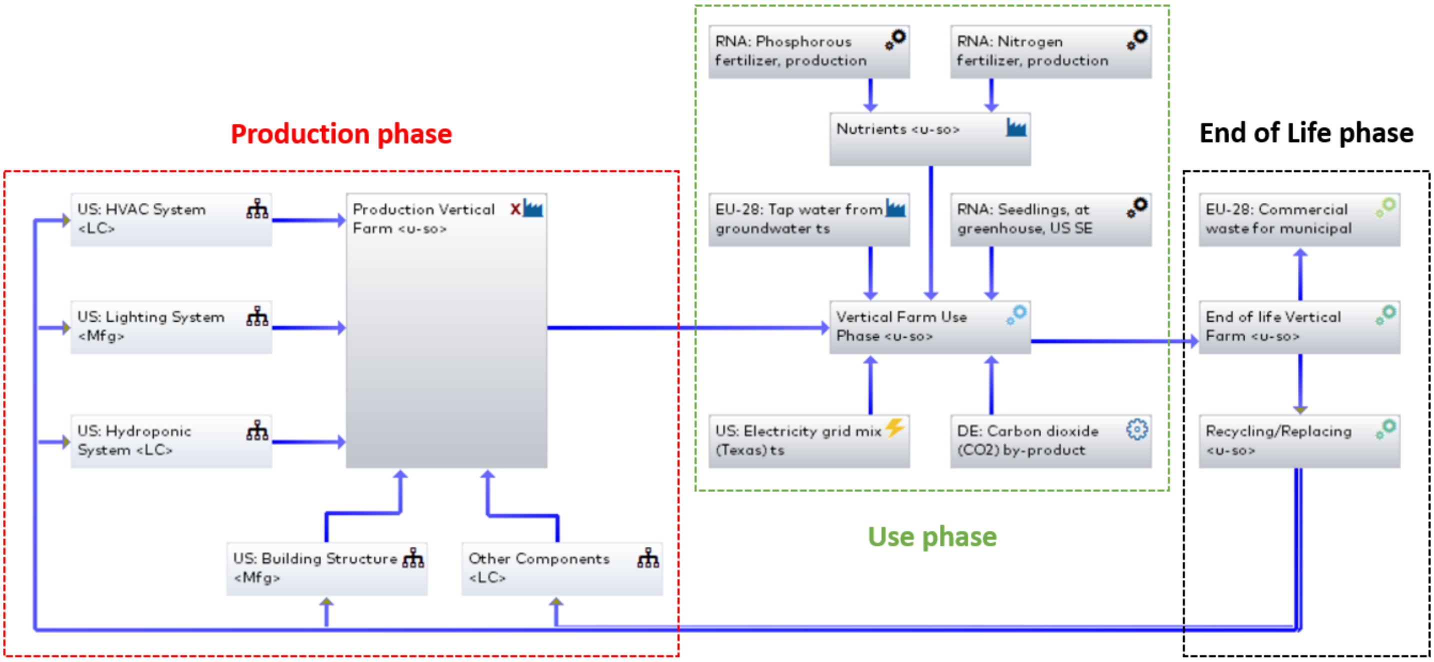

Figure 22 Vertical farming GaBi model (adapted for visual aspect)

The modelling phase uses a lot of data on all processes, elements and flows. Most of this data is known with the Life Cycle Inventory Analysis and other calculated data. However, after the production, certain vertical farming systems and components need to be transported to the location, which releases emissions into the air. This requires the location of production in order to calculate the distance which is set as a parameter for the amount of diesel needed, and the amount of emissions released. These values are shown in Appendix D. For all relevant input materials, the transport distances are estimated using georeferenced Google maps data. Besides this, let's say this building will be placed and built up in 2020. At this moment in time, a lot of studies are done on recycling and circular economy, to lower the costs and environmental impacts of unnecessary resource extraction. (Addis, 2006) This study is interested in low environmental impacts in particular and therefore this building will be built using a lot of recycled content. Therefore, life expectancies and recycle rates are needed for further modelling. The life expectancies are given in Table 8 or in small columns at the end of each subchapter in Appendix C. The recycle rates of components and resources are shown in Appendix D with corresponding sources.

As the GaBi model had some minor errors preventing the model to connect its end of life scenario output through a recycling stage and back into the production phase, it has been chosen to embed the recycling rates into the initial resource input in the production phase. The method of choice, formulas and eventual model input values are given in Appendix E. In this method of choice it is assumed that the initial building material is also already a recycled material at the start of the vertical farm construction. It is also assumed that this recycled content does not affect the longevity of the materials, which in reality it might do. This is however to complex to simulate in the scope of this study.

5.5.1. Production

With the second order LCA, the production of this life cycle analysis consists of only the production of the vertical farm itself. This farm consists of a building structure in which a system structure is situated. With the system analysis in chapter 4.2 the most important systems are discussed which have been modelled in the production phase of the LCA, shown in Figure 23 Production phase GaBi model. The monitoring system, shown in the LCIA table, is not modelled in the production phase as its components are very small and will have an insignificant impact in the eventual analysis (about 0.03%).

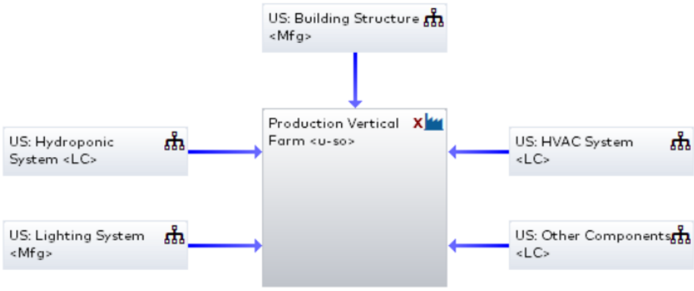

Figure 23 Production phase GaBi model

Building structure

In Figure 23 Production phase GaBi model, the upper plan or “Building structure” consists of all materials and processes included in the building structure as displayed in the LCAI table (Table 8) and the transport to building site (by truck). The full plan is shown in Appendix F.1.

Hydroponic system

The upper left plan “Hydroponic System”, shown in Appendix F.2, follows this same logic, however this plan is more complex. It consists of different resources linked to multiple processes and a separate transport flows towards the construction site over different lengths of distance. Even though the cultivation beds are placed under the ‘Cultivation area structure’ classification, this plan models them as they are produced in the same factory as the hydroponic system, thus with the same distance towards the construction site.

Lighting system

The lower left plan, “Lighting system” is shown in Appendix F.3. This plan consists of LED diodes and light racks, creating light modules together. LED diodes are not available in the database of this program, therefore through literature a possible input is modelled. This input consists of the outputs of a LCA on LED lighting products (Scholand & Dillon, 2012), in which the outputs are environmental impacts such as Global Warming, Acidification, and so on. These flows are available in the database and therefore are possible to use as an input into the production phase.

HVAC system

The upper right plan, “HVAC system”, is shown in Appendix F.4. This is a fairly complex plan for just a small system. Research on HVAC systems in vertical farms is quite scarce, therefore a multitude of sources are used to assume which resources are used as well as the weight and the electricity use.

(Hunter, 2015; Shah, Debelle, & Ries, 2007; Yang, 2005; Li, 2012) The lower right resources (copper, aluminum, steel sheet and galvanized steel) are all connected to both the air conditioning and the gas furnace (heating system). The two quantities given at the edge of the air conditioning and gas furnace box are not the summed up quantities but rather the last quantity given in the properties, due to the non-overlapping visual aspect of the program. The HVAC system is made in a different factory than the ducts, as they can be manufactured locally, which is shown in two transportation flows.

Cultivation area structure

The lower right plan, "Other components" also known as Cultivation area structure, is given in Appendix F.5. Warehouse racks are the only thing modelled in this plan as the cultivation beds are modelled by the hydroponic system plan. The data on the racks are based on warehouse shelving (in the paper called 'uprights') discussed in. (Nadal, 2014)

5.5.2. Use Phase

The use phase is the phase in which the vertical farm produces produce (lettuce), shown in Figure 24 Use phase GaBi model. In this phase (in between the construction (production) and the demolition (end of life)), the vertical farm and its systems make use of various resources such as electricity, water, CO_2, nutrients and seeds.

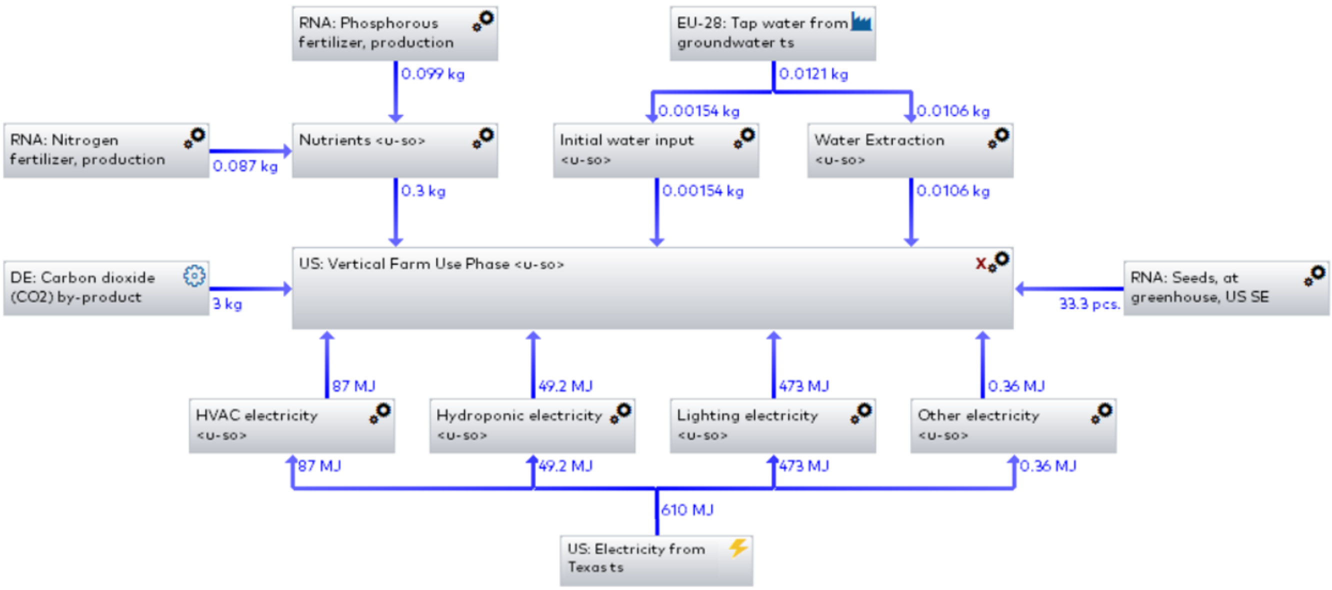

Figure 24 Use phase GaBi model

The electricity is divided among the different systems, in which 'other electricity' is predominantly the monitoring system. The water input in the system consists of an initial input (to fill all water tanks) and a constant water addition (extracted from groundwater) to counteract the water loss from harvesting water intensive lettuce. The nutrients are built up by fertilizer resources, though "potassium" is not given, because the database of this program using an educational license did not contain any potassium processes or resource extractions, only as a byproduct in other processes. Even though potassium is the highest concentration element in the mineral solution, it has the least effect on the environment, apart from the eutrophication impact category where is has a similar effect as nitrogen and phosphorous. (Lenntech, n.d.) In the eventual results and discussion this will be kept in mind. The carbon dioxide is given as a by-product, though the input needs and output emissions of the carbon dioxide production is still within this resource. The seed input is set at 33.3 pieces as it takes 33.3 crops of lettuce to reach 1 kg dry lettuce weight.

5.5.3. End of Life

The End of Life stage consist of recycling and disposal. While the recycling has been embedded in the production phase, it is shown in Figure 25 End of life phase GaBi model, as a single flow. For visual and mass balance reasons this flow has been added, however the recycling process does not influence the plan any further. The disposal however, is not purely visual as it calculates the outputs from waste management. The disposed amount is calculated using the total weight of the waste from the use phase minus the recycled content shown in the Appendix D. The amount of each flow towards different incineration and landfill processes is deducted from the amount of each component present in the vertical farm.

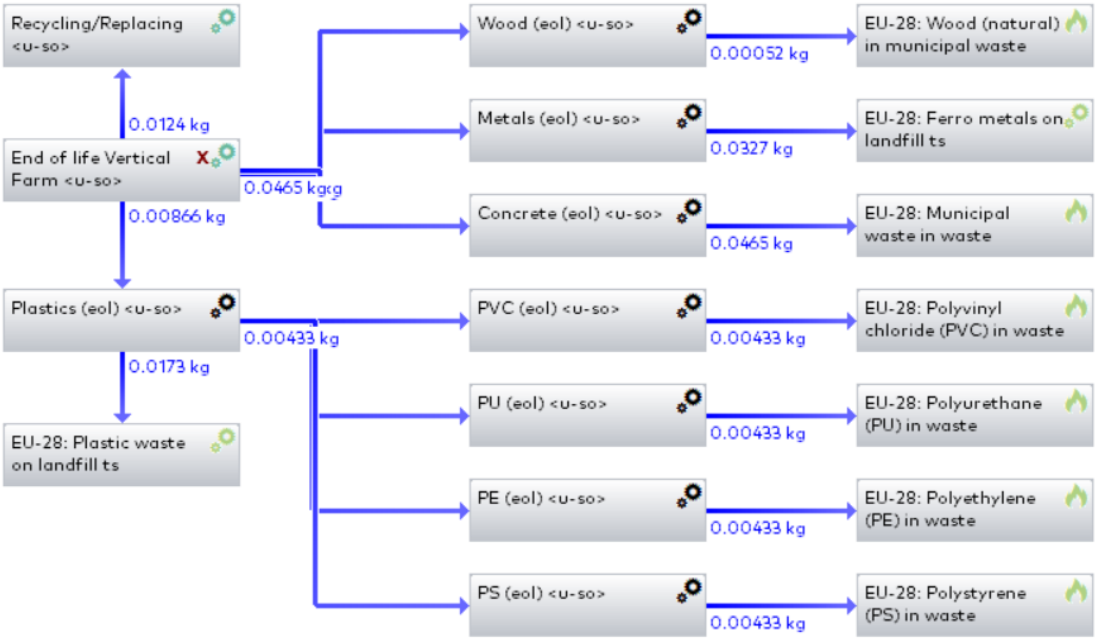

Figure 25 End of life phase GaBi model

6. Life Cycle Analysis results

This chapter shows all the results from the Life Cycle Analysis of the vertical farm. With the modelled flows and processes, shown in the LCA Modelling chapter, GaBi can run the model and calculate all impact category values. The impact categories chosen are a category combination of the ReCiPe 2016 v1.1 Midpoint (H) and Environmental Footprint 2.0 method. First, the chosen impact categories are reviewed and the results discussed. Within these categories there appear some odd results, which will be discussed at the end of this chapter. Secondly, a sensitivity analysis is set up, in which multiple electricity production methods are inserted into the model and the resulting environmental impacts are compared. It is important to notice that every value in this chapter is per kilogram of dry lettuce (functional unit).

6.1. Impact category results

6.1.1. Climate Change

Executing Gabi's calculation methods on the model shown in the previous chapter yields various LCA impact assessment options and impact categories. With the use of the ReCiPe 2016 v1.1 Midpoint (H) method one of the most analyzed impact categories can be calculated, the Climate change (or Global Warming Potential). This category models the emissions of a greenhouse gas in kg, "which will lead to an increased atmospheric concentration of greenhouse gases (ppb) which, in turn, will increase the radiative forcing capacity (w/m^2), leading to an increase in the global mean temperature (°C), ultimately resulting in climate change." (Steinmann, 2016) The graphs resulting from the calculation are shown in Figure 26 Climate change impact of the different phases in the vertical farm life cycle (given in kg CO_2-eq/kg dry lettuce).

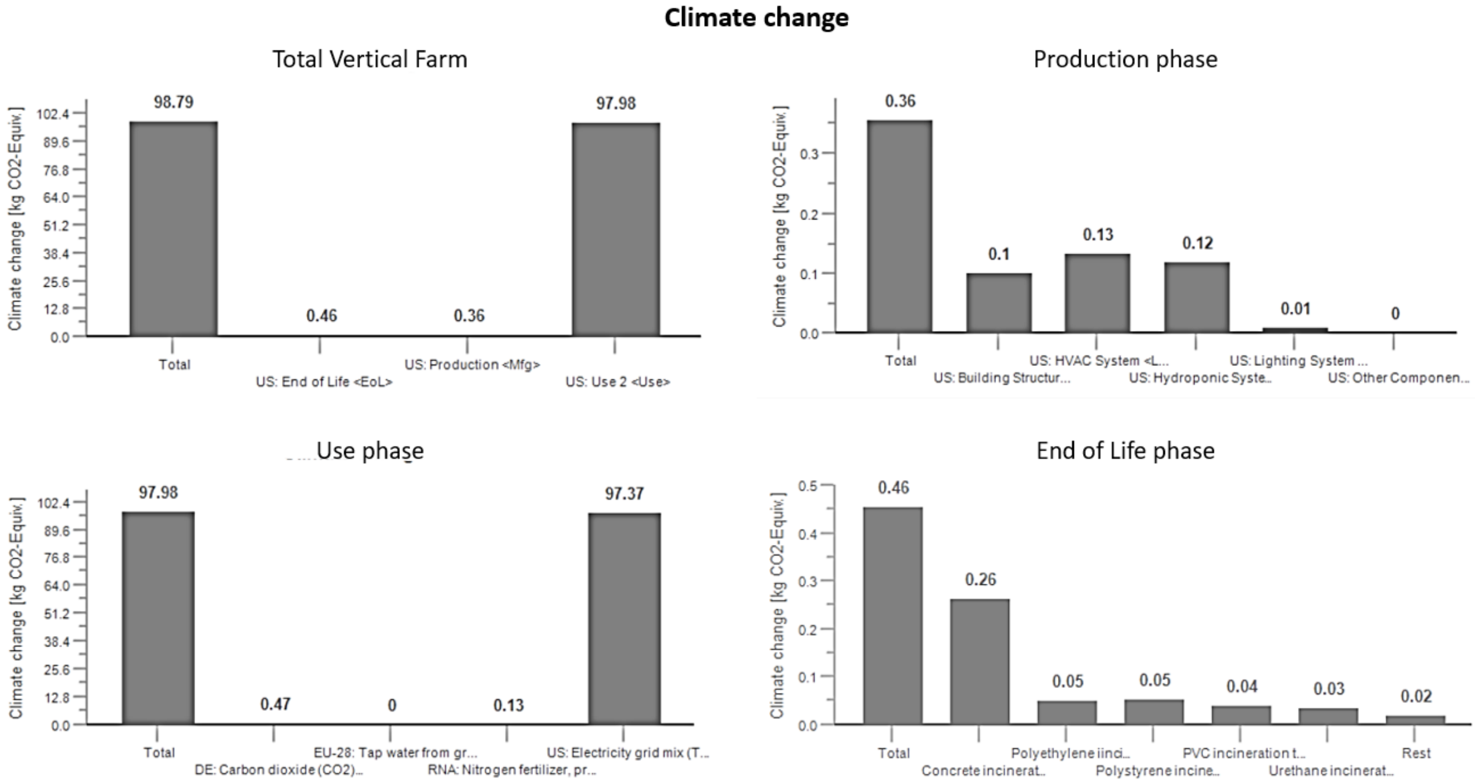

Figure 26 Climate change impact of the different phases in the vertical farm life cycle (given in kg CO_2-eq/kg dry lettuce)

These graphs show the impact of the total vertical farm on the environment, as well as the three major processes (Production – Use – End of Life) of a Life Cycle. The 'Total Vertical Farm' graph shows the use phase as having the highest impact, which is a logical consequence, as it is the longest period (60 years) in which new resources are constantly needed to keep it running. Though, the large difference between the phases is interesting and is explained at the end of this chapter (which is the case for all impact categories). The Production phase, while being able to be very impactful on the environment is situated in a very short timespan, while the Use phase is a 50 year period of constant resource demand. Especially with the large energy demand of the systems present in the vertical farm (shown in Use phase graph), the Use phase has high impacts on the environment on a Climate Change perspective.

In the 'Total Vertical Farm' graph the End of Life phase appears to have a larger impact in terms of Climate change than the Production phase. This is not logical, as the production of the materials used is usually more intensive than the waste disposal of these same materials. The reason for it having a higher impact is the way the two major processes are modelled. As explained earlier on in the report, the Educational License of the GaBi program has limitations, under which the absence of pre-modelled elements such as ventilation systems or lighting systems, which had to be modelled from raw materials. By modelling these systems from scratch in a second order perspective, no electricity input was added (which is an assembly of the assembly (3^{rd} order)). The incineration and other waste disposal processes, however, were present in this license with their representative locked electricity demand, increasing the impact of the End of Life phase. Adding the electricity demand of the assembly of the systems in the Production phase would likely increase the impact beyond the End of Life phase, based on estimations and electricity demand from studies regarding the separate systems. (Shrivastava & Chini, 2011; Yang, 2005; Nadal, 2014; Scholand & Dillon, 2012)

In the production phase itself, the HVAC and hydroponic system are more impactful than the concrete building structure. Even though the building structure is the largest weight contributor by far, the materials used in the other systems such as plastics (polyvinylchloride (PVC), PE, PU), steel and other materials seem to exceed the building structure on climate change impact.

6.1.2. Terrestrial Acidification (TA)

With the same ReCiPe 2016 v1.1 Midpoint (H) method, the Terrestrial Acidification (or Acidification Potential) can be calculated. This category models "the atmospheric deposition of inorganic substances, such as sulphates, nitrates and phosphates." (van Zelm & Huijbregts, 2016) "This causes a change in acidity in the soil, which can lead to a deviation in the plant species acidity levels. This change from an optimum causes shifts in a species occurrence." (Goedkoop, et al., 2009) The graphs resulting from the calculation are shown in Figure 27 Terrestrial Acidification impact of the different phases in the vertical farm life cycle (given in kg SO_2-eq/kg dry lettuce).

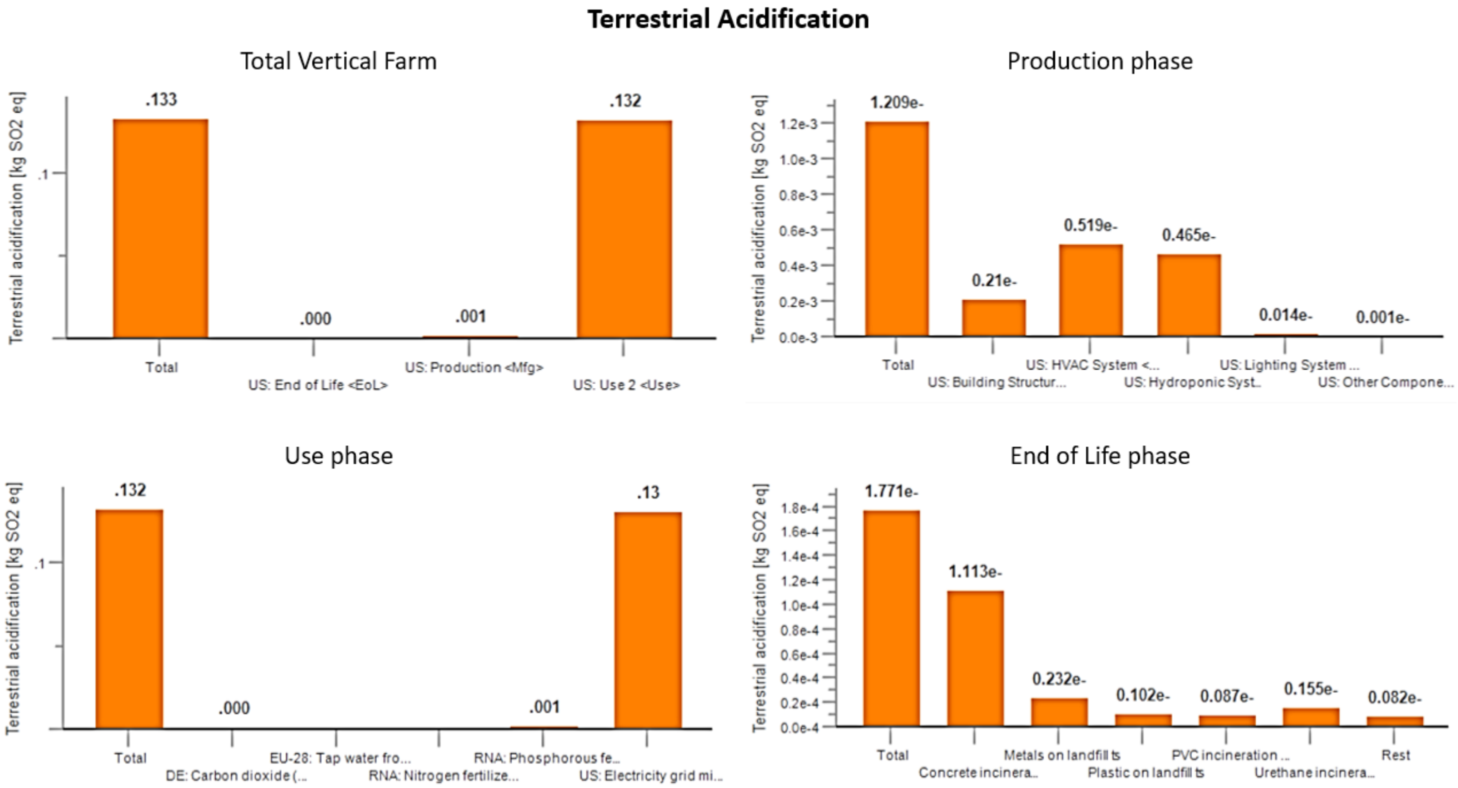

Figure 27 Terrestrial Acidification impact of the different phases in the vertical farm life cycle (given in kg SO_2-eq/kg dry lettuce)

The graphs of terrestrial acidification have a lot of similarities with the graphs of climate change. This shows that the resources produced and used in the vertical farm resulting in CO_2 emissions also results in acidification. In the 'Total Vertical Farm' graph the 'Use phase' has a very high percentage of the overall acidification which is again linked to the generation of electricity, shown in the 'Use phase' graph. Also in this graph, the nutrients being added to the water flow (Nitrogen, Phosphorous) and the carbon dioxide input all have acidic properties due to their creation, often using acids in the process. In the End of Life phase, the concrete incineration has the highest percentage of acidification potential, due to emissions emitted to the air during the burning process. Though, there are some changes, as metals and plastic on landfills cause some soil pollution which puts them higher on the acidification graph.

6.1.3. Freshwater Eutrophication

Using the ReCiPe 2016 v1.1 Midpoint (H) method, the Freshwater Eutrophication can be calculated. This category models "the discharge of nutrients into soil or into freshwater bodies and the subsequent rise in nutrient levels, with for example phosphorus and nitrogen. This can cause a chain reaction of autotrophic organisms depleting the freshwater of oxygen and light, leading to a loss of species in this freshwater body. (Huijbregts, Azevedo, Verones, & van Zelm, 2016) The graphs resulting from the calculation are shown in Figure 28 Freshwater Eutrophication impact of the different phases in the vertical farm life cycle (given in kg P-eq/kg dry lettuce).

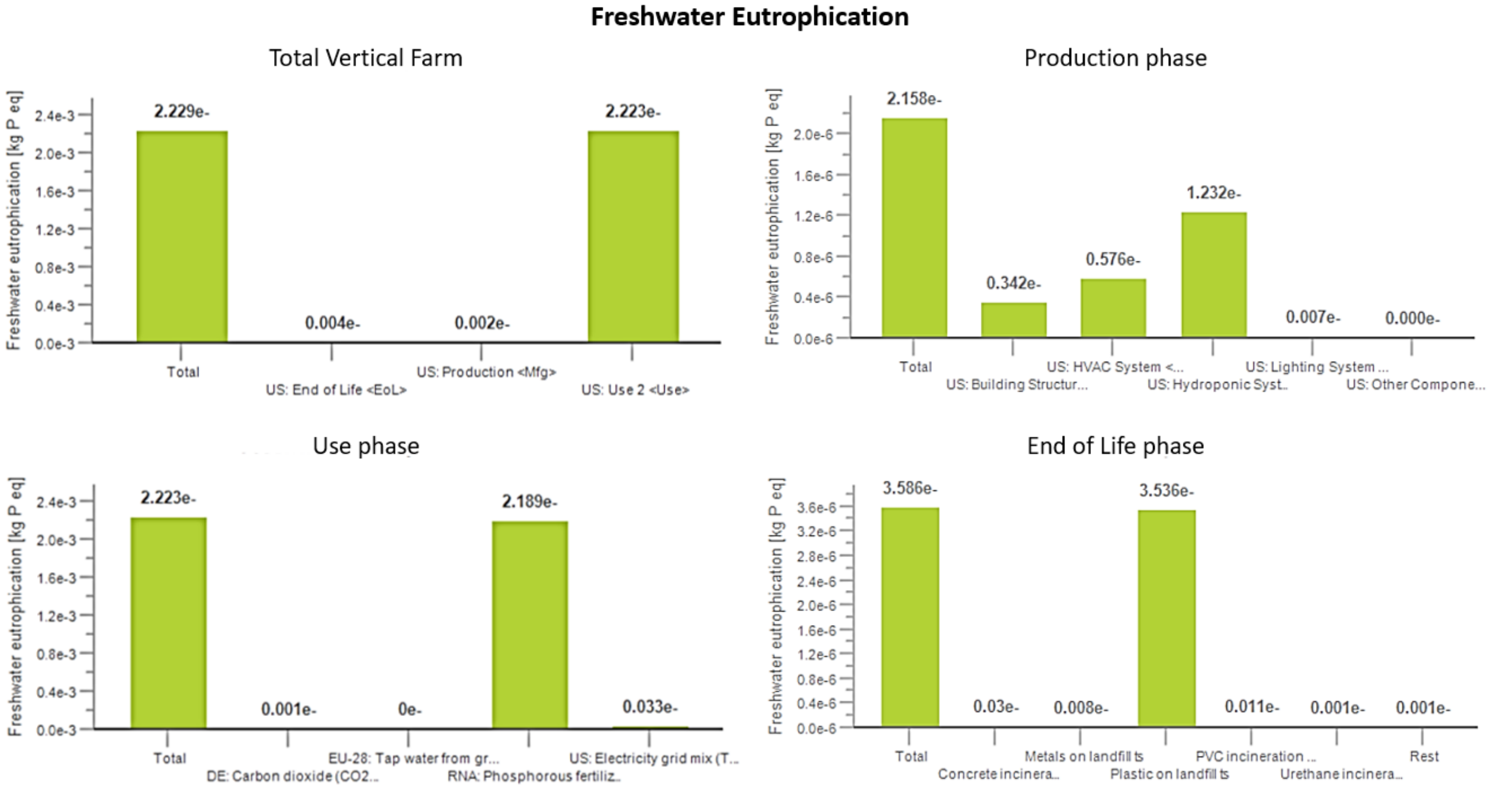

Figure 28 Freshwater Eutrophication impact of the different phases in the vertical farm life cycle (given in kg P-eq/kg dry lettuce)

The use phase plays a major role in the freshwater eutrophication, though in this impact category it is the phosphorous fertilizer creation that is dominant instead of the electricity generation. During this creation a significant amount (relatively speaking) of phosphate is released into freshwater bodies. In the Production phase the Hydroponic and HVAC system both release mostly nitrogen in freshwater bodies at the production of PVC gutters and galvanized steel ducts. For the End of Life phase the plastics on the landfill eventually release nutrients into the environment, causing eutrophication in neighboring freshwater bodies.

6.1.4. Water Footprint

With the use of the Environmental Footprint 2.0 method, the Water Footprint (WF) can be calculated. This category calculates "the water consumption, based on water that is evaporated, incorporated into products, transferred to other watersheds or disposed into the sea. Water that has been consumed is thus not available anymore in the watershed of origin for humans nor for ecosystems." (Fazio, et al., 2018; Verones & Huijbregts, 2016) The graphs resulting from the calculation are shown in Figure 29 Water Footprint impact of the different phases in the vertical farm life cycle (given in m^3/kg dry lettuce).

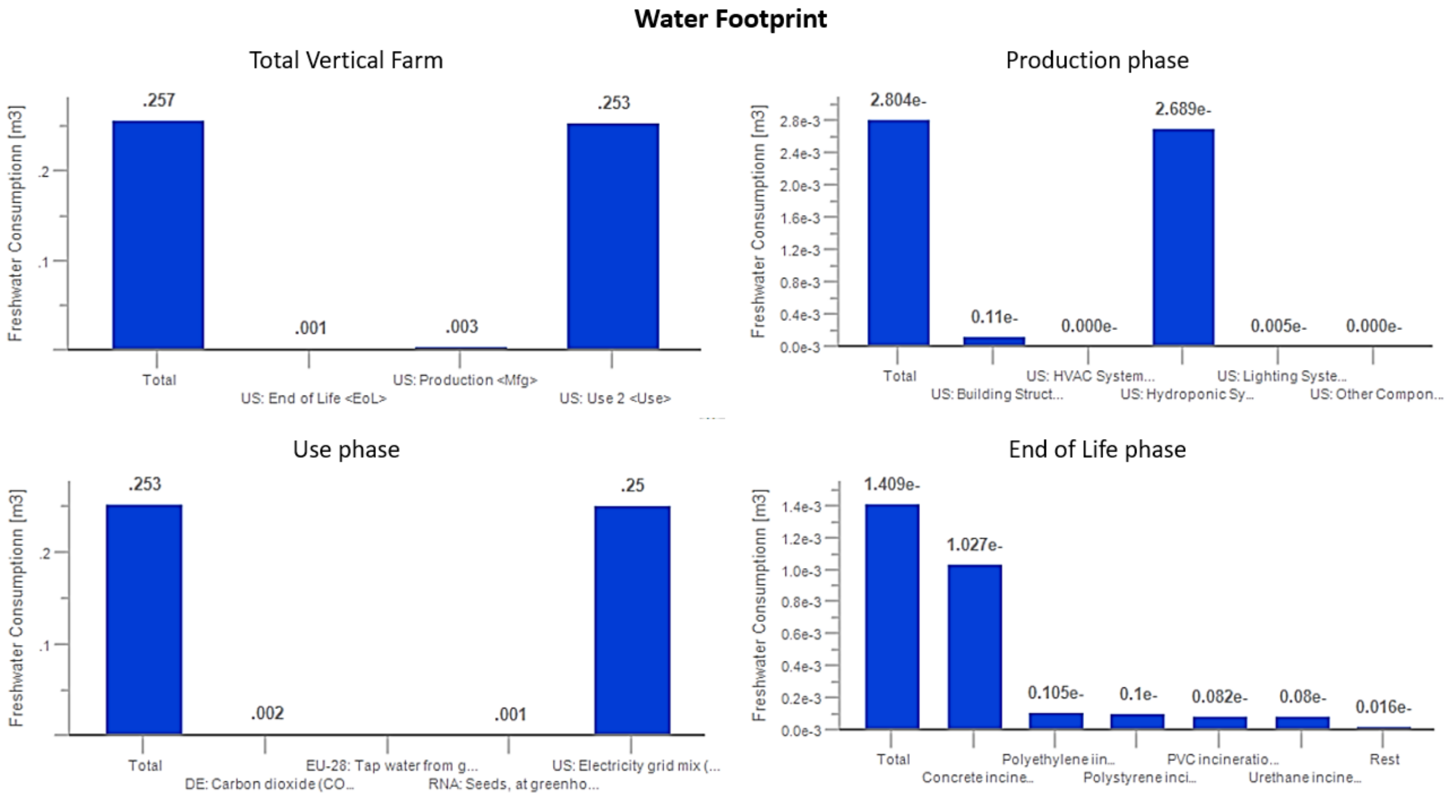

Figure 29 Water Footprint impact of the different phases in the vertical farm life cycle (given in m^3/kg dry lettuce)

Similar to the other graphs, the Use phase has the largest impact within this impact category. This is due to the water needed to produce the amount of electricity needed to run the vertical farm. Interesting in the Use phase is the Tap water being insignificant in the impact, due to the vertical farm being a (semi-)closed system only losing water through the crops that are harvested and transported out. This water replenishment (and initial filling) is so little over the years that it deems insignificant compared to the water use of other processes in the vertical farm. Even though the impacts are very low, the largest impact within the production phase is the hydroponic system as it contains the manufacturing of a lot of PVC causing some water consumption. In the End of Life phase, within the incineration processes there is a need for water. As the concrete has the highest volume of material it is likely to be the highest in the End of Life phase considering water footprint impact.

6.1.5. Land Footprint

With the use of the Environmental Footprint 2.0 method, the Water Footprint (WF) can be calculated. This category calculates "the sum of the area of land occupation and the transformation of land for production of the product" (including all sublayers of resource production and use). (Benini, Castellani, Vidal-Legaz, De Laurentiis, & Pant, 2019) This is a midpoint calculation method. The endpoint indicators would have generally focused on the damage caused by land use and land use change to biodiversity, which would make it difficult to compare it to the rural agriculture as very few researchers have studied this relation. (De Baan, Alkemade, & Koellner, 2013; Souza, Teixeira, & Ostermann, 2015)

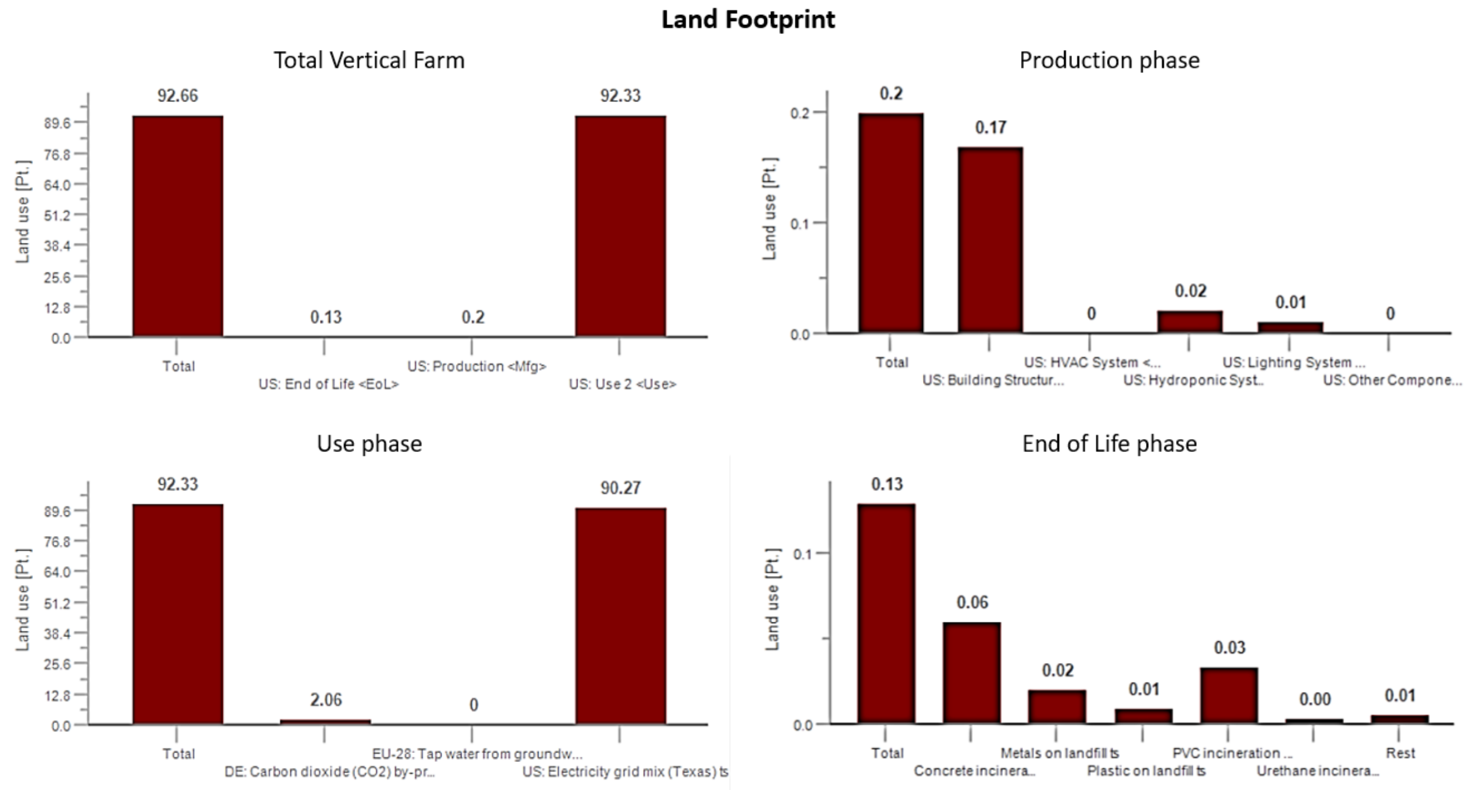

Figure 30 Land Footprint impact of the different phases in the vertical farm life cycle (given in Pt./kg dry lettuce)

The graphs above are given in a unit of Pt. which is the amount of "Points". (Crenna, Secchi, Benini, & Sala, 2019) Points can be converted to a surface area unit, where 1 points = 40.46825 m^2. (Miri City Sharing, n.d.). The current graphs shown above are related to the Production, Use and End of Life phase, which each have their own land footprint based on the m^2 needed to produce the demanded resources. However, in the Use phase the actual building land footprint is not yet taken into account in the model, therefore the land footprint in the Use phase has to be increased with the building surface are of 1600 m^2 divided by the number of plants and their respective dry weight within a kilogram of dry weight lettuce. This increases the land footprint slightly as it is a very small number.

In this series of graphs the Use phase is once again dominant, as the generation of electricity demands quite some square meters of land, when extrapolated over 60 years. Also the Carbon dioxide needed in the vertical farm is high compared to the other phases due to the small amount of land footprint needed to produce it multiplied by the large amount of kilograms needed for photosynthesis of the plants. In many of the other processes mostly the diesel mix needed by the transportation trucks has the highest impact.

6.1.6. Impact on Oklahoma

A lot of the impact categories in a LCA method are related to the impact on the global environment, this creates easier comparison between products while also being able to be linked to a country (or state) when diving deeper into the LCA stages on which the impacts are based. Many of the items or processes used in a Life Cycle Analysis are not within the country (or state) of the final product, as nowadays general raw material extraction and production processes are often outsourced to a country where wages are lower and specialized processes are often outsourced to a country or state that has a large production plant for these specific processes. Therefore, the actual impact of the fictive vertical farm on the state of Oklahoma, throughout its whole life, is different than the global impact. They are however closely related in this study in particular as the largest impact on most categories is the electricity grid mix. This electricity production is stated in the model as Texas grid mix, however, this can be seen as Oklahoma electricity production, because they are both within the Southwest Power Pool (SSP). (AECT, 2018; Logan, et al.).

With the original lettuce production in California and Arizona, there were close to zero environmental impacts in the state of Oklahoma. Only the trucks transporting lettuce in to or out of the state of Oklahoma cause emissions and thus environmental impacts. With the vertical farm, located in Oklahoma City the local environmental impacts are higher. The Climate Change impact, with its kg CO_2 indication, is locally very high (due to the electricity). Even though this impact category is considered a global effect, the extra emissions in Oklahoma State can trap more heat in the Oklahoma air and thus increase temperatures locally. With the current climate high temperatures are not uncommon thus higher temperatures would not be desirable. The terrestrial acidification, also due to electricity production, causes ground pollution and creates inhabitable contamination hot spots. Even though these impacts should be limited and are harmful to the environment, compared to other impacts, this small amount of acidification is not a major problem in the large and open terrain in Oklahoma where population density is very low. Water eutrophication is a major problem in local agriculture as it the effect takes place a few meters from the actual agriculture and destroying habitats. In this instance however, it is in the production of the nutrients, which are most likely not directly in the vicinity of the farm. The production of these nutrients is possible in factories in Oklahoma and therefore will have a local impact, though it is quite a low impact on the eutrophication. Water Use is an important category for both the rural agriculture (which is known for its high water use) and the local impact of the vertical farm in Oklahoma, because water in Oklahoma is quite scarce and droughts are not uncommon. With the low water use of the vertical farm, there is an increase in Oklahoma, because the comparable rural agriculture is located in California. Land use is a complex category to link to a specific county or state. In the state of Oklahoma there is a lot of space, though a large portion of it is occupied, contaminated, or according to laws not buildable (Cialella, 1996). Also land use is a category that changes a lot over the years that the vertical farm is active. One of the claims on vertical farms in this study is a low land use, in order to maintain or reintroduce the natural environment. Which is needed as a large part of the world is turning into agricultural ground to support the constant demand of food. The results from this specific study shows that land use is in fact quite large and situated around the electricity generation and thus within Oklahoma. This concludes that placing a vertical farm with the current model in Oklahoma would actually cost a lot of land, which could be used for other purposes.

6.1.7. Result analysis

In the discussion on the results in the previous chapter, the Use phase is logically one of the larger contributors to the environmental impacts due to its timespan and resource demand intensity. The Use phase, however, is a factor 1000 higher than the other categories which seems like an incorrect result, caused by the electricity use of the systems. The electricity production is the electricity grid mix (mostly electricity from natural gas and coal) from Texas (as it is the closest neighbor), which is a normal pre-modelled process in the program.

Studying similar studies on greenhouses, plant factories and vertical farms, it shows that most of these studies have a "climate change" or "global warming potential" total of in between 0.5 and 3 kg CO_2-equivalent per kg dry lettuce while having a similar amount of electricity demand (on some studies converted, interpolated or extrapolated from the total kg-CO_2 equivalent and electricity use with the use of characteristics of the farm in that study). The results of the Production and End of Life phase of the studies that properly separated the phases, are quite similar to this study's Production and End of Life phase results, not only in the climate change impact category but in multiple categories. Indicating that there are odd results in the Use phase and in particular the electricity production process. (Zeidler, Schubert, & Vrakking, 2017; Banerjee & Adenaeuer, 2013; Kikuchi, Kanematsu, Yoshikawa, Okubo, & Takagaki, 2018; Graamans, Baeza, van den Dobbelsteen, Tsafaras, & Stanghellini, 2018; Hallikainen, 2019; de Geyter, 2018)

However, in the comparison between the studies, there is one key difference. In a lot of the studies, the method of electricity generation is not mentioned. As the Use phase, and within this the electricity production, has the highest impact on the environment, changing this source could change results massively. (Toxopeus, 2020) Therefore a sensitivity analysis has been set up in chapter 6.2.

6.2. Sensitivity Analysis

From the LCA results it can be deduced that the largest environmental impacts are caused by the Use phase, due to its 60 year run period and using a lot of resources to stay as efficient as possible. The other phases do have an impact, however, changing the single impacts in these phases would not result in significant changes on this vertical farm's impact scale (not even for example removing the whole process of recycling materials). From these resources, the generation of electricity has a very large or even the largest impact on most of the impact categories. Therefore, it has been decided to create a sensitivity analysis with multiple scenarios, in which the electricity input is taken from different sources: natural gas, hard coal, nuclear energy and renewable energy (wind, solar and hydropower). How the model results are affected by these changes is discussed and shown in Appendix G. Using the results shown in Appendix G, a graph is created depicting the changes of the total impact of the vertical farm due to the change of electricity generation technique, Figure 31 Electricity generation Sensitivity Analysis results (CC = Climate Change, TA = Terrestrial Acidification, FE = Freshwater Eutrophication, WF = Water Footprint, LF = Land Footprint) per kg dry lettuce.

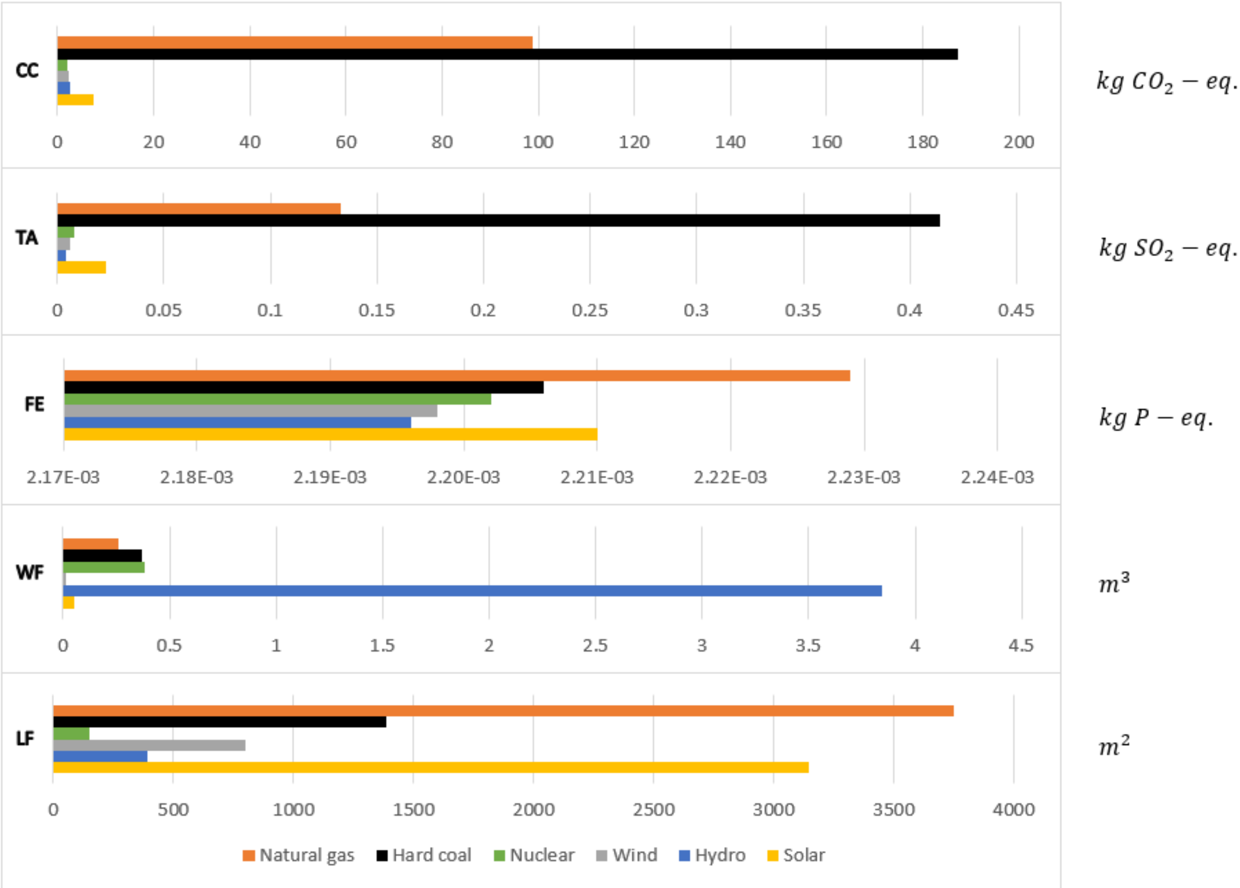

Figure 31 Electricity generation Sensitivity Analysis results (CC = Climate Change, TA = Terrestrial Acidification, FE = Freshwater Eutrophication, WF = Water Footprint, LF = Land Footprint) per kg dry lettuce

This graph shows the total impact of a vertical farm on the environment during its whole life time (cradle to grave) for six different electricity generation techniques (with impact category abbreviations). The graph clearly shows that the current use of natural gas and hard coal (electricity grid mix Texas) as a means of electricity generation for the vertical farm has a lot of impact on the environment compared to the other techniques. Especially in the Climate Change impact category the amount of kg CO_2 emitted is huge for the natural gas and hard coal alternatives. Following the current trend in America, where renewables and nuclear energy are in an uprising compared to traditional electricity generation methods, the vertical farm would benefit from receiving electricity generated by renewables, and in particular wind energy, which has the lowest overall impact to the environment (Appendix G). (Banerjee & Adenaeuer, 2013; EIA, 2020) Within this statement it is important to realize that the overall impact to the environment is an average, which is not related to the specific problems a certain country or state might have. The state of Oklahoma, for example, has serious droughts almost every year, which has a large impact on the available water supply. (The National Drought Mitigation Center, 2020) Even though the water demand of the vertical farm is not grand, the use of Hydro power generated electricity, calls upon a lot of water which would have a negative impact on this already limited available water supply. A best fit for the fictive vertical farm in this study, located in Oklahoma, would be the use of electricity generated by Wind Power. As a very windy state, with open space for placing wind turbines, while having one of the lowest Climate Change, Terrestrial Acidification, Freshwater Eutrophication and Water Use would be an ideal way of generating local electricity for the vertical farm.

Studies with a similar objectives have found similar results when implementing different electricity production methods. The study of (Hallikainen, 2019) has found similar changes in for example Climate Change kg CO_2-eq/kg dry lettuce, in which coal has the highest impact, followed by natural gas and solar energy and a small difference between nuclear, wind and hydro power as electricity generation techniques (Figure 32 Different energy sources per kg dry lettuce).

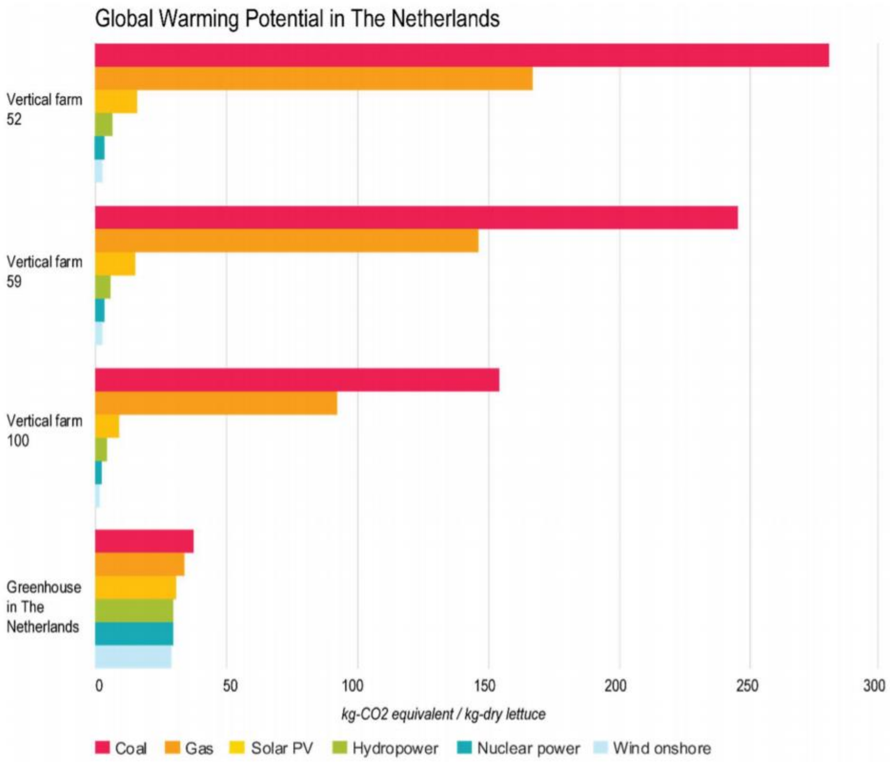

Figure 32 Different energy sources per kg dry lettuce (Hallikainen, 2019)

The study of (Goldstein, Hauschild, Fernándeze, & Birkved, 2016) has found similar results in Climate Change impact on the different electricity sources used in a "modular hydroponic unit" (which can be a semi-controlled environment, in between a greenhouse and a vertical farm), where the electricity grid (mostly coal use), has the most impact followed by solar, and a close difference between electricity generated by hydro power and wind power. In this study the Land Use has been discussed as well, though in a different unit. It shows, in this particular unit, that the distribution of impacts is quite similar to the LCA results of this study with hydro having the lowest impact, and solar having the highest, with wind and coal electricity production in between. Though the scaling of solar is extremely large, which could be due to the different unit or the different calculation methods in the model.

Table 9 Environmental impacts of different electricity sources per kg dry lettuce (Goldstein, Hauschild, Fernándeze, & Birkved, 2016)

	NPCC grid	Photovoltaic	On-shore Wind	Hydro
	Lettuce (GB-C2)			
CC (kg CO_2 eq.)	8.65	1.65	0.903	0.515
LU (kg C deficit)	8.78	136	3.63	1.95
RD (kg Sb eq.)	$4.3*10^{-5}$	$8.8*10^{-4}$	$2.4*10^{-5}$	$1.4*10^{-5}$

Given these results, the use of renewable and nuclear energy sources in a vertical farm are highly encouraged and the change of electricity to a more renewable focused electricity grid in the USA is a change for the better. Even with renewables having such a lower impact on the environment in most of the categories, every country/state has to consider the best energy source to use regarding the trade-offs of environmental impacts and the local environment's resilience to these impacts.

7. Comparison

This chapter uses the LCA model results and the studies, papers and reports on rural agriculture of lettuce to compare the environmental impacts of both. This comparison could lead to interesting results on the viability of the concept of vertical farming, the justification of the correctness of the claims made on vertical farming (stated in chapter 2) and it shows the drawbacks of both rural agriculture and vertical farming. In many of the studies on rural agriculture, the LCA performed on the agricultural techniques also includes the environmental impacts of greenhouses. Therefore, in this comparison greenhouses are taken into account as well, if its characteristics are similar to those of the vertical farm. In this chapter all values used in environmental impacts are per kilogram of dry lettuce (functional unit).

The modelled vertical farm, located in Oklahoma, is retrieving its resources from local sources thus depleting resources in Oklahoma State and surrounding states. The rural agriculture of lettuce however, is predominantly present in California and Arizona and shipped to Oklahoma using local resources respectively. Even though these methods of farming are centered around different sources in different states, the LCA results of both studies can be compared with the use of environmental impacts. It is however a more accurate comparison if both types of studies have similar characteristics, in which the most important characteristic is the climate in which the study is located in. The climate has a lot of influence on the resources used and extracted, for example the Open Field agriculture in a very arid climate (such as in Morocco) usually has a very high water footprint due to all the irrigation needed to keep the crops alive, while in a very wet climate (such as in large parts of Brazil) almost no irrigation is needed, leading to a low water footprint. Therefore, out of the LCA studies on lettuce production and cultivation in an Open Field or Greenhouse setting, only studies have been chosen for the comparison that have a climate that is similar or close to that of California or Arizona. In the Köppen Climate Classification, these states have a large range of different climates, though using maps of lettuce production and linking these production locations to the Köppen Climate Classification map, shows that most of the lettuce is cultivated in a Hot summer Mediterranean climate (Csa) (and partly a Hot desert climate (BWh)). (USDA, 2019; USGAO, 2019; Beck, et al., 2018; Baker, 2016)

7.1. Rural Agriculture

Even though rural agriculture is one of the oldest forms of food production, the amount of Life Cycle Analysis studies is limited, especially with assessing only lettuce production. With search terms such as “lettuce production”, “lettuce cultivation”, “Life Cycle Analysis”, “Environmental impact”, there is a very scarce amount of papers worth mentioning. Though, fortunately most of the LCA studies on lettuce cultivation in rural agriculture (or conventional agriculture) happen to be located in countries with the exact or similar climate to that of California and Arizona. Further research into these studies has resulted in a compilation of data shown in Table 10 Comparison data, extracted, converted and inter- and extrapolated to fit the functional unit of this study, displaying all similarities and differences in general statistics, LCA characteristics and eventual environmental impact results. A side note to this table: Not all studies assessed the same impact categories, leading to some blank spots and due to differences in indicators and functional units used in the studies, a lot of the data had to be converted using multiple factors (such as fresh weight to dry weight) to fit the data of this study and create a comparable dataset.

Table 10 Comparison data, extracted, converted and inter- and extrapolated to fit the functional unit of this study

Source	**Model results**	**Plawecki et al. 2013**	**Winans et al. 2020**	**Bartzas, Zaharaki & Komnitsas 2015**		**Romero-Gámez, Audsley & Suárez-Rey 2014**		**Foteinis & Chatzisymeon 2016**
General Information								
Type	Vertical Farm	Open field	Open field	Greenhouse	Open field	Open field	Greenhouse	Open field
Location	Oklahoma, US	California, US	California, US	Albenga, Italy	Albenga, Italy	South Spain	Spain	Greece
Abbreviation	OK VF	CF OF 1	CF OF 2	I GH	I OF	ES OF	ES GH	GR OF
Climate	Cfa/BSk	Csa/BWh	Csa/BWh	Csa/Cfb	Csa/Cfb	Bsk/Csa	Csa/Cfb	Csa/BSk
Size (m2)	1600	1210000					144	10000
Size Prod. (m2)	43623	1210000		200			400	10000
Yield (nr crops/m2)	36	6		6	8	8	10	6
Seed to harvest (days)	48	130						73
Lifespan (years)	60			25			15	
Irrigation	Hydroponics	Surface irrigation	Drip irrigation	Drip irrigation	Drip irrigation	Drip irrigation	Drip irrigation	Drip irrigation
LCA Information								
Scope	Cradle to grave	Cradle to shelf	Cradle to farm gate	Cradle to farm gate	Cradle to farm gate	Cradle to farm gate	Cradle to farm gate	Cradle to farm gate
Exception from LCA scope		Including transport to retailer		Including waste management	Including waste management	Including waste management	Including waste management	
Programs used	GaBi (educational licence)	Simapro 7.3	Excel, VisualBasic Macros, ArcGIS	GaBi commercial version 6	GaBi commercial version 6	Cranfield Arable and Horticultural Life Cycle Inventory (CAHLCI)	Cranfield Arable and Horticultural Life Cycle Inventory (CAHLCI)	Simapro 8
Data sources	Research, books, papers, environmental databases, GaBi database	Studies, Ecoinvent 2.2 Database	Studies, USDA, IPCC, farm interviews, Gabi database Service pack 32, Ecoinvent databases	Ecoinvent v3.1 database, Professional database, estimations models	Ecoinvent v3.1 database, Professional database, estimations models	Field measurements, ministry reports, agricultural studies, Ecoinvent v2.2 database	Field measurements, ministry reports, agricultural studies, Ecoinvent v2.2 database	Farm data, Simapro's LCI databases, studies
Indicators	ReCiPe 2016 v1.1 midpoint, Environmental Footprint 2.0	GHG Protocol, Eco-indicator 99	GWP100, TRACI	CML 2001, Cumulative Energy Demand (CED)	CML 2001, Cumulative Energy Demand (CED)	Independent impact categories	Independent impact categories	IPCC 2013 v1.0, ReCiPe v1.01
Environmental impacts								
CC (kg CO2-eq)	9.88E+01	1.43E+01	1.75E+00	3.42E+00	4.05E+00	4.17E-01	6.12E-01	1.05E+00
TA (kg SO2-eq)	1.33E-01		1.63E-02	1.61E-02	2.00E-02	3.33E-03	5.17E-03	3.00E-03
FE (kg P-eq)	2.23E-03	7.17E-02	1.26E-02	1.42E-02	1.82E-02	1.83E-03	1.50E-03	9.33E-02
WF (m3)	2.57E-01	4.71E+00	2.33E+00	1.39E+00	1.04E+00	1.97E+00	1.02E+00	
LF (m2)	3.75E+03	2.00E-01		5.00E-03	3.75E-03	3.33E-03	1.50E-03	1.25E-01
Highest impact points	Electricity	Transport (fuel)	Diesel production (CC), Fertilizers (FE, TA), Electricity (WF)	Compost production & Electricity	Compost production & Fertilizers	Fertilizer & Auxilery equipment	Fertilizer, Structure production & Auxilery equipment	Electricity & Machinery

7.2. Differences and Similarities

The table given above shows a lot of information and data which is difficult to grasp in perspective to the model results. Therefore, in this chapter the differences and similarities will be shown in a more clear perspective. Results are shown in graphs depicting all agricultural techniques and a comparison and short discussion is given on the meaning of the graphs. Some graphs may give odd indications, these are mainly discussed in the sub-chapter itself, however, small differences in values that are not discussed can be caused by the difference in data sources, impact indicators and models used.

7.2.1. Climate change

Climate Change (or Global Warming Potential) is one of the, if not the most, common environmental impacts, as the climate change is an important topic in current times. Therefore, every study, paper and research used in this comparison has studied this environmental impact.

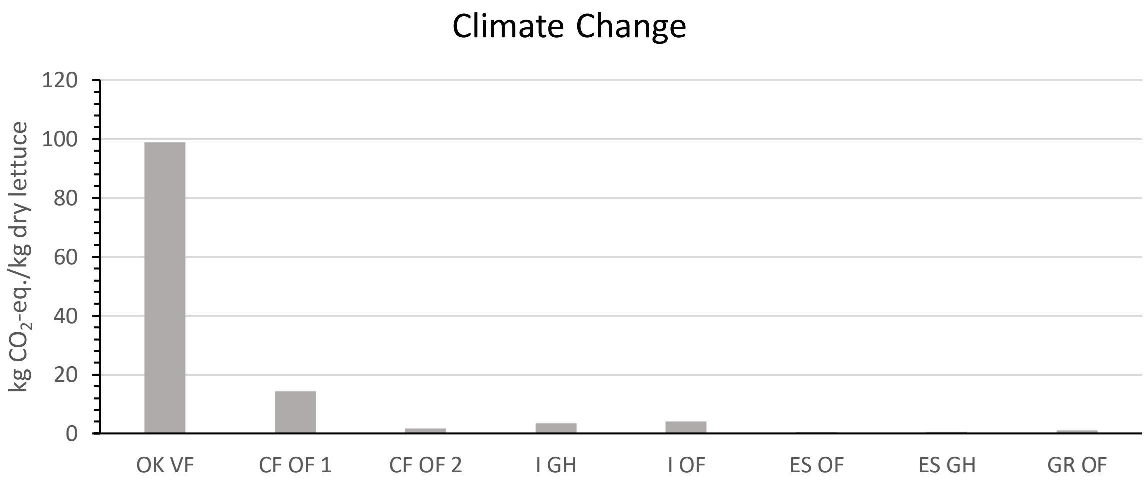

Figure 33 Comparison of the Climate Change impact in different studies (per kg dry lettuce)

The graph shows a clear distinction between the model results and the results of other studies. Logically, the climate change impact for a cradle-to-gate analysis of a vertical farm would be higher than a cradle-to-gate analysis of smaller greenhouses (as shown in the studies) or open field agriculture. This is due to the amount of CO_2 that is released by means of the production phase, with its building construction, and the use phase, with its large electricity use. Even though the Climate Change impact of a Vertical Farm is higher in a cradle to gate approach, it is an even higher number due to the cradle-to-grave approach used in this study which takes a whole extra LCA step into account. The effect of this can be partly seen in the CF OF 1 compared to the other OF classes, as the CF OF1 uses a cradle-to-shelf approach which takes into account transport to the retailer, increasing the CO_2 emissions.

The CO_2 emissions by transport, however, are a very important part of the impact of lettuce production and distribution on the environment. In the study of (Plawecki, Pirog, Montri, & Hamm, 2013) with the CF OF1 class, it is mentioned that the largest portion of the environmental impacts is caused by this transport. Transport is often not taken into account as it is very variable (depending on location) and very difficult to predict (the amount of kilometers, which transportation, etc.), however in places such as the US, it is a very important factor in LCA studies on crops that need to be transported. (Striebig, Smitts, & Morton, 2019; van Hauwermeiren, Coene, Engelen, & Mathijs, 2007; Yi & Elliot, 2017) In the case of Oklahoma the California the study of CF OF1 (Plawecki, Pirog, Montri, & Hamm, 2013) has around the right distance, but the study of (Winans, Marvinney, Gillman, & Spang,

2020) would have an increased impact similar to that of CF OF1. Concluding, the vertical farm has the largest climate change impact by far due to its large electricity use, compared to the open field and greenhouse studies used, even when the studies are included with a transport to and from the state of California to Oklahoma City.

7.2.2. Terrestrial Acidification

Terrestrial Acidification is an impact category that is often included in almost all impact indicators. It is important, as acidification of the soil, in large enough quantities, destroys ecosystems (flora and fauna) and results in locations being marked “contaminated” or “inhabitable”.

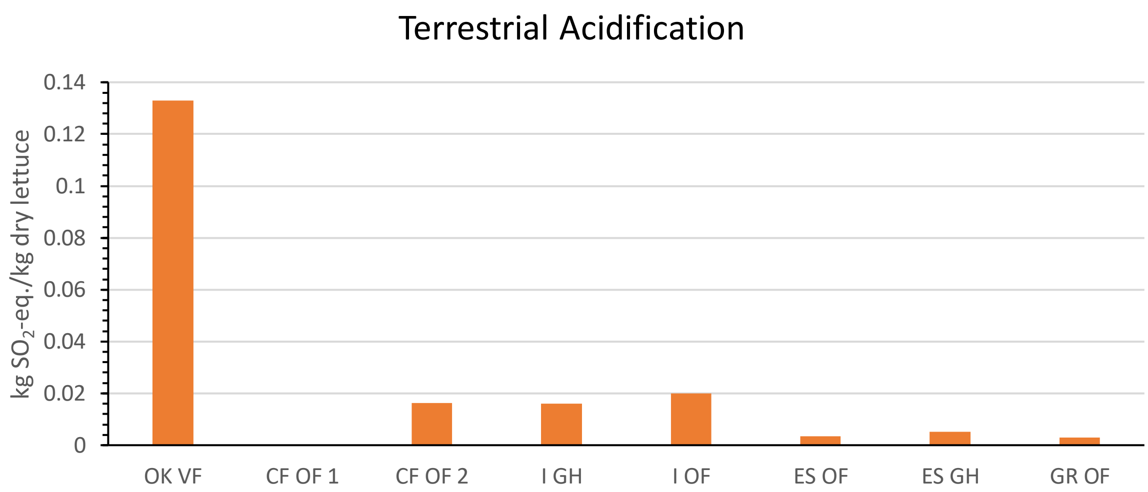

Figure 34 Comparison of the Terrestrial Acidification impact in different studies (per kg dry lettuce)

Though this impact indicator is used in many of chosen studies, the actual impact of open field agriculture is quite low. Often Terrestrial Acidification is a result of use of many chemicals in either production of a material or chemicals used in processes. Pesticides used in Open Field agriculture are often the cause of chemicals in the ground (though this has a larger effect on air quality than ground quality) (Borrion, Khraisheh, & Benyahia, 2012). Fertilizer use in agriculture often consists of only nutrients such as Nitrogen, Phosphorous and Potassium which also contribute to the acidification potential (Wallace, 1994). The vertical farm has a much larger acidification impact due to the high electricity use (which uses chemicals and other land contaminations to produce electricity) and the production of the vertical farm itself. Concluding, there is a higher environmental impact based on the acidification of the ground due to the vertical farm, therefore it is not desirable, however all values of acidification in this comparison are quite low all together.

7.2.3. Freshwater Eutrophication

Even though Freshwater Eutrophication is barely existent in a vertical farm (because no fertilizers are used, the nutrients are distributed through the water and the water is in a closed loop), it is an important indicator for the comparison, because it is a common known problem in Open Field agriculture.

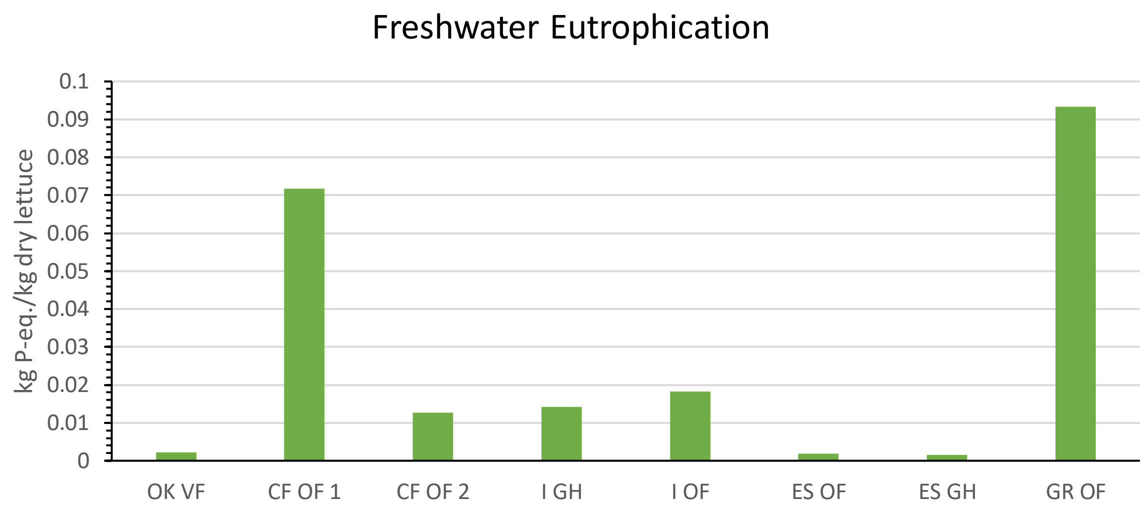

Figure 35 Comparison of the Freshwater Eutrophication impact in different studies (per kg dry lettuce)

If fertilizers on farms are used in excess (which is often done to ensure enough nutrients reaching the crops), the irrigation water will flush the excess fertilizer nutrients into the streams and gullies around the farmland. The excess of nutrients in the waterbody interacts with the biotic life, causing eutrophication (quick excessive algae growth, eventual destruction of the eco-system). In the specific cases in Greece and California 1 it can be assumed that a lot of fertilizers were used, and less in the open field agriculture in California 2, Italy and Spain. In Greenhouses often fertilizers are used, however these fertilizers are not disposed through wastewater which lowers the impact on eutrophication in freshwater bodies. The greenhouse located in Italy has a high eutrophication compared to for example both cases in Spain, while having a lower eutrophication than the Open Field agriculture in Italy from the same study. This may seem like an odd result, but it is plausible that the difference of characteristics (for example the difference in method of assessment) of the studies has caused one study to have an increase by a certain factor, compared to the other study. Concluding, the vertical farm has a much lower impact on the freshwater ecosystem and is therefore desirable over standard rural agricultural techniques.

7.2.4. Water Footprint

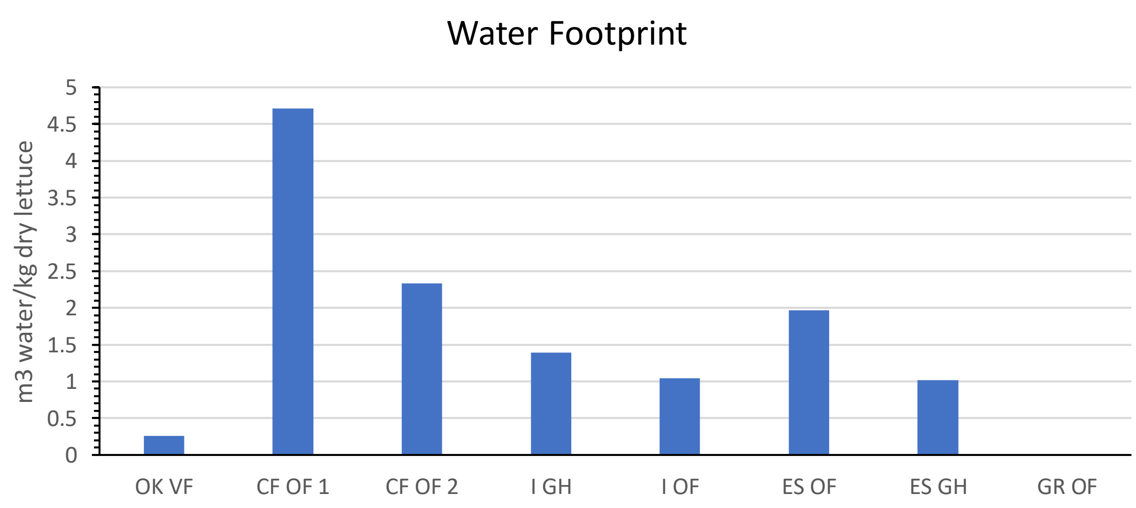

Figure 36 Comparison of the Water Footprint impact in different studies (per kg dry lettuce)

The water footprint is one of the most important impact indicators in this study. In Oklahoma there is a major water scarcity, therefore it is undesirable to develop agriculture that requires a lot of water. Also in states such as California and Arizona where the rural agricultural lettuce is originating from, there is a very arid climate and water is scarce.

In previous chapters it has been discussed that the hydroponics and the (semi-) closed loop system of the vertical farm ensures a low water use. In the graph this is also clearly visible, as the vertical farm has a water footprint of 0.257 m^3 water/kg dry lettuce, while greenhouses and open field agriculture have a water use that is five to twenty times higher. The water footprint, besides being dependent on the climate, is largely influenced by the irrigation technique used. Older techniques such as surface irrigation and sprinkler irrigation are known for a large water footprint (inefficient), while more advanced irrigation techniques such as drip irrigation have a way lower water footprint (efficient). In the graph this is depicted by the large water footprint of CF OF1 (Plawecki, Pirog, Montri, & Hamm, 2013) which uses surface irrigation, while the other open field (and greenhouse) studies use drip irrigation. Concluding, the water use by standard rural agriculture techniques is very high when older techniques are used, high when more advanced techniques are used, low when hydroponics are used and very low when a vertical farm is used. With Oklahoma, California and Arizona in mind the vertical farm would be highly desirable, considering water conservation alone.

7.2.5. Land Footprint

The land footprint (or land use) contains one of the most used claim supporting vertical farming. In various sources, from journals and reports to news articles and interviews, it is stated that the land footprint of a vertical farm is significantly lower due to the many floors of cultivation on the same surface area. (Al-Chalabi, 2015; Banerjee & Adenaeuer, 2013; Despommier, Farming up the city: the rise of urban vertical farms, 2013; Benke & Tomkins, Future food-production systems: vertical farming and controlled-environment agriculture, 2017) This is often made visible by means of yield, where the vertical farm has a much larger yield than open field agriculture and greenhouses. This is most clearly depicted in Figure 37 Yield potential for a vertical farm, semi-closed greenhouse (United Arab Emirates), conventional greenhouse (Netherlands and Sweden) and open field cultivation by the study of (Hallikainen, 2019).

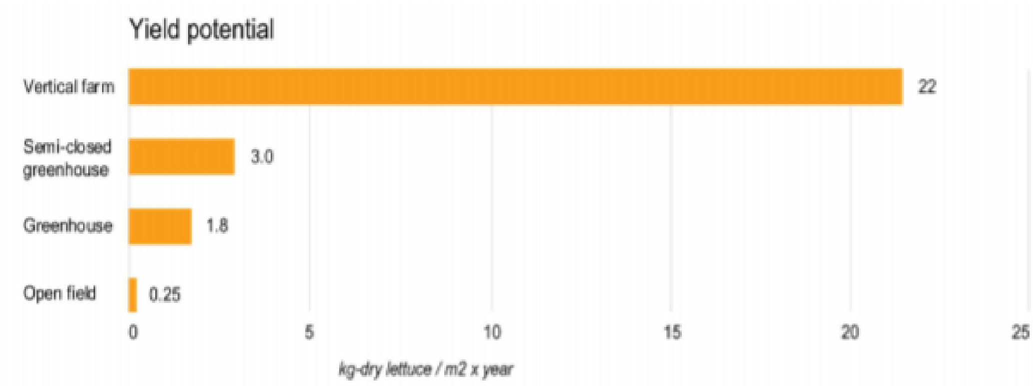

Figure 37 Yield potential for a vertical farm, semi-closed greenhouse (United Arab Emirates), conventional greenhouse (Netherlands and Sweden) and open field cultivation (Hallikainen, 2019; Graamans, Baeza, Stanghellini, Tsafaras, & van den Dobbelsteen, 2018; Kikuchi, Kanematsu, Yoshikawa, Okubo, & Takagaki, 2018)

This is a supportive argument to place a vertical farm in an urban area, however, this is the yield or yield potential and not the actual land footprint from a LCA point of view. The actual land footprint takes into account all of the different Life Cycle phases of a product besides only the physical dimensions of the farm.

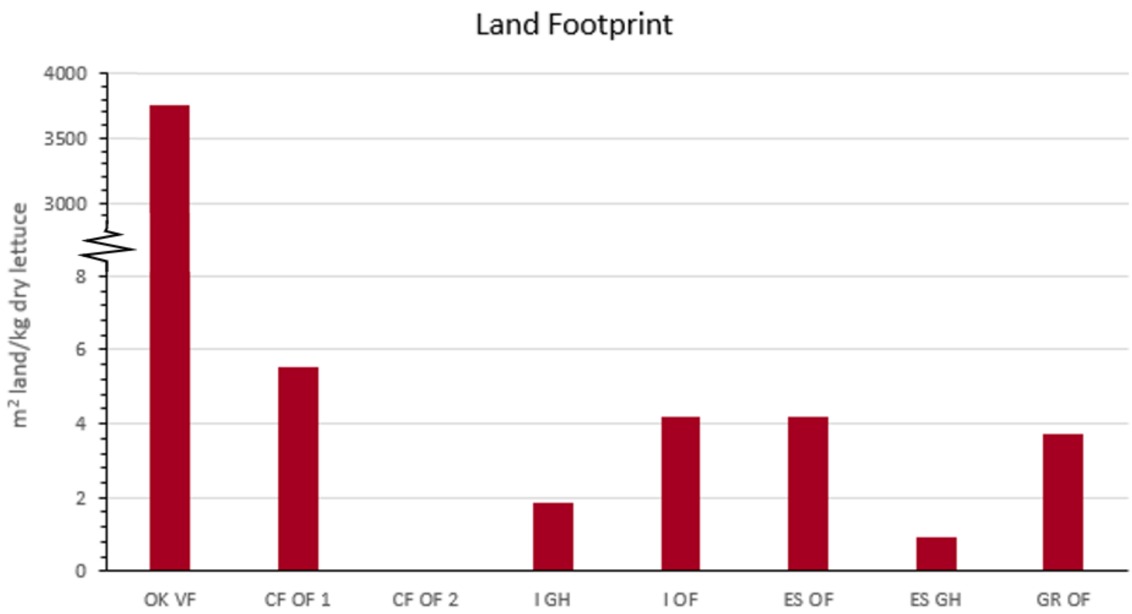

Figure 38 Comparison of the Land Footprint impact in different studies (per kg dry lettuce)

When calculating the actual land footprint, the graph tells a whole different story. The vertical farm has a land use that is almost a thousand times the land use of other types of agricultural practices. There are multiple reasons for the results in this graph. As mentioned earlier, the land use of the vertical farm is enormous, which is mainly due to its Use phase and within this phase the production of electricity. With the current Texas grid mix, this figure is quite large. Even with other types of renewable or 'minimal land use' electricity production options such as nuclear, the land footprint would still remain far greater than all other agricultural practices (shown in the sensitivity analysis Figure 31 Electricity generation Sensitivity Analysis results (CC = Climate Change, TA = Terrestrial Acidification, FE = Freshwater Eutrophication, WF = Water Footprint, LF = Land Footprint) per kg dry lettuce). Due to the use of a cradle-to-gate analysis by the other studies, their values are lower respectively, however even when including the End of Life phase, it is assumed the values are very low comparing to the vertical farm. The End of Life phase, when included will add some land footprint to the studies, because of the space needed for a landfill or an incineration, though this LCA phase in rural agriculture does not account for massive land footprint values (Jan, Tostivint, Turbé, O'Conner, & Lavelle, 2013). Concluding, a vertical farm may seem like a good choice based on the yield and the idea of taking up less space in the world, however, taking into account all Life Cycle phases of a vertical farm from cradle to grave shows a very large land footprint. This land footprint is mostly impacting the country where the electricity is produced.

8. Discussion

With the results of the Life Cycle Analysis discussed in both chapter 6 and 7, this chapter mainly discusses the influence of model choices, the limitations of the model and the outcome compared to the claims made on vertical farming, stated in chapter 2.

8.1. Model choices

Many choices on the vertical farming systems and the model have been discussed in their respective chapters, though some more detailed alternatives have not been addressed (due to it being controversial, not yet studied or no data was available), though some alternatives could have had large impacts given the current knowledge of the environmental impacts.

To create a vertical farm, the dimensions have been determined by other high rise buildings in the same area of the city. Even though a tower has been the desired building, the land footprint that this building was meant to lower has proven very large. This is mostly related to electricity usage which might have been lowered due to efficiency when creating a vertical farm that uses larger floors with less walkways and longer rows of high density crops in a low rise industry hall building. The specific density of the crops can also be altered, in which 36 plants per square meter (which is used in this report) is the maximum researched density. A lower density, however, could change the composition of the environmental impacts and lower the overall impacts per kilogram of dry lettuce.

In the sensitivity analysis, some electricity generation techniques are shown as the best possible options. These options such as nuclear are the best in the given impact categories, though could have negative effects on other impact categories. In the case of nuclear energy for example, nuclear waste is a significant problem which has to be dealt with when converting to mostly nuclear energy. Therefore, even though it might be shown as one of the best techniques in this research it might not be the overall best for the country or state and its environmental policies and laws.

Looking back on the largest environmental impacts such as the electricity production through mostly lighting, massive changes could be made to ensure a lower electricity demand. First of all windows could be added. Even though this would allow more temperature to escape through the poorer insulation of a window, sunlight can induce the plant growth and with lights that adapt to the light levels on the plant and add additional missing light, this would reduce the electricity costs. The trade-off between the insulation loss and the additional light gain, especially in a state with many sunny days, would favor the electricity reduction. This would work the best in combination with a lower rise building, as a lot of plants would be exposed to sunlight in contrary to only the upper floor of the tower. Other systems such as the HVAC system also contribute to the electricity bill. This system is heavily dependent on the outside climate. In the model the HVAC

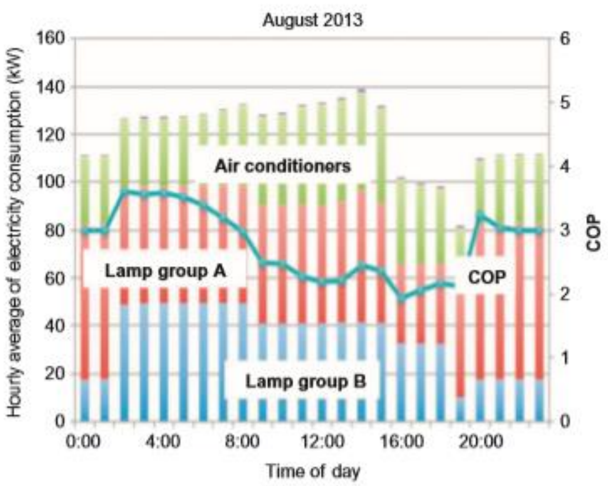

Figure 39 Kozai's vertical farm electricity consumption during different hours of the day for various systems (Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016)

system electricity demand has been set as a constant value over the year, while in reality it could be adapted to fit certain temperatures. Shown in Figure 39 Kozai's vertical farm electricity consumption during different hours of the day for various systems (Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016), is an electricity time schedule of multiple systems present in the vertical farm, which would yield in the most efficient way of using the systems in a vertical farm in Japan. The COP given on the right of the graph is relation to the cooling load and the difference between inside and outside temperature, shown in Appendix B.

In the eventual Life Cycle Analysis, all comparable studies that were deemed useful, appeared to have a life cycle approach of cradle-to-gate or cradle-to-shelf. Therefore, a cradle-to-gate analysis on the fictive vertical farm in this study would have been enough for the comparison. Even though this is true, the End of Life phase increases the awareness and adds to the amount of studies on this subject. Furthermore a lot of critique can be given on the LCA modelling stage, as many sources can be altered and slightly changed creating a different outcome. This model is built in an educational version of the program (limited resources) with the 5% rule in combination with my own perception on the importance of certain processes and materials within a 2nd order analysis. Nonetheless most results are close to my personal expected results and within the same range of values of similar studies. In the comparison of the results, from the small range of studies, studies have been chosen that have the same climate. Although this is a great starting point, the studies still show large differences in characteristics and systems used, as well as missing data that could be crucial to the difference in results, which is unfortunately unavoidable. Fortunately, even without the missing data and the differences a good comparison including side notes has been made.

One of the largest question marks in this study is the enormous land footprint per kg dry lettuce. With a factor thousand more compared to rural agriculture studies, it exceeds expectations small land footprint. The main cause of this is the large electricity generation in the use phase. While the large electricity use is the source of many high impact outcomes, in other impact categories this intensity is within a logical range, as explained in chapter 6.1.7 'Result Analysis'. Though, for land footprint, the difference to other studies, with a factor thousand, is an odd result. Therefore, a closer look into the electricity use is taken, extracting data from studies on electricity generation. With a scarce amount of literature on land footprint only a few studies are applicable to this research, though they all show the same range of values. Applying and converting the data from the studies of (Mahlooji, Ludovic, Ristic, & Madani, 2020; Balezentis, Streimikiene, Melnikiene, & Zeng, 2019; Fritsche, Berndes, Johnson, & Cowie, 2017; Ristic, Mahlooji, Gaudard, & Madani, 2019) to dry lettuce in the vertical farm, shows values of land footprints in the range of 12m^2 to 100m^2 for electricity generation/production. This is much lower than the results of this study, showing a much lower footprint per kg of dry lettuce. Even though this does not change the message of the study as the land footprint of the vertical farm remains the highest compared to rural agriculture studies, it does influence the trade-off between the negatives and the positives of creating vertical farms.

8.2. Limitations of the study

Most of the limitations of the study have been mentioned throughout the study. First of all, the time for this thesis has been one of the limitations. With the limited time in mind this study has been set-up to accommodate only one vertical farm, with only one crop instead of a comparison between multiple vertical farms or a more logical mix of crops with different growing seasons (to maximize profits). (Michael, 2017) The time limitation also had an effect on the LCA in which the model is detailed enough to show the major impacts, though not as detailed as it could be within the second order LCA method.

In the introduction it is mentioned that the lack of data and studies would limit this study in finding the best comparison. Eventually more data, papers and studies were recovered that deemed useful in the system analysis, the life cycle modelling and the comparison. In the life cycle modelling, however, there were some bottlenecks that limited the ability to model the life cycle of the vertical farm. This was linked to the limited available database of the educational licence of the program GaBi. Therefore many estimations were made based on existing papers and credible websites. The program also limited the amount of possible life cycle indicators and with an additional error in the program this amount was even further decreased. Eventually this increased the difficulty in the comparison, in which a lot of values had to be converted.

The lack of specific data and quantative studies led to many estimations based on non-vertical farm related studies. Mainly in the modelling procedure, where the database led the model to its final form, meaning that not all Life Cycle Inventory materials were present in the database which caused some compromises and some adapting of other materials and processes to represent the LCI material. All these changes have introduced a certain level of uncertainty in the results. This uncertainty was expected with the little data that is available on the subject. As the uncertainty in both the results and the comparison is a multilayer uncertainty (uncertainty on uncertainty) the results of this study must be taken with some consideration and should not be simply copied.

8.3. Claim review

A lot of claims have been made by websites, papers and studies on this revolutionary vertical farming technique. Though, only as claims with little substantiation, these hold little to no scientific proof. In this subchapter, the claims stated in chapter 2 are analyzed and compared to the results from this study.

One of the claims about the benefits of vertical farming is that the water use of a vertical farm is significantly lower than rural agriculture. This claim is correct as the water use of the vertical farm is 18 times lower due to its (semi) closed loop system and its high end water distribution technology, compared to old fashioned systems such as surface or sprinkler irrigation and 4 to 9 times lower than more technological advanced drip irrigation. Even though the vertical farm increases the water use in a state slightly, when it replaces rural agriculture in other states, it significantly lowers the pressure on the overall water system of the US (especially if the vertical farm were to be implemented in large numbers). Another claim that is correct is the amount of lettuce produced in a vertical farm compared to traditional ways of agriculture. Due to its controlled climate and closed area, the yield that a vertical farm produces is very high and very stable (88 times more yield than an OF setting and 8 to 13 times more yield than a greenhouse per year). The days from seed to harvest is decreased and the efficiency of growing is massively increased, because with the help of studies on the characteristics and growing habits of lettuce a perfect climate can be constructed that meets every demand of the densely planted crop. Also within this shell of a building, the crop is sealed off from any external factor that might influence it, such as extreme weather conditions, diseases and insects. Therefore, the use of pesticides is also nullified, creating less chemical waste and contaminations due to pesticide production and use. Fertilizer use has also been massively reduced in the form of only the nutrients added to a water flow, thus decreasing the nutrient waste. The eutrophication as a result of these fertilizers is reduced by 70 to 90% compared to rural agriculture (in most studies). From this study it is seen that the air and freshwater pollution is decreased because of those reasons, though the contamination of the ground is increased because of the production of metal, plastics and other components. Thus, the claims on pollution are predominantly correct. Even though the yield is high, the land use is not reduced. At first glance a tower would reduce the amount of land use, as it uses stacked layers and a very dense cultivation process, resulting in very little land use per crop of lettuce. Though, taking into account all processes of the vertical farm, the production of electricity demands a lot of land use, which outweighs the land use gained from stacking crops in a tower. Thus, the claim that a vertical farm uses less land is incorrect, taking into account all life cycle steps of a vertical farm. The Land Footprint is according to the model around a 1000 times larger than that of traditional rural agriculture model. According to scientific papers it is also higher, but with a more modest 3 to 15 times compared to rural agriculture. With the tower located in an urban area, little transport is needed to move the lettuce from the cultivation location to the retailer within the same city and with the high yield of one tower already, the demand of a large city can be easily met which would nullify all long distance transport from far away states for this one crop. A vertical farm has a transport distance of a tens of kilometers while rural agriculture from California (the largest producer) has a transport distance of around 2000 kilometers. Thus, claims on urbanizing and transport are also correct, taking into account the yield that is needed to meet the demands of a city. Economic, social and political claims have not been researched, as it is out of the scope of this study. Though, it is referenced in multiple peer-reviewed studies and municipal reports that the economic costs of a vertical farm are initially very high and lower during the use phase. This causes a vertical farms to be very expensive to built, but profitable after launch, if there is a proper connection to the niche market or if there is funding from the state. (Banerjee & Adenaeuer, 2013; Zeidler, Schubert, & Vrakking, 2017)

9. Conclusion

This study discusses and analyzes the concept of vertical farming from a Life Cycle Analysis perspective on a fictive vertical farm in Oklahoma City. The outcome of the analysis shows many environmental impacts, though one clearly stands out, the Land Footprint. The Land Footprint is exceptionally large for a vertical farm in the modelled result, around a factor 1000 larger than rural agriculture, due to the land use of the electricity production. This result is possibly to high, as scientific papers hint to a more modest factor of 3 to 15 times larger than rural agriculture. These results are diametrically opposed to the claim that vertical farms have a lower land footprint and should be built with this advantage in mind, which is based solely on the vertical farm's surface area, instead of the land used in all of the life cycle phases combined.

The largest contributor to most of the impact categories is the huge influence of the electricity production. This vertical farm has a large electricity demand operating in the Use phase, in which the lighting system accounts for 77.6%, the ventilation system for 14.3% and the water system for 8% of the total electricity use. Using a different method of electricity production than coal and natural gas can significantly lower the impact in each category. The original production of coal and natural gas are in most cases the most impactful on the environment with for example ~100 to 190 kg CO_2 emissions, while in the case of this study, the use of nuclear power or wind power (respectively the third and fourth most used electricity source in the US) would be the least impactful over all impact categories, with for example ~2 to 3 kg CO_2 emissions (Appendix G)

Placing a vertical farm in a state where the lettuce is not originally produced but transported to, will result in higher local environmental impacts as there were none to begin with (except CO_2 emissions from transport trucks). In this case of a fictive vertical farm in Oklahoma, the same logic is apparent, because the original lettuce production location is California/Arizona. The impacts on the local environment in Oklahoma are tolerable, as the largest problem in Oklahoma related to the impacts is the water scarcity, while the water footprint in a vertical farm is quite low. On the other hand, the large land footprint is concerning in Oklahoma. Even though this is a state that contains a lot of open space, the space is among other things required for nature to grow instead of using it for the needs of a vertical farm.

Most of the claims stated in Chapter 2 of this study are marked as correct, which is expected as they are based on some sort of logical thinking. However, as mentioned earlier, one claim that is used a lot on the top of the list of major vertical farm advantages, is in fact not true according to this study: The Land Footprint. Even though most of the claims set on the vertical farm are true, when investing in a vertical farm (with high initial costs) some trade-offs have to be made between impacts on the environment, which are related to the local conditions of the country or state. The vertical farming concept is not a perfect solution to all problems, but more a trade-off between solving high profile problems (such as food security) while causing a less significant problem in that location to increase in severity (such as terrestrial acidification). For the specific case presented in this study, the vertical farm would be a good solution to the food supply of Oklahoma City. With a low water use, less water pollution and a close distance to the retailer, it would outweigh the negatives of land use and climate change, if and only if the vertical farm is powered by renewable or nuclear energy. With the current fossil based energy sources, the land use and CO_2 emissions would be simply to high to simply call it a positive change.

The climate and the severity of the extreme local conditions control a large portion of the trade-off between advantages and disadvantages of a vertical farm. (Graamans, Baeza, Stanghellini, Tsafaras, & van den Dobbelsteen, 2018) If a country has an extreme climate (extremely hot or extremely cold), where certain high demanded crops cannot grow, a vertical farm would be a possible solution. In these extreme climates, the trade-off would most likely shift towards the benefits of the vertical farm over the negatives. Though, if a country has a climate that is highly suitable for the crop to grow in, with a very low rate of natural hazards, diseases or insect plagues, the vertical farm would not add enough to the crop growth to outweigh the negative impacts on the climate.

Cultivation under artificial lighting in a vertical farming tower appears to be a high energy intensive cultivation method. In the current fossil based economy, this cultivation strategy leads to high environmental impacts. However, in the future, where fossil energy sources are slowly being replaced by nuclear power and renewable energy (this transition is already happening (EIA, 2020)), this method of cultivation could be a great solution for food security and feeding an ever growing world population, while having lower negative impacts. Also, vertical farms on their own can contribute to a countries/states local food security, but to tackle the food security as a world problem, many vertical farms have to be built in many different climates. To accomplish this, a lot of knowledge is required on the impact of the climate on the vertical farm, the characteristics of the country, the systems used in that specific country in relation to the ideal climate of the vertical farm and even economic and social aspects of the vertical farm. Therefore, it is important that more studies on this topic are published and more test cases and commercial farms (which distribute their data) are created. Only with more knowledge and quantitative data on the specifics of this concept, will the concept of vertical farming be relevant for the future of farming and a possible solution for a part of the worlds food problems.

10. Future perspective

There is a lot of potential in the concept of vertical farming. In this research the focus has been on one particular vertical farming set-up, with a fictive vertical farm in a specific climate, with a specific crop, using standard vertical farming systems of which much is known. Still, there are many other aspects to vertical farming, for example using other crops that are not as researched, using completely different techniques or even environments that are not very common.

Crops in vertical farming studies have never been very diverse. Most of these studies are based on lettuce or other leafy greens or herbs, which are easy to cultivate crops which do not require a lot of space and can be stacked easily. Since a couple of years some studies have diverged from the standard and have examined tomatoes in vertical farms, which is a crop that is more difficult to cultivate. Deviating from this standard and researching the unknown vegetables and even fruits (O'Sullivan, et al., 2020) in a vertical farm can open a lot of doors and create a lot of possibilities for lower impacts on the global climate. With the current techniques for creating an ideal climate, it is possible to grow different crops with different demands in vertical farms, however, it is for research to decide if it is profitable and if the environmental impacts of local production outweigh the negatives of resource input. For example: Pineapples. In Europe the largest part (75%) of pineapples are originate from Costa Rica (Central America) (Consumer International, 2010; Bananalink, n.d.), which requires long distance travel, a high climate impact. When these tropical fruits would be cultivated in vertical farms in countries in Europe, this would remove the long travel and create an independent local food source. Whether this would outweigh the negatives that come from high electricity costs and other systems, has to be researched, however, this could be a very interesting development in the vertical farming future. The resulting socio-economic consequences from shifting global trade would also need to be modeled before scaling up.

The systems presented in this vertical farm are based on papers and books on vertical farming and according to these sources the systems they present most efficient or the best in particular situations. The systems presented, however, are common systems which have been tested and researched a lot. The more controversial systems, which could make a difference in the outcome in the environmental analysis, are not presented. Such systems are for example implementing a system that directly captures water to lower the pumping of water over the course of a year, or a system that captures electricity from sunlight through solar power, directly on top of the vertical farm. These systems are shown in Figure 40 Alternative additional systems, adapted from .

Another aspect of these systems is the use of green walls (another form of urban agriculture) and green roofs in order to lower the urban heat island effect in a city and give the vertical farm a more natural look. (Akbari, et al., 2014; Rakhshanderhoo, Yusof, & Arabi, 2015) More research on these kind of subjects could change the impact of a vertical farm on the depletion of resources and generation of electricity.

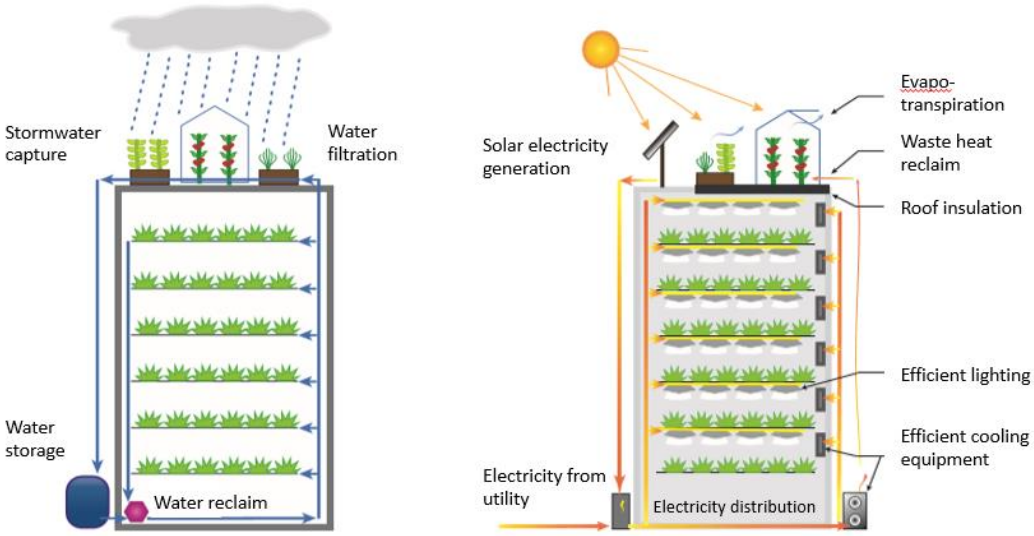

Figure 40 Alternative additional systems, adapted from (Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016; Sabeh, HVAC Systems for Controlled Environment Agriculture, 2015)

Due to their closed loop systems, a vertical farm can be built in all climates on earth. The future of vertical farms can even go beyond growing crops in extreme climates on earth and "may take us into space." (Vago, 2018) "In fact, if you were growing crops on Mars you would need to use this kind of technology because there is no soil." (John Innes Centre, 2020) On other planets or moons, it is impossible to grow earthly crops in the climate that the planets and moons within range present. If space travel is more common in the future, "we'll need to grow our food indoors, rather than weigh down a ship with a stockpile of food, or try and grow crops in inhospitable alien soil." (Vago, 2018) When this day arrives, the techniques used in vertical farming on earth will be crucial and adapting these techniques to fit the food production in other planetary climates is important.

Even with the current struggles of vertical farms, with their difficult trade-offs in environmental impacts, early economical disadvantages and the public opinion on growing crops in buildings, it is highly likely that vertical farms will play a role in future farming in one way or another and therefore research on this topic in any direction or form is recommended and important to our growth as a society.

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Appendix

A. Daily Light Integral (DLI) graph

PPFD	1	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800	850	900	950	1000
Hours	DLI																			
1	0,0036	0,4	0,5	0,7	0,9	1,1	1,3	1,4	1,6	1,8	2,0	2,2	2,3	2,5	2,7	2,9	3,1	3,2	3,4	3,6
2	0,0072	0,7	1,1	1,4	1,8	2,2	2,5	2,9	3,2	3,6	4,0	4,3	4,7	5,0	5,4	5,8	6,1	6,5	6,8	7,2
3	0,0108	1,1	1,6	2,2	2,7	3,2	3,8	4,3	4,9	5,4	5,9	6,5	7,0	7,6	8,1	8,6	9,2	9,7	10,3	10,8
4	0,0144	1,4	2,2	2,9	3,6	4,3	5,0	5,8	6,5	7,2	7,9	8,6	9,4	10,1	10,8	11,5	12,2	13,0	13,7	14,4
5	0,0180	1,8	2,7	3,6	4,5	5,4	6,3	7,2	8,1	9,0	9,9	10,8	11,7	12,6	13,5	14,4	15,3	16,2	17,1	18,0
6	0,0216	2,2	3,2	4,3	5,4	6,5	7,6	8,6	9,7	10,8	11,9	13,0	14,0	15,1	16,2	17,3	18,4	19,4	20,5	21,6
7	0,0252	2,5	3,8	5,0	6,3	7,6	8,8	10,1	11,3	12,6	13,9	15,1	16,4	17,6	18,9	20,2	21,4	22,7	23,9	25,2
8	0,0288	2,9	4,3	5,8	7,2	8,6	10,1	11,5	13,0	14,4	15,8	17,3	18,7	20,2	21,6	23,0	24,5	25,9	27,4	28,8
9	0,0324	3,2	4,9	6,5	8,1	9,7	11,3	13,0	14,6	16,2	17,8	19,4	21,1	22,7	24,3	25,9	27,5	29,2	30,8	32,4
10	0,0360	3,6	5,4	7,2	9,0	10,8	12,6	14,4	16,2	18,0	19,8	21,6	23,4	25,2	27,0	28,8	30,6	32,4	34,2	36,0
11	0,0396	4,0	5,9	7,9	9,9	11,9	13,9	15,8	17,8	19,8	21,8	23,8	25,7	27,7	29,7	31,7	33,7	35,6	37,6	39,6
12	0,0432	4,3	6,5	8,6	10,8	13,0	15,1	17,3	19,4	21,6	23,8	25,9	28,1	30,2	32,4	34,6	36,7	38,9	41,0	43,2
13	0,0468	4,7	7,0	9,4	11,7	14,0	16,4	18,7	21,1	23,4	25,7	28,1	30,4	32,8	35,1	37,4	39,8	42,1	44,5	46,8
14	0,0504	5,0	7,6	10,1	12,6	15,1	17,6	20,2	22,7	25,2	27,7	30,2	32,8	35,3	37,8	40,3	42,8	45,4	47,9	50,4
15	0,0540	5,4	8,1	10,8	13,5	16,2	18,9	21,6	24,3	27,0	29,7	32,4	35,1	37,8	40,5	43,2	45,9	48,6	51,3	54,0
16	0,0576	5,8	8,6	11,5	14,4	17,3	20,2	23,0	25,9	28,8	31,7	34,6	37,4	40,3	43,2	46,1	49,0	51,8	54,7	57,6
17	0,0612	6,1	9,2	12,2	15,3	18,4	21,4	24,5	27,5	30,6	33,7	36,7	39,8	42,8	45,9	49,0	52,0	55,1	58,1	61,2
18	0,0648	6,5	9,7	13,0	16,2	19,4	22,7	25,9	29,2	32,4	35,6	38,9	42,1	45,4	48,6	51,8	55,1	58,3	61,6	64,8
19	0,0684	6,8	10,3	13,7	17,1	20,5	23,9	27,4	30,8	34,2	37,6	41,0	44,5	47,9	51,3	54,7	58,1	61,6	65,0	68,4
20	0,0720	7,2	10,8	14,4	18,0	21,6	25,2	28,8	32,4	36,0	39,6	43,2	46,8	50,4	54,0	57,6	61,2	64,8	68,4	72,0
21	0,0756	7,6	11,3	15,1	18,9	22,7	26,5	30,2	34,0	37,8	41,6	45,4	49,1	52,9	56,7	60,5	64,3	68,0	71,8	75,6
22	0,0792	7,9	11,9	15,8	19,8	23,8	27,7	31,7	35,6	39,6	43,6	47,5	51,5	55,4	59,4	63,4	67,3	71,3	75,2	79,2
23	0,0828	8,3	12,4	16,6	20,7	24,8	29,0	33,1	37,3	41,4	45,5	49,7	53,8	58,0	62,1	66,2	70,4	74,5	78,7	82,8
24	0,0864	8,6	13,0	17,3	21,6	25,9	30,2	34,6	38,9	43,2	47,5	51,8	56,2	60,5	64,8	69,1	73,4	77,8	82,1	86,4
		0-5		5-10		10-15		15-20		20-25		30-35		35-40		40->				

B. Cooling load and COP

The lower the COP, the higher the electricity consumptions of air conditioners, and thus the electricity cost, especially during 13:00 – 16:00. IT is important to set the light period at nighttime (when air temperature outside is lower than daytime) to achieve a higher COP, even if a nighttime discount of electricity charge Is not available.

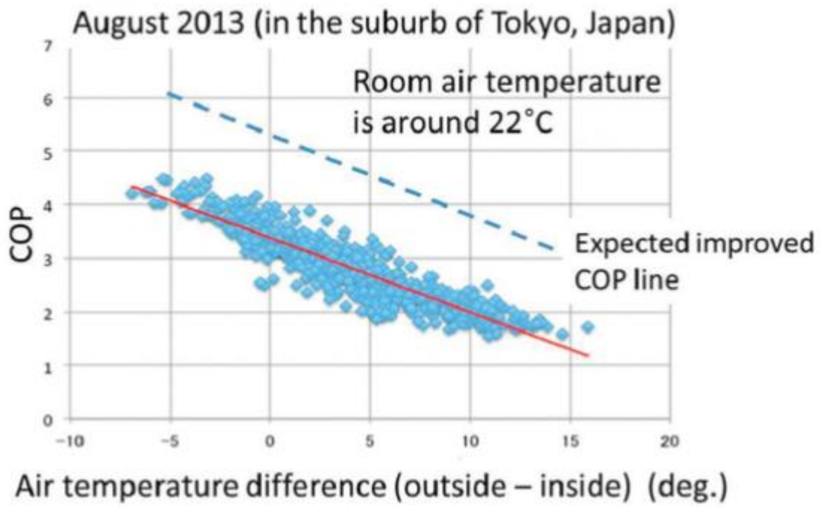

Figure 41 COP affected by Air temperature difference

COPs of air conditioners in August as affected by air temperature difference between inside and outside. Electricity cost for air conditioning is halved when COP is doubled. The dashed line indicates the maximum possible COP which is achieved when the cooling load is around 70% of the cooling capacity.

C. Life Cycle Inventory Analysis (LCAI) calculations

C.1. Building Structure

For the building structure, which includes features such as the foundation, walls, floors and all other hard structural aspects of a vertical farm, rules of thumb will be used as well as many construction and building physics sources and estimated guesses based on prior Civil Engineering knowledge. “There is a great diversity of problems in the construction area. All these considerations mean that the construction industry uses a relatively large number of “rules of thumb”, perhaps even more than any other sector of technology.” (Czarnecki & van Gemert, 2016) In this subchapter the building structure will be calculated from the roof down to the foundation, as is the usual calculation method to consider all loads and masses. Though, as this LCA does not require the exact details but a mere estimation on the amount of materials used, iterations and/or taking steps back and re-calculating the building, are not necessary.

Roof & Ceiling

For the roof a typical common commercial low-sloped roof is used (Sentry Roofing, 2018). This roof has an almost unnoticeable slope, but transports the rain while being flat enough for vertical farming systems (for example HVAC to stand on). The roof will be made out of profiled steel roof sheets (Figure 42 Steel profile roof panel). With the roof thickness depending on the length of the various sections, rules of thumb of TU Delft will be used. Columns and a steel truss construction will be used to support the steel roof panels. Using 3 columns in the 40m length creates 10m wide span lengths. The truss construction will bridge these gaps and create 5m wide span lengths for the roof panels.

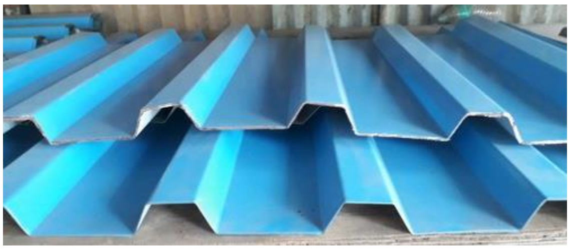

Figure 42 Steel profile roof panel (Dehli F.N. Steel, 2020)

Using (TU Delft, 2013) this computes to a 5*(1/40) = 0.125m high roof panel profile. With the thickness of the roof panels often being 0.8 mm (22 gauge), this results in a guessed estimate of 40*40*(0.8/1000)*1.25 (roof profile factor) = 1.6 m^3 or 12.5 tons of steel needed for the roof panels (with a steel density of 7800kg/m3). (Legacy Service, 2020; DWG, 2018)

The truss construction (Figure 42 Steel profile roof panel) is made of steel and calculate to a height of 10*(1/10) = 1m. (TU Delft, 2013) With the use of steel profiles as provided in the “vakwerk figure” in (Nijsse, 2012), every 10m will consist of 0.38 m3 steel which calculates to 4.53 m3 or 35.6 tons of steel for the complete truss construction. Per floor. This calculates to a total amount of construction steel of 41m3 or 320 tons (with a steel density of 7800kg/m3)

Figure 43 Truss construction (Cisc-icca, 2017)

With a lot of different sources (reports and websites) claiming various life expectancies of a steel roof between 20 to 60 years. It is chosen to use 30 years, half of the buildings own life expectancy as the life expectancy of the low sloped steel roof. (Wu, et al., 2015)

Columns & Walls

Both the columns and outer walls will be made of concrete, it is a common material used in the world and a lot of the surrounding buildings are made out of the same material. It is assumed that all outer walls and columns bear the complete weight of this building while the inner walls do not redirect any forces, apart from their own weight. It is chosen that the outer walls on all levels are the same width of 20.3 cm, which is mentioned as above minimum for load-bearing concrete walls. (USAID/OAS, 2001) This results in a total concrete use of 300m3 or 750 tons of concrete (with a concrete density of 2500 kg/m3). The inner walls are also the same width on the lower two levels where they are implemented, using wood partition walls estimated to a total of 90m3 or 63 tons of wood, using dimensions and characteristics of (Inlook, 2019).

"In general, wooden partitions have 20 years remaining. Existing corridor partitions are sound, though finish materials are dated and in need of replacement." (Juneau, n.d.)

The columns have the length of the height of the story which is 7.5m using rule of thumbs and this will calculate to a width of 0.63m (TU Delft, 2013). With all dimensions known, the amount of concrete needed for one column is 2.9 m3 and thus 26.8 m3 per floor and 242 m3 or 603 tons of concrete for the total building (with a concrete density of 2500 kg/m3)

Floor & Beams

With the use of prestressed TT concrete panels (Figure 44 TT-floorpanels), with dimensions of 10m by 2.5m (TU Delft, 2013), a total amount of concrete per panel is 1.6m3 (Willy Naessons), extrapolating this into one complete floor calculates to 107m3 concrete per floor and thus 962 m3 concrete for the entire building, which translates to 2404 ton concrete.

Figure 44 TT-floorpanels (Hoco beton, n.d.)

Floor beams are calculated with the use of rules of thumb, resulting in 10*(1/20) = 0.5m high and 0.5*(1/2) = 0.25m wide prestressed concrete floor beams for a span of 10m (TU Delft, 2013), laid down every 2.5m. This results in a total of 1.25m3 concrete per beam. Extrapolated this computes to 80m3 concrete per 40m by 40m floor area. For the complete building this calculates to 640m3 or 1600 tons of concrete.

Foundation

For the calculation and the type of the foundation the soil profile of the location has to be known. Because the location is not precisely known and no vertical soil profile of Oklahoma is available for the public, a satellite view soil map will be used. On the soil map created by geological surveys on the area of Oklahoma (Figure 45 Oklahoma City soil map), the east of Oklahoma city is represented by NCT soil (shallow, sandy and loamy, moderately acid, and humus-poor soils and the west of Oklahoma city consists of CRRP soil (clayey and humus-rich soils on very gentle slopes) with a couple of sand hills (very deep, loamy and sandy, well-drained and slightly acidic soils on moderately steep slopes distributed along the river. (Carter & Gregory, 2008)

With the top ground profile, the assumption is made that most of the ground around Oklahoma city is quite clayey in the higher ground layers and will not bear a lot of weight of high-rise buildings. Therefore, a pillar foundation is used, which are long prefab concrete pillars reaching a deep layer that can bear forces (usually sand) while also leaning on the friction and adhesive forces of the clay layers it punctures through. Supporting the whole building with all structural elements as well as production elements, an assumption is made on the weight of 10.000 tons and thus a force on the foundation of 98.000 kN using estimated structural building elements as well as an assumption for the weight of the elements inside of the building. It is assumed that the sand layer is between 5 and 10 meters deep, using a pile of 20m to be sure. With 3000 kN per pillar computes to 33 pillars. With the use of 36 pillars, 6 in a row on both sides, is assumed to support the building. These piles will have a diameter of 1.2m to measure up to the length to diameter ratio (Hafshejani, Hajiannia, Pousti, & Noroozi, 2016). This results in a total concrete use of 746m3 or 1866 tons of concrete.

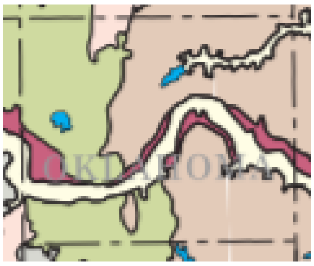

Figure 45 Oklahoma City soil map (Carter & Gregory, 2008)

Building life expectancy

De life expectancy of a normal building is generally assumed 30, 50 or 60 years, depending on the occupation. (Struhala & Stranska, 2016) Most literary sources on building life expectancy, lifespan or useful life is set at 60 years (Waclaw, 2014; Dias, 2003), therefore in this study the life expectancy of the building is 60 years, which includes individual components of the building structure, such as the concrete walls and foundations.

C.2. Vertical Farming Structure

Germination, nursery and cultivation area structure

This chapter is about the process of germination and seedling in the nurseries as well as the inner structure and floor plan, which is covered by (Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016) and (Nadal, 2014).

Racks

The racks in which the growing trays and the hydroponic system are located, are modern steel shelving (shown in Figure 46 Vertical Farm modern racks). To keep a logical structure with enough strength to hold up all the trays, existing vertical farm methods of distributing racks have been investigated and an assumption has been made based on these observations. These racks can be the width of the production areas, thus 3m wide. The length of 34 meters however, is too long for one rack, considering the forces that would act on the middle of this long shelf. In most existing vertical farms a series of racks next to each other is used, to ensure enough strength to hold up the growing system, in which every rack is about a 4 to 3 or 1 to 1 ratio in length to width, resulting in a chosen length of 4m per rack in

Figure 46 Vertical Farm modern racks (Universiteit Leiden, 2018)

this vertical farm. This results in a total of: 34/4 = 8 racks per production area (with extra space for the water pipes and other wiring and installations) , thus a total of 8*6+5 = 53 racks per floor (of second growing stage) and a total of 417 racks in the whole building (for all stages combined. With a weight of 50kg per rack, this calculates to a total weight of 20.850 kg

The life expectancy of these structural racks is related to the indoor conditions and weight (overloading). As the racks are fully steel (and coated) they will not be affected by the constant humidity. Also the racks are designed for a constant weight of the crops and the systems which does not vary greatly, thus overloading will not happen. Therefore the racks life expectancy is set at 60 years. (Nadal, 2014)

Seeds

One of the general inputs for lettuce cultivation is the seeds that will grow to the desired lettuce. It is decided to use naked, shell-less and untreated seeds, as this is said to decrease intruding diseases or deformations. (Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016) The seeds are in linear relation with the eventual crop yield, thus 1.192.320 seeds are needed, in optimal conditions and no seeds are non-germinating, for one full harvest of the vertical farm (48 days), which calculates to 24.840 seeds per day. It is assumed that every seed will grow into a crop of lettuce, as the low percentage of seeds non-germinating (depending on age, storage and climate) does not impact the life cycle analysis significantly. (Rhoades, 2020) The weight of a lettuce seed is roughly 1*10^-6 kg or more clearly stated as 1000 seeds per 1 gram. (Hazera, n.d.)

Cultivation structure

The cultivation structure consists of all panels and mats in which the crops are situated, located inside the racks. The following text is extracted and summarized from (Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016).

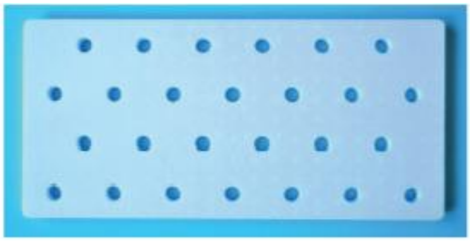

Figure 47 Urethane mat holding crops (Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016)

"Prepare a sponge-like or foamed urethane seeding mat (28*58*2.8 cm) consisting of 300 cubes or cuboids (2.3*2.3*2.8 cm) each with a small hole (7–10 mm in diameter, 5–10 mm in depth) on the upper surface of the cube. Each cube can be separated easily by hand from the mat. This calculates 4.25*10^-3 m3 of urethane per mat and with one mat per 300 seeds (plants) this calculates to 1.42*10^-5 m3 urethane per plant.

Prepare a foamed plastic tray (outside dimensions: 30*60*4.0 cm) to hold the mat. Which calculated to 2.65*10^-3 m3 polystyrene, with 300 seeds (plants) this calculated to 8.84*10^-6 m3 polystyrene per plant

Cover the mat surface with thin plastic film (0.02 mm thick) to keep its surface always moist during the germination stage. Calculates to 1.2*10^-8 m3 of plastic per plant

Thin plastic plate to apply pressure (0.5 to 1mm). Calculates to 1.8*10^-3 m3 per tray, which calculates to 6*10^-6 m3 per plant

The seedlings start growing quickly 10–12 days after seeding. The seedlings 14–16 days after seeding are suitable for the first transplanting to a culture panel (30*60*1.4 cm) having 24–30 holes, shown in Figure 47 Urethane mat holding crops . These panels have the same characteristics as they use the same format of urethane hard board with a soft foam mat inside of it (which is reused from the previous stage). Which calculates to 2.34*10^-3 m3 urethane per panel, which calculates to 9.01*10^-5 m3 urethane per plant.

The second transplanting is conducted using a culture panel (formed, foamed urethane board) with 6–8 holes. Formed culture panel first transplant (relatively hard board) with 6 holes (2.2 cm in diameter) for the first transplanting (29.8 cm wide, 59.6 cm long, 1.4 cm thick). Again this uses the same material and dimensions, just different sets of holes and different amount of plants. This calculates to 2.48*10^-3 m3 urethane per panel, or 4.13*10^-4 m3 urethane per plant.

The life expectancy of urethane is 25 year in a high use system while not experiencing frigid temperatures. (Polyurethanes, n.d.), the life expectancy of polystyrene (several hundreds to thousands of years) is very high and surpasses the life expectancy of the building, as well as the hard plastics used in the process. (Bio-tech, n.d.). The cultivation trays and mats can be reused in the vertical farm as long as their life expectancy in high use systems.

Hydroponic System

Gutters & pipes

The gutters span across the length of the production area, where they are split up in two sections to decrease the distance from the full 34m to 17m, in order to create a well distributed nutrition flow between the plants, especially for the 'plants which roots are downstream in the trough' (van Os, Gieling, & Lieth, 2019). Following the panels width of 30cm the gutters will be 25 cm wide. As there are 10 trays wide in the 3 m width of the rack, there will be 12 gutters of 25cm wide and 17m long. The gutters have of a dept of 0.1 m, thus creating shallow gutters (Stephanie & Rakesh, 2016) in which an ideal flow rate between 3 and 8 L/m^2/h is possible (van Os, Gieling, & Lieth, 2019). The material is often polyethylene liner, polyvinyl chloride (PVC), polypropylene, and coated metal (van Os, Gieling, & Lieth, 2019; Stephanie & Rakesh, 2016; Touliatos, Dodd, & McAinsh, 2016), in this instance plastic is used (PVC). "Compared to some metal gutters, plastic does not easily lose its shape when it bows and PVC gutters are less costly and more convenient to install than metal guttering systems." (JTC Roofing Contractors LTD, n.d.) The thickness of typical smaller PVC elements is 3 mm and increasing as the pipe gets larger. (PVCFittings, 2016) Therefore a thickness of 8mm is chosen. For water pipes supplying the water from the tank to the gutters, an assumption has been made based on the floor plan designed, resulting in a PVC use of 11m^3. The lay-out of the water distribution system is shown in Figure 48 Simplified lay-out of the hydroponic system (one of the six floors of the maturing stage). In this floor plan the water pipes bring water to all the first racks (the start of the

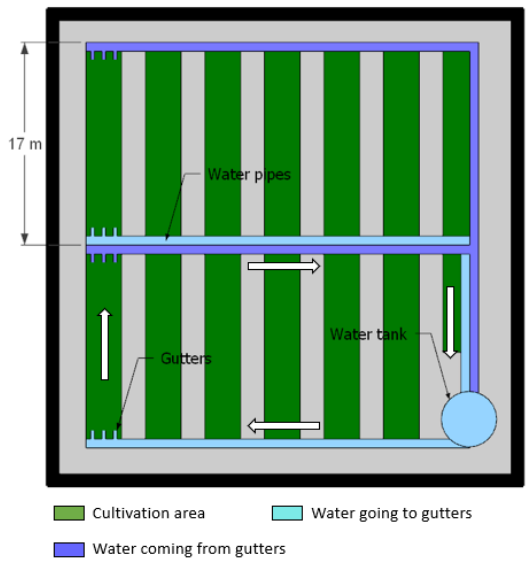

Figure 48 Simplified lay-out of the hydroponic system

gutter) and water is transported over half the length (17m) and recirculated into the tank.

This calculates to a PVC usage one gutter of (0.25*17*0.008+2*0.1*17*0.008) = 0.0612 m3 PVC, extrapolating this is a total PVC use for one floor: 58,8 m3 PVC and for the whole production area of cultivation, nurseries and seeding: 470 m3 PVC. For the water pipes an estimation has been made based on the floor plan as well as the hydroponics system, location and water amount, resulting in an estimated guess of 11 m3 of PVC for water pipes on one floor resulting in a total of about 100m3 PVC water pipes running into the hydroponic system.

PVC in gutters and other shapes which have a relatively thin wall can be recycled roughly seven times and has a lifespan of around 140 years. (Bellussi, et al., 2011)

Pump

With a NFT system, a constant flow of recycled water 24/7 is required. The water depth is shallow, only a few millimeters (¼ inch or so). So there is no need for a large volume of water to be pumped through it. Typically NFT systems are constructed using long tubes that are angled so the water flows downhill as it flows through the tube. The angle of the tube will control the water depth, as well as the speed in which the water flows through it (not the pump). The pump just needs to be able to keep up with how fast the water is flowing out of the tubes. (Home Hydro Systems, n.d.)

Figure 49 Water pump 1HP example (Kirloskar, 2020)

With the use of flow equations it is calculated that every module contains 34 L per tube if it is filled completely at the right depth. With the slope this calculates to recirculating of water every 5 minutes, this calculates to 345 L/h per gutter or 3450 L/h per one level of one production area. Using for example a 1 HP water circulation pump, able to circulate 2400-6000 L/h with a usage of 1.3kW and extrapolating this data over the production areas and floors, will result in a total electricity use for the circulation of the hydroponic system of 1.3*8*6.75*6 = 421.2 kW, which calculates to 10109 kWh/day for the entire building. (Passiontech, n.d.)

Due to the loss of water as crops are harvested (retained water in the lettuce), the hydroponic system has to be refilled now and again. The best way of calculating this figure without to much complexity, the end harvest is used as the amount of water that leaves the system. With this the water loss a day is taken as a linear relationship, which in reality it is not. The fresh weight of the lettuce is 350g and the dry weight is 30g, which calculates to a water storage of 320g. With the harvest of 24.800 lettuce a day, this would result in a 24.800*(320/1000) = 7.936 L water loss a day from the system. This results in a refilling rate of 331 L/h, which a simple pump of 10 W can handle. Resulting in a total electricity use of 0.24 kWh /day.

The pump’s life expectancy depends on the active duty time and the quality of the pump as well as the sediment amount. In the case of this hydroponics there is no sediment to wear it down, however the active duty time is 24 hours a day, which takes a toll on the machine. It is expected to be replaced every 10 years. (A-1, 2017; Nelson, 2018; InspectAPedia, 2009)

Air compressor

Usually the water flowing through a hydroponic system will be deprived of oxygen over time. In household and small scale hydroponic systems this is counteracted using small compressors or pump (called 'air stones') which aerate the water back to its original state. In larger systems, air compressors are used on a large scale. These compressors however, have not been an interest in research and have not been specified in any of the vertical farm sources used in this study. Because the apparent insignificance of the air compressors in other analysis results and my very limited knowledge of air compressors, it is excluded from this study.

Tanks

"For a fully grown lettuce (last growing stage), the transpiration rate is 3 liter per m^2 per day, and a water buffer of 27 liter per m^2 per day was assumed. For a 5.000 m^2 cultivation area, this amounts to 150 m3 per day or 30 liter per m^2 per day for each lettuce module. The distributed nutrient solution tanks are 75m3 (75.000 liter) per module." (Zeidler, Schubert, & Vrakking, 2017) Using the reasoning behind this set-up, with the total production area of 5520 m^2 per floor for the vertical farm in this study, this calculates to 165.600 L per floor or 993.000L in total for the upper 6 stories containing only the last growing stage.

For the nurseries and germination containing all seedlings and seeds a water demand of 22.5L per m^2 including the water buffer, deducted from (Both, 2014; Zeidler, Schubert, & Vrakking, 2017). This calculates to 108.000L per floor. For the lower two floors. A total water demand is needed of 1.206.000 L/day or 1206 m3/day for the whole farm. With a closed system this water demand is within the vertical farm itself, though to start the whole process there is a need of an initial water input, filling the water tanks with a total of 1.206.000 L.

There are the main nutrient tanks which can be buried in the soil or above g round. These tanks can be between 2,500 L and 500,000 L. The main nutrient tank can either be positioned above soil or below soil. They can also be positioned above the hydroponic system or below. (Antonius, 2013) It is a possibility to create a tank per story with a size of 166 m3 (this will also not overload the structure as tanks with 500,000 L would be a significant weight on the structure.

These 6 tanks, if 6 meters in height, will have a diameter of about 6 meter. Tanks of this size (GT170) often have a thickness of 1.2mm. (Joshua, 2019) The 6 tanks with these dimensions calculate into 0.2 m3 of steel per tank, or 1.6 m3 steel for the total building. Somewhat comparable to the tank in Figure 50 6m high 200m3 water tank example , though a smaller diameter.

An assumed life-span of 50 years for each tank type was determined through documents of interviews with industry contacts and publicly available information. (Everhart, 2010)

Figure 50 6m high 200m3 water tank example (Vertical Steel Tank Vol. 200CBM (AST-200), 2020)

Solution

The composition of nutrients in the fertilizer mix is based on fertilizer data from the Ecoinvent v3.6 database. (Ecoinvent, 2019) This results in a mix of nitrogen (N), phosphorus (P) and potassium (K) (respectively 29%N, 33% P, 38%K). In addition, it was assumed that there were no fertilizer emissions to the environment due to the closed loop system. With the use of the study of (Kikuchi, Kanematsu, Yoshikawa, Okubo, & Takagaki, 2018) a mass can be estimated on the fertilizer nutrient solution. With the figure of a total of 0.3 kg of nutrients per 1kg of dry lettuce, a distribution can be made of 87g Nitrogen, 99g Phosphorus and 114g Potassium per 1kg of dry lettuce

Lighting System

General

Plants are cultivated using lighting provided by 2m by 3m 170W LED Grow Lamps spaced 350mm apart and 250mm above the NFT channels trays. (Philips, 2019) Which calculates to approximately 140 W/m^2, comparable to similar studies (Hallikainen, 2019; Graamans, Baeza, Stanghellini, Tsafaras, & van den Dobbelsteen, 2018) These lamps are used for both the nursery stage as the second growing phase, having different PPFD outputs.

Lighting

Lettuce plants are spaced 166mm apart. This equates to 36 lettuce heads per square meter using 62.5 Watt per lettuce per day. (Lomax, 2017). For the second growing cycle this calculates to 5 lamps of 2 m length in the 3 m wide racks, creating a 6 m^2 space where 5 lamps illuminate 6*36 = 216 plants. Extrapolating this figure with the production area gives: 33120/6*5 = 27600 lamps. the grow lamps run for 16 hours each day and produce on average a PPFD = 250 and a Lux = 15 500 measured at the top surface of the channel. (Lomax, 2017)

For nurseries seedlings are close together (26*6) = 156 seedlings per square meter using 14.5 Watt per seedling per day. The same racks and dimensions are used as the second growing phase. Where 5 lamps illuminate 6*156 = 936 seedlings, resulting in 9600/6*5 = 8000 lamps. In this case the grow lamps run for 16 hours each day and produce on average a PPFD = 200 to 225.

For germination 150 W lamps emitting 150 PPFD are used in the 81 m^2 production area. With the same lamp layout as before using 2 meter lamps, a total of 60 lamps is used in one layer of this production area. One layer of production area is equal to 1.192.320/ = 149.040 seeds. Resulting in a value of 1 lamp per 2.484 seeds. With 8 stacked layers this will result in a use of 60*8 = 480 lamps

The total amount of growing lamp modules used in the buildings is 36080 lamps. The total growing light power consumption: ((27.600+8.000)*170 +480*150)/1.000 = 6.124 kW per hour or 6.124*16 (active hours per day) = 97.984 kWh/day

The life expectancy of grow lights or any lights of sorts are given in the unit of lighting hours. It is stated that “When operated at appropriate temperatures, i.e. that well below the maximum operating temperature LEDs can last for up to 60,000 hours. This is greatly reduced when LEDs operate at higher temperatures because of ambient temperature or being driven with higher currents”. (Blakey, 2018) Horticultural led lights exposed to high temperatures usually have a life expectancy of over 25000 hours. (van der Zwart, 2018) When operating under 25 degrees Celsius ambient temperature, LED operating temperature is around 35 to 45 degrees Celsius. (LEDTronics, 2000).

Thus, even though the HVAC system controls the airflow and temperature to stay at 23 degrees Celsius, LEDs are close together and create a warmer ambient temperature around the grow lamps, resulting in a decision of a life expectancy of 40.000 hours which with 16 hours a day calculates to a life expectancy of 6.8 years

Light racks

With lights of 2m by 20cm spaced apart every 35cm, light racks are needed with roughly the same dimensions spanning over the whole length of the cultivation areas. The light racks are estimated to be 0.001m3 per m^2 cultivation area with these dimensions, resulting in 43.54 m3 of steel in total. The light racks, like the warehouse racks, are objects made fully from steel. This ensures a very long life expectancy, usually based on the bearing load and local conditions. As mentioned at the warehouse racks, both the load and local conditions are constant and the racks have been dimensioned to withstand the forces and humidity. The life expectancy of the light racks is set to 50 years (the buildings life expectancy).

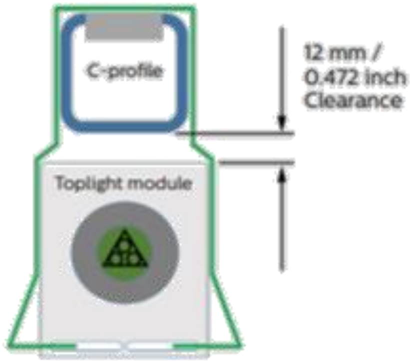

Figure 51 Lighting module on a section of the lightrack (steel C-profiles) (Philips, 2019)

Climate Control

To tie everything together the climate control uses fans, cooling and heating to keep conditions optimal by countering the output of the other systems and the plants. The heat from the lighting system is cooled, the humidity from the evaporation of water from the gutters and plants is lowered by dehumidifying and the CO_2 and O_2 from the plants is regulated by the fans. “The desired conditions inside the lettuce production area are 23°C and 80 % relative humidity (RH) (Jasper den Besten, HAS university). Often in studies, the climate control is calculated as a whole, though some sources separate it into a ventilation and a cooling + heating component.

Ventilation

For ventilation the Plant Factory book is consulted. With their setup using "a small air circulation fan (electricity consumption: 6 W, air flow rate: 2.9 m3/min) is installed for each plug tray, or four fans for four plug trays. With this arrangement, relatively laminar horizontal air current is generated over the plug trays and through the transplant canopy in each shelf. By using fans with an inverter for controlling the fan rotation speed, the air current speed over the transplant canopy is continuously controlled in a range between 20 cm/s and 100 cm/s, depending on the transplant growth stage, planting density, transplant morphology, etc. The horizontal air current within the transplant canopy with a height of about 10–15 cm keeps the relative humidity in the transplant canopy lower than 85%, and hence elongation of hypocotyl (stem) can be avoided even at a planting density of 1.5–2.0 times that in a greenhouse." (Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016) These design choices are based on ideal ranges for VPD (Vapour pressure deficit 0.8 - 0.95) CO_2 concentration (500-2000ppm) and air speed (0.2 - 1m/s) (Niu, Kozai, & Sabeh, 2015) If this setup is adapted for the growing area of this report and extrapolated over all plant production areas (germination, nurseries and second grow stage) a total of 6989 kWh/day is used for the ventilation of the growing facility to keep the climate conditions ideal. The method used for the duct system for maintaining the flow of air to and from the HVAC system, is shown in Figure 52. This system creates a uniform flow of air at the right speed over the canopy of the crops, to ensure a proper CO_2 level.

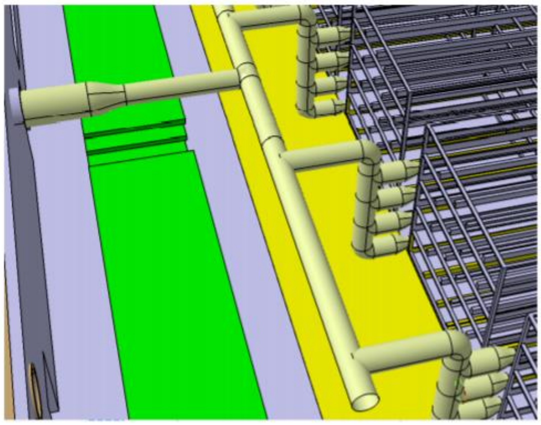

Figure 52 Special duct system (Zeidler, Schubert, & Vrakking, 2017)

Humidity

With the use of a lighting system for optimal growth, temperature increases rapidly, therefore heavy cooling is needed in a vertical farm, usually by means of air conditioning in a HVAC system. It is assumed that most of the evapotranspiration of the plants occurs during lighting hours." (Zeidler, Schubert, & Vrakking, 2017) The photoperiod of these chosen lights are 16 hours and evapotranspiration was only considered for the photoperiod of 16 hours. The maximum evapotranspiration is the maximum uptake of water, thus 3L per m^2 per 16 hours. This calculates to a water vapor addition to the air of $167g/m^2$.

HVAC

With the lack of insight to a model that calculates energy balances in a vertical farm (Graamans, van den Dobbelsteen, Meinen, & Stanghellini, 2017), it is decided to use research papers and journal articles (which have used an extensive model) to estimate the climate control elements in this fictive vertical farm. However, the energy balance and the way HVAC interacts with it is delicate and there is a large uncertainty in these estimations. This is due to the extra effects of changing the size of a cultivation area, as used sources have a relatively small vertical farming area compared to this fictive vertical farming tower. The most comparable set-up is from (Zeidler, Schubert, & Vrakking, 2017), using a production area as large as a single floor of the fictive vertical farm. As the power consumption of climate control is dependent on the local external climate, climate details about the studies are also given.

- Extrapolating and dimensioning the study of (Graamans, Baeza, van den Dobbelsteen, Tsafaras, & Stanghellini, 2018), located in The Netherlands, yields a power consumption of 20.846 kWh/day. This location has a temperate maritime climate (cool summers, moderate winters, quite humid). Thus, less energy consumption compared to Oklahoma due to less cooling during summers. No heating with moderate winters.

- Also from this study, located in the United Arabic Emirates, yields a power consumption of 34.743 kWh/day. This location has a desert climate (mild winters, very hot sunny summers + extreme humidity). Thus, more energy consumption compared to Oklahoma due to extreme active cooling. No heating, only constant cooling.

- Also from this study, located in Sweden, yields a power consumption of 15.897 kWh/day. This location has a dry continental/subarctic climate (cold to moderate summers, cold winters, no dry season, quite humid) Thus, less energy consumption compared to Oklahoma due to less cooling during summers and winters. Heating is not required according to. (Graamans, Baeza, Stanghellini, Tsafaras, & van den Dobbelsteen, 2018)

- Extrapolating and dimensioning the study of (Kikuchi, Kanematsu, Yoshikawa, Okubo, & Takagaki, 2018), located in Chiba, Japan, yields a power consumption of 16.114 kWh/day. This location has a warm oceanic/humid subtropical climate (warm humid summers, mild winters, humid). Thus, almost the same climate as Oklahoma, though a bit more humid. The energy consumption will be roughly the same.

- Extrapolating and dimensioning the study of (Zeidler, Schubert, & Vrakking, 2017), with refence climate of Germany, yields a power consumption of 13.295 kWh/day. This location has a temperate seasonal climate (moderate to warm summers, mild winters, moderately humid). Thus, less energy consumption compared to Oklahoma due to less cooling during summers. No heating with moderate winters.

- Extrapolating and dimensioning the study of (Lalonde, Talbot, & Monfet, 2019), located in Montreal, Canada, yields a power consumption of 21.476 kWh/day. This location has a semi-continental climate (warm humid summers, very cold winters). Thus, more energy consumption compared to Oklahoma due to cooling during summer and increased heating in the cold winters.

Taking into account the power consumptions and climates above, as well as the different set-ups of these vertical farms, indoor cultivation buildings and plant factories (such as different parameters for the machines, different systems and size), it has been chosen to use a power consumption of 18.000 kWh/day for the total HVAC/Climate Control system.

To somewhat ensure the correctness of the estimation, the book of (Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016) is called upon, as well as the paper of (Ohyama, et al., 2002), for a check in power consumption. It is stated that "Climate control accounts for approximately 20% of all energy consumption in PFAL" (Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016) and it is stated from a case study that "most (72-86%) of the electric energy was consumed by lamps. The rest was consumed by air conditioners (7-17%) and other equipment (5-15%)." (Ohyama, et al., 2002) With the lighting and hydroponic power consumption calculated it can be estimated that the climate control, with approximately 15%, should have a power consumption of (97984+10109+75)/80*15 = 20.282 kWh/day according to, according to (Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016). According to (Ohyama, et al., 2002) this figure should be between: (97984/72)*17 = 23.135 kWh/day and (97984/86)*7 = 7.975 kWh/day. The checks show that the chosen power consumption for a Climate Control system is indeed a representative value.

In this HVAC, ventilation is 6.979/18.000 = 39% of the total energy consumption, cooling will take approximately 50%, dehumidification (even though integrated in the others) approximately 10% and 1% for reheating air. This complies with the statistics given in (Kozai, Niu, & Takagaki, Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2016)

HVAC systems as a whole are often not fully replaced. Because they contain a lot of different parts which break on different moments. As it is (almost) always on and handles very humid and warm air, its life expectancy is lower than that of standard HVAC systems for commercial buildings. Every part of the HVAC is given a life expectancy by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, in which the AC is set at 15 years, the heaters at 20 years, the ventilation at 15 years and the dehumidification unit at 20.

Ducts

The air coming from or towards any of the elements of the HVAC needs to be distributed around the vertical farm. Just like any other HVAC system in commercial buildings a lay-out of air ducts is used, which are galvanized steel tubes. It has been estimated that the vertical farm uses a total amount of 2056 tons of steel for the duct system.

Figure 53 Standard steel ductwork (Superior Air Duct, 2019)

A ventilation duct system from steel elements usually has a life expectancy of 10 - 100 years, leaning towards 20 - 40 years, as it is quite variable among sources. (CLF, 2018; BH Home; True Professionals, 2017; ASHRAE, 2015) As this duct system is in constant use, by means of transporting air from and to the HVAC system, it is expected to have a life expectancy of 20 years.

CO_2 supply

In order for the lettuce to grow they need significant amounts of CO_2. In rural agriculture this is dependent on the CO_2 in the air, however in this automatized farm, it can be supplied in the right amount. According to many of the sources used before, a CO_2 level of 1000 parts per million (ppm) is ideal for lettuce to grow. (Kozai, Smart Plant Factory, 2018; Kikuchi, Kanematsu, Yoshikawa, Okubo, & Takagaki, 2018; Zeidler, Schubert, & Vrakking, 2017) To assure this constant, a supply of CO_2 has to be added to the air every now and again. From (Graamans, Baeza, Stanghellini, Tsafaras, & van den Dobbelsteen, 2018), (Zeidler, Schubert, & Vrakking, 2017) and (Kikuchi, Kanematsu, Yoshikawa, Okubo, & Takagaki, 2018) can be deducted that the average CO_2 supply in a vertical farm should be in range of 2 – 3 kg CO_2 per 1 kilogram dry weight lettuce. In this vertical farm because of the high density plants an average CO_2 supply in the vertical farm of 3 kg CO_2 per kg dry weight lettuce has been chosen.

Monitoring

To create a healthy growing environment, temperature, relative humidity (RH) and CO_2 have to be carefully controlled. For optimum control, a climate controller located in the core of each module is installed to measure temperature, RH and CO_2 sensors. Environmental conditions are constantly monitored and are electronically maintained. (Zeidler, Schubert, & Vrakking, 2017)

Using the Priva E-measuring boxes, with one on every floor measuring the climate, this results in a total of 8 Priva measuring boxes. These boxes weight approximately 3kg with a peak power of 300W/h (Zeidler, Schubert, & Vrakking, 2017; Priva, n.d.). Thus a total of 8*3 = 24kg and 8*24* 300/1000 = 57.6 kWh/day.

Connected to this Priva box is a climate computer, controlling the environment, having a total peak power of 500 W/h or 12 kWh/day.

A standard workstation computer uses a peak electrical consumption of 300 to 400 W/h, depending on its inner components. The screens or monitors of these pc's have a power consumption of 25 to 45 W/h. These values are derived from the average over mulitple website sources. (Fisher, 2018; iswitch, n.d.; Windows, n.d.; Strong, n.d.). Resulting in a total electricity use of 5 kWh/day.

The monitoring system has a total electricity use of 74.6 kWh/day.

D. Life Cycle Modelling additional data

This appendix shows all recycle rates of materials and system components, as well as the production locations and distances for travel.

D.1. Building Structure

Recycle rates

Foundation

Due to the nature of ground treatment and ground retention products, most ground products are not suited to removal and reuse in a new location, as the original design would be based on ground conditions and it is not likely that identical conditions will exist on another site. However, if new foundations are needed, it may be possible to use materials with a recycled content, for example, concrete made with aggregate substitutes or cement replacement materials. Though this is often not used in pile foundations. (Addis, 2006)

Structure

The value of reusing structural components from another building can be environmental, such as using less primary resources and reducing impacts from manufacturing processes and transport. It may also be commercial – the cost of second-hand (reclaimed) structural timber can be less than the new equivalent. (Addis, 2006) At present it is likely that only precast concrete building elements might be salvaged and reused. In recent years in The Netherlands, for example, a number of industrialized building systems have been developed with the intention that they should be able to be dismantled and re-erected elsewhere. This technique is called circular economy building. (Addis, 2006)

Steel (roof and ceiling)

There are strong environmental reasons for reusing steel sections: by reusing a steel beam there is a twin saving of energy – the energy needed to melt the steel in the recycling process and the energy expended in making the new steel beam that would otherwise be needed. In principle all rolled-steel sections and elements of roof structures can be reused. It can be mixed (between 25 and 50 per cent) with virgin steel to make 'new' steel. (Addis, 2006)

Inner walls

Wood that has been pressure treated, painted, varnished or otherwise finished is not a good candidate for recycling. As discussed previously, the main uses for recycled wood are compost and garden amendments like mulch. Many people who claim to recycle wood burn it for heat or energy. (RecycleNation, 2014)

Transport

Even though Oklahoma has concrete distributers, the production of concrete materials is expected to come from one of the larger concrete production plants. One of which is located in Houston, Texas. It will be assumed that all structural elements are originating from this location. This location is approximately 700 km away.

D.2. Vertical Farming Structure

Cultivation area structure

Recycle rates

Warehouse shelving consists of pure steel. Steel is the most recycled material on the planet, more than all other materials combined. Depending on the steel the recycle rate can vary, though the steel used in these racks retain an extremely high overall recycling rate, which in 2014, stood at 86 percent. Therefore, this value is used in steel racks / warehouse shelving (SRI, 2019)

The cultivation beds are urethane. Shredder treatment technology and the further refinement by companies such as Salyp or Sicon, and new post shredder technologies have shown the cost and limits of achieving the 85 % R&D quota of urethane. (AISBL, 2016)

Polyethylene a common plastic has a recycle rate that is in accordance with PET plastic which has a recycle rate of 30%. (EPA, 2017; Perugini, Mastellone, & Arena, 2004) A different common plastic, polystyrene is believed to have a recycle rate of 12% (Kelly, n.d.)

Transport

Steel racks or warehouse shelving is made in Dallas Texas. Which is approximately 350km away. (SEC, 2020)

Hydroponic system

Recycle rates

Pumps are highly suitable for reuse. Reconditioned pumps are available, and engineering companies specializing in pump refurbishment will normally provide a warranty. (Addis, 2006) Usually parts are replaced within the pump and therefore a recycle rate of 80% has been chosen to represent this action.

The gutters and water pipes are made from PVC. For a long time this material has not been recycled due to small recycle rate compared to high costs. However, with a new vision of reusing old material and decreasing pressure on resource extraction, pvc can be recycled with a rate of 9%. (VinylPlus, Recovinyl, EUCertPlast, 2015; Brown, et al., 2000)

Thus, the combined recycled content is as follows: Post-consumer recycled content – hot-dip galvanized steel Pre-consumer recycled content – hot-dip galvanized steel (1.8 x 14.6%) + (98.2 x 56.9%) = 56.1% (1.8 x 15.6%) + (98.2 x 31.4%) = 31.1% 31.1% / 2 = 15.6% With more than 70% (56.1% + 15.6%) recycled content value (71.7%). Thus the recycle rate of galvanized steel is 71.7%. (AGA, 2011)

Transport

The location of production of hydroponic systems is located in Surna (Colorado, Boulder), which is a designer and installer of indoor cultivation equipment. Products include climate control systems, automated environmental monitoring systems, air pollution control equipment, greenhouses, grow lighting fixtures and spare parts. Additional services include consulting, engineering, biosecurity, odor control and installation support. This city is located approximately 1100km away from Oklahoma City. (Surna, 2020)

The pipes and gutters placed around the vertical farm to supply water to the cultivation beds are produced in Ottowa, Kansas, which is located approximately 500km away. (US pipe, 2020)

Lighting system

Recycle rates

LEDs are environmentally friendly during their lifespan, but can be even more beneficial to the environment if recycled. Over 95% of an LED bulb is recyclable and there are waste management companies that will collect and recycle LEDs for a small fee. (Thoman, 2012)

The lightracks used are pure steel like the warehouse racks, these are recyclable by 86%.

Transport

These specialized growing lamps (with lightrack) are made in Philips factories, of which the closest is in Phoenix, Arizona, which calculates to an approximate 1580km distance.

HVAC system

Recycle rates

Plant used for heating, ventilation and air-conditioning (HVAC) has the greatest potential for reuse. Even in the absence of recycling legislation, HVAC equipment is probably reused more than any other type of building service. All heating and cooling systems are suitable for reuse in situ if placed in a building with the same demand load. Replacing worn out or faulty elements of this system and placing it back is a likely possibility. (Addis, 2006) All elements of a HVAC can be replaced, which are chosen to be represented by "recycle rates" of 80%.

Modern central AC units should never need a recharge (replacement of cooling fluid) unless it has a leak. (HomeAdvisor, 2020)

The ventilation ducts are made out of pure galvanized steel which has a recycle rate of 71.7% as mentioned in the hydroponic system column of this appendix.

Transport

Both Trane and American Standard are manufactured in the same facility. Not only are both brands manufactured in the same facility (in Tyler, Texas), they go down the same assembly line. (Morgan, 2019). This facility is approximately 490km away from Oklahoma City. Ventilation ducts are made locally, resulting in a distance by truck of 10km

E. Model input quantities

With the use of recycle rates shown in the previous appendix, the LCIA list values can be updated to actual model input values. These values are created by using the formulas given below. In which the number of replacement rate affects the structure of the formula.

With replacement rate value 1:

$$Static\ Model\ quantity\ (n/kg) = (ASQ * r) \tag{5}$$

With replacement rate value 2:

$$Static\ Model\ quantity\ (n/kg) = (ASQ * r) * \left(1 + r^{(R_{replacement}-1)}\right) \tag{6}$$

With replacement rate value 3:

$$Static\ Model\ quantity\ (n/kg) = (ASQ * r) * \left(1 + r^{(R_{replacement}-1)} + r^{(R_{replacement}-2)}\right) \tag{7}$$

Etc.

In which the ASQ or Adapted Static Quantity is explained in Formula 2 (in the main text), $R_{replacement}$ is the replacement rate of the element (given in Table 11) and r is given in the following formula:

$$r = 1 - R_{recycle} \tag{8}$$

In which $R_{recycle}$ is the recycle rate of a certain material or component, shown in the table below.

The main formula is based on the assumption that the initial building material is also already a recycled material at the start of the vertical farm construction. The final model input values are given in the table below with the corresponding units.

Table 11 Extended life cycle analysis table with life expectancy, recycle rates and a model quantity (including recycling)

System components	**Material**	**Quantity**	**Unit**	**Life expectancy**	**Recycle rate**	**Model quantity**	**Unit**
	Building structure						
Roof	Steel sheets	1.60E-05	kg/kg	30	72%	5.79E-06	kg/kg
Ceiling	Steel bars	4.08E-04	kg/kg	60	86%	3.51E-04	kg/kg
Columns	Concrete	7.70E-04	kg/kg	60	0%	7.70E-04	kg/kg
Inner walls	Oak wood	8.04E-05	kg/kg	20	0%	8.04E-05	kg/kg
Outer walls	Concrete	9.57E-04	kg/kg	60	0%	9.57E-04	kg/kg
Floor	Concrete	3.07E-03	kg/kg	60	0%	3.07E-03	kg/kg
Foundation	Concrete	2.38E-03	kg/kg	60	0%	2.38E-03	kg/kg
	Vertical Farm System structure						
	Cultivation area structure						
Warehouse racks	Steel	2.66E-05	kg/kg	60	86%	3.73E-06	kg/kg
Plant seeds	Naked, shell-less untreated seeds	3.33E+01	seeds/kg	-	-	3.33E+01	seeds/kg
Mat (germ.)	Urethane	8.64E-06	kg/kg	25	85%	1.52E-06	kg/kg
Tray (germ.)	Polystyrene	6.05E-07	kg/kg	60	12%	5.33E-07	kg/kg
Film (germ.)	Polyethylene	8.21E-10	kg/kg	60	30%	5.75E-10	kg/kg
Plate (germ.)	Polyethylene	4.11E-07	kg/kg	60	30%	2.88E-07	kg/kg

Cultivation bed (nurseries)	Urethane	4.94E-06	kg/kg	25	85%	8.68E-07	kg/kg
Cultivation bed (maturing)	Urethane	2.26E-05	kg/kg	25	85%	3.98E-06	kg/kg
	Hydroponic System						
Gutters	Polyvinylchloride	7.80E-04	kg/kg	140	9%	7.10E-04	kg/kg
Water pipes	Polyvinylchloride	1.83E-05	kg/kg	140	9%	1.66E-05	kg/kg
Re-circulating pump	Metal machine	1.37E+01	kWh/kg	10	80%	1.37E+01	kWh/kg
Extraction pump	Metal machine	3.22E-04	kWh/kg	20	80%	3.22E-04	kWh/kg
Water tanks	Steel	1.64E-05	kg/kg	60	72%	4.65E-06	kg/kg
Nutrient supply	Initial water	1.54E-03	kg/kg	-	-	1.54E-03	kg/kg
	Water replenishment	1.06E-02	kg/kg	-	-	1.06E-02	kg/kg
	Nitrogen (nutrients)	8.70E-02	kg/kg	-	-	8.70E-02	kg/kg
	Phosphorus (nutrients)	9.90E-02	kg/kg	-	-	9.90E-02	kg/kg
	Potassium (nutrients)	1.14E-01	kg/kg	-	-	1.14E-01	kg/kg
	Lighting System						
Philips Spectrum Lamps	Lamp	1.31E+02	kWh/kg	6.8	95%	1.31E+02	kWh/kg
Light racks	Steel	4.47E-04	kg/kg	60	86%	6.26E-05	kg/kg
	HVAC System						
Ventilation	Metal machine	9.38E+00	kWh/kg	15	80%	9.38E+00	kWh/kg
Air conditioning	Metal machine	1.21E+01	kWh/kg	15	80%	1.21E+01	kWh/kg
Dehumidification	Metal machine	2.42E+00	kWh/kg	20	80%	2.42E+00	kWh/kg
Heating system	Metal machine	2.83E-01	kWh/kg	20	80%	2.83E-01	kWh/kg
CO_2 supply	CO_2	8.00E+00	kg/kg	-	-	8.00E+00	kg/kg
Ducts	Steel	2.62E-03	kg/kg	20	72%	1.01E-03	kg/kg
	Monitoring System						
Priva E-measuring box	Metal machine	7.73E-02	kWh/kg	-	-	7.73E-02	kWh/kg
Climate computer	Electronics	1.61E-02	kWh/kg	-	-	1.61E-02	kWh/kg
Workstation PC	Electronics	5.37E-03	kWh/kg	-	-	5.37E-03	kWh/kg
Screens	Electronics	1.34E-03	kWh/kg	-	-	1.34E-03	kWh/kg

F. Visual representation calculation model

F.1. Building structure

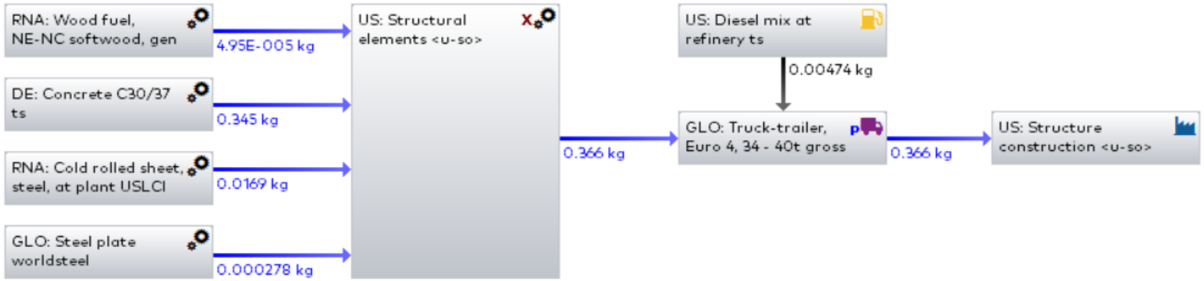

Figure 54 GaBi model of the building structure (per kg dry lettuce)

F.2. Hydroponic system

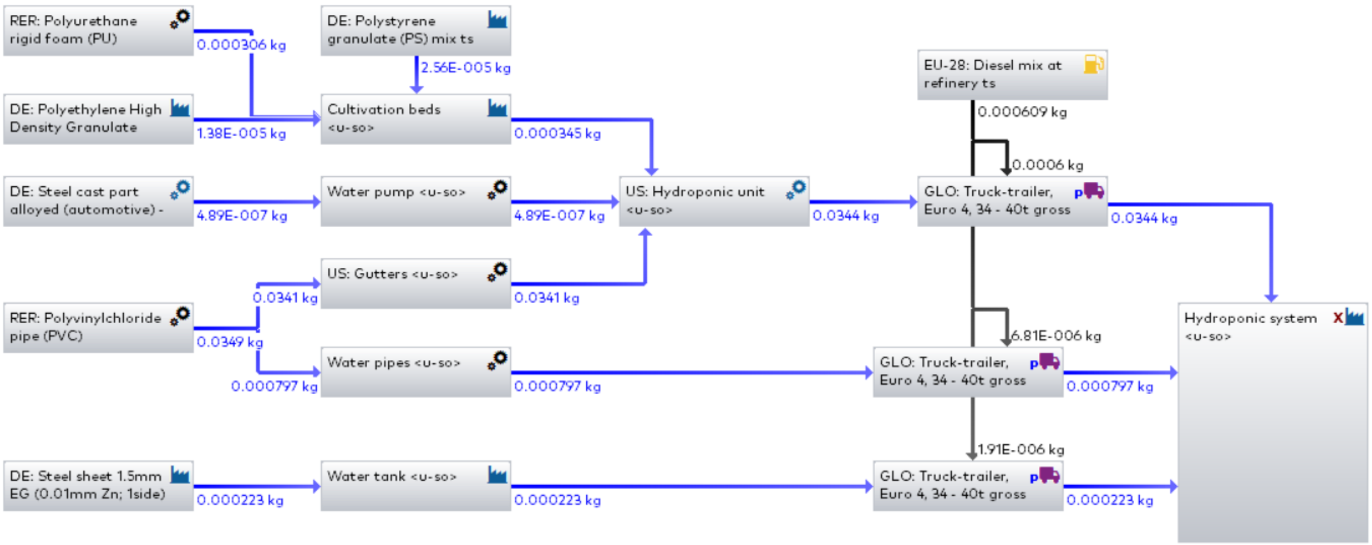

Figure 55 GaBi model of the hydroponic system (per kg dry lettuce)

F.3. Lighting system

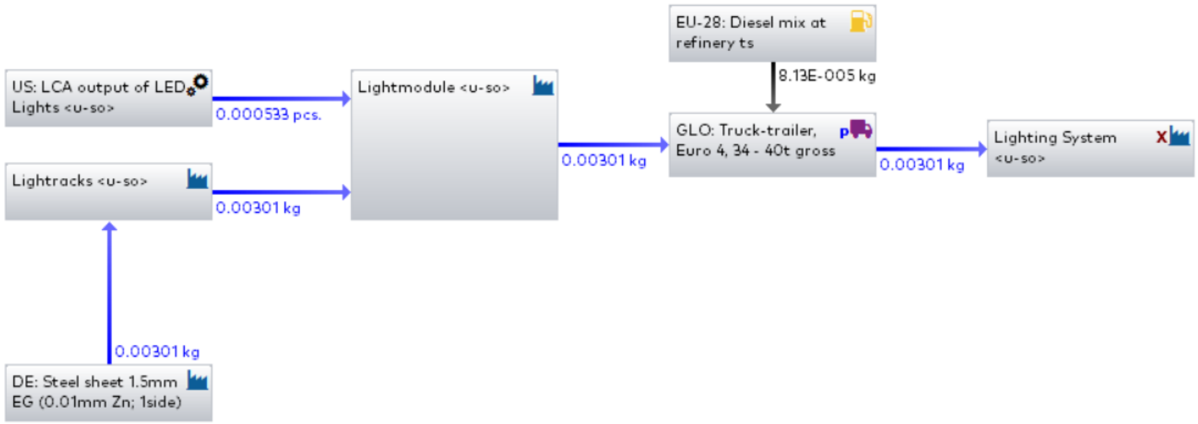

Figure 56 GaBi model of the lighting system (per kg dry lettuce)

F.4. HVAC system

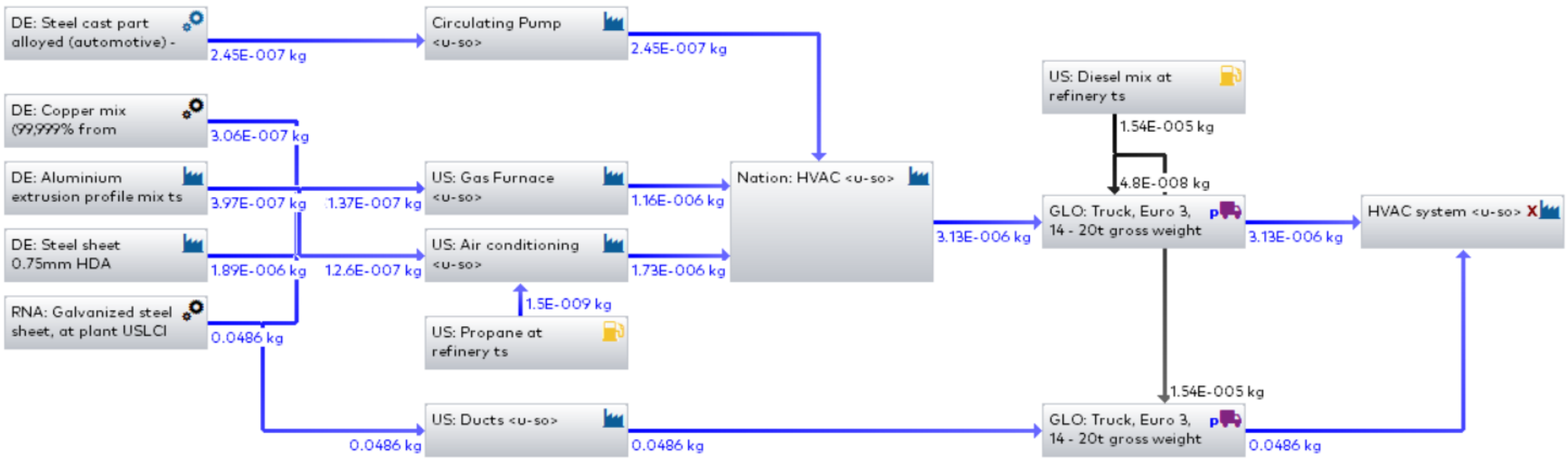

Figure 57 GaBi model of the HVAC system (per kg dry lettuce)

F.5. Cultivation area structure

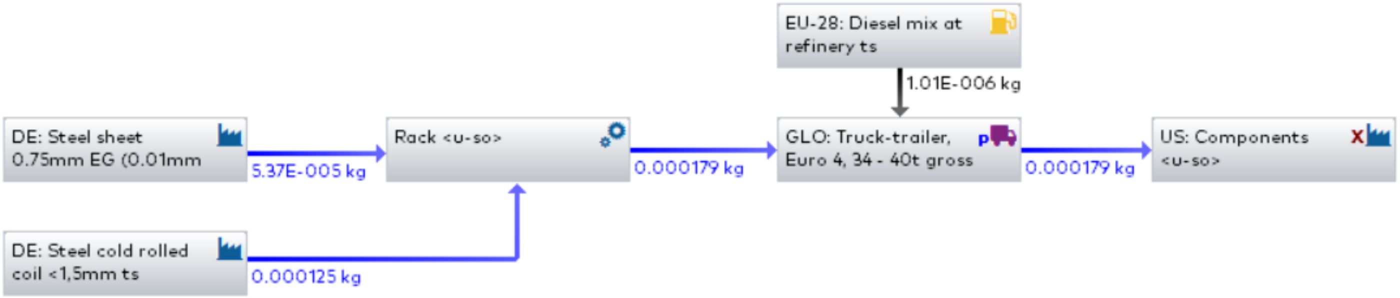

Figure 58 GaBi model of the cultivation area structure (per kg dry lettuce)

G. Sensitivity Analysis

In the results of the LCA it is clear that the most impactful phase on the environment is the Use phase. Within this phase the electricity use is, in most cases, the most impactful. Therefore, a sensitivity is set up to create scenarios with different electricity uses to view how the largest impact factor affects the model outcome when it is changed.

The vertical farm's electricity use is based on the electricity need of the systems combined. These electricity values are at the moment constant over time and could be changed to a time dependent value, however it is even more impactful to look at the provider of the electricity. The provider is often seen as just the general electricity grid network of the state or a state close by, which is usually electricity from natural gas or coal. Though changing this to for example electricity from nuclear, or renewables such as wind, solar, biomass, etc. could have a great impact on the results.

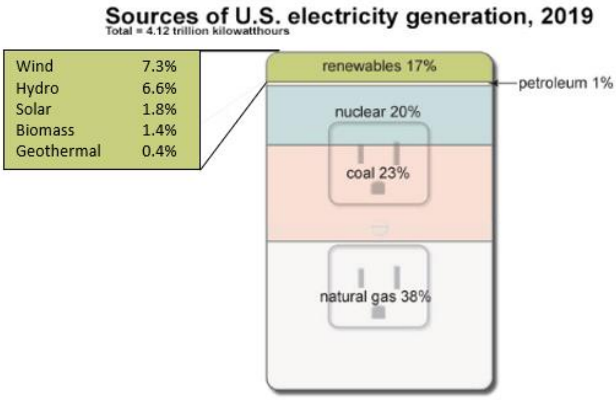

Figure 59 Sources of electricity generation (U.S.) (EIA, 2020)

For a long time (until 2015) the United Stated of America generated most of its electricity from coal. From 2015 onwards, coal electricity generation has significantly gone down and other electricity sources have made an uprising. One of which is natural gas which is currently the most used electricity generation resource, with about 38% of the electricity generation, shown in Figure 59 Sources of electricity generation (U.S.) . (EIA, 2020)

The current model is made using energy from natural gas, which resulted in quite odd results. Natural gas is not the most environmental way of creating energy, which will be shown in the results as well. In this sensitivity analysis, besides natural gas, coal, nuclear, wind, hydro and solar power are modelled as electricity generation sources and discussed shortly. With a recent increase in renewable energy in the US, together with the "recent developments in the field of renewable energy, like Photovoltaics, Solar-Thermovoltaics, Wind or even Pumped-storage Hydroelectricity, these are noteworthy opportunities." (Banerjee & Adenaeuer, 2013; EIA, 2020)

The six most influential energy generation methods in the U.S. are implemented in the model as different scenarios. The results of the scenarios of this sensitivity analysis are shown in the Table 12. The impact color indicator (low to high) is based on the impact in relation to the other values of the same impact category.

	Natural gas	Hard coal	Nuclear	Wind	Hydro	Solar	Unit
Climate change	98.790	187.320	2.200	2.500	2.630	7.490	*kg CO_2-eq.*
Terrestrial Acidification	0.133	0.414	0.008	0.006	0.004	0.023	*kg SO_2-eq.*
Freshwater Eutrophication	0.002	0.002	0.002	0.002	0.002	0.002	*kg P-eq.*
Water Footprint	0.257	0.372	0.381	0.011	3.846	0.054	*m3*
Land Footprint	5349.788	2983.609	1748.923	2402.485	1989.305	4747.620	*m3*

Table 12 The results of different electricity productions on the environmental impact of a vertical farm