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Assessment of Environmental Impacts of Vertical Farming by Utilisation of the Life Cycle Assessment Technique

By

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A report submitted in partial fulfilment of the requirements for the MSc and/or the DIC.

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Assessment of Environmental Impacts of Vertical Farming by Utilisation of the Life Cycle Assessment Technique

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Abstract

Current agricultural practices are unsustainable and are responsible for significant environmental problems worldwide including deforestation, eutrophication, biodiversity loss and soil degradation. At the same time, food production systems are under immense pressure to meet growing food demand. In response, vertical farming has been posed as an alternative food production method due to the perceived benefits of higher resource efficiency, no pesticide use, lower transportation distances and year-round production. However, criticism has grown regarding high energy consumption and limited suitable plants types.

Due to the emergent nature of the technology, limited studies exist which accurately quantify and evaluate the environmental impacts of such systems. The purpose of this research is to investigate these impacts of vertical farming and evaluate the sustainability of the method from this perspective by utilising a Life Cycle Assessment (LCA) technique. A cradle-to-gate attributional LCA on hydroponic lettuce production was completed based on real data from an experimental vertical farm in Italy. The environmental impacts were calculated for all impact categories of the midpoint ReCiPe methodology in the SimaPro LCA software.

Results confirmed literature is correct in that no pesticide and low water and nutrient use is a benefit of vertical farming, but at the cost of high electricity consumption predominantly due to lighting and artificial climate control. Electricity use was found to be the largest contributor to environmental impacts and was a hotspot in 14 impact categories. Substrate use was also found to be a major contributor to environmental impacts.

Conflicting impact categories make determining sustainability problematic. However, as a food system, vertical farming is not currently sustainable due to the factors noted above. Potential does exist for this to improve if optimisation and efficiencies improve through sophisticated design, individual equipment efficiency improvements and increasing availability of renewable energy, preferably onsite. This may require intervention through policy decisions.

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Table of contents

List of figures

Figure 12 Comparison of the environmental impacts of producing 1 kg of lettuce by using different substrate types – coconut coir and perlite mix as in the standard model (baseline), peat or rockwool. 56

List of tables

Abbreviations

CEA	Controlled Environment Agriculture
EC	Electrical Conductivity
EU	European Union
FAO	Food and Agriculture Organisation
FEco	Freshwater ecotoxicity
FEut	Freshwater eutrophication
FRS	Fossil resource scarcity
GDP	Gross Domestic Product
GW	Global warming
HCT	Human carcinogenic toxicity
HNT	Human non-carcinogenic toxicity
HVAC	Heating, Ventilation and Air Conditioning
IR	Ionizing radiation
ISO	International Organisation for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
LED	Light Emitting Diode
LU	Land use
ME	Marine eutrophication
MEco	Marine ecotoxicity
MRS	Mineral resource scarcity
NFT	Nutrient Film Technique
OF – HH	Ozone formation, Human health
OF – TE	Ozone formation, Terrestrial ecosystems
PMF	Fine particulate matter formation
SDG	Sustainable Development Goals

SOD	Stratospheric ozone depletion
TA	Terrestrial acidification
TE	Terrestrial ecotoxicity
UN	United Nations
WC	Water consumption

1. Introduction

1.1 Introduction to the thesis

Research has shown the population will exceed 9.7 billion by 2050 (UN, 2019b). Food demand is subsequently expected to increase by 70% (UN, 2019b). Agriculture is already responsible for some of the worst large-scale environmental problems worldwide including deforestation, eutrophication, biodiversity loss and soil degradation (Campbell et al., 2017). In order to meet growing demand, agricultural systems by 2050 will need to meet demand not only by increasing yields and cropping intensities but also by transforming an additional 70 million hectares of land to grow food (FAO, 2009). This figure rises to 120 million hectares when considering the expected arable land lost due to soil erosion and degradation (FAO, 2009). Subsequently, associated environmental impacts are expected to increase to the detriment of the planet's ecosystems. The question is, can the supply chain for human food production be increased to meet demand whilst also reducing associated environmental impacts? And how do we do it? In answer to these questions, vertical farming has been posed as an alternative food production method to meet growing demand that is also able to reduce the environmental issues associated with conventional farming practices (Al-Chalabi, 2015; Al-Kodmany, 2018; Despommier, 2009; Despommier, 2011).

1.2 Vertical farming – consensus and criticism

Vertical farming is to farm upwards on horizontally stacked growing racks in highly controlled environments, commonly in warehouses or shipping containers (Al-Chalabi, 2015; Al-Kodmany, 2018; Despommier, 2009; Despommier, 2011). The technique has several potential benefits which include the following:

- **Economic** benefits from investments into local economy and derelict areas as well as more consistent food pricing;
- **Social** benefits including increased **food security** due to higher yields, year-round production and less reliance on importing food, as well as increased access to fresh foods, especially in urban areas;
- Beneficial **environmental** impacts:

- Improvements to air and noise pollution due to reduced transportation distances;
- Higher resource efficiency of land, water, nutrients;
- Limited to no use of chemical pest controls;
- Less pollution from runoff and emissions of farm machinery (Al-Chalabi, 2015; Kozai, Niu & Takagaki, 2016; Marris, 2010; Pinstrup-Andersen, 2018).

Many of these benefits correspond to the interrelated Sustainable Development Goals developed by the UN (2019a) which has generated a lot of interest and investment into the emerging technology (Agrilyst, 2018). However, criticism has been growing and raised some important disadvantages of the technology:

- Economics benefits are dependent on companies succeeding when start-up capital and operating costs are far higher than conventional farmed produce (Banerjee & Adenaeuer, 2014);
- Limited plant types can be grown commercially in vertical farms, reducing the impact of improving access to fresh foods and food security;
- High energy consumption to grow produce in controlled environments using LED lighting increases environmental impacts (Barbosa et al., 2015; Graamans et al., 2017; Harbick & Albright, 2016; Kozai, Niu & Takagaki, 2016).

These advantages and disadvantages highlight how complex it can be to determine the ‘sustainability’ of vertical farming. Whilst it is important to address issues outlined above, this study will predominantly focus on the environmental impacts. There is a broad consensus on the topic; there is a trade-off between lower transportation distances, higher resource efficiency and no pesticide use with the higher energy consumption needed for vertical farming. However, there are limited studies that quantify and evaluate these impacts based on real data to see if the trade-off is beneficial and to establish if the technology should be encouraged further.

1.3 Research scope

This study will focus on the environmental impacts of vertical farming and evaluate the sustainability of the method from this perspective. A vertical farming company currently in a research and development phase prior to commercial launch will act as a case study for this research and provide data on growing food hydroponically in the laboratory. Although the set-up is experimental, the results should provide a good baseline of the environmental impacts and for which a comparison with different methods can be made.

This thesis will use the Life Cycle Assessment (LCA) technique to understand the impacts of producing lettuce at the laboratory. The LCA tool was used due its comprehensive nature and lifecycle approach (PRé, 2016). In this case, the LCA study will be a cradle-to-gate study as the company is not yet commercial. The LCA approach will allow for analysis of the most significant factors in vertical farming, such as energy consumption and substrate choice.

1.4 Aims and Objectives

The aim of this research is to assess the sustainability of hydroponic vertical farming by quantifying the resource use and environmental impacts by using the Life Cycle Assessment technique. The idea behind this is to create a baseline of environmental impacts to inform researchers and further improve understanding of methods to move to sustainable agriculture.

This study has the following objectives:

I. Conduct a Life Cycle Assessment (LCA) to evaluate the environmental impact of hydroponic vertical farming at the Italian vertical farming company;
II. Identify hotspots in terms of environmental impact;
III. Complete a sensitivity analysis of the effect of electricity consumption and substrate type;
IV. Investigate how environmental impacts may change due to increasing renewable energy usage by completing a sensitivity analysis on different energy scenarios;
V. To assess the sustainability of vertical farming.

2. Background

2.1 Overview

This chapter will situate the research in terms of the broader context and highlight key literature relevant to the project. The chapter will include the following sections:

- An introduction to why food is critically important and associated challenges;
- A description of what sustainable food is and what concept is used during this study
- An introduction to the concept of vertical farming
- An evaluation of the sustainability of vertical farming from previous literature

2.2 Importance of food

Food is critical to human health and welfare, however access to it is not guaranteed to the detriment of individuals and society. Alongside the main issue of food supply, several significant challenges are associated with methods of food production.

Ensuring secure food supply has been, and remains, the single largest challenge when addressing issues of food production. Everyone has the right to enough food and balanced nutrition as declared by the Universal Declaration of Human Rights in 1948 (UN, 1948). However, in 2019 an estimated 10.8% of people worldwide in 2018 were undernourished. This is due to a variety of factors impacting food supply chains, including extreme weather events and conflicts (FAO et al., 2019). Food insecurity is particularly the case in drought prone regions which has seen a 45.6% increase in undernourished people since 2012 (FAO et al., 2019). Undernourishment can occur anywhere, regardless of socio-economic factors and wealth due to complex and interrelated problems such as climate change, poverty, conflict, but also due to political reasons, such as increasing and unstable prices or trade sanctions (EU Parliament, 2014). Another relevant issue is the occurrence of ‘food deserts’ located in rural and urban areas. A combination of poverty, poor transportation and insufficient shopping options limits access to certain foods, leading to an unbalanced diet and malnutrition (Butler, 2018).

The effects of malnutrition are far-reaching. Undernourishment accounts for 45% of under 5-year-old deaths and can reduce a country's GDP by up to 16% (EU Parliament, 2014). Another study from the US demonstrated that the benefits of a healthy, nutritious and well-balanced diet can include an improved quality of life due to a reduction in weight related illnesses and diseases, and reduced occurrence of mental health issues such as depression and higher productivity (Anekwe & Rahkovsky, 2013). Subsequently, significant attention and policy has been dedicated to ensuring food supply. The United Nations introduced Zero Hunger in the Sustainable Development Goals in 2015 with the aim of eradicating world hunger and ensuring a balanced nutritious food supply for all by 2030 (UN, 2019a).

Food production is ubiquitous to all societies. Poorly implemented post-industrial agricultural practices can have far-reaching and damaging effects on the environment. Planetary boundaries are limits for nine critically important and interconnecting Earth systems that identify a "safe operating space" for humanity (Steffen et al., 2015). Agriculture is the main driver for breaching the safe limits of four planetary boundaries including biodiversity and biogeochemical flows of nitrogen and phosphorus which are both at high risk, freshwater use and land-system change which are at increasing risk and is also a significant driver for breaching the safe limits of climate change (Campbell et al., 2017).

Arguably, food supply systems cause environmental damage because governments previously focused on ensuring food security at the expense of the environment, with the 'true' costs are not being paid. For every £1 directly spent on food in the UK at a retailer, there is an additional £1 of external costs not directly paid for by the consumer; 36.3p of this is 'spent' on natural land degradation and biodiversity loss (Fitzpatrick et al., 2017). Eventually, many of these hidden costs will be paid through taxes and insurance, or through long-term mitigation costs associated with environmental degradation and climate change (Fitzpatrick et al., 2017). There may be disagreement regarding the ethics of putting a price on nature and the study's methodology, however it does prove useful to highlight hidden costs that food has on the environment.

2.3 What is sustainable food?

Given the issues with food production highlighted in the previous section, a criterion is needed to assess the sustainability of food. No legal definition of sustainable food currently exists. According to the Cambridge dictionary, ‘sustainable’ means *“causing little or no damage to the environment and therefore able to continue for a long time”* (McIntosh, 2013). One can therefore assume that at every stage throughout the lifecycle of food, from production, distribution, consumption and waste disposal, little or no net damage to the environment can happen for the food to be sustainable. This definition is noble, however in practice how can this be identified?

Many different initiatives, ecolabels and frameworks exist to assess sustainability of food and provide information to consumers to differing effect. Some initiatives have acquired a legal definition, such as organic farming, whilst other schemes assess sustainability without legal definition. These include Rainforest Alliance and Marine Stewardship Council certified fish. They tend to look at one specific issue such as origin and distance to travel, working conditions of people along the supply chain or specific animal welfare targets (Engels, Hansmann & Scholz, 2010). However, the effect of these ecolabels was found to play a limited role on consumer choice (Grunert, Hieke & Wills, 2013).

With many piecemeal initiatives each offering an opinion on sustainability, it can be confusing and difficult to make an informed choice as a consumer, business or government. As environmental damage derived for agricultural and food production processes have become more apparent, there have been movements away from relying on consumer choice and ecolabels towards taking a system led approach in order to improve food sustainability (Grunert, Hieke & Wills, 2013; Nguyen & Neven, 2018). A system approach can combine competing policy needs by looking at all activities during the lifecycle of food products and the subsequent outcomes regarding food security, socio-economic and environmental parameters (van Berkum, Dengerink & Ruben, 2018).

For simplicity, the author has chosen to use the Sustainable Food System concept and framework designed by the Food and Agriculture Organisation within the United Nations and released alongside the SDG in 2015 (Nguyen & Neven, 2018). The concept requires meeting food security and nutritional needs whilst ensuring economic, social and environmental sustainability whereby it is profitable, produces a wide variety of benefits for society and results in a neutral or positive impact on the environment (Nguyen & Neven, 2018). Only the environmental sustainability will be discussed in this study to any length as defined by Morelli (2011): *"as meeting the resource and services needs of current and future generations without compromising the health of the ecosystems that provide them, ...and more specifically, as a condition of balance, resilience, and interconnectedness that allows human society to satisfy its needs while neither exceeding the capacity of its supporting ecosystems to continue to regenerate the services necessary to meet those needs nor by our actions diminishing biological diversity."*

2.4 What is vertical farming?

Vertical farming is to farm vertically upwards, as opposed to horizontal traditional open field farming, typically in highly controlled environments (Al-Chalabi, 2015; Al-Kodmany, 2018; Despommier, 2009; Despommier, 2011). It has rapidly gained momentum since Despommier reawakened the idea in the 2000's when proposing the idea to his students, leading to significant investments into vertical farms (Agrilyst, 2017).

The author acknowledges that there is some confusion in terminology regarding vertical farming and that there are several different terms associated with it (indoor farming, plant factories with artificial lighting, urban agriculture and container farming for example). On top of this, due to the emerging nature of the technology, vertical farms can be found in and on many different types of buildings (Al-Kodmany, 2018). This study refers to vertical farming that consists of horizontal stacked layers within highly controlled environments (Beacham, Vickers & Monaghan, 2019). These farms are usually characterised by an enclosed room with conditions controlled for optimal growing conditions. These include:

- Climate control systems;
- Multi-layered shelving units adequately spaced apart to ensure required air flow;
- Artificial lighting on each level;

- CO_2 enrichment system (Kozai, Niu & Takagaki, 2016).

For clarification this also consists of Controlled Environment Agriculture (CEA), which according to Cornell University (2014) is a combination of technological and agricultural techniques that range in sophistication from low grade sheeting on open fields to completely enclosed controlled systems with automated indoor growing systems. In the case of vertical farming, methods vary but are technologically sophisticated and can include hydroponic, aeroponic, aquaculture and aquaponic systems (Al-Kodmany, 2018). This study will focus on hydroponic systems that use an ebb-and-flow technique. Ebb-and-flow suspends the plant in a soilless growing medium, such as coconut coir, perlite or peat, which is then periodically immersed in a solution to meet all nutritional requirements for healthy plant growth whilst allowing for enough air flow to roots (Benke & Tomkins, 2017).

Vertical farming has been offered as a solution to feeding the world's growing population whilst also minimising the negative environmental impacts associated with traditional agriculture. The population is projected to grow by a further 2.3 billion people by 2050 resulting in an increase of food demand of around 70% (UN, 2019b). The proportion of people in urban areas is also expected to increase from 55% in 2019, to 68% 2050, resulting in urban sprawl and encroachment on surrounding agricultural lands (UN, 2018). The resultant growing food demand is projected to originate from increasing agricultural yields and cropping intensity, however land expansion of roughly 70 million ha may also be necessary to meet remaining demand and to account for lands lost to degradation, climate change and urbanisation infringement (FAO, 2009). Traditional open field agriculture contributes to numerous environmental crises which include, soil degradation, eutrophication of waterways, biodiversity and ecosystem collapse due to chemical pest controls and land clearances for agricultural development (Campbell et al., 2017). Vertical farms offer a potential solution by producing food more efficiently with higher yields per land area, reduced amounts of resources use due to recycling (water, fertiliser and pesticides etc.), reduced risk of disease outbreaks and lowers pollution due to the controlled nature of production (Al-Kodmany, 2018; Goodman & Minner, 2019; Pinstrup-Andersen, 2018). Despommier (2009) has suggested that a 30-storey building in a 5 acre plot could provide as much as 2,400 acres (971 ha) of grow space that produces year-round.

This is not to say however that the technique does not come without challenges and limitations. Firstly, supporters of vertical farming claim that it offers a real alternative to traditional agriculture as it can grow everything and with better yields (Kozai, Niu & Takagaki, 2016). However, the current generation of vertical farms can only grow produce that fit certain criteria;

- a size small enough for shelving;
- quick growth;
- high value product;
- suitable for growth under artificial lighting and;
- 85% of weight can be sold as produce (Kozai, Niu & Takagaki, 2016).

Primarily, these have been micro greens (6%), small herbs (11%) and leafy greens (57%) as reported by Agrilyst (2018). Many fruiting plants, such as tomatoes, peppers, cucumbers, berries, are more productive in greenhouses with natural light, whilst staple crops have not yet been grown productively in CEA (Kozai, Niu & Takagaki, 2016). Corn, rice and wheat provide 51% of calories worldwide (Pariona, 2019) so it’s difficult to see how current vertical farming approaches can offer a viable alternative to open field agriculture when calorific needs are considered. Additionally, high start-up costs and ongoing operating costs make the long term viability of vertical farms economically risky (Benke & Tomkins, 2017). This can somewhat be diminished if land is purchased away from expensive urban areas however this may then reduce the benefits of locating in urban areas. Finally, a major concern relates to the high energy consumption of vertical farms as a result of lighting and HVAC requirements (Kozai, Niu & Takagaki, 2016). This will be discussed further in Section 2.5.

2.5 How sustainable is vertical farming?

Sustainability of a food system relies on three factors: economic, societal and environmental (Nguyen & Neven, 2018). ***Table 1*** summarises several compelling reasons that support the idea of vertical farming as suggested from reviewed literature.

The scope of this study primarily investigates the environmental sustainability of the technology only; however, it was deemed important to highlight associated economic and social benefits as well.

Table 1 Possible advantages of vertical farming as identified in literature.

Economic benefits	Price stability – Consistent yields and year-round production guarantees income and allows farmers to harvest and maximise profitability;
	Boost local economy with new business development and employment opportunities;
Social benefits	Food security – increased productivity and urban self-sufficiency, unaffected by extreme weather and year-round production, reduced occurrence of 'food deserts';
	Rejuvenate vacant or derelict areas;
	Educational programmes;
Environmental benefits	Higher resource efficiency – low water usage, more efficient use of nutrients, reduced land area use and no use of pesticides, herbicides or fungicides;
	Reduced transportation distance – Lowers associated transportation emissions and improves air quality, lowers risk of food wastage, less complex distribution network needed;
	Reduced pollution – nutrient recycling so limited agricultural runoff, transportation and machinery emissions reduced;
	Opportunity to restore agricultural lands back to nature to improve ecosystems and previously lost biodiversity.
(Al-Kodmany, 2018; Benke & Tomkins, 2017; Despommier, 2009; Despommier, 2011; Kozai, Niu & Takagaki, 2016)	

There seems to be a clear consensus that land, water, nutrient and pesticide (herbicide/fungicide etc) use is more efficient in vertical farms than conventional farming, but that this comes at the expense of much higher energy usage (Barbosa et al., 2015; Graamans et al., 2017; Harbick & Albright, 2016; Kikuchi et al., 2018; Kozai, Niu & Takagaki, 2016; Molin & Martin, 2018a; Molin & Martin, 2018b; Pennisi et al., 2019).

Land use efficiency of vertical farming is much higher than that of conventional farming although it depends on the number of growing levels of the vertical farm. The larger the building, the more available grow space there is and thus will have a higher yield for that footprint of land, but also an increase in associated energy consumption (Graamans et al., 2017). It has been suggested by Touliatos et al, that land use efficiency could be increased further by switching to a vertical hydroponic growing method as opposed to the usual horizontal hydroponic growing within vertical farms (2016). It was shown that although the weight per plant decreased, the vertical system could produce more crop per unit area.

Studies have found that water consumption for vertical farms is considerably lower than that for greenhouse growing and conventional farming, however these calculations are theoretical and limited real data exists (Kikuchi et al., 2018). In the study by Barbosa et al. (2015), water use for hydroponic lettuce production in a hypothetical greenhouse (with supplemental lighting) was roughly 13 times less than when compared to conventional outdoor farming. Another study compared water use in greenhouses and vertical farms in three different climates (Graamans et al., 2017). It was found that water consumption could be reduced by between 28 and 95% in comparison to greenhouses, dependent on local climate. Calculations were based on a closed system with 100% of water recycled excluding water content of produce. The importance of such a feature is reiterated by Kozai et al. (2016) who claim a closed system could improve water efficiency of vertical farms by 50% in comparison to greenhouses, although these results were theoretical and not impacted by real-world conditions. One such real-world issue is bacterial and algal outbreaks (Kozai, Niu & Takagaki, 2016). Various methods exist to eliminate the outbreaks with chemicals, but it could likely necessitate a total wash of the system, increasing total water consumption per kg of produce (Morgan, 2017).

In relation to pest control, most research claims that no pesticide, fungicide or insecticide is needed for vertical farming and thus greatly reduces associated environment impacts when compared to conventional farming, for example biodiversity loss (de Backer et al., 2009; Kozai, Niu & Takagaki, 2016). No soil is used which limits the risk of pest or disease outbreaks, however bacterial and algal outbreaks can still occur. Options to mitigate this problem vary and are debated as to the effectiveness and subsequent environmental impact, but they include flushing the growing system with chlorine, ozonated water, hydrogen peroxide (biocide) or using UV lighting (which adds to the energy consumption) (Kozai, Niu & Takagaki, 2016). Limited literature exists detailing pest control solutions in a real-life scenario, so it may be the case that chemical preventions are used in certain cases.

Energy consumption is by far the most concerning environmental impact of vertical farming and greatly exceeds consumption seen in greenhouse and conventional farming (Barbosa et al., 2015; Graamans et al., 2017; Harbick & Albright, 2016; Kikuchi et al., 2018; Kozai, Niu & Takagaki, 2016; Molin & Martin, 2018a; Molin & Martin, 2018b; Pennisi et al., 2019). First, it must be noted that most studies reviewed were not based on accurate, real-life energy consumption of vertical farms but made use of modelled simulations. As a result, it's difficult to attribute energy consumption to certain technologies accurately, however lighting and HVAC systems seem to be the largest contributors (Graamans et al., 2017; Harbick & Albright, 2016). This uncertainty does limit the reliability of conclusions however as actual energy consumption can differ dramatically, particularly for technologies such as HVAC systems whereby energy use is dependent on size, insulation of building and local climate, which can vary considerably (Kozai, Niu & Takagaki, 2016). The following will detail findings of the more relevant studies.

Two studies by Molin and Martin (2018a; 2018b) compared the environmental impacts of real-life vertical farms with conventional farming. This includes two separate cradle-to-gate LCA studies with the aim of developing more sustainable methods for the companies involved by reviewing energy consumption and associated carbon footprint (Molin & Martin, 2018a; Molin & Martin, 2018b). The first study assessed cress grown hydroponically on hemp fibre within a shipping container at Node farm in Stockholm (Molin & Martin, 2018b). Per functional unit, in this case one finished pot of cress including plastic packaging, produced 0.017kg CO_2- eq and used 0.37 MJ energy (0.103 kWh). Interestingly, the plastic packaging was the largest contributor to both energy consumption and carbon footprint, meanwhile heating, lighting and the growing material contributed to less than 5% of the total energy consumption. They found it difficult to locate enough studies on conventional farming in order to do an adequate comparison between the techniques however they did conclude that energy consumption is higher for vertical farms, but it is much lower for other resources used such as water, nutrients and land. The second LCA study by Molin and Martin evaluated the impacts of growing basil hydroponically at Gronska vertical farm in Stockholm (2018a). This study showed again that energy consumption is higher for vertical farms. To produce a packaged basil plant in a plastic pot consumed 4.9 MJ (1.306 kWh) of energy of which soil was the largest contributor at 47% of energy used and lighting the second largest with 32%. By changing the type of growing medium used from soil to coir in a sensitivity analysis, the contribution of growing medium reduced from 47% to only 1% of amount used. This highlights the importance of choice of growing medium on environmental impacts (Barrett et al., 2016; Quantis, 2012).

In a comparison study between a hypothetical greenhouse (with supplemental lighting) and conventional open field farming, energy consumption was on average 82 times higher for greenhouse lettuce (1100 versus 90000 kJ/kg/year) (Barbosa et al., 2015). The authors argued energy demand was high due to the location (Arizona, USA) and subsequent HVAC needs in order to maintain optimal growing temperature. In more moderate climates, they claimed energy consumption would be lower. Therefore, hydroponic vertical farming may not be viable in excessively hot or cold climates. This is supported also by Kozai et al. (2016), however they did argue energy use of HVAC system for heating can be abated somewhat by adequate insulation and by using heat from electrical equipment. Other options to improve energy efficiency including light choice and efficiency, although the effectiveness has been debated, and using pre-existing available heat in sections of residential buildings for example (Pennisi et al., 2019; Shimizu et al., 2011).

Renewable energy is claimed to be able to reduce the environmental impact of the electricity use of vertical farming, although empirical data is limited (Graamans et al., 2017; Kozai, Niu & Takagaki, 2016). On-site solar generation may only be able to meet a limited amount of the electricity demand; a study by Graamans et al (2017) found that for a hypothetical farm only 2.72% of the annual electricity requirement was found to be met by solar panels based on the surface area of the building. No studies were found that explored the effect of local energy mixes and how this affects the total environmental impacts of vertical farming even though electricity production by fuel type can vary drastically (IEA, 2018).

A major claim why vertical farming is more sustainable then conventional farming is due to the reduced transportation distances. However, transportation has been found to account for only 11% of the environmental impacts of conventionally grown produce and thus has limited impact on the overall environmental impact (Weber & Matthews, 2008). Although outside of the scope of this study, additional research using real life data is needed to quantify the reduction in distances and evaluate associated changes to the environmental impact of vertical farming.

To summarise, in order to understand the environmental sustainability of vertical farming, the trade-off between higher resource efficiency of land, water, nutrients, no use of pesticides and lower transportation distances with a significantly higher energy consumption needs to be fully understood. So far limited studies have done this based on accurate real-life data, so it is difficult to establish sustainability. Proceeding identification of the literature gap, a life cycle assessment was identified as an appropriate tool to quantify and evaluate the environmental impacts of a vertical farm sufficiently. In this study, the author specifically evaluates the environmental impacts of a vertical farm based in Italy via a Life Cycle Assessment tool (LCA) but will also aim to set within the context of improving food sustainability. The next chapter will detail the methodologies used in order to meet the objectives of the project.

3. Research Methods

3.1 Overview of research methods

The following chapter will detail the research methodology and outline each of the stages taken to complete the objectives of the project.

An Italian vertical farm agreed to be a collaborator on the research project. This relationship was established prior to starting the project through contacts within the Centre of Environmental Policy on the understanding that an LCA would be completed on their current practices. Initially, a detailed literature review was undertaken to establish an understanding of indoor agriculture, vertical farming, hydroponic growing as well as LCA methodology, prior to commencement of the LCA.

3.2 Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is a well-established and comprehensive methodology developed to quantify environmental impacts and resource use of a product throughout its life cycle. The four stages of the assessment framework are outlined below and in ***Figure 1**,* based on ISO standards (BSI & ISO, 2006; BSI & ISO 2018):

1. Define the goal and scope of the project;
2. Compile comprehensive and appropriate Life Cycle Inventory Analysis (LCI) of inputs and outputs of the system;
3. Use Life Cycle Impact Assessment (LCIA) methodology to assess environmental impacts of materials;
4. Interpret the LCIA results.

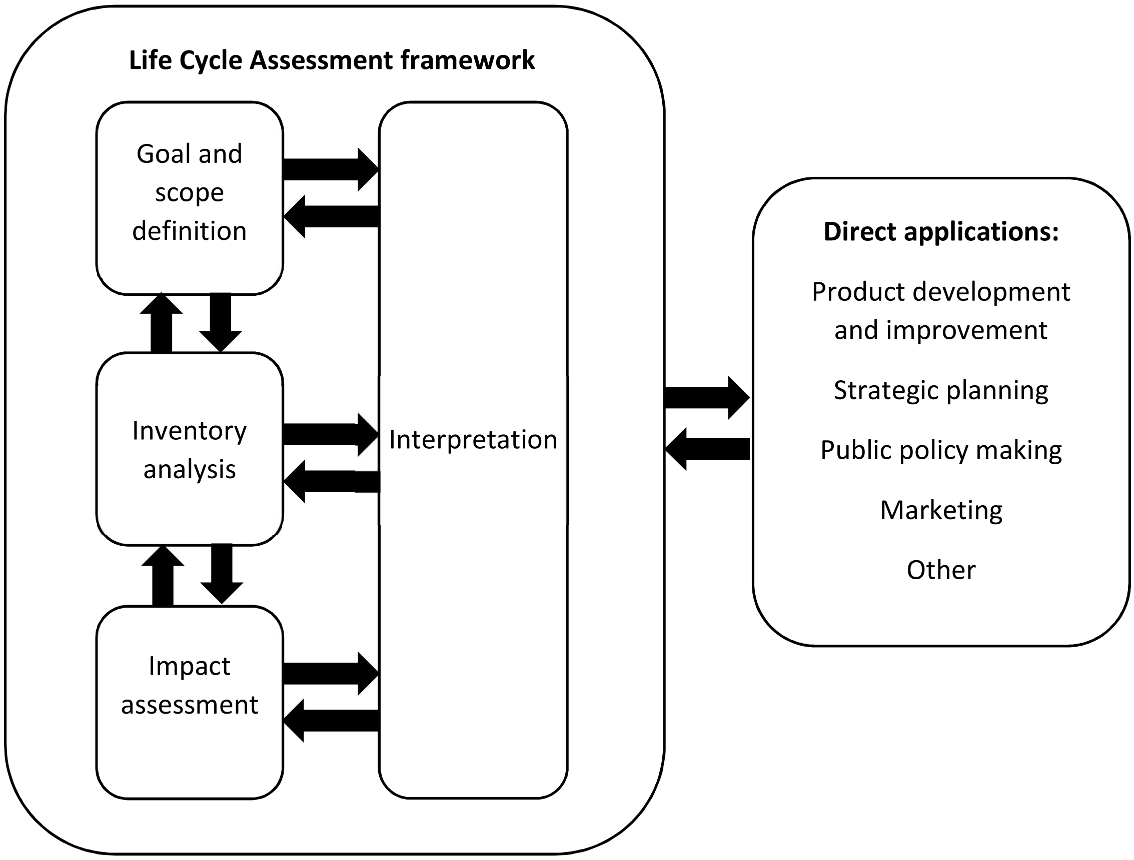

Figure 1 Stages of an LCA derived from the ISO standards which highlights the iterative nature of the framework (BSI & ISO, 2006).

3.2.1 Goal and scope definition

This is arguably the most important step in the overall process of carrying out an LCA as it dictates the purpose of the study, why it is being carried out and what product or process the LCA will be evaluating (BSI & ISO, 2018). This step involves fully outlining the product system and every unit process involved in producing that product and from this, deciding which of these processes will be included in the LCA, within what is known as the system boundaries of the project. A functional unit will also be defined with the aim of allowing for comparison with alternative products, as well as making clear any assumptions needed for the purpose of this study. Allocation procedures will be described in the instance that more than one product is produced during processes in the production of the lettuce. Often throughout an LCA study, the scope of the project will be changeable due to changing information and the need to still meet the goal of the overall study. Impact categories and the life cycle impact assessment methodology with be outlined as well as any assumptions made within the data requirements.

The aim of this LCA study is to quantify the environmental impacts of producing lettuce hydroponically within an indoor vertical farming system. Following this, "hotspot inputs", which disproportionately contribute to environmental impacts, can be identified and different scenarios (such as total electricity consumption via changing lighting) can be simulated to identify best operating practice with the lowest environmental impacts. The results will be shared with the company to improve environmental performance. The study will also assess future environmental impacts by changing electricity production share of renewable energy to inform fellow researchers and policymakers.

The system to be studied is an experimental indoor Control Environment Agricultural laboratory in Italy. The company is currently in a research phase to improve growing efficiencies of various indoor crops prior to commencement of commercial production at their vertical farm in late 2019. As such, the study is limited to reviewing the farming of lettuce in the laboratory in a cradle-to-gate LCA (see ***Figure 2***). An attributional LCA modelling framework will be used as per SimaPro guidance (PRé, 2016).

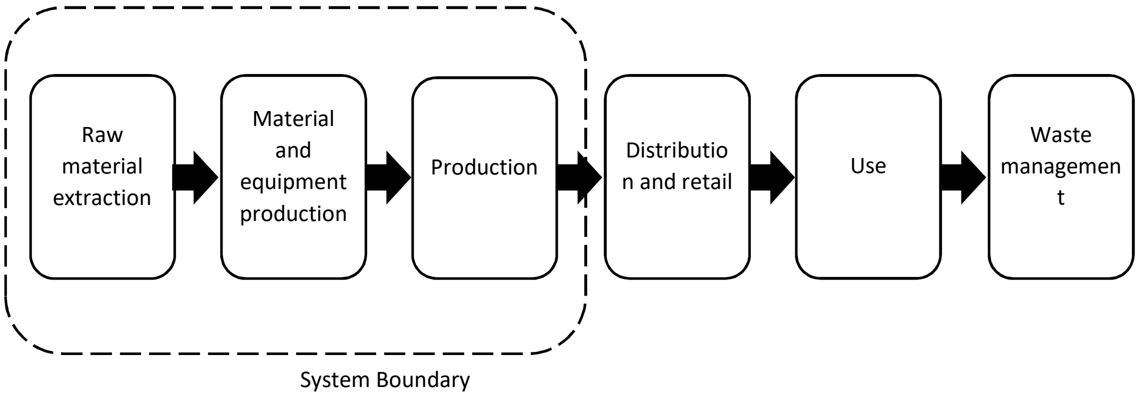

Figure 2 Different stages throughout the lifecycle of a product. Those included within this cradle-to-gate study are highlighted by the dashed system boundaries line.

3.2.1.1 System Boundaries

The unit processes to be included in the study are shown in ***Figure 2*** and include the acquisition of raw materials for major inputs, production of inputs, transportation of inputs to the laboratory, and the energy and materials required during production of 1 kg of lettuce, at the "gate" of the laboratory. All possible processes after harvest such as packaging, transportation, consumption and waste management are excluded from this study. The lifecycle of the laboratory and capital goods used during production of the lettuce have not been included within the system boundaries as this is beyond the scope of the project. In addition, due to data limitations, waste packaging produced from inputs to the system have been excluded. Production of any capital goods used within the system boundaries will not be included in the LCA due to time restraints.

3.2.1.2 Functional unit

The functional unit is a key reference unit which relates the amount of inputs and outputs required to the production of a certain amount of product (BSI & ISO, 2018). For this study, the functional unit will be 1 kg of lettuce without packaging, as is common with similar vertical farming studies (Romeo, Vea & Thomsen, 2018).

Figure 3 Set-up of the hydroponic grow system at the Italian vertical farming company's laboratory, with an example tray of lettuce produce.

3.2.1.3 System in detail

The Italian vertical farming company's controlled environment laboratory is housed within a larger space that contains an office, a small workspace and input storage area. Within the laboratory, plants are hydroponically grown on six vertical shelving racks using an ebb-and-flow grow system, as can be seen in photographs taken during the visit in June 2019 (***Figure 3***). The ebb-and-flow system contains a water tank at the base of the shelving unit with a water pump, piping and drain trays. Also contained on the racks are six fans to ensure adequate ventilation, LED lighting and growing trays. Other electrical equipment includes the HVAC system and a dehumidifier. There is currently no carbon dioxide (CO_2) enrichment system in the laboratory. The laboratory also contains a small workspace area with a sink and germination pod.

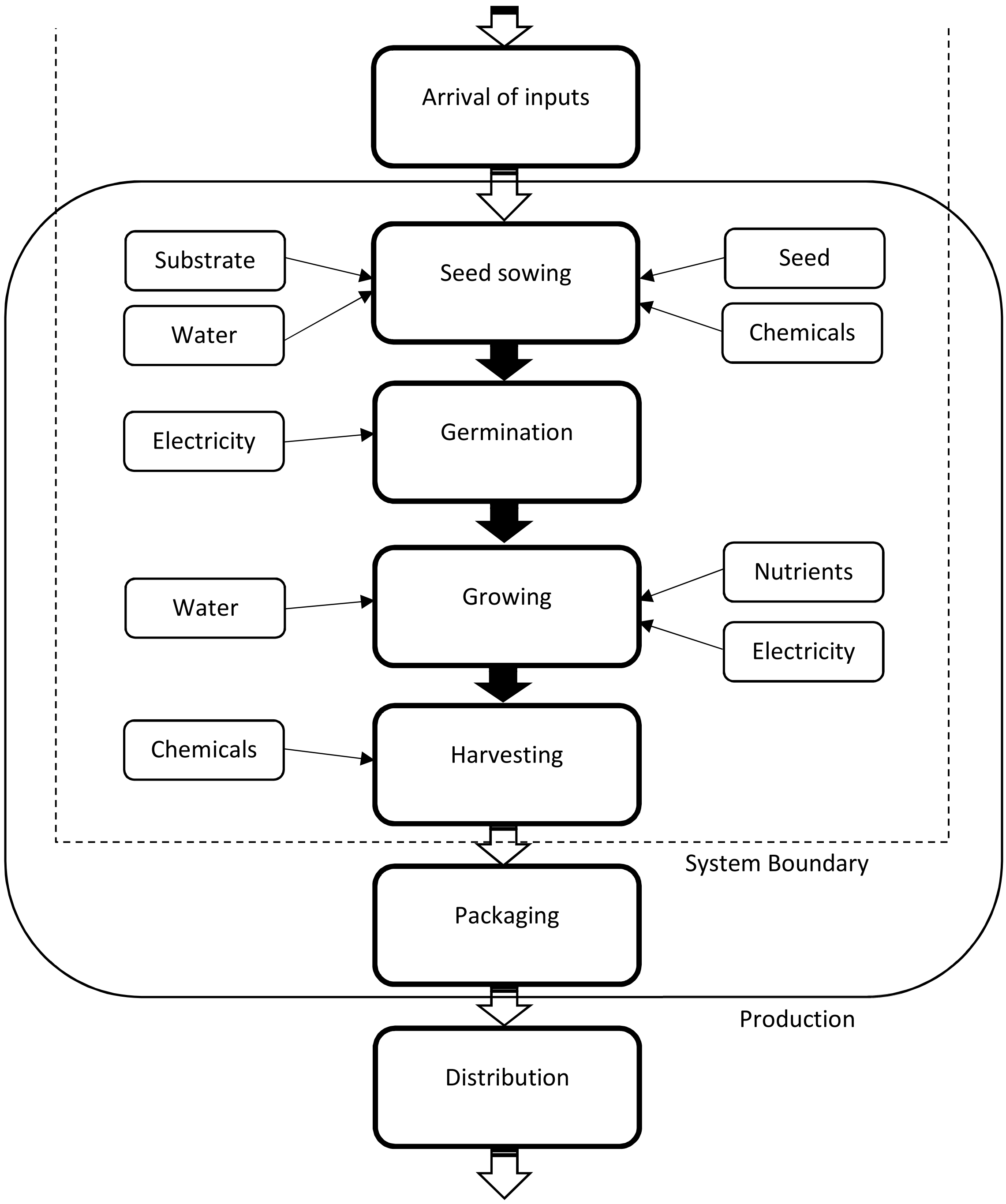

Figure 4 Unit processes and inputs involved in the production of lettuce at the the Italian vertical farming company's laboratory. Unit processes are surrounded by a thick black line and inputs with a thin black line. The dashed line highlights those unit processes and inputs that are included within the system boundaries of producing the functional unit.

The unit processes involved in generic plant production within the system are shown ***Figure 4*** and proceeds as follows. Seed sowing is undertaken in the workspace area outside of the controlled environment laboratory and involves cleaning the workstation to prevent contamination, mixing the substrate (if necessary), filling the grow trays with substrate (or unpacking prepared rockwool trays), submerging them in water, planting seeds and moving the grow trays to the germination pod inside the laboratory. Germination then takes place in the dark and requires limited input, with only electricity needed for the HVAC system and dehumidifier. Following germination, the trays are moved to the six shelving racks for the required growth period. Processes during this time involve a daily preparation of nutrient solution (using a dried powder and water) that are manually added to the ebb-and-flow water tank, as well as cleaning of the laboratory to ensure continual hygiene. Electricity is also required during this stage to power lighting, the HVAC system, water pumps, fans and the dehumidifier. The final process within the system boundaries is harvesting which involves moving the final product in grow trays from the controlled environment to the outside workstation and harvesting all produce. Roots and any damaged leaves are disposed of and all equipment used during the entire production is cleaned, including the laboratory. All jobs are done manually as there are no automated systems.

Major inputs and at what stage they are used during production are also detailed in ***Figure 4***. Due to the experimental nature of the laboratory, different types of each input were trialled including various substrates, seeds and nutrients. Substrates include a coconut coir and perlite mix, peat moss and rockwool. Both a premixed nutrient solution and individual nutrients that require precise measuring and mixing have been used. Finally, different types and brands of seeds have been trialled including lettuce, basil and rocket amongst others. Other inputs include water, whereby generic Italian tap water is used which does not undergo any filtration process, and electricity, provided by a standard Italian energy company. Lastly, chemicals involved in production include sulphuric acid used to ensure consistent water pH in the grow systems, Bac50 biocide used to clean all equipment and surfaces, as well as an EC standard calibration fluid and a pH calibration fluid for use in ensuring accuracy of technical equipment. Plastic gloves, plastic pipettes, plastic shoe covers, and paper tissue roll are also inputs used during production, however so few of them are used during production, the amount per functional unit is almost negligible and thus they have not been included in the study or ***Figure 4***.

Outputs change regularly due to the experimental nature of the laboratory and the trialling of different plants. More recently, outputs have included lettuce, basil and rocket, as well as smaller amounts of mustard.

3.2.1.4 Allocation

In the case of lettuce production at the Italian vertical farming company, lettuce is the main product, however damaged leaves and root material are also produced as a by-product. All inflows of materials and energy during production are to produce both products, so an allocation procedure is necessary to decide how to partition the inputs between them. According to the ISO 14044 standards (BSI & ISO, 2018), allocation can be applied by three different steps:

1. Ideally, allocation would be avoided by expanding the product system and dividing the process into sub-processes. However, in the case of lettuce production it is not possible to precisely allocate what inputs are related to lettuce or the waste biomass;
2. The next option would be to partition the inputs based on a physical component of both products such as mass or energy. Data provided by the Italian vertical farming company regarding the amount of by-product produced was insufficient, thus this option could not be used;
3. If all other allocation steps are not possible, the final option partitions inputs based on economic value of the products and is often used in practice (PRé, 2016).

No prices can be provided by the company as they have yet to go commercial. Instead prices were taken from the current market whereby the price of lettuce varied, and waste biomass is worthless. As a result, the waste biomass has been allocated a zero share of the process inputs and the main lettuce product allocated 100% of the inputs and thus, the environmental impacts.

3.2.1.5 Data requirements

This study involved primary data collection from the Italian vertical farming company for the unit processes and inputs and outputs used directly at the laboratory. A four-day trip was taken in late June 2019 to ensure accurate data collection and full understanding of processes used. The trip consisted of an in-depth tour of the laboratory to understand indoor plant production using the systems in place, an inventory of all processes involved in production and a complete list of all inputs and outputs. ***Table 2*** presents a summary of inputs used to produce the functional unit (1 kg of lettuce), as defined by the system boundaries.

Table 2 Summary of inputs used during the production of 1 kg of lettuce using the standard model (see Section 3.2.2).

Input	Type used in standard model	Quantity	Units
Seed	Lettuce – Batavia	0.0006	Kg
Substrate	Coconut coir and perlite mix	3.35	Kg
Nutrients	Individual powder nutrients: Calcium nitrate, Potassium nitrate, Ammonium nitrate, Dipotassium phosphate, Magnesium sulphate, Potassium sulphate, Ferric EDTA, Zinc EDTA, Copper EDTA, Boric Acid and Manganese EDTA	0.0692	kg
Water	For germination, growing and cleaning	75.14	L
Electricity	HVAC system, lighting, pumps, fans and dehumidifier	79.49	kWh
Chemicals	Sulphuric acid, biocide Bac50, pH buffer, EC and pH calibration fluid	0.03311	kg

Data collection involved listing the amount of every input and output for all processes during the entire lifecycle of a product, not just during the direct production of lettuce. This can be very time-consuming and an expensive task to carry out and it can be particularly difficult to obtain data if looking at confidential, commercial processes. In response to this, LCA databases have been developed by different institutions to provide data on common materials or processes and their associated environmental impacts to ensure access to required information and to allow for quicker results (PRé, 2018). Ideally, given more time and resources, all data within the system would be collected first hand as these databases are not comprehensive and come with certain assumptions and limitations. However, they are a useful tool when lack of resources necessitates their use and will be conclusive enough for a screening LCA such as this.

Any data relating to sourcing of the raw materials, processing of inputs, packaging and transportation, energy, reuse, recycling and disposal of co-products was classed as background data and sourced from existing LCI databases, Agri-Footprint 4.0 (Durlinger et al., 2017) and Ecoinvent Version 3 (Wernet et al., 2018). SimaPro version 8.5.2 LCA software tool was used due to the accessibility of essential databases (PRé, 2017).

3.2.2 Life cycle inventory analysis (LCIA)

The purpose of the LCIA is to compile and quantify a complete list of inputs and outputs for all processes involved in production of the functional unit throughout the entire lifecycle of the product. This includes various steps:

- defining processes involved;
- data collection of inputs and outputs for each process (either from primary or secondary sources);
- data calculation to relate this to the functional unit, and lastly;
- allocation calculations if necessary.

All processes within the system boundaries were defined (as detailed in ***Figure 4***) and the amount of each input and output used inventoried during the site visit in June 2019. On completion of data collection, calculation took place in order to relate each input and output to the functional unit. Details of this are described below, including any assumptions made and why they were needed.

As previously stated, a variety of plants and inputs are trialled in the laboratory to establish the most preferred growing conditions. This makes it difficult to ascertain the exact output produced over a certain period and attribute inputs specifically to growing the functional unit. Most recently, lettuce, rocket and basil have been trialled, with the aim to split the available grow space equally between them at any one time. To equate the input used per functional unit, the mass output for each output (i.e. rocket, basil and lettuce) needs to be known. However, limited trials for rocket have taken place so no data exists regarding mass output. As a result, no inputs can be attributed to rocket production. To resolve the issue of how to attribute any shared inputs, rocket will not be considered as a product and instead, it has been assumed that the total grow space (12.28 m^2) will be equally split between producing lettuce and basil only. Given that there are six growing racks it can then be assumed that three shelving units are used for lettuce at any one time.

Different types of lettuce and basil are trialled in the laboratory and each one has a different growing density, growth cycle length and mass output. To attribute inputs specifically to the functional unit, it was necessary to assume that only one type of lettuce – Batavia – and one type of basil – Genovese – has been grown to ensure consistent growing density, growth cycle length and mass output for the two products. Note that these figures are not disclosed due to their commercially sensitive nature.

To account for transportation of inputs from location of production to the laboratory premises a place of origin and journey has been estimated for each input. These can be seen in Section 8.1.2 of the Appendix. To simplify transportation calculations, inputs either travelled by road or ship and regardless of location, the same lorry type was used for each input, also detailed in the Appendix (Section 8.1.3).

Given that several inputs used during production have been changed regularly for different trials, it was necessary to design a standard model for which the LCA study would focus on. The attributes of the standard model are described in ***Table 3***. Seed, substrate, nutrients and number of lights were chosen as they are the current preference at the laboratory. Alternative scenarios have been highlighted and will be explored during the sensitivity analysis in Section 3.3.

Table 3 Attributes of the standard method of lettuce production. Alternatives listed are explored during sensitivity analysis explained in Section 3.3.

Input	Type used in standard model	Alternatives
Seed	Batavia lettuce (*Lactuca sativa)*	
Substrate	Coconut coir and perlite mix	Peat OR Rockwool
Nutrients	Individual powder nutrients which include: Calcium nitrate, Potassium nitrate, Ammonium nitrate, Dipotassium phosphate, Magnesium sulphate, Potassium sulphate, Ferric EDTA, Zinc EDTA, Copper EDTA, Boric Acid and Manganese EDTA	
Lighting	4 LEDs used per grow shelf	5 LED lights
HVAC system operating time	80%	50%

3.2.3 Life Cycle Impact Assessment - Impact categories and methods

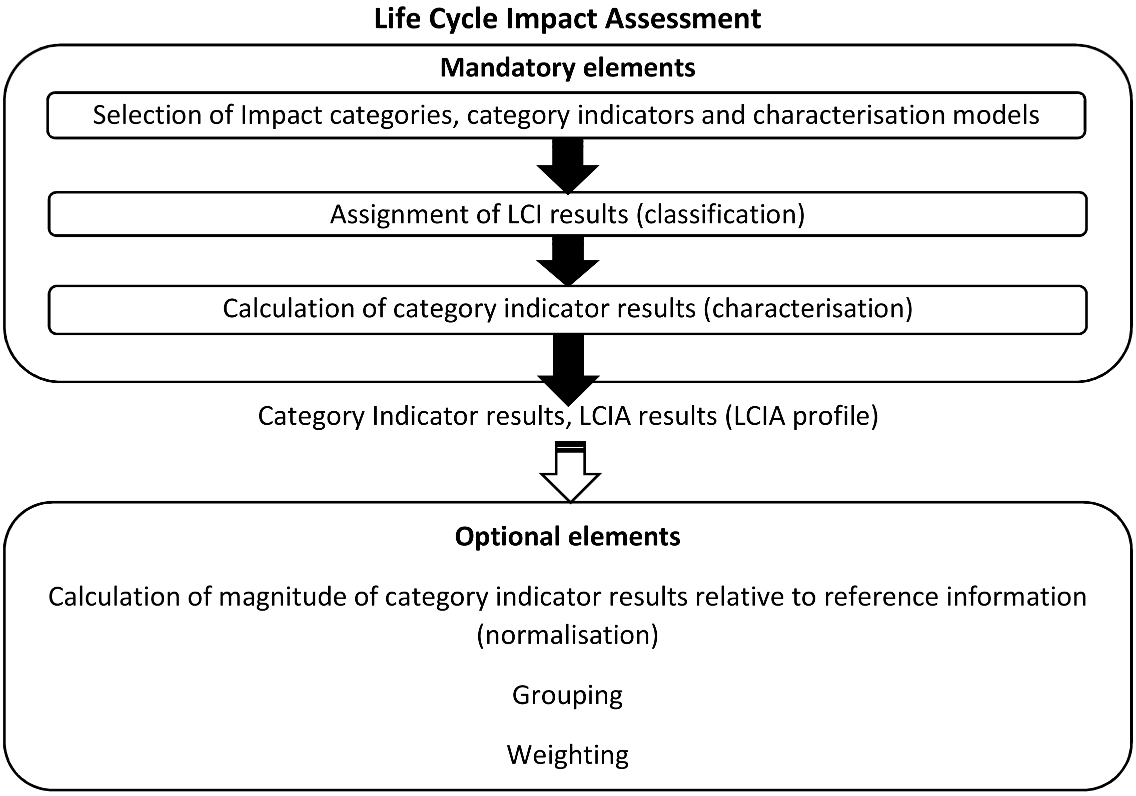

Figure 5 Different stages of the lifecycle impact assessment as taken from the ISO standards (BSI & ISO, 2006).

After compiling the extensive LCI results required to produce the functional unit, the significance of any possible environmental impact within the goal and scope of the study is evaluated during the LCI assessment stage. To do this, inventory results are assigned and aggregated to specific impact categories depending on expected environmental damage (BSI & ISO, 2006). Following this classification, characterisation takes place whereby for each impact category, every input and output is designated a corresponding magnitude of environmental impact by a characterisation factor to allow for comparison between LCI results (Huijbregts et al., 2016a). Further steps can include normalisation, grouping and weighting (as seen in ***Figure 5***), but have not be included in this study due to increased uncertainties and to be in accordance with ISO standards (BSI & ISO, 2018).

The ReCiPe 2016 LCIA methodology was chosen for its well-established, clear methodology and due to the broad set of 18 impact categories (see ***Table 6***) (Huijbregts et al., 2016a). It uses two different ways to derive characterisation factors, either by a midpoint or an endpoint level. Midpoint indicators provide information on individual impact categories. In the endpoint indicators, individual impact categories are aggregated to provide an environmental impact results for three main areas; effect on human health, effect on biodiversity, and the effect of resource scarcity. The latter option simplifies the results of the LCIA, however the uncertainties also increase, and it is more difficult to trace environmental impacts to the original product or process, so the midpoint method was used (Huijbregts et al., 2016a). The hierarchist perspective was chosen as it was most appropriate (PRé, 2016).

3.2.4 Interpretation phase

LCI and LCIA findings are subjective and differ due to the different methodologies used so require interpretation before results can be draw. Both the LCI results and LCIA findings, along with the scope of the study and any limitations will be considered together in order to determine the environmental impacts of the product. The main aim is to provide a clear and concise result of the LCA by highlighting significant environmental issues from the lifecycle and where possible, recommendations to rectify these issues.

3.3 Sensitivity Analysis

Due to the experimental nature of the Italian vertical farming company's laboratory, it was necessary to design the standard model which has certain assumptions regarding the type and amount of inputs used (***Table 3***). To fully understand the environmental impacts of lettuce production, it is necessary to explore how changing the inputs may change as a result. Four additional models were run where the substrate type and electricity consumption were altered (***Table 4***).

Table 4 Alternative models chosen for the sensitivity analysis.

	Input	Standard model	Alternative model
1	Number of LED lights per grow rack	4	5
2	Operating time of HVAC system	80%	50%
3	Substrate type	Coconut coir & perlite	Peat AND Rockwool
4	Electricity	General Italian energy mix	2017 V 2030 energy mix

3.3.1 Altering lighting requirements

The Italian vertical farming company has trialled using either four or five LED lights per grow rack to optimise growing conditions. By using five lights, productivity and output of lettuce increase, however electricity consumption also increases. The alternative model using five lights has been run to understand how changing the number of lights will affect the environmental impacts of producing the lettuce.

3.3.2 Altering HVAC system operating time

With no access to accurate energy consumption data for the HVAC system, consumption was calculated based on the energy requirements of the system whilst assuming it was in operation for 80% of the time. Given the inaccuracy of this assumption for the standard model, an alternative model was run whereby the operating time was reduced to 50% to understand the implications of this assumption.

3.3.3 Altering substrate type

A variety of substrates have been trialled including the coconut coir and perlite mix as used in the standard model, but also peat and rockwool have also been used. Two additional models were run to understand the environmental impacts of using each substrate type to evaluate the most sustainable option.

3.3.4 Comparing the current and future energy mix

Sensitivity analysis was run to understand how the environmental impacts may change as the share of renewable energy in the electricity production mix increases. 2030 was chosen as the future date due to the importance of meeting decarbonisation goals and for the availability of national climate plans from the Italian government (UN, 2019a). For the standard model, a general Italian electricity mix based on 2014 production figures was used to represent electricity consumption due to its inclusion of a greater number of system processes in the dataset, so was more appropriate for use an the LCA. However, the greater complexity made it incompatible for comparison with the 2030 electricity mix, as the latter only includes production types i.e. oil, gas, wind etc. Subsequently, in order to compare current and future energy mixes, electricity consumption for the 2017 and 2030 scenarios (see ***Figure 6***) were represented by different production methods in SimaPro. Consequently, the environmental impacts of the 2017 model differ from the standard model due to differences in the datasets used. Whilst this limitation exists, it provides a useful comparison to gauge the change in environmental impacts. Total electricity consumption was kept the same in both 2017 and 2030 scenarios.

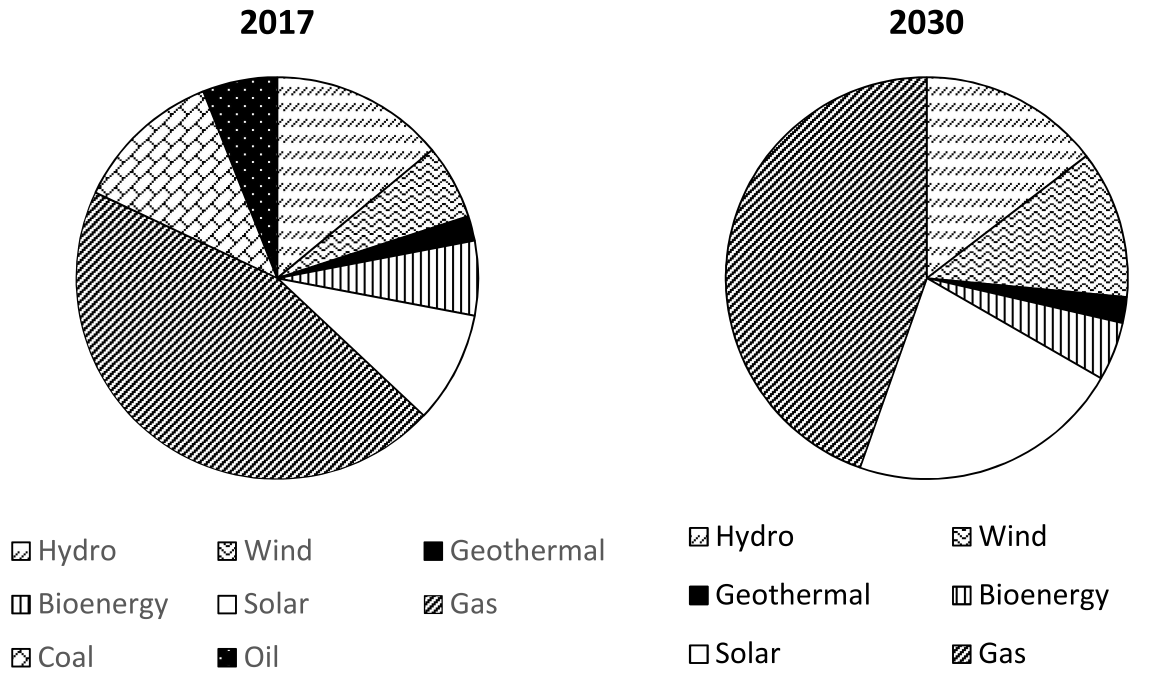

Figure 6 Electricity mix by fuel type in 2017 (Statista Research Department, 2019) and the 2030 electricity mix commitment from the Italian government in order to meet the EU Climate and Energy Framework targets (Italy, 2018).

4. Results

4.1 Introduction

This chapter will present the main findings from the LCA study and subsequent sensitivity analysis. Further comments regarding implications and situating the findings within existing literature will occur in the following chapter.

The following results are in reference to the standard model of producing 1 kg of lettuce in the laboratory unless stated otherwise. This standard model consists of the following main assumptions of inputs used; a perlite and coconut coir substrate, 4 LED lights per grow shelf, 80% productivity of the HVAC system and when representing the electricity consumption, a general Italian energy production mix was selected from the Ecoinvent database. For reasons why these assumptions have been made, please see Section 3.3.

4.2 Inventory results

The inventory results are a compilation of all raw materials used, waste produced, and substances emitted into water, soil or air which occur within the system boundaries (Section 3.2.1.1) of producing 1 kg of lettuce hydroponically in the laboratory. Inventory results are often very lengthy and difficult to interpret; however, it is worthwhile to examine the contents as the numbers have not yet undergone characterisation and thus, the certainties are higher. The top ten for each compartment are detailed in ***Table 5***. For the standard model, 1988 substances were identified as emitted or used within these system boundaries of producing lettuce during the cradle-to-gate production. Out of the 1988 substances defined, 738 are not characterised by the ReCiPe method used and thus are not included in the following LCIA results.

Table 5 Top ten substances in the inventory for each of the following compartments; raw materials used, waste produced and the emissions to air, soil and water. Radioactive substances, land and energy used have been omitted from these result as they could not be measured in kg.

Raw Materials		**kg**	**Emissions to: Air**	**kg**	**Soil**	**kg**	**Water**	**kg**	**Waste Produced**	**kg**
1	Coal, hard	6.9	Carbon dioxide, fossil	30.34	Oils, unspecified	0.0044	Sulfate	0.84	Spoil, unspecified	0.027239
2	Carbon dioxide, in air	3.0	Carbon dioxide, biogenic	5.03	Calcium	0.0021	Calcium	0.25	Slags	0.010476
3	Gravel	2.4	Carbon dioxide, land transformation	1.27	Glyphosate	0.0014	Chloride	0.19	Mineral waste	0.009504
4	Coal, brown	1.4	Used air	1.14	Carbon dioxide, to soil or biomass stock	0.0014	Sodium	0.13	Tailings, unspecified	0.002578
5	Air	1.4	Water	0.73	Azadirachtin	0.0012	Silicon	0.13	Demolition waste, unspecified	0.000603
6	Oil, crude	1.3	Carbon dioxide	0.31	Chloride	0.0009	Nitrate	0.11	Waste, toxic	0.000004
7	Oxygen	0.9	Sulfur dioxide	0.11	Sodium	0.0009	Magnesium	0.11	Waste, industrial	0.000001
8	Inert rock	0.6	Methane, fossil	0.10	Carbaryl	0.0005	Iron	0.08	Bauxite residue, from aluminium production	0.000001
9	Calcite	0.4	Nitrogen oxides	0.06	Iron	0.0005	Potassium	0.06	Refractory	0.000001
10	Calcium carbonate	0.3	Carbon monoxide, fossil	0.02	Carbon	0.0005	Phosphate	0.03	Chemical waste, inert	0.000001
Total substances:		**180**	**426**		**334**		**323**		**19**	

4.3 Inventory Impact Assessment

The LCIA phase involves relating the inventory results to the impact categories by category indicators. ***Table 6*** shows the absolute amounts of each impact category indicator produced during production of 1 kg of lettuce in order to understand the magnitude of associated environmental impacts.

Table 6 Absolute values of each impact category indicator for 1 kg of lettuce produced hydroponically in the Italian vertical farming company's laboratory.

Impact category	Abbreviation	Total	Unit
Global warming	GW	37.18817	kg CO_2 eq
Stratospheric ozone depletion	SOD	0.00005	kg CFC_{11} eq
Ionizing radiation	IR	5.61236	kBq Co-60 eq
Ozone formation, Human health	OF – HH	0.06615	kg NO_x eq
Fine particulate matter formation	PMF	0.05114	kg $PM_{2.5}$ eq
Ozone formation, Terrestrial ecosystems	OF – TE	0.06708	kg NO_x eq
Terrestrial acidification	TA	0.15834	kg SO_2 eq
Freshwater eutrophication	FEut	0.01129	kg P eq
Marine eutrophication	ME	0.00717	kg N eq
Terrestrial ecotoxicity	TE	78.77209	kg 1,4-DCB
Freshwater ecotoxicity	FEco	2.51236	kg 1,4-DCB
Marine ecotoxicity	MEco	3.14491	kg 1,4-DCB
Human carcinogenic toxicity	HCT	1.08464	kg 1,4-DCB
Human non-carcinogenic toxicity	HNT	22.71517	kg 1,4-DCB
Land use	LU	6.51889	m^2a crop eq
Mineral resource scarcity	MRS	0.06065	kg Cu eq
Fossil resource scarcity	FRS	9.54103	kg oil eq
Water consumption	WC	2.48417	m^3

Initially this study planned to analyse the following impact categories in more detail: global warming, marine and freshwater eutrophication, land use, fossil resource scarcity and water consumption, due to their relevance as highlighted in literature (Goldstein, 2018; Romeo, Vea & Thomsen, 2018). However, subsequent analysis of results highlighted additional impact categories with high indicator amounts. As such, the study will include all impact categories of the ReCiPe method and analyse key features from them all.

4.3.1 Contribution analysis

Figure 7 presents the contribution of each input involved in the production of 1 kg of lettuce for the standard model within the system boundaries as a share of the total environmental impact for each impact category. The different impact categories are presented on the X-axis; the Y-axis shows the contributing inputs to the total environmental impact for each category in percentages. Although the absolute amounts differ widely between impact categories (as seen in ***Table 6***), this is a useful graph to show the relative importance of each input to contributing to the environmental impacts. Following the rules as suggested by Zampori et al. (2016), a hotspot analysis can be found in ***Table 7*** whereby inputs that contribute to greater than 50% of environmental impact in an impact category or where two inputs combined are greater than 80% associated impacts are identified as hotspots. Electricity consumption has been identified as a hotspot in 14 impact categories, substrate in 2 and both of those combined as the hotspot for the SOD impact category.

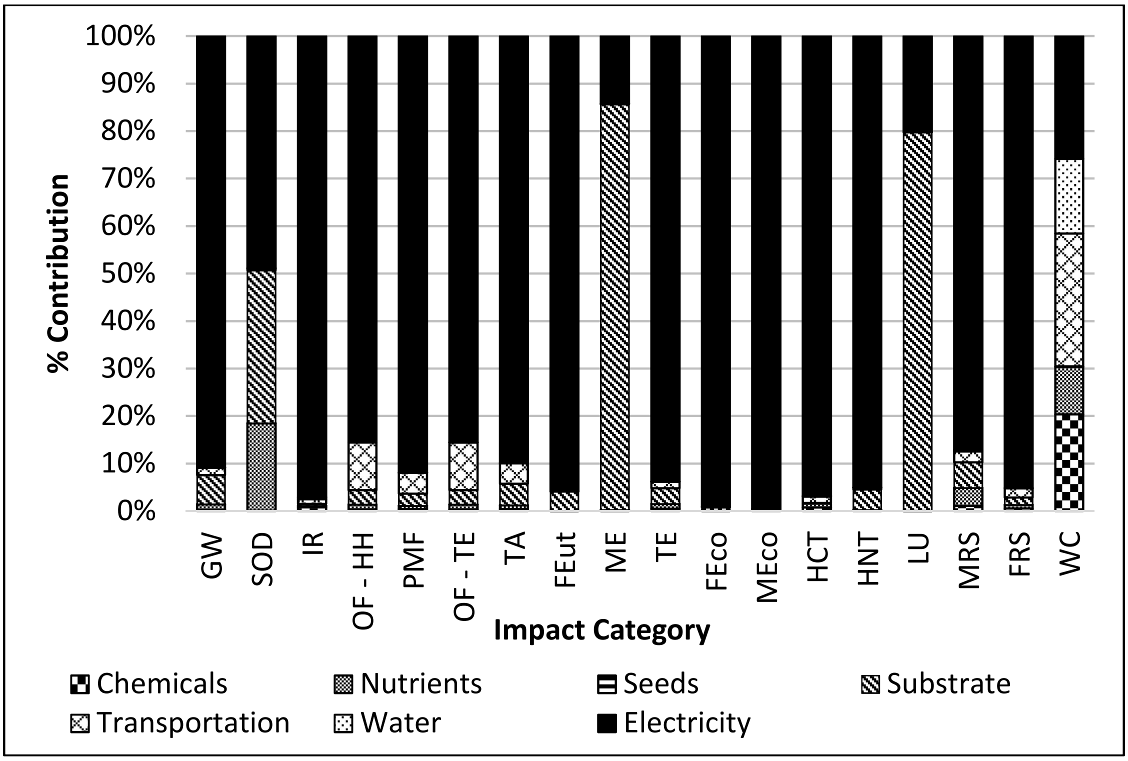

Figure 7 Contribution of different inputs (in %) to the environmental impact indicators in the production of 1 kg of lettuce when using the standard model.

Electricity consumption is by far the largest contributor to associated environmental impacts and accounted for between 85% to >99% of impacts in all impact categories excluding SOD, ME, LU and WC. Coconut coir and perlite mixed substrate used has also been identified as a major contributor, accounting for 85% and 80% of the impacts in the ME and LU impact categories. In the land use category, even though the land required per functional unit is only 0.13 m^2, when including the production of substrate used and electricity consumption, the total land used is 6.5 m2a crop eq (i.e. land occupation in m^2 per year). In the WC category direct consumption of water in the laboratory only accounts for 16% of the water footprint. Additional water used during transportation of inputs contributes 28%, for production of electricity 26%, chemicals 20% and nutrients 10% accounts for the remainder of the total water footprint (2.5 m^3).

Table 7 Hotspot analysis of each impact category for the standard model.

Impact category	**Hotspot**	**Contribution**
Global warming	Electricity	91%
Stratospheric ozone depletion	Electricity & Substrate	81%
Ionizing radiation	Electricity	97%
Ozone formation, Human health	Electricity	86%
Fine particulate matter formation	Electricity	92%
Ozone formation, Terrestrial ecosystems	Electricity	86%
Terrestrial acidification	Electricity	90%
Freshwater eutrophication	Electricity	96%
Marine eutrophication	Substrate	85%
Terrestrial ecotoxicity	Electricity	94%
Freshwater ecotoxicity	Electricity	>99%
Marine ecotoxicity	Electricity	>99%
Human carcinogenic toxicity	Electricity	97%
Human non-carcinogenic toxicity	Electricity	95%
Land use	Substrate	80%
Mineral resource scarcity	Electricity	87%
Fossil resource scarcity	Electricity	95%
Water consumption	No hotspot	-

Two impact categories are mentioned where their combined contribution equals >80% of total environmental impact (Zampori et al., 2016).

As it became clear electricity consumption is the highest contributing factor in many impact categories, it was necessary to investigate this input further. ***Table 8*** shows the electricity consumed by each electrical equipment used within the system boundaries of the standard model as a percentage of the total amount of electricity used.

Table 8 Share of electricity consumption by equipment type and absolute amount consumed to produce 1 kg of lettuce at the laboratory.

Electricity consumption	**HVAC system**	**Lights**	**Fans**	**Pumps**	**Dehumidifier**
Share %	46%	21%	19%	9%	5%
kWh	36.18	16.82	15.13	7.51	3.85

Figure 8 presents a modified version of ***Figure 7***, whereby the contribution of different inputs (in %) to the total environmental impact is shown for the different impact categories, however the electricity consumption has now been split into consumption per electrical equipment used. For example, in the GW impact category, the contribution of electricity consumption to environmental impacts is 91%, of which the HVAC system accounts for 41%, lighting is 19%, fans are 17%, ebb-and-flow pumps account for 9% and finally the dehumidifier for 4%, whilst substrate accounts 6%.

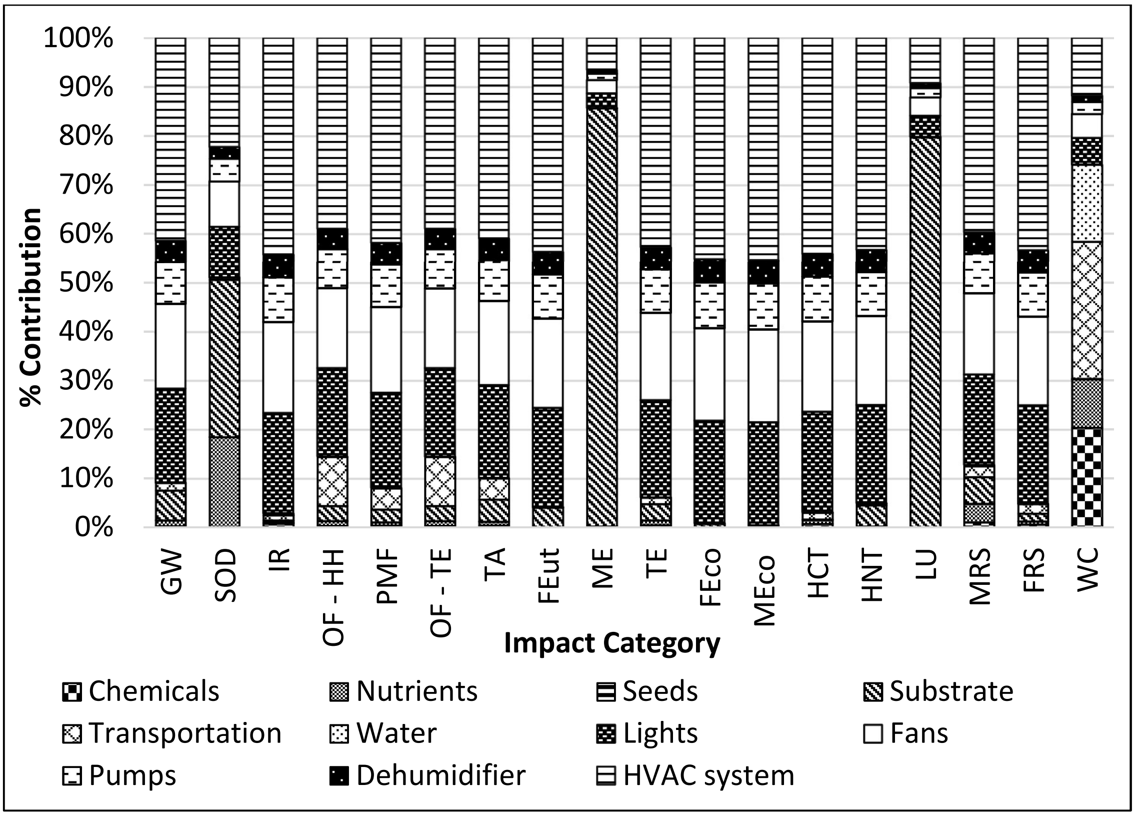

Figure 8 Contribution of different inputs (in %) to the environmental impact indicators in the production of 1 kg of lettuce when using the standard model. Electricity consumption is represented per equipment type (Lights, Fans, Pumps, Dehumidifier or HVAC system).

4.3.2 Contribution analysis excluding electricity

As the electricity consumption is the main contributing factor to environmental impacts for many impact categories, it is difficult to understand the relative effects of all other inputs. To resolve this, a contribution analysis excluding electricity consumption is presented in ***Figure 9****.* Any hotspot inputs (when electricity in excluded) have been identified as shown in ***Table 9***.

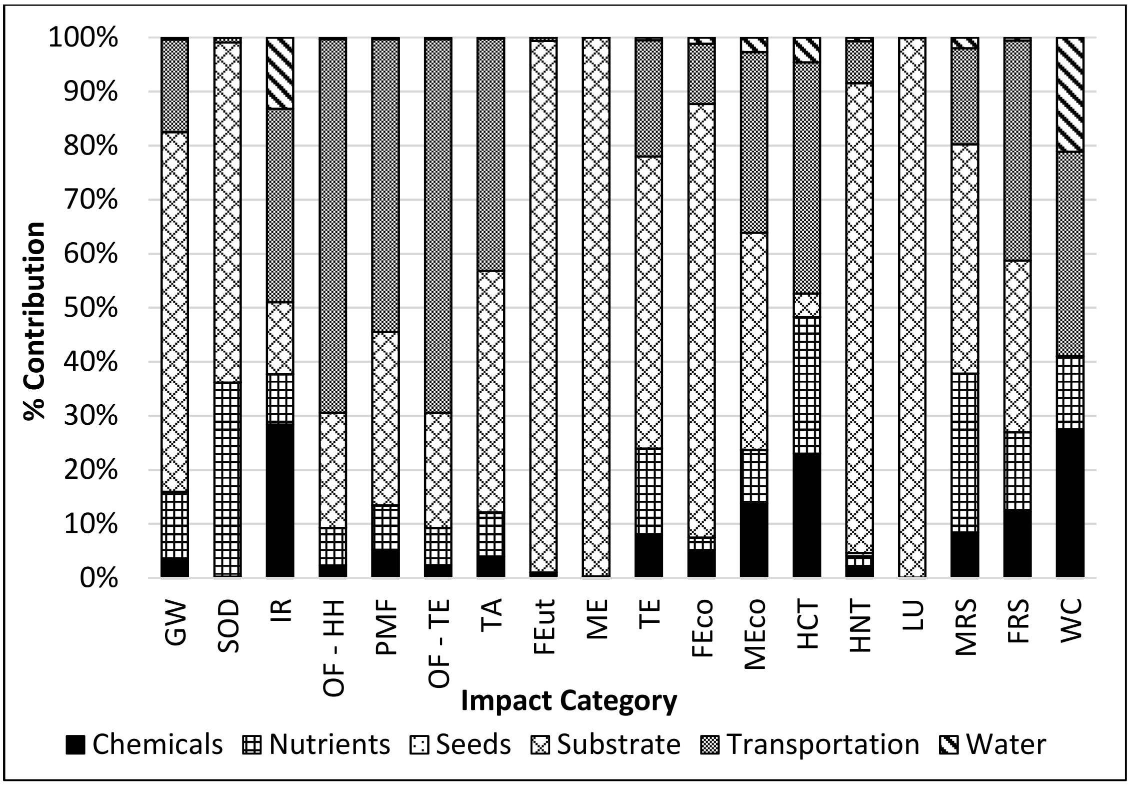

Figure 9 Contribution of different inputs, excluding electricity, (in %) to the environmental impact indicators in the production of 1 kg of lettuce when using the standard model.

By removing the electricity consumption, the environmental impacts are more spread between the inputs. Throughout the impact categories, substrate and/or transportation of inputs are the largest contributing factors to environmental impacts as can been seen in the hotspot analysis (whilst excluding electricity) in ***Table 9***. In the global warming impact category, substrate and transportation accounted for 67% and 17% respectively of the environmental impact which equates to a 2.85 kg CO_2 eq. The same inputs also contributed 54% and 21% respectively to the terrestrial ecotoxicity impact category (total 4.9 kg 1,4-DCB each). In the land use impact category, substrate contributed to >99% of the environmental impacts (5.2 m^2a crop eq). Lastly, although there is no clear hotspot in the water consumption impact category, transportation (38%), chemicals (28%) and water (21%) are the largest contributing factors for environmental impacts.

Table 9 Hotspot analysis of each impact category when excluding environmental impact of electricity consumption. Total contribution when including electricity is highlighted in final column to give perspective of this analysis.

Impact category	**Hotspot**	**Contribution**	**Total (inc. electricity)**
Global warming	Substrate	67%	6%
Stratospheric ozone depletion	Substrate	63%	32%
Ionizing radiation	No hotspot		
Ozone formation, Human health	Transportation	69%	10%
Fine particulate matter formation	Transportation	54%	4%
Ozone formation, Terrestrial ecosystems	Transportation	69%	10%
Terrestrial acidification	Substrate & transportation	88%	8.5%
Freshwater eutrophication	Substrate	98%	4%
Marine eutrophication	Substrate	>99%	85%
Terrestrial ecotoxicity	Substrate	54%	3%
Freshwater ecotoxicity	Substrate	80%	0.5%
Marine ecotoxicity	No hotspot		
Human carcinogenic toxicity	No hotspot		
Human non-carcinogenic toxicity	Substrate	87%	4%
Land use	Substrate	>99%	80%
Mineral resource scarcity	No hotspot		
Fossil resource scarcity	No hotspot		
Water consumption	No hotspot		

Two impact categories are mentioned where their combined contribution equals >80% of total environmental impact.

4.4 Sensitivity analysis

Given that electricity consumption has been identified as the dominant contributing factor for associated environmental impacts in all impact categories, it was deemed appropriate to complete a sensitivity analysis on the amount of electricity consumed. Three different sensitivity analyses relating to electricity were completed. First, the number of LED lights used during production were increased from 4 per grow level to 5. The second model reduced the amount of time the HVAC system was in operation in the laboratory from 80% to 50%. Finally, is a comparison between 2017 and 2030 electricity mixes in Italy.

In addition to altering electricity consumption, different substrate types were also modelled to offer suggestions as to the most environmentally sustainable option based on available information. For further information regarding the choices behind the analysis undertaken see Section 3.3.

4.4.1 Increasing numbers of LED lights

The effect of the number of LED lights on each grow shelf has on plant output has been trialled by the Italian vertical farming company. A sensitivity analysis was run to understand the change in associated environmental impacts. The standard model assumes that four lights are used, however using five lights is also an option so a comparative analysis between the two scenarios is shown in ***Figure 10*** using the standard model as a baseline. By increasing the number of LED lights used, the energy consumption increased by 24.9%, from 16.83 kW to 21.02 kW. Associated environmental impacts increased by 0.8 – 5.0% across the different impact categories (also see ***Table 12***). The GW impact category increased by 4.6% which is equivalent to 1.8 kg CO_2 eq. To put this into perspective, according to a greenhouse gas equivalencies calculator this is the same as driving an average car an extra 4 miles (US EPA, 2015).

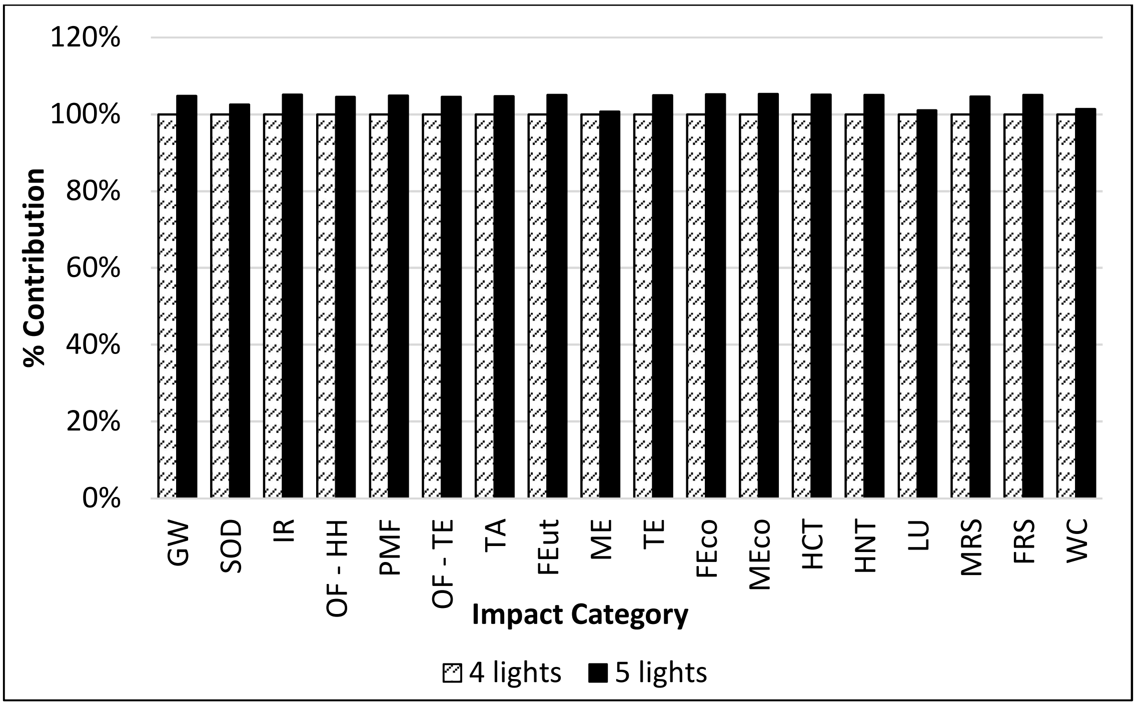

Figure 10 Comparison of the environmental impacts of producing 1 kg of lettuce with either 1) 4 LED lights per grow shelf (i.e. the standard model) or, 2) 5 LED lights.

4.4.2 Reducing HVAC system operating time

Given the difficulties in calculating energy requirements of the HVAC system and the dominance of electricity consumption in associated environmental impacts (detailed in Section 3.3.2), a sensitivity analysis was completed in which the time the HVAC system operates is reduced from 80% (baseline) to 50% to understand the implication of the assumption. By doing so, the electricity consumption of the HVAC system decreased by 37.5%, from 36.18 kWh to 22.61 kWh, and reduced the total electricity usage to 65.92 kWh. Unsurprisingly, associated environmental impacts in each category decreased by 2 – 17%, as can be seen in the comparative analysis in ***Figure 11***. For example, in the GW impact category, the CO_2 eq declined by 16% to a total of 31.4 kg CO_2 eq produced.

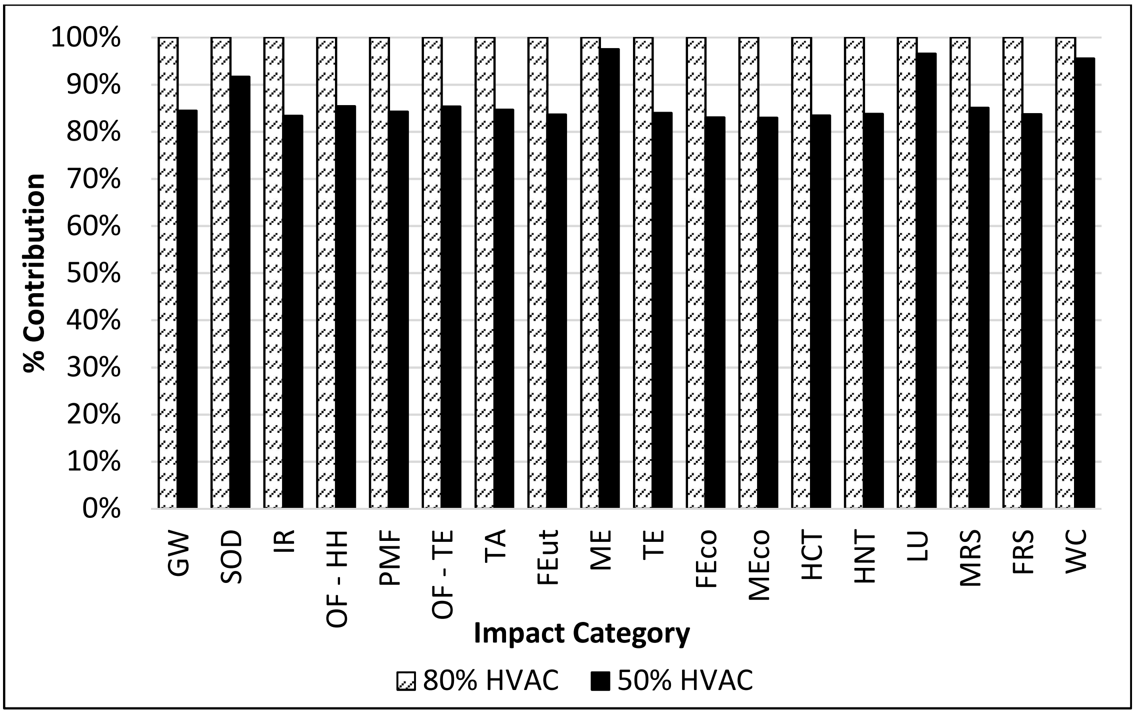

Figure 11 Comparison of the environmental impacts of producing 1 kg of lettuce with the HVAC system operating at 1) 80% (i.e. the standard model) or, 2) 50% of the time.

4.4.3 Changing substrate type

Different substrates described in ***Table 10*** have been trialled in the laboratory to find the best option commercially and to improve growing productivity. ***Figure 12*** summarises how changing the substrate type changes associated environmental impacts by using the using the standard model as a baseline.

Table 10 Substrate types trialled in the hydroponic grow system.

Substrate Material	Input Material	Estimated Source
Standard model - Coconut coir and perlite mix	80% coconut coir	India
	20% perlite	Greece
Peat	100% processed peat	Ireland
Rockwool	100% rockwool	Netherlands

Altering substrate type to peat results in large decreases in the SOD (- 46%), ME (- 582%) and LU (- 386%) impact categories. However, this comes at the expense of an increase of 9.5% in the OF – HH, 9.6% in the OF – TE, 11.6% in the FRS and finally a 33% increase in WC. A similar pattern can be found when altering substrate type to rockwool, however the subsequent increases in OF – HH, OF – TE and FRA as seen when using peat, in this case have resulted in a decrease by 11.9% in both OF – HH and OF – TE and a 2.2% decrease in the FRS impact category.

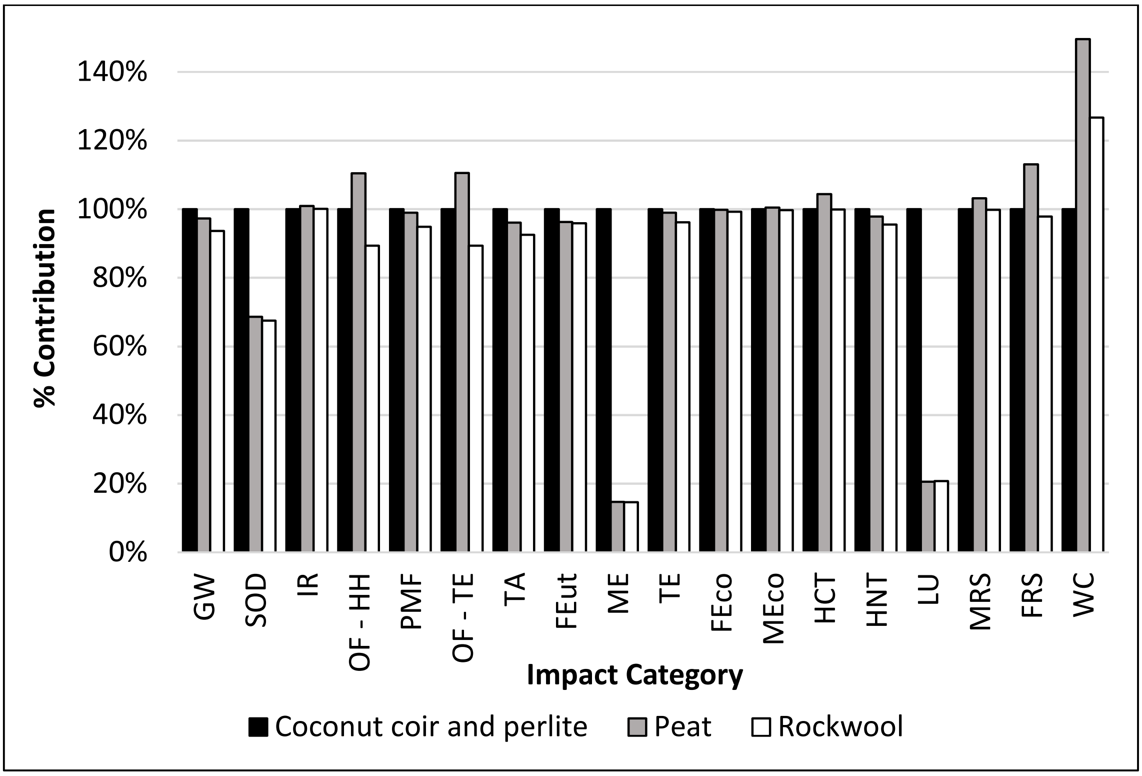

Figure 12 Comparison of the environmental impacts of producing 1 kg of lettuce by using different substrate types – coconut coir and perlite mix as in the standard model (baseline), peat or rockwool.

4.4.4 Future contribution analysis

Electricity consumption was identified as a hotspot early in the research and given the transient nature of the energy mix and movements towards renewable energy production worldwide, it seemed prudent to investigate how the environmental impacts could vary depending on the energy mix. 2030 was chosen as a reference point due to its importance in meeting decarbonisation goals and due to the commitments of the Italian government (Italy, 2018). Compared are the impacts of producing 1 kg of lettuce hydroponically in 2017 and in 2030 as presented in ***Table 11*** using 2017 as a baseline. As opposed to the standard model in which a general Italian electricity dataset for 2014 was used, in the 2017 and 2030 scenarios electricity consumption has been split by the production method. For further methodology explanation refer to Section 3.3.4.

Table 11 Comparison of the environmental impacts of producing 1 kg of lettuce when the electricity consumption has been calculated by fuel type for 2017 (baseline) and 2030. The black and white arrows indicate an increase or decrease in environment impacts for each impact category.

		Impact indicator score and % of baseline				
Impact Category	**Unit**	**2017 Energy Mix**		**2030 Energy Mix**		
GW	kg CO_2 eq	43.44	100%	29.65	**68%**	⬇
SOD	kg CFC_{11} eq	0.00004	100%	0.00003	**87%**	⬇
IR	kBq Co-60 eq	0.96	100%	0.86	**90%**	⬇
OF – HH	kg NO_x eq	0.09	100%	0.05	**53%**	⬇
PMF	kg $PM_{2.5}$ eq	0.04	100%	0.01	**33%**	⬇
OF – TE	kg NO_x eq	0.09	100%	0.05	**54%**	⬇
TA	kg SO_2 eq	0.13	100%	0.05	**34%**	⬇
FEut	kg P eq	0.001	100%	0.001	**102%**	⇧
ME	kg N eq	0.01	100%	0.01	**99%**	⬇
TE	kg 1,4-DCB	40.12	100%	43.19	**108%**	⇧
FEco	kg 1,4-DCB	0.04	100%	0.04	**103%**	⇧
MEco	kg 1,4-DCB	0.07	100%	0.06	**89%**	⬇
HCT	kg 1,4-DCB	0.27	100%	0.28	**106%**	⇧
HNT	kg 1,4-DCB	1.91	100%	2.00	**105%**	⇧
LU	m^2a crop eq	5.34	100%	5.26	**98%**	⬇
MRS	kg Cu eq	0.05	100%	0.08	**149%**	⇧
FRS	kg oil eq	13.21	100%	9.68	**73%**	⬇
WC	m^3	207.40	100%	226.39	**109%**	⇧

Results indicate that by increasing the share of renewables (as detailed in Section 3.3.4) does not automatically decrease all environmental impacts. Environmental impacts decrease in 11 out of 18 impact categories as seen in ***Table 11.*** The most substantial decreases are seen in the GW (32%) and the FRS (27%) impact categories which can both be attributed to the decline of oil and coal produced electricity. However, there is a trade-off with increased renewables use as increased environmental impacts occurred in impact categories such as TE, HNT, MFS and WC**.** In the TE and MRS impact categories the impacts increase by 8% and 49% respectively which can both be attributed to the increased share of solar power in the energy mix. Additionally, WC increased between 2017 and 2030 by 9%, to a total of 226.4 m^3, which can be attributed to increases in solar power and hydroelectric power.

4.4.5 Sensitivity analysis summary

Table 12 has been designed to provide an overview of the findings of the electricity and substrate sensitivity analysis previously discussed for easy communication with the Italian vertical farming company. For each scenario, the change in environmental impact is shown in two separate ways. The first column describes the percentage change of the individual inputs in question, such as the environmental impacts of electricity. The second column then shows the percentage change to the overall environmental impact to highlight how an input's impact may decrease substantially but the overall impact may not change. In the case of substrate scenarios, it must be mentioned that whilst the substrate impacts may decrease, the total scenario impacts can increase due to the associated change in transportation of inputs which has not been included in the summary table. Also, the change in individual impact of electricity is the same across impact categories as it is either increase or decrease. However, in the case of switching substrate types, the subsequent impact of the substrate changes across the impact categories due to associated trade-offs of the different materials.

Table 12 Comparison of the environmental impacts of producing 1 kg of lettuce in different scenarios. Electricity consumption changed by a) altering the number of LED lights per grow rack from 4 to 5 or, b) HVAC system operating time from 80% to 50%. Substrate type changed to a) Peat, or b) Rockwool. Standard model used as baseline. All inputs remain the same in each scenario unless stated. Note in the substrate scenarios, the transportation has also altered which can increase total environmental impact even if the substrate impact has decreased.

	Altered electricity consumption:				**Altered substrate type:**			
	4 to 5 lights		**80% to 50%**		**Peat**		**Rockwool**	
Impact Category	Electricity impact (lights)	Total system impact	Electricity impact (HVAC)	Total system impact	Substrate impact	Total system impact	Substrate impact	Total system impact
Global warming (GW)	+ 25% in all impact categories	+ 4.8%	- 37.5% in all impact categories	- 15.5%	- 94.8%	- 2.7%	- 82.7%	- 6.4%
Stratospheric ozone depletion (SOD)		+ 2.6%		- 8.3%	- 99.8%	- 31.3%	- 99.6%	- 32.4%
Ionizing radiation (IR)		+ 5.1%		- 16.6%	- 62.4%	+ 1.0%	+ 268.1%	+ 0.1%
Ozone formation, Human health (OF – HH)		+ 4.5%		- 14.6%	- 89.1%	+ 10.5%	- 57.0%	- 10.7%
Fine particulate matter formation (PMF)		+ 4.9%		- 15.7%	- 86.1%	- 1.0%	- 40.5%	- 5.2%
Ozone formation, Terrestrial ecosystems (OF – TE)		+ 4.5%		- 14.6%	- 89.1%	+ 10.6%	- 56.3%	- 10.6%
Terrestrial acidification (TA)		+ 4.7%		- 15.3%	- 95.7%	- 3.9%	- 73.4%	- 7.4%
Freshwater eutrophication (FEut)		+ 5.1%		- 16.4%	- 91.6%	- 3.7%	- 99.4%	- 4.1%
Marine eutrophication (ME)		+ 0.8%		- 2.4%	- 99.9%	- 85.3%	- 99.9%	- 85.4%
Terrestrial ecotoxicity (TE)		+ 5.0%		- 16.0%	- 95.5%	- 1.0%	- 80.8%	- 3.8%
Freshwater ecotoxicity (FEco)		+ 5.2%		- 16.9%	- 89.9%	- 0.1%	- 94.8%	- 0.7%
Marine ecotoxicity (MEco)		+ 5.3%		- 17.0%	- 54.8%	+ 0.5%	- 71.5%	- 0.2%
Human carcinogenic toxicity (HCT)		+ 5.1%		- 16.5%	+ 129.2%	+ 4.4%	+ 726.6%	- 0.1%
Human non-carcinogenic toxicity (HNT)		+ 5.0%		- 16.2%	- 94.8%	- 2.2%	- 97.9%	- 4.5%
Land use (LU)		+ 1.1%		- 3.4%	- 99.9%	- 79.4%	- 99.4%	- 79.2%
Mineral resource scarcity (MRS)		+ 4.6%		- 14.9%	- 95.8%	+ 3.2%	+ 29.1%	- 0.1%
Fossil resource scarcity (FRS)		+ 5.0%		- 16.2%	+ 580.5%	+ 13.1%	- 29.5%	- 2.1%
Water consumption (WC)		+ 1.4%		- 4.4%	+ 11.5%	+ 49.6%	+ 50466.4%	+ 26.7%

5. Discussion

5.1 Introduction

This chapter will discuss the findings of the study, highlight differences with literature and evaluate implications regarding sustainability of vertical farming, including possibilities in the future.

5.2 Electricity consumption

Electricity consumption is responsible for most environmental impacts associated with producing lettuce in the experimental vertical farm which further validates what was found in literature (Barbosa et al., 2015; Graamans et al., 2017). This resulted in large impacts in global warming, terrestrial ecotoxicity, fossil resource scarcity and water consumption impact categories.

Lighting and HVAC system were also confirmed as the largest energy users within vertical farms (Graamans et al., 2017; Harbick & Albright, 2016). However, the extent of HVAC system requirements was 45% and higher than those found in literature, which estimated 20-30% (Kozai, Niu & Takagaki, 2016). Uncertainties in the data quality may be partly responsible for this difference as seen in the sensitivity analysis (***Figure 11***), reflecting a limitation of the study. Implications of this mean that the total energy consumption may not be accurate and subsequently the associated environmental impacts. Another point to consider is the differences in HVAC requirements in different locations as demonstrated by Graamans et al. (2017) indicating when these figures are accurate, impacts will differ dependent on local climate and thus general extrapolations of results are difficult. There is greater confidence in the electricity consumption of lighting which represents 21% of the total amount consumed.

The difference in energy consumption for vertical farms and greenhouse growing is significant due to the additional lighting and HVAC used in the closed vertical farming system (Graamans et al., 2017; Harbick & Albright, 2016). However, the disparity between energy use of vertical farms and conventional farming is even larger, as established by Barbosa et al. (2015). Energy consumption associated with conventional farming, typically due to machinery and irrigation, is only 4% of the consumption of vertical farming, on a per kg of output basis. If an equivalent LCA were to be performed on conventional farming, the implications of this would be a drastic reduction in environmental impacts associated with electricity production across all impact categories. Using these figures as an example, CO_2 eq emissions would decrease by 87%, equivalent to driving 71 miles in the average car (US EPA, 2015).

The impacts were high due to the absolute amount consumed by each piece of equipment but also due to the electricity production mix in Italy (see ***Figure 6***) which was dominated by gas, oil and coal based production, which stood at 55% in 2014 (Statista Research Department, 2019). It must be noted that the energy mix may have changed slightly since 2014 as Italy works to increase the share of renewables to meet the EU Climate and Energy framework requirements (European Commission, 2018). Subsequently, the impacts may slightly differ to the energy scenario used in the standard model. The sustainability of vertical farming, in the context of electricity usage, is discussed further in Sections 5.5 and 5.6.

5.3 Substrate use

The extent of the environmental impacts of the substrate type was surprisingly high as substrate is not often included in environmental studies of vertical farms or highlighted as a potential environmental issue (Al-Kodmany, 2018; Kozai, Niu & Takagaki, 2016; Naus & Plantlab, 2018). This difference may be due to different grow systems whereby substrates are either not used or only used in limited quantities during seed propagation. Literature and articles also portray the idea that substrates have a high reuse value (Kozai, Niu & Takagaki, 2016), however even if they can be reused, there are only a limited number of times that this can happen (Elliot, 2017) and often at a cost of high risk of contamination and complex cleaning routines; as was seen in the experimental laboratory, they are not reused at all. Thus, environmental impacts subsequently increase which implies that other studies for which substrate has not been included in the analysis may have underestimated associated environmental impacts.

In the sensitivity analysis (***Figure 12***), by changing the main substrate type from a coconut coir and perlite mix to a peat substrate or a rockwool substrate subsequently changed the environmental impacts of the system. It is difficult to say exactly which one may be the most sustainable due to the trade-offs between them as was indicated previously in literature (Barrett et al., 2016; Quantis, 2012). Whilst peat and rockwool reduces the impacts of Stratospheric Ozone Depletion, Marine Eutrophication and Land Use, Water Consumption and Fossil Resource Scarcity both increase amongst a few others. Assuming they all fulfil the same function, this highlights the difficulty in choosing a substrate type based on their associated environmental impacts.

5.4 Other inputs used – water, nutrients

Although the electricity consumption dominates the environmental impacts of vertical farming, the sustainability also relies upon the resource efficiency of the system, particularly regarding water and nutrient use, and lack of pesticide use.

Direct water consumption in this case study was found to be considerably higher than in other vertical farm and greenhouses studies, however it was still lower than conventional farming. To produce 1 kg of lettuce in the laboratory requires 75 L of direct water to be used. In comparison, the methodology used by Romeo et al. (2018) calculates that 7.5% of this figure would be required per kg of leafy greens produced in a vertical farm. Similarly, the methodologies of Barbosa et al. (2015) and Nicholson et al. (2019) calculate that 26-27% of the laboratory figure is needed for greenhouse growing. Arguably, most of the discrepancy between this study and other vertical farm and greenhouse growing in literature could be attributed to the lack of onsite water recycling systems and limited efficiencies of scale (Kozai, Niu & Takagaki, 2016). However, the difference may also be in part due the practicalities of real growing consumption data that may not be represented by calculations based on assumptions of a closed loop system. Furthermore, these studies do not adequately incorporate some practical aspects of a vertical farm, for example the occasional need to perform a complete flush of the growing racks (Kozai, Niu & Takagaki, 2016).

Additionally, in conventional farming systems, Barbosa et al. (2015) and Kikuchi et al. (2018) calculated direct water consumption to be 250 L and 459.4 L of water used per kg of lettuce produced. This would indicate that vertical farming systems could be particularly useful, and a more sustainable option, in areas of water scarcity due to more efficient water use. A specific advantage of the method due to the projected increase in drought-prone regions as indicated by the FAO (2019).

When considering the total water consumption from the LCA results per kg of lettuce produced requires the consumption of 2480 L, 26% of which is as a result of the electricity used. Part of consumption may be due to hydropower electricity production which accounts for 22% in the 2014 Italian electricity mix. In the sensitivity analysis, which considers the 2030 energy mix, total water consumption increases by 9% which may be due to the increase of hydropower in the energy mix. It may not be fair to compare this to conventional farming values mentioned previously as they are not from a lifecycle perspective, but they do indicate the stark water requirement needed for electricity consumption. Research is needed to clarify water consumption of conventional farming from a lifecycle perspective.

The environmental impacts from nutrient use were relatively small, accounting for 18% and 10% in the Stratospheric Ozone Depletion and Water Consumption impact categories, with very limited absolute impacts to the FE and ME impact categories. This indicates a large improvement in comparison to conventional farming practices whereby nutrient use (and pesticide use) is responsible for the majority of environmental impacts (de Backer et al., 2009). These findings are unsurprising given the claims relating to increased resource efficiency of nutrient use in vertical farms (Al-Kodmany, 2018; Kozai, Niu & Takagaki, 2016).

Land use is also considered as an important resource. The vertical farm studied only utilised one production floor with three shelving layers and for every 1 kg of lettuce produced required direct use of 0.13 m^2 for the duration of the grow cycle (less than one month). In comparison, to produce 1 kg of conventional farmed lettuce in Greece requires 0.37 m^2 over the course of a year (Foteinis & Chatzisymeon, 2016). The area used in the vertical farm only includes the area directly used for growing, however it represents a significant reduction in land use when in comparison to conventional farming and reflects results in literature (Al-Kodmany, 2018; Benke & Tomkins, 2017; Despommier, 2011). Further land use efficiency is also possibly with increasing floors in the building, as would be expected in a commercial-scale vertical farm (Kozai, Niu & Takagaki, 2016).

However, it must also be mentioned that in the Land Use impact category, a very small proportion is attributed to direct land use when producing the functional unit, most impacts can be related to electricity consumption and production of substrate. To fully understand these implications a comparison LCA is needed to investigate between a vertical farm and conventional farming.

A notable factor worth briefly discussing is the non-existent use of pesticide in vertical farming. The only pest control used is a small amount of biocide and as can be seen in ***Table 2***, has very little environmental impact. When compared to conventional farming, this a major benefit in terms of sustainability; this corroborates literature findings (Goldstein, 2018; Kozai, Niu & Takagaki, 2016; Pinstrup-Andersen, 2018).

5.5 So how sustainable is vertical farming?

An aim of this thesis is to assess the sustainability of vertical farming in its current state by considering findings from this study and comparing to literature. This is best done via a comparison to conventional farming. The following are criteria which will be considered when assessing the sustainability of vertical farming:

- Biodiversity preservation;
- Use of renewables is at a rate within regenerative capacity;
- Non-renewables used below rate of renewable development;
- Reuse and recycling incorporated into system design;
- Waste emissions below assimilative capacity of the environment;
- Sustainable energy sources (Morelli, 2011).

Initially, vertical farming appears more sustainable than conventional farming due to the reduction in direct inputs used such as water, fertiliser and pesticides. Pesticides are not used at all within the system and the small amounts of biocide used has limited impacts in the LCA results (see Chemicals in ***Figure 7***) which reduces the risk of biodiversity loss (McLaughlin & Mineau, 1995). Resource efficiency for water and nutrients are higher than conventional farming with potential to increase further if recycling technologies are implemented (Kozai, Niu & Takagaki, 2016). However, uncertainty increases on the sustainability of vertical farming when considering the impacts of substrate use and energy consumption.

As discussed in Section 4.3.1, high electricity consumption in the studied farm substantially increases environmental impacts across the impact categories due to production methods and non-renewable energy use. Consequently, it could be argued that a vertical farming system is at risk of using non-renewables at too high a rate resulting in waste emissions above the assimilative capacity of the environment, such as emissions of CO_2. This would be improved if the case study system uses an electricity mix with a high proportion of renewable energy.

The impacts of electricity consumption are not surprising as it has always been highlighted as a disadvantage of vertical farming. However, the use of substrate and associated impacts are not as well known. News articles often claim the sustainability of the technique is due to the ‘soilless’ hydroponic growing method (Goldstein, 2018). Whilst it is the case that no soil is used, some sort of substrate is needed to anchor the root system and deliver water and nutrients to the plants as they grow (Beacham, Vickers & Monaghan, 2019). Various substrates exist – coconut coir, perlite, rockwool, pine bark, wood fibre etc. – and each one has different environmental impacts as seen in the sensitivity analysis (see Section 4.4.3) and supported by literature (Barrett et al., 2016; Quantis, 2012). Repurposed waste materials, such as coconut coir, can be used however environmental impacts can still be high due to the extensive processing required to make a sterile and efficient substrate (Barrett et al., 2016).

When considering the lifecycle impacts of the system including those of electricity and substrate use, environmental sustainability criteria are not being met. However, there is clear scope for the sustainability of vertical farming to be improved.

5.6 How sustainable could vertical farming become?

If vertical farming is not yet sustainable for this case study example, is there potential for the technology to become more sustainable in the future? Possibly, but this is predicated on several key improvements.

Predominantly, the prospects of vertical farming will depend on improvements to energy efficiency and energy sources. The first concern is improving energy efficiency of the electrical equipment used with the focus being on the lighting and HVAC system requirements, but it is also important to consider the requirements of minor equipment as well as in this system they contributed to 33% of energy consumption.

The system used in this study uses LED lighting, typical of vertical farming (Kozai, Niu & Takagaki, 2016). The efficiency of LED lighting for domestic uses has improved drastically in the last 20 years, with a further 25% improvement expected by 2030 (EIA, 2014). There are differences between LEDs used in the domestic and farming settings, it can be assumed that LEDs used for agriculture will also achieve a similar level of improvement in efficiency. The improvement in efficiency would result in a reduction of whole-system energy consumption of 5.3%.

The number of lights used per grow rack is an important factor influencing energy consumption. Using the laboratory in this case study as an example, an increase in the number of lights by 25% would be more costly, but plant output would increase. However, the whole-system environmental impact would increase by 5%. This demonstrates the importance of considering these impacts when designing the system as what could be thought of as a simple design choice has significant ramifications.

Energy requirements for HVAC systems greatly differ due to several reasons, one of which is the location of the vertical farm (Barbosa et al., 2015; Graamans et al., 2017). During the design stage, options to reduce energy consumption can include locating in moderate climates where heating and cooling can rely on generation from electrical equipment and natural ventilation (Barbosa et al., 2015). However, one future use for vertical farming is locating them in areas of resource scarcity which often coincide with areas of extreme climate and thus would have higher HVAC energy requirements. In these situations, further options to increase energy efficiency will need to be explored.

Improvements in efficiency of 'lesser' electrical equipment and systems used in vertical farms needs to be considered. Fans, ebb-and-flow water pumps and dehumidifier were found to contribute 33% of energy consumption, considerably higher than the 20-30% suggested by Kozai et al. (2016) which also included HVAC energy requirements. The author notes that the case study system does not benefit from economies of scale, however the results of this study are a useful indicator of the significance of these systems. In order to improve the efficiency of these sub-systems, it would be useful to investigate the different energy requirements of different hydroponic growing methods on the assumption that different pumping requirements would change energy consumption. A comparison study of grow systems such as passive, drip, ebb-and-flow, Nutrient-Film-Technique (NFT), deep water and aeroponics is needed which considers energy requirements but also economic costs and practicalities of each system.

Additionally, sustainability could be improved by increasing the amount of renewable electricity used by the system. This can occur either by relying on the increasing share of renewables in the country-specific mix or on-site renewable energy production, or a combination of the two. From this case study the impacts from changing the share of renewables gives mixed results due to the trade-offs between renewables and non-renewables. For example, as seen in ***Table 11*** the Global Warming Potential decreases by 32% due to the reduction of fossil fuels used in the energy mix whilst mineral resource scarcity increases by 60% presumably due to the increase in solar power and associated need for rare elements used during construction. To extrapolate the findings to vertical farming generally is difficult due to the high variance in energy production mixes in each country and their associated renewable projections (IRENA, 2018). The other option is to instigate onsite renewable power to reduce environmental impacts and increase self-sufficiency. However, there is criticism in the literature regarding the ability of such systems to meet the entire demand of a vertical farm (Graamans et al., 2017).

On-site renewable power generation has the added benefit of providing an independent electricity source for the farm. This will increase resilience to grid outages and resultant crop failure, although resilience will only be truly achieved if coupled with battery storage to protect against the unpredictable generation of most renewables. This independent power generation could also increase access to fresh foods in areas without grid access and offers opportunity to address SDG2 – zero hunger. Additionally, independent power generation could be more useful in the future when frequency of extreme weather events increases (C2ES, 2018). Modular vertical farms are currently being developed, such as those from the Modular Farms Co Australia, which can offer the opportunity to provide fresh foods in areas of need (Modular Farms Australia, n.b.). Modules do not yet seem to be available with renewables included however this should be an area of research due to the mobility of the design which could allow for use after disasters for example. Further research into the viability of such systems are needed to address their effectiveness and to understand the extent of risk in relation to loss of power.

Further reductions in resource use from implementation of closed-loop recycling systems is needed to improve sustainability although the practical effectiveness of such systems is debated. In this case study, no recycling occurred with all water, nutrients and chemicals disposed of. For sustainability to improve in this regard, future, commercial-scale vertical farms should seek to implement some degree of recycling, although this is currently a challenge due to difficulties in maintaining accurate control of nutrient concentrations when a recycling loop is introduced. This is mainly due to a lack of a quick and accurate method of measuring nutrient concentration (Kozai, Niu & Takagaki, 2016).

It is important to recall that vertical farming, in its current state, is not able to produce high-calorie, staple crops such as rice, maize and wheat. Arguably, this falls under 'social sustainability', however the environmental impact of this will increase with demand for these crops. Therefore, a major challenge of vertical farming, if it is to become sustainable, is to be able to produce staple crops. Assuming that the benefits of vertical farming that have been highlighted in this case study can be achieved for these staple crops, then significant reductions in water and pesticide use could be gained.

In summary, current vertical farming methods are not environmentally sustainable as a method of food production. There are sustainable aspects through biodiversity preservation by the reduction in pesticide use, however it can be argued that this is negated by the negative impact of electricity needs. In the future, with developments of efficiency of system components, increasing renewable power and improvements to system design, the sustainability may increase. In reference to the SDGs, as a method to reduce hunger worldwide, it will have limited impact. Reliance on electricity and associated cost of production means farms are limited to areas with ensured supply and niche markets. Improvements to modular transportable vertical farms with attached renewable energy generation may change this perspective however limited evidence has been found yet. That being said, it may come to the point whereby these systems are vital due to increasing environmental crises.

Perhaps the future of vertical farming lies down a different avenue in which the trade-off of high energy consumption permissible. Other uses for the technology include production of plant seedlings or transplants and the production of high-quality pharmaceutical plants to produce medication (Kozai, Niu & Takagaki, 2016). Benefits of growing from transplants in conventional or greenhouse systems include assurance of propagation rates as less affected by weather conditions, overall higher yields and uniformity allowing for accurate harvesting times (Kozai, Niu & Takagaki, 2016).

5.7 Wider implications

Beyond the immediate scope of the sustainability of vertical farming, there are other aspects to consider. For example, this work has highlighted the need to move towards non-fossil fuel based electricity generation as more and more industries become electrified in some way.

Vertical farming is still an emergent technology, and as such has very little policy devoted to it. For it to become a viable food production system i.e. be able to provide significant calorific value, it will likely need support from policymakers through Research and Development funding. Without this step, vertical farming will likely be used for niche, high-value products. In the event of this development in vertical farming, the impact on rural economies may need to be managed. With one of the benefits of vertical farming being an ability to grow close to urban centres, there will be an inevitable reduction in demand from conventional farmers. However, the author believes that as vertical farming stands at the moment, industry first needs to demonstrate it can achieve the theoretical benefits of vertical farming before it can be endorsed by policymakers.

5.8 Limitations

Several limitations of the research need to be noted:

- One case study of an experimental farm will not accurately represent a full-scale vertical farm that in theory is a commercially sound, scaled-up, efficient and optimised;
- Although the general implications of the results have been discussed in Section 5, the results are only from one place and time (i.e. an experimental laboratory and Italian energy mix) so there is a limit as to how far the implications can be accurately extrapolated. Considering the significance of electricity consumption, the effect of changing farm demand, through HVAC requirements for example, and supply, through the electricity generation mix of different countries. Some conclusions can be made by referring to literature however the study alone cannot answer everything.
- There is an uncertainty relating to some of the input data which may affect the reliability of results. HVAC electricity requirements were assumed based of wattage and operating time which as indicated by sensitivity analysis can have a large impact on subsequent environmental impacts and have increased the uncertainty of the results. Secondly, total input amounts were calculated on the assumption that half of the available grow space was for lettuce when the output was continually changing. So, inputs may be not be correctly attributed to lettuce production.
- Lower transportation is a potential advantage of vertical farming not investigated in this study due to the cradle-to-gate nature of the LCA. Subsequently, limited implications of this reduction when in comparison to conventional farming can be made.

6. Conclusions and Recommendations

6.1 Overview

The main aim of this thesis was to quantify the environmental impacts and identify key environmental hotspots of hydroponic lettuce production at an Italian experimental vertical farm. Additionally, the current and possible sustainability of the system was to be evaluated. The following details the main conclusions from this study.

Literature is correct in that low water and nutrient use is a benefit of vertical farming, this is at the cost of high electricity consumption. In addition, this study has found that previous work has underestimated water use due to lack of consideration of practical aspects e.g. system flushing.

Electricity consumption was the dominating factor of environmental impacts for the majority of impact categories studied. Substrate choice also contributes a significant amount. This work has looked at substrate type with more consideration than previous studies, especially when viewing vertical farming as a whole system.

Lighting and HVAC systems are the largest contributors to electricity consumption in the real system, confirming literature findings. However, there is uncertainty regarding the accuracy of HVAC electricity requirements, which may impact the results of this study. Additionally, this work has highlighted how design choices can significantly alter the direct inputs and the associated environmental impacts through the recycling of water and nutrients and the number of lights used.

As a food system, vertical farming is not currently sustainable when compared to conventional farming. This is due to the issues of substrate use and high energy consumption, despite the benefits of lower water, nutrient and land use. Potential does exist for this to change if optimisation and efficiencies improve through sophisticated design, individual equipment efficiency improvements and increasing availability of renewable energy, preferably onsite.

This study has highlighted the trade-off in environmental impacts when developing a more sustainable system. Many impact categories, such as Global Warming and Fossil

Resource Scarcity improve, whereas Mineral Resource Scarcity worsens. The net benefit will depend on policy priorities e.g. if the focus is on limiting global warming, then there is a net sustainability benefit. There is a similar trade-off when comparing substrate types.

This study has shown that vertical farming has some positive aspects in terms of sustainability, with potential for gains to be made in others. For vertical farming to become more sustainable, policymakers should consider making funding available for research, such as expanding into staple crops. To reduce other environmental impacts, such as disposal of nutrient solutions, a regulatory framework is needed.

6.2 Recommendations for further work

Considering the findings of this case study, the following areas are recommended for further research:

- The next steps would be to complete a more detailed LCA analysis of a working vertical farm using real production data. Whilst other studies have carried out such analysis, data collection of input use has relied on theoretical calculations which may not accurately reflect practicalities of a working farm. Real data would allow for more realistic discussion.
- Complete an LCA study on different plant types to precisely quantify the different environmental impacts and identify which plants are more suitable for vertical farming.
- This study has focused on the impacts of the energy consumption and supply of a vertical farm in Italy. To extrapolate this information further, more studies are needed on vertical farms in different locations, which would consider different energy mixes and different HVAC requirements due to local climates. Subsequently, a framework could be designed to identify ideal country-specific locations based on the local energy mix and projections.
- As previously mentioned, to fully understand the sustainability of vertical farming as an alternative farming method, both the economic and social aspects of the food production also need to be considered. A Cost-Benefit Analysis could

be completed along-side a social LCA which considers both environmental and social impacts. This will then allow an evaluation more in line with the SDGs.

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8. Appendices

8.1 Life cycle inventory

8.1.1 Input data used in SimaPro

Input	Subtype	Database	Dataset
Substrate	Coconut coir	Agri-footprint	Coconut husk, from dehusking, at plant/ID Mass
	Perlite	Ecoinvent 3	Perlite, at mine/DE S
	Peat	Ecoinvent 3	Peat {RoW]production APOS, S
	Rockwool	Ecoinvent 3	Rock wool, packed, at plant/CH S
Seed	Lettuce	Agri-footprint	Spinach, seed, at farm/NL Mass
Nutrients	Calcium nitrate	Ecoinvent 3	Calcium nitrate, as N, at regional storehouse/RER S
	Potassium nitrate	Ecoinvent 3	Potassium nitrate, as N, at regional storehouse/RER S
	Ammonium nitrate	Agri-footprint	Ammonium nitrate, as 100% (NH4)(NO3) (NPK 35-0-0), at regional storehouse/RER Mass
	Dipotassium phosphate	Agri-footprint	PK compound (NPK 0-22-22), at regional storehouse/RER Mass
	Magnesium sulphate	Ecoinvent 3	Magnesium sulphate, at plant/RER S
	Potassium sulphate	Ecoinvent 3	Potassium sulphate, as K2O, at regional storehouse/RER S
	Ferric EDTA	Ecoinvent 3	Iron sulphate, at plant/RER S EDTA, ethylenediaminetetraacetic acid, at plant/RER S
	Zinc EDTA	Ecoinvent 3	Zinc sulphide, ZnS, at plant/RER S EDTA, ethylenediaminetetraacetic acid, at plant/RER S
	Copper EDTA	Ecoinvent 3	Copper oxide, at plant/RER S EDTA, ethylenediaminetetraacetic acid, at plant/RER S
	Boric Acid	Ecoinvent 3	Boric acid, anhydrous, powder, at plant/RER S
	Manganese EDTA	Ecoinvent 3	Manganese, at regional storage/RER S EDTA, ethylenediaminetetraacetic acid, at plant/RER S

Water	Tap water	Ecoinvent 3	Tap water, at user/CH S
Electricity	General	Ecoinvent 3	Electricity, low voltage {IT}| market for | APOS, S
	Hydro	Ecoinvent 3	Electricity, hydropower, at power plant/IT S
	Wind	Ecoinvent 3	Electricity, at wind power plant/CH S
	Geothermal	Ecoinvent 3	Electricity, high voltage {IT}| electricity production, deep geothermal | Cut-off, S
	Bioenergy	Ecoinvent 3	Electricity, at cogen with biogas engine, allocation exergy/CH S
	Solar	Ecoinvent 3	Electricity, production mix photovoltaic, at plant/IT S
	Gas	Ecoinvent 3	Electricity, natural gas, at power plant/IT S
	Coal	Ecoinvent 3	Electricity, hard coal, at power plant/IT S
	Oil	Ecoinvent 3	Electricity, oil, at power plant/IT S
Chemicals	Sulphuric acid	Agri-footprint	Sulfuric acid (98% H2SO4), at plant/RER Mass
	Bac50 biocide	Ecoinvent 3	Biocides, for paper production, unspecified, at plant/RER S
	EC standard calibration fluid	Ecoinvent 3	Sodium chloride, powder, at plant/RER S
	pH calibration fluid – 4 and 7	Agri-footprint Ecoinvent 3	Sodium hydroxide (50% NaOH), production mix/RER Mass Sodium hydroxide (50% NaOH), production mix/RER Mass

8.1.2 Estimated transportation of inputs

Input	Estimated Origin	Journey
Substrate - Coconut coir	Pollachi, India	Road Pollachi - Kochi
	Largest coconut producing region in	Ship Kochi - Genoa
	India.	Road Genoa - Milan
Substrate - Perlite	Athens, Greece	Ship Piraeus (Athens) - Genoa
	Brand location	Road Genoa - Milan
Substrate - Peat	Leabeg peat mine, Ireland	Road Leabeg - Dublin
	Brand location	Ship Dublin - Holyhead
		Road Holyhead - Dover
		Ship Dover - Calais
		Road Calais - Milan
Substrate - Rockwool	Roerland, Netherlands	Road Roermond - Distributor
	Brand location	Road Distributor - Milan
Seeds - Lettuce	Worcestershire, UK	Road Eversham - Dover
	Brand location	Ship Dover - Calais
		Road Calais - Milan
Nutrients - all	Turin, Italy	Factory - Turin
	Brand location	Turin - Milan
Chemical – Sulphuric acid	Milan, Italy	Factory – Milan
Chemical - Biocide	Beith, Scotland	Road Beith - Dover
	Brand location	Ship Dover - Calais
		Road Calais - Milan
		Road Around Milan
Chemical - EC calibration	Somerset, UK	Road Taunton - Dover
and pH 4 & 7 buffer solution	Brand location	Ship Dover - Calais
		Road Calais - Milan

8.1.3 Transportation type used in SimaPro

When used	Database	Dataset
All road journeys	Ecoinvent 3	Transport, lorry 20-28t, fleet average/CH S
All sea journeys < than 1000 km.	Agri-footprint	Transport, sea ship, 5000 DWT, 50%LF, short, default/GLO Mass
All sea journeys > than 1000 km.	Ecoinvent 3	Transport, transoceanic freight ship/OCE S

8.2 Output from SimaPro

8.2.1 Impact Assessment - Standard model initial output

Impact category	Unit	Total	Chemicals	Nutrients	Seeds	Substrate - cc&p *	Transportation of inputs - cc&p *	Water	Electricity, low voltage {IT}| market for | APOS, S
Global warming	kg CO2 eq	37.18817	0.121117	0.42105	0.000366	2.26342	0.582179	0.012486	33.78756
Stratospheric ozone depletion	kg CFC11 eq	4.73E-05	5.29E-08	8.69E-06	9.18E-09	1.52E-05	2.21E-07	5.24E-09	2.31E-05
Ionizing radiation	kBq Co-60 eq	5.612363	0.046008	0.015093	1.48E-06	0.021603	0.057979	0.021398	5.450282
Ozone formation, Human health	kg NOx eq	0.066145	0.000222	0.000665	3.47E-07	0.002044	0.006632	2.73E-05	0.056555
Fine particulate matter formation	kg PM2.5 eq	0.05114	0.000217	0.000337	1.36E-06	0.001323	0.002236	1.32E-05	0.047013
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.06708	0.000228	0.000672	3.51E-07	0.00207	0.006707	2.8E-05	0.057373
Terrestrial acidification	kg SO2 eq	0.158338	0.000635	0.001296	1.07E-05	0.007157	0.006868	3.33E-05	0.142339
Freshwater eutrophication	kg P eq	0.011286	2.53E-06	2.03E-06	1.97E-07	0.00046	2.67E-06	1.61E-07	0.010818
Marine eutrophication	kg N eq	0.007173	1.59E-06	1.41E-05	2.67E-06	0.006126	1.01E-06	6.27E-08	0.001028
Terrestrial ecotoxicity	kg 1,4-DCB	78.77209	0.386766	0.775277	0.000115	2.619775	1.041018	0.024232	73.92491
Freshwater ecotoxicity	kg 1,4-DCB	2.512364	0.001083	0.000486	3.17E-06	0.01688	0.002346	0.000242	2.491324
Marine ecotoxicity	kg 1,4-DCB	3.144913	0.001824	0.001315	7.07E-06	0.005339	0.004438	0.000354	3.131636
Human carcinogenic toxicity	kg 1,4-DCB	1.084641	0.007983	0.008739	2.85E-07	0.001518	0.014846	0.001584	1.049972
Human non-carcinogenic toxicity	kg 1,4-DCB	22.71517	0.025068	0.020257	0.006964	0.980472	0.087254	0.007499	21.58765
Land use	m2a crop eq	6.518887	0.001061	0.002317	0.000753	5.194196	0.003667	0.001303	1.31559
Mineral resource scarcity	kg Cu eq	0.060651	0.000653	0.002288	3.37E-08	0.003297	0.001381	0.000153	0.052879
Fossil resource scarcity	kg oil eq	9.541033	0.056517	0.06799	3.04E-05	0.146754	0.187796	0.002664	9.079282
Water consumption	m3	2.484173	0.506614	0.247258	7.55E-06	0.002498	0.695893	0.389213	0.642689

8.2.2 Sensitivity analysis – 5 light output

Impact category	Unit	Total	Chemicals	Nutrients	Seeds	Substrate - cc&p *	Transportation of inputs - cc&p *	Water	Electricity, low voltage {IT}| market for | APOS, S
Global warming	kg CO2 eq	38.97765	0.121117	0.42105	0.000366	2.26342	0.582179	0.012486	35.57703
Stratospheric ozone depletion	kg CFC11 eq	4.85E-05	5.29E-08	8.69E-06	9.18E-09	1.52E-05	2.21E-07	5.24E-09	2.43E-05
Ionizing radiation	kBq Co-60 eq	5.901024	0.046008	0.015093	1.48E-06	0.021603	0.057979	0.021398	5.738944
Ozone formation, Human health	kg NOx eq	0.069141	0.000222	0.000665	3.47E-07	0.002044	0.006632	2.73E-05	0.059551
Fine particulate matter formation	kg PM2.5 eq	0.05363	0.000217	0.000337	1.36E-06	0.001323	0.002236	1.32E-05	0.049502
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.070118	0.000228	0.000672	3.51E-07	0.00207	0.006707	2.8E-05	0.060412
Terrestrial acidification	kg SO2 eq	0.165877	0.000635	0.001296	1.07E-05	0.007157	0.006868	3.33E-05	0.149878
Freshwater eutrophication	kg P eq	0.011858	2.53E-06	2.03E-06	1.97E-07	0.00046	2.67E-06	1.61E-07	0.011391
Marine eutrophication	kg N eq	0.007227	1.59E-06	1.41E-05	2.67E-06	0.006126	1.01E-06	6.27E-08	0.001082
Terrestrial ecotoxicity	kg 1,4-DCB	82.68735	0.386766	0.775277	0.000115	2.619775	1.041018	0.024232	77.84016
Freshwater ecotoxicity	kg 1,4-DCB	2.644311	0.001083	0.000486	3.17E-06	0.01688	0.002346	0.000242	2.623271
Marine ecotoxicity	kg 1,4-DCB	3.310773	0.001824	0.001315	7.07E-06	0.005339	0.004438	0.000354	3.297496
Human carcinogenic toxicity	kg 1,4-DCB	1.140251	0.007983	0.008739	2.85E-07	0.001518	0.014846	0.001584	1.105581
Human non-carcinogenic toxicity	kg 1,4-DCB	23.85851	0.025068	0.020257	0.006964	0.980472	0.087254	0.007499	22.73099
Land use	m2a crop eq	6.588564	0.001061	0.002317	0.000753	5.194196	0.003667	0.001303	1.385267
Mineral resource scarcity	kg Cu eq	0.063452	0.000653	0.002288	3.37E-08	0.003297	0.001381	0.000153	0.055679
Fossil resource scarcity	kg oil eq	10.0219	0.056517	0.06799	3.04E-05	0.146754	0.187796	0.002664	9.560145
Water consumption	m3	2.518211	0.506614	0.247258	7.55E-06	0.002498	0.695893	0.389213	0.676728

8.2.3 Sensitivity analysis – 4 and 5 light comparison output

Impact category	Unit	1) General, 4 lights, 80% HVAC, cc&p *	3) General, 5 lights, 80% HVAC, cc&p
Global warming	kg CO2 eq	37.18817	38.97765
Stratospheric ozone depletion	kg CFC11 eq	4.73E-05	4.85E-05
Ionizing radiation	kBq Co-60 eq	5.612363	5.901024
Ozone formation, Human health	kg NOx eq	0.066145	0.069141
Fine particulate matter formation	kg PM2.5 eq	0.05114	0.05363
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.06708	0.070118
Terrestrial acidification	kg SO2 eq	0.158338	0.165877
Freshwater eutrophication	kg P eq	0.011286	0.011858
Marine eutrophication	kg N eq	0.007173	0.007227
Terrestrial ecotoxicity	kg 1,4-DCB	78.77209	82.68735
Freshwater ecotoxicity	kg 1,4-DCB	2.512364	2.644311
Marine ecotoxicity	kg 1,4-DCB	3.144913	3.310773
Human carcinogenic toxicity	kg 1,4-DCB	1.084641	1.140251
Human non-carcinogenic toxicity	kg 1,4-DCB	22.71517	23.85851
Land use	m2a crop eq	6.518887	6.588564
Mineral resource scarcity	kg Cu eq	0.060651	0.063452
Fossil resource scarcity	kg oil eq	9.541033	10.0219
Water consumption	m3	2.484173	2.518211

8.2.4 Sensitivity analysis – HVAC 50% output

Impact category	Unit	Total	Chemicals	Nutrients	Seeds	Substrate - cc&p *	Transportation of inputs - cc&p *	Water	Electricity, low voltage {IT}| market for | APOS, S
Global warming	kg CO2 eq	31.42019	0.121117	0.42105	0.000366	2.26342	0.582179	0.012486	28.01957
Stratospheric ozone depletion	kg CFC11 eq	4.34E-05	5.29E-08	8.69E-06	9.18E-09	1.52E-05	2.21E-07	5.24E-09	1.92E-05
Ionizing radiation	kBq Co-60 eq	4.681927	0.046008	0.015093	1.48E-06	0.021603	0.057979	0.021398	4.519847
Ozone formation, Human health	kg NOx eq	0.056491	0.000222	0.000665	3.47E-07	0.002044	0.006632	2.73E-05	0.0469
Fine particulate matter formation	kg PM2.5 eq	0.043115	0.000217	0.000337	1.36E-06	0.001323	0.002236	1.32E-05	0.038987
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.057285	0.000228	0.000672	3.51E-07	0.00207	0.006707	2.8E-05	0.047579
Terrestrial acidification	kg SO2 eq	0.134039	0.000635	0.001296	1.07E-05	0.007157	0.006868	3.33E-05	0.11804
Freshwater eutrophication	kg P eq	0.009439	2.53E-06	2.03E-06	1.97E-07	0.00046	2.67E-06	1.61E-07	0.008971
Marine eutrophication	kg N eq	0.006997	1.59E-06	1.41E-05	2.67E-06	0.006126	1.01E-06	6.27E-08	0.000852
Terrestrial ecotoxicity	kg 1,4-DCB	66.15212	0.386766	0.775277	0.000115	2.619775	1.041018	0.024232	61.30494
Freshwater ecotoxicity	kg 1,4-DCB	2.087062	0.001083	0.000486	3.17E-06	0.01688	0.002346	0.000242	2.066022
Marine ecotoxicity	kg 1,4-DCB	2.610301	0.001824	0.001315	7.07E-06	0.005339	0.004438	0.000354	2.597024
Human carcinogenic toxicity	kg 1,4-DCB	0.905397	0.007983	0.008739	2.85E-07	0.001518	0.014846	0.001584	0.870728
Human non-carcinogenic toxicity	kg 1,4-DCB	19.02987	0.025068	0.020257	0.006964	0.980472	0.087254	0.007499	17.90235
Land use	m2a crop eq	6.294298	0.001061	0.002317	0.000753	5.194196	0.003667	0.001303	1.091001
Mineral resource scarcity	kg Cu eq	0.051624	0.000653	0.002288	3.37E-08	0.003297	0.001381	0.000153	0.043852
Fossil resource scarcity	kg oil eq	7.991078	0.056517	0.06799	3.04E-05	0.146754	0.187796	0.002664	7.529328
Water consumption	m3	2.374457	0.506614	0.247258	7.55E-06	0.002498	0.695893	0.389213	0.532974

8.2.5 Sensitivity analysis – 80% and 50% HVAC comparison output

Impact category	Unit	1) General, 4 lights, 80% HVAC, cc&p *	2) General, 4 lights, 50% HVAC, cc&p
Global warming	kg CO2 eq	37.18817	31.42019
Stratospheric ozone depletion	kg CFC11 eq	4.73E-05	4.34E-05
Ionizing radiation	kBq Co-60 eq	5.612363	4.681927
Ozone formation, Human health	kg NOx eq	0.066145	0.056491
Fine particulate matter formation	kg PM2.5 eq	0.05114	0.043115
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.06708	0.057285
Terrestrial acidification	kg SO2 eq	0.158338	0.134039
Freshwater eutrophication	kg P eq	0.011286	0.009439
Marine eutrophication	kg N eq	0.007173	0.006997
Terrestrial ecotoxicity	kg 1,4-DCB	78.77209	66.15212
Freshwater ecotoxicity	kg 1,4-DCB	2.512364	2.087062
Marine ecotoxicity	kg 1,4-DCB	3.144913	2.610301
Human carcinogenic toxicity	kg 1,4-DCB	1.084641	0.905397
Human non-carcinogenic toxicity	kg 1,4-DCB	22.71517	19.02987
Land use	m2a crop eq	6.518887	6.294298
Mineral resource scarcity	kg Cu eq	0.060651	0.051624
Fossil resource scarcity	kg oil eq	9.541033	7.991078
Water consumption	m3	2.484173	2.374457

8.2.6 Sensitivity analysis – Peat output

Impact category	Unit	Total	Chemicals	Nutrients	Seeds	Substrate - peat	Transportation of inputs - peat	Water	Electricity, low voltage {IT}| market for | APOS, S
Global warming	kg CO2 eq	36.19313	0.121117	0.42105	0.000366	0.118394	1.732162445	0.012486	33.78756
Stratospheric ozone depletion	kg CFC11 eq	3.25E-05	5.29E-08	8.69E-06	9.18E-09	3.11E-08	5.88642E-07	5.24E-09	2.31E-05
Ionizing radiation	kBq Co-60 eq	5.667702	0.046008	0.015093	1.48E-06	0.008134	0.126785589	0.021398	5.450282
Ozone formation, Human health	kg NOx eq	0.073092	0.000222	0.000665	3.47E-07	0.000223	0.015398914	2.73E-05	0.056555
Fine particulate matter formation	kg PM2.5 eq	0.050609	0.000217	0.000337	1.36E-06	0.000184	0.002843552	1.32E-05	0.047013
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.074197	0.000228	0.000672	3.51E-07	0.000225	0.015669522	2.8E-05	0.057373
Terrestrial acidification	kg SO2 eq	0.152161	0.000635	0.001296	1.07E-05	0.000306	0.007541338	3.33E-05	0.142339
Freshwater eutrophication	kg P eq	0.010871	2.53E-06	2.03E-06	1.97E-07	3.87E-05	1.00808E-05	1.61E-07	0.010818
Marine eutrophication	kg N eq	0.001052	1.59E-06	1.41E-05	2.67E-06	2.52E-06	3.08484E-06	6.27E-08	0.001028
Terrestrial ecotoxicity	kg 1,4-DCB	77.9926	0.386766	0.775277	0.000115	0.119002	2.762300575	0.024232	73.92491
Freshwater ecotoxicity	kg 1,4-DCB	2.508708	0.001083	0.000486	3.17E-06	0.001709	0.013861386	0.000242	2.491324
Marine ecotoxicity	kg 1,4-DCB	3.159836	0.001824	0.001315	7.07E-06	0.002416	0.022283213	0.000354	3.131636
Human carcinogenic toxicity	kg 1,4-DCB	1.132252	0.007983	0.008739	2.85E-07	0.003479	0.06049518	0.001584	1.049972
Human non-carcinogenic toxicity	kg 1,4-DCB	22.22563	0.025068	0.020257	0.006964	0.051134	0.527049023	0.007499	21.58765
Land use	m2a crop eq	1.340973	0.001061	0.002317	0.000753	0.004766	0.015183676	0.001303	1.31559
Mineral resource scarcity	kg Cu eq	0.062611	0.000653	0.002288	3.37E-08	0.00014	0.006498964	0.000153	0.052879
Fossil resource scarcity	kg oil eq	10.79182	0.056517	0.06799	3.04E-05	0.99862	0.586717832	0.002664	9.079282
Water consumption	m3	3.715132	0.506614	0.247258	7.55E-06	0.002786	1.926564293	0.389213	0.642689

8.2.7 Sensitivity analysis – Rockwool output

Impact category	Unit	Total	Chemicals	Nutrients	Seeds	Substrate - rockwool	Transportation of inputs - rockwool	Water	Electricity, low voltage {IT}| market for | APOS, S
Global warming	kg CO2 eq	34.821	0.121117	0.42105	0.000366	0.392276	0.086153	0.012486	33.78756
Stratospheric ozone depletion	kg CFC11 eq	3.2E-05	5.29E-08	8.69E-06	9.18E-09	5.82E-08	2.94E-08	5.24E-09	2.31E-05
Ionizing radiation	kBq Co-60 eq	5.618782	0.046008	0.015093	1.48E-06	0.079526	0.006474	0.021398	5.450282
Ozone formation, Human health	kg NOx eq	0.059092	0.000222	0.000665	3.47E-07	0.000879	0.000743	2.73E-05	0.056555
Fine particulate matter formation	kg PM2.5 eq	0.048503	0.000217	0.000337	1.36E-06	0.000787	0.000134	1.32E-05	0.047013
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.059964	0.000228	0.000672	3.51E-07	0.000905	0.000756	2.8E-05	0.057373
Terrestrial acidification	kg SO2 eq	0.146568	0.000635	0.001296	1.07E-05	0.001905	0.000349	3.33E-05	0.142339
Freshwater eutrophication	kg P eq	0.010826	2.53E-06	2.03E-06	1.97E-07	2.9E-06	5.14E-07	1.61E-07	0.010818
Marine eutrophication	kg N eq	0.001048	1.59E-06	1.41E-05	2.67E-06	2.1E-06	1.55E-07	6.27E-08	0.001028
Terrestrial ecotoxicity	kg 1,4-DCB	75.75605	0.386766	0.775277	0.000115	0.503876	0.140876	0.024232	73.92491
Freshwater ecotoxicity	kg 1,4-DCB	2.49472	0.001083	0.000486	3.17E-06	0.000875	0.000708	0.000242	2.491324
Marine ecotoxicity	kg 1,4-DCB	3.137797	0.001824	0.001315	7.07E-06	0.001524	0.001136	0.000354	3.131636
Human carcinogenic toxicity	kg 1,4-DCB	1.083907	0.007983	0.008739	2.85E-07	0.012545	0.003084	0.001584	1.049972
Human non-carcinogenic toxicity	kg 1,4-DCB	21.69483	0.025068	0.020257	0.006964	0.020652	0.026736	0.007499	21.58765
Land use	m2a crop eq	1.354734	0.001061	0.002317	0.000753	0.032935	0.000776	0.001303	1.31559
Mineral resource scarcity	kg Cu eq	0.060561	0.000653	0.002288	3.37E-08	0.004256	0.000332	0.000153	0.052879
Fossil resource scarcity	kg oil eq	9.339238	0.056517	0.06799	3.04E-05	0.103408	0.029347	0.002664	9.079282
Water consumption	m3	3.147287	0.506614	0.247258	7.55E-06	1.263098	0.098407	0.389213	0.642689

8.2.8 Sensitivity analysis – Substrate comparison output

Impact category	Unit	1) General, 4 lights, 80% HVAC, cc&p *	5) General, 4 lights, 80% HVAC, peat	6) General, 4 lights, 80% HVAC, rockwool
Global warming	kg CO2 eq	37.18817	36.19313	34.821
Stratospheric ozone depletion	kg CFC11 eq	4.73E-05	3.25E-05	3.2E-05
Ionizing radiation	kBq Co-60 eq	5.612363	5.667702	5.618782
Ozone formation, Human health	kg NOx eq	0.066145	0.073092	0.059092
Fine particulate matter formation	kg PM2.5 eq	0.05114	0.050609	0.048503
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.06708	0.074197	0.059964
Terrestrial acidification	kg SO2 eq	0.158338	0.152161	0.146568
Freshwater eutrophication	kg P eq	0.011286	0.010871	0.010826
Marine eutrophication	kg N eq	0.007173	0.001052	0.001048
Terrestrial ecotoxicity	kg 1,4-DCB	78.77209	77.9926	75.75605
Freshwater ecotoxicity	kg 1,4-DCB	2.512364	2.508708	2.49472
Marine ecotoxicity	kg 1,4-DCB	3.144913	3.159836	3.137797
Human carcinogenic toxicity	kg 1,4-DCB	1.084641	1.132252	1.083907
Human non-carcinogenic toxicity	kg 1,4-DCB	22.71517	22.22563	21.69483
Land use	m2a crop eq	6.518887	1.340973	1.354734
Mineral resource scarcity	kg Cu eq	0.060651	0.062611	0.060561
Fossil resource scarcity	kg oil eq	9.541033	10.79182	9.339238
Water consumption	m3	2.484173	3.715132	3.147287

8.2.9 Sensitivity analysis – 2017 energy mix by fuel type output

Impact category	Unit	Total	Chemicals	Nutrients	Seeds	Substrate - cc&p*	Transportation of inputs - cc&p*	Water	Electricity, hydropower, at power plant/IT S	Electricity, at wind power plant/CH S	Electricity, high voltage {IT}| electricity production, deep geothermal | Cut-off, S	Electricity, at cogen with biogas engine, allocation exergy/CH S	Electricity, production mix photovoltaic, at plant/IT S	Electricity, natural gas, at power plant/IT S	Electricity, hard coal, at power plant/IT S	Electricity, oil, at power plant/IT S
Global warming	kg CO2 eq	43.44191	0.121117	0.42105	0.000366	2.26342	0.582179	0.012486	0.04849	0.089769	0.132587	0.926623	0.500793	24.15653	9.939161	4.247332
Stratospheric ozone depletion	kg CFC11 eq	4.03E-05	5.29E-08	8.69E-06	9.18E-09	1.52E-05	2.21E-07	5.24E-09	1.99E-08	4.1E-08	3.88E-08	1.67E-06	2.96E-07	8.57E-06	2.76E-06	2.67E-06
Ionizing radiation	kBq Co-60 eq	0.958941	0.046008	0.015093	1.48E-06	0.021603	0.057979	0.021398	0.00759	0.016834	0.0122	0.297061	0.13756	0.082332	0.172306	0.070978
Ozone formation, Human health	kg NOx eq	0.085429	0.000222	0.000665	3.47E-07	0.002044	0.006632	2.73E-05	0.00015	0.000204	0.000274	0.001114	0.001135	0.03144	0.027936	0.013586
Fine particulate matter formation	kg PM2.5 eq	0.042465	0.000217	0.000337	1.36E-06	0.001323	0.002236	1.32E-05	6.89E-05	0.000177	0.000264	0.000592	0.000709	0.006987	0.01814	0.011398
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.087005	0.000228	0.000672	3.51E-07	0.00207	0.006707	2.8E-05	0.000153	0.000209	0.00028	0.001144	0.001198	0.032499	0.028058	0.013758
Terrestrial acidification	kg SO2 eq	0.133738	0.000635	0.001296	1.07E-05	0.007157	0.006868	3.33E-05	0.000114	0.000341	0.000464	0.00199	0.001938	0.022096	0.053798	0.037
Freshwater eutrophication	kg P eq	0.000582	2.53E-06	2.03E-06	1.97E-07	0.00046	2.67E-06	1.61E-07	7.58E-07	3.77E-06	6.05E-05	1.83E-06	1.39E-05	1.73E-05	1.09E-05	5.39E-06
Marine eutrophication	kg N eq	0.006311	1.59E-06	1.41E-05	2.67E-06	0.006126	1.01E-06	6.27E-08	7.59E-08	4.44E-06	3.69E-06	7.6E-07	2.71E-05	1.25E-06	1.48E-05	0.000114
Terrestrial ecotoxicity	kg 1,4-DCB	40.12455	0.386766	0.775277	0.000115	2.619775	1.041018	0.024232	0.077571	1.090579	0.164133	0.657975	14.15843	0.917989	3.400888	14.8098

Freshwater ecotoxicity	kg 1,4-DCB	0.042479	0.001083	0.000486	3.17E-06	0.01688	0.002346	0.000242	0.000208	0.001851	0.003549	0.0013	0.004484	0.003205	0.003377	0.003465
Marine ecotoxicity	kg 1,4-DCB	0.072176	0.001824	0.001315	7.07E-06	0.005339	0.004438	0.000354	0.000334	0.002944	0.004858	0.002565	0.011616	0.009831	0.006969	0.019782
Human carcinogenic toxicity	kg 1,4-DCB	0.268066	0.007983	0.008739	2.85E-07	0.001518	0.014846	0.001584	0.004121	0.027611	0.012346	0.012309	0.034614	0.084648	0.033565	0.024183
Human non-carcinogenic toxicity	kg 1,4-DCB	1.914588	0.025068	0.020257	0.006964	0.980472	0.087254	0.007499	0.004176	0.033061	0.098516	0.032213	0.24602	0.078956	0.118463	0.175668
Land use	m2a crop eq	5.343989	0.001061	0.002317	0.000753	5.194196	0.003667	0.001303	0.001542	0.007845	0.001852	0.00503	0.010692	0.009347	0.099314	0.005068
Mineral resource scarcity	kg Cu eq	0.052211	0.000653	0.002288	3.37E-08	0.003297	0.001381	0.000153	0.001918	0.014075	0.000985	0.00213	0.012863	0.006563	0.003983	0.001921
Fossil resource scarcity	kg oil eq	13.20715	0.056517	0.06799	3.04E-05	0.146754	0.187796	0.002664	0.008615	0.024553	0.029703	0.204541	0.138464	8.711925	2.364981	1.262622
Water consumption	m3	207.4007	0.506614	0.247258	7.55E-06	0.002498	0.695893	0.389213	185.7039	0.533197	0.000813	4.254169	10.00841	1.420409	2.404442	1.233914

8.2.10 Sensitivity analysis – 2030 energy mix by fuel type output

Impact category	Unit	Total	Chemicals	Nutrients	Seeds	Substrate - cc&p *	Transportation of inputs - cc&p *	Water	Electricity, hydropower, at power plant/IT S	Electricity, at wind power plant/CH S	Electricity, high voltage {IT}| electricity production, deep geothermal | Cut-off, S	Electricity, at cogen with biogas engine, allocation exergy/CH S	Electricity, production mix photovoltaic, at plant/IT S	Electricity, natural gas, at power plant/IT S
Global warming	kg CO2 eq	29.64951	0.121117	0.42105	0.000366	2.26342	0.582179	0.012486	0.050762	0.176732	0.138388	0.714272	1.2213783	23.94736
Stratospheric ozone depletion	kg CFC11 eq	3.48E-05	5.29E-08	8.69E-06	9.18E-09	1.52E-05	2.21E-07	5.24E-09	2.09E-08	8.07E-08	4.05E-08	1.29E-06	7.213E-07	8.5E-06
Ionizing radiation	kBq Co-60 eq	0.861999	0.046008	0.015093	1.48E-06	0.021603	0.057979	0.021398	0.007945	0.033142	0.012734	0.228984	0.3354933	0.081619
Ozone formation, Human health	kg NOx eq	0.045229	0.000222	0.000665	3.47E-07	0.002044	0.006632	2.73E-05	0.000157	0.000402	0.000286	0.000858	0.0027671	0.031168
Fine particulate matter formation	kg PM2.5 eq	0.013937	0.000217	0.000337	1.36E-06	0.001323	0.002236	1.32E-05	7.21E-05	0.000349	0.000276	0.000457	0.0017288	0.006927
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.046592	0.000228	0.000672	3.51E-07	0.00207	0.006707	2.8E-05	0.00016	0.000412	0.000292	0.000882	0.0029227	0.032217
Terrestrial acidification	kg SO2 eq	0.045437	0.000635	0.001296	1.07E-05	0.007157	0.006868	3.33E-05	0.00012	0.00067	0.000484	0.001534	0.0047256	0.021904
Freshwater eutrophication	kg P eq	0.000592	2.53E-06	2.03E-06	1.97E-07	0.00046	2.67E-06	1.61E-07	7.93E-07	7.43E-06	6.31E-05	1.41E-06	3.391E-05	1.72E-05
Marine eutrophication	kg N eq	0.006226	1.59E-06	1.41E-05	2.67E-06	0.006126	1.01E-06	6.27E-08	7.94E-08	8.74E-06	3.85E-06	5.86E-07	6.616E-05	1.24E-06
Terrestrial ecotoxicity	kg 1,4-DCB	43.19485	0.386766	0.775277	0.000115	2.619775	1.041018	0.024232	0.081205	2.147077	0.171314	0.507189	34.530838	0.91004
Freshwater ecotoxicity	kg 1,4-DCB	0.043722	0.001083	0.000486	3.17E-06	0.01688	0.002346	0.000242	0.000218	0.003645	0.003704	0.001002	0.0109357	0.003177
Marine ecotoxicity	kg 1,4-DCB	0.064548	0.001824	0.001315	7.07E-06	0.005339	0.004438	0.000354	0.00035	0.005797	0.005071	0.001977	0.0283308	0.009745
Human carcinogenic toxicity	kg 1,4-DCB	0.284052	0.007983	0.008739	2.85E-07	0.001518	0.014846	0.001584	0.004314	0.054359	0.012886	0.009488	0.0844195	0.083915

Human non-carcinogenic toxicity	kg 1,4-DCB	2.00292	0.025068	0.020257	0.006964	0.980472	0.087254	0.007499	0.004372	0.065089	0.102826	0.024831	0.6000143	0.078273
Land use	m2a crop eq	5.261511	0.001061	0.002317	0.000753	5.194196	0.003667	0.001303	0.001615	0.015445	0.001933	0.003878	0.0260771	0.009266
Mineral resource scarcity	kg Cu eq	0.078039	0.000653	0.002288	3.37E-08	0.003297	0.001381	0.000153	0.002008	0.027711	0.001028	0.001642	0.0313722	0.006506
Fossil resource scarcity	kg oil eq	9.681963	0.056517	0.06799	3.04E-05	0.146754	0.187796	0.002664	0.009018	0.04834	0.031002	0.157667	0.3376992	8.636486
Water consumption	m3	226.3924	0.506614	0.247258	7.55E-06	0.002498	0.695893	0.389213	194.4035	1.049732	0.000849	3.279255	24.409399	1.408109

8.2.11 Sensitivity analysis – 2017 and 2030 comparison

Impact category	Unit	1a) 2017, 4 lights, 80% HVAC, cc&p *	1b) 2030, 4 lights, 80% HVAC, cc&p *
Global warming	kg CO2 eq	43.44191	29.64951
Stratospheric ozone depletion	kg CFC11 eq	4.03E-05	3.48E-05
Ionizing radiation	kBq Co-60 eq	0.958941	0.861999
Ozone formation, Human health	kg NOx eq	0.085429	0.045229
Fine particulate matter formation	kg PM2.5 eq	0.042465	0.013937
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.087005	0.046592
Terrestrial acidification	kg SO2 eq	0.133738	0.045437
Freshwater eutrophication	kg P eq	0.000582	0.000592
Marine eutrophication	kg N eq	0.006311	0.006226
Terrestrial ecotoxicity	kg 1,4-DCB	40.12455	43.19485
Freshwater ecotoxicity	kg 1,4-DCB	0.042479	0.043722
Marine ecotoxicity	kg 1,4-DCB	0.072176	0.064548
Human carcinogenic toxicity	kg 1,4-DCB	0.268066	0.284052
Human non-carcinogenic toxicity	kg 1,4-DCB	1.914588	2.00292
Land use	m2a crop eq	5.343989	5.261511
Mineral resource scarcity	kg Cu eq	0.052211	0.078039
Fossil resource scarcity	kg oil eq	13.20715	9.681963
Water consumption	m3	207.4007	226.3924