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Growth perspectives of indoor vertical farming systems in cities: The sustainable energy-based approach

PhD dissertation

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Executive Summary

Indoor vertical farms (IVFs) is a novel concept of agriculture that consists of the most advanced and promising technologies in recent times to produce food locally. Vertical farming projects are gaining ground around the world to meet the demand for food in densely populated urban areas while reducing CO_2 emissions from trucks that deliver fresh and nutritious vegetables, fruits and herbs to cities on a daily basis. Indoor vertical farming production facilities enable the cultivation of food in isolated and almost airtight environment, where plants grow in horizontal (and vertical) layers while artificial light sources on each shelf layer provide the optimal light for the plants' growth and development. The crop's growing environment is automated and constantly monitored by advanced hardware and software while necessary equipment such as air conditioners, fans for air circulation, CO_2 supply systems, soilless cultivation techniques and systems for supplying nutrients provide to plants the optimal growth conditions. In IVFs, the quality of the crops is increased (with better taste, aroma, appearance, nutritional value, durability and safety) while both the quality and quantity are completely independent of weather, climate change and location. However, although IVFs can provide large energy savings and maximise production by more than 100 times on a significantly smaller area of cultivation compared to conventional agriculture, there are challenged with high start-up and operating costs for lighting.

Light is one of the most important factors for plant growth. Natural outdoor sunlight spans a wide spectrum; from ultra-violet (UV) light to infrared light. Green wavelength is reflected and transmitted from the plant leaves, while red and blue wavelengths are absorbed more efficiently and utilised in photosynthesis. Light acts as a signal to plants that causes them to develop in a certain way, such as forming a larger leaf mass, a larger leaf area, developing longer stems or increasing flowering. Hence, light is essential to maximise growth, manipulate color, or shorten the growth period of plants from sowing to harvest. In IVFs, the plants are usually illuminated between 15 to 24 hours a day, so that they can perform photosynthesis and maximise the quality and quantity of the crops. This entails high operating costs to cover the lighting needs of indoor food production. At the same time, companies in Northern Europe can benefit from flexible electricity consumption through the Nordpool collaboration around a common electricity exchange. Denmark in particular, which is a leader in wind energy in terms of gross energy production, produces sustainable and green energy from wind turbines.

Despite the great technological advancement, the transition to a more energy-friendly and green environment is crucial for IVFs. Firstly, this is due to the great effect light has on the quality and quantity of food production, but also to the high electricity consumption associated with vertical farming. The challenges in the operation of lighting technology are well documented, especially in the field of horticulture, i.a. in the form of studies of the effect of light on plant physiology and growth as well as techno-economic studies of e.g. capital and operating costs compared to other types of agricultural installations that partially (or not) use artificial lighting. However, if IVFs can be used to reduce CO_2 emissions in cities and food establishments, it is necessary to understand and examine their impact across different system levels as well as assess, identify and suggest ways to promote their sustainability and efficiency. It should be mentioned that the speed of technological progress is constantly promoting the development of the vertical farming market; thus, IVFs have gone from being a pilot project or experimental models to shooting up all over the world with a constantly increasing market share that is expected to amount to $7.3 billion in 2025 compared to $2.9 billion in 2020.

This research focuses on the risks associated with light operation in IVFs. For this purpose an alternative method with a daily light period that can be connected to a modern electricity grid is being investigated. By using a flexible lighting system, both sustainability and light efficiency are optimised to improve the plants' growth and development rate and reduce the energy footprint of the farms. To investigate the IVFs potential and the possibility of a flexible electricity consumption for lighting, this PhD dissertation proposes three research questions. Based on peer-reviewed articles, these questions should examine technological specifications in the field of vertical farming and identify the main bottlenecks in order to develop and propose an optimisation method that can be used to improve sustainability and energy efficiency in indoor agriculture while maintaining or even optimise the growth rate of the plants. The research questions are:

- **Research Question 1:** What are the benefits and challenges of indoor vertical farms?
- **Research Question 2:** How can the risks associated with the duration of artificial lighting for indoor food production be limited?
- **Research Question 3:** What impact does the application of interrupted photoperiodic illumination have on the energy footprint and growth of plants grown in an indoor vertical farm in a Nordic context?

To answer these research questions, nine research articles have been submitted, six of which are described in this dissertation. Research Question 1 contains two articles with the titles: 1) *How energy innovation in indoor vertical farming can improve food security, sustainability, and food safety* and 2*) Indoor Vertical Farming in the Urban Nexus Context: Business Growth and Resources Savings*. Research Question 2 includes two published journal articles: 3) *Optimisation of Photoperiod and Quality Assessment of Basil Plants Grown in a Small-Scale Indoor Cultivation System for Reduction of Energy Demand* and 4) *Basil Grown under Intermittent Light Stress in a Small-Scale Indoor Environment: Introducing Energy Demand Reduction Intelligent Technologies.* Finally, Research Question 3 includes two journal articles entitled: 5) *Minimising the energy footprint of indoor food production while maintaining a high growth rate: Introducing disruptive cultivation protocols* and 6) *Reduction of Energy Costs in Indoor Farms for Artificial Lighting by Shifted Energy Demand Response.*

The research questions and articles apply a research strategy with different methods to cover the complexity of techno-economic studies and agricultural studies. The interdisciplinary requirements to combine agricultural science with economic analysis have resulted in a holistic return for the benefit of stakeholders in IVFs and academia. At the same time, due to the multidisciplinary nature of the project, the results and recommendations are expected to be used for risk management within IVFs in the Nordic countries. Specifically, the results of this project, although focusing on the Danish electricity market, can also be easily transferred to other countries that benefit from flexible energy consumption, including Sweden, Finland, Norway, Germany, the Netherlands and many more. The results and insights from this research project are therefore, not only applicable to specific geographical areas, but also to other technologies, e.g. batteries for energy charging as well as renewable technologies for the spread of IVFs. Last but not least, this PhD dissertation aims to investigate the potential for energy optimisation within IVFs and the use of flexible electricity consumption (both in the Nordic countries and internationally) as well as map the development of lighting and its current distribution.

The first article *(How Energy Innovation in Indoor Vertical Farming Can Improve Food Security, Sustainability and Food Safety)* focuses on Research Question 1 *("What are the benefits and challenges of indoor vertical farms?")* by examining the effectiveness of the utilisation of resources in vertical farming production facilities and comparing it with the efficiency of the utilisation of resources in conventional agriculture and greenhouses. The study explores the methods, technologies and agricultural techniques used for the massive production of food worldwide. Therefore, the article analyses the different resource inputs that are important for crop growth and development, as well as the food security status for each of the three farming types. In addition, the bottlenecks that exist across the supply chain in vertical food production and inhibit the spread of IVFs in society and among consumers are identified. The study uses a multi-theoretical approach based on peer-reviewed publications, reports and book chapters; thus, ensures a real basis comparison that provides a detailed description of the efficiency of resource utilisation for each farming type. As one of the most important parameters, the article also examines the differentiation of the status of food security between the three types of agriculture, as well as what actions can improve and affect food security. The result shows that IVFs have a significantly higher efficiency in terms of water utilisation compared to greenhouses and conventional agriculture, as water consumption can be reduced by up to 95% by using cultivation techniques without the use of soil, e.g. closed hydroponic and aeroponic systems with constant water and nutrient supply that are recycled and reused in close loops. In addition, the amount of fertilisers in closed systems is greatly reduced; in fact by up to 50%, as the nutrients are recycled at the growing area and only the necessary amount of fertiliser is needed for the plants to grow. CO_2 emissions fall by 40-75% compared to greenhouses and conventional agriculture. This is due to the high level of efficiency that can be achieved with the airtight systems, the amount of CO_2 returned to the atmosphere, the increased air exchange and the difference in the CO_2 concentration in an indoor cultivation environment as opposed to an outdoor one. IVFs do not use pesticides and chemicals as they are kept clean and free from insects and other threats. It should also be mentioned that the land use efficiency in IVFs has been significantly maximised (approx. 95%), at the same time as the yield is significantly higher (60-95%) compared to the other two agricultural methods. Finally, this article also identifies the risks of IVFs, as well as the efficiency of resource utilisation, as the energy consumption associated with this type of agriculture is mainly due to the great necessity for artificial light. Since artificial light is the only light energy in the cultivation chamber, it is necessary to use many LED lamps to initiate photosynthesis so that plants can keep growing. The results of this research show that the energy consumption of IVFs is increased by 40-300% compared to greenhouses and conventional farms, respectively, which use only supplementary lighting or not for food production. With this article, this dissertation provides a status on sustainability and efficiency in vertical agriculture, both in terms of future prospects and the challenges of growing food indoors in cities.

The second article *(Indoor Vertical Farming in the Urban Nexus Context: Business Growth and Resources Savings)* also focuses on answering Research Question 1 *("What are the benefits and challenges of indoor vertical farms?")* by examining and quantifying the operating and capital costs of IFVs compared to greenhouses in order to examine the profitability opportunities behind vertical farming investments. Considering that the spread of IVFs is only in its infancy in Europe, it is important to look at a data model that can show whether this type of agriculture is economically advantageous and assess lighting as one of the main challenges in indoor food production. Therefore, this article presents a financial framework to investigate an IVF case study and the business opportunities of vertical agriculture in Denmark under different cash flow scenarios.

To this end, the study uses data from a techno-economic model developed for a case study and compares the economic values of a capital investment (CAPEX), resource flows and operating costs (OPEX) required for food production in an indoor vertical farm and a greenhouse. Regarding CAPEX, the results of this case study showed that the initial cost of IVFs is approximately 40% higher than for greenhouses, which is due to the advanced technology requirements, various equipment as well as the several LED lights that must be installed in each growing layer. In addition, the model pointed out that IVFs has almost the same OPEX as greenhouses due to the counterbalance achieved between artificial lighting, water consumption, heating costs and rent. Still, light can be a significant barrier to the spread of IVFs in Europe, as it is not immediately a profitable business. This multidimensional approach to making comparative studies of different business models in agriculture is followed by the study of different cash flow scenarios. The research results indicate that Denmark, due to the growing urban areas, high demand for fresh fruit and vegetables and (most importantly) the large production of renewable energy, can achieve better economic gains with IVFs than greenhouses. In other words, IVF cash flow scenarios shows that investors can get their investment back within 3 to 6 years when the wholesale price of basil is > € 6.36 / kg (similar price for organic products). Finally, the analysis shows that IVFs still accounts for a low proportion of food produced, which is due to the high operating and capital costs of LED lighting. Based on the conclusions in this article, the present dissertation examines the lighting problem as well as the possibilities for a flexible lighting, so that the optimal photosynthesis is achieved while utilising the flexible electricity market, ie. the hours when electricity prices are low and from which the Nordic and Baltic countries can benefit.

The third article *(Optimisation of Photoperiod and Quality Assessment of Basil Plants Grown in a Small-Scale Indoor Cultivation System for Reduction of Energy Demand)* examines Research Question 2 ("How to limit the risks associated with the duration of artificial lighting to indoor food production?") by looking at how different photoperiods affects the growth and development rate of basil plants. The aim is to evaluate the effect of a reduced photoperiod on a long-light plant cultivar *(Ocimum basilicum)*, which is one of the most important and most frequently cultivated species in IVFs. The article is based on experiments that took place in a small culture chamber in a chemistry lab at the Department of Business Development and Technology (BTECH), Aarhus University. Primary data collection, statistical analysis, and peer-reviewed literature have been used to explain the results of plants' response to their physiological development as well as yield. First of all, the quantitative results showed that the basil plants grown during a three-hour reduced photoperiod (P11D13L) grew and developed more slowly than the plants grown during a controlled treatment with 16-hour continuous daylight (P8D16L). Reduced light energy affected both the chlorophyll content of the plants and their physiological indices such as leaf and substrate temperature as well as the harvested biomass, indicating that basil plants could not sufficiently stimulate their photosynthetic activity and absorb and process the limited light energy. In contrast, a reduced photoperiod of two hours, i.e. a photoperiod with 14-hour continuous daylight (P10D14L), showed a positive effect on plant growth and development rate compared to the control treatment with the 16-hour continuous daylight (P8D16L), i.a. with a high chlorophyll content and other physiological indices. In addition, measurements of plants' dry biomass between respectively P8D16L and P10D14L showed a larger production volume, which, however, was not statistically significant. Therefore, this article not only confirms the importance of light energy for plant growth and development; it also defines the first part of an energy optimisation strategy that could potentially make IVFs more sustainable, especially when it comes to economies of scale. The third article demonstrated that although lighting poses a risk associated with IVFs development, close monitoring and control of the environmental conditions in each growing area can further reduce energy consumption. But instead of a reduced photoperiod that did not show a visible difference in the growth and development rate of basil plants, farmers could instead make use of a more flexible lighting system with shorter light intervals that light turns off the light during hours of high electricity prices and turns on the at the hours that electricity is cheapest.

Therefore, the fourth article in this dissertation *(Basil Grown under Intermittent Light Stress in a Small-Scale Indoor Environment: Introducing Energy Demand Reduction Intelligent Technologies)* focuses on Research Question 2 *("How to limit the risks associated with the duration of artificial lighting for indoor food production?")* and investigates how interrupted light intervals can affect the growth and development rate of basil plants. Despite the immediate savings from IVFs, which can be achieved (as described in the third article) by reducing the daily photoperiod of basil plants by two hours, it still requires many hours of continuous light, which limits farmers' ability to take advantage of the low hourly rates on electricity. This article introduces a new method that uses intermittent light intervals with short light periods of 10 minutes duration followed by 50-minute darkness. The total amount of daylight is still 14 hours, but the light supply is divided into a normal interval, so it is possible to move the energy consumption to times when the electricity is cheapest. This article is based on an experimental protocol for data collection that took place in a small culture chamber in the chemistry lab at the Department of Business Development and Technology (BTECH), Aarhus University in Herning. Primary data collection followed by a statistical analysis for the purpose of gaining knowledge about the influence of plants during different light treatments as well as peer-reviewed literature were used to explain and analyse the results.

The quantitative results of the experiment showed a positive effect on the growth, development and biomass production of basil plants for the plants that received the reduced and interrupted light treatment (I10D14L) compared to the plants that received continuous daylight (C8D16L). Measurements of the photosynthetic rate indicated that basil plants during the I10D14L treatment with short light periods of 10 minutes duration compared to the C8D16L treatment began to show signs of stress on the 19th day of the experiment (the plants were harvested on the 25th day of the experiment), which had an impact on the total photosynthesis per day. Throughout the experiment, however, the plants showed no significant differences during a light period of four hours of the I10D14L treatment compared to the control treatment, indicating that the leaf cells were able to absorb enough light energy for photosynthesis without affecting their final production. The results of the plants' ability to regulate (open and close) their stomata (slit openings), their chlorophyll content and various pigments on the plant leaves showed no significant differences between the two treatments, indicating a stable transpiration rate and a fine CO_2 uptake in plants' leaves. Finally, measurements of biomass production, leaf area and plants' height showed a small but insignificant increase for the plants grown during a reduced and intermittent photoperiod, but with a lower electricity consumption of almost 14 kWh compared to the C8D16L treatment, which resulted in a saving in lighting power of approx. 6 €/m^2/day. This article examines the need to use new lighting systems in IVFs that can make optimal use of the flexible electricity market, and also introduces the system effects of intermittent light periods on plants' development and growth and develops a new interdisciplinary approach to be investigated further.

The fifth article *(Minimising the energy footprint of indoor food production while maintaining a high growth rate: Introducing disruptive cultivation protocols)* answers Research Question 3 *("What impact does the application of interrupted photoperiodic lighting have on the climate footprint and growth of plants grown in an indoor vertical farm in a Nordic context? ")* by examining whether the growth and development rate of basil plants is affected by a lighting duration with normal distributed intermittent light intervals and a lighting duration with intermittent light that is based on a flexible electricity consumption. The method was used in an experiment with three identical cultivation chambers installed in 'Kyritsis', a laboratory at the Department of Natural Resources Management & Agricultural Engineering, Agricultural University of Athens, Greece. The article uses the same method as the fourth article, ie. the control treatment with 16 hours of continuous daylight (C8D16L) and the treatment under normalised intermittent light (I10D14L). In addition, a third treatment with a reduced and intermittent photoperiod based on a flexible electricity consumption was added (I10D14Ls). The experiment was to investigate whether intermittent light intervals, which simulate the fluctuating electricity prices, have an impact on the growth and development rate of basil plants. The article concludes that interrupted light based on a flexible electricity consumption had a positive influence on the photosynthetic rate of plants, as there was no significant difference between the two intermittent treatments and the control treatment when it comes to the overall average of photosynthetic rate. We can therefore conclude that basil plants – in regards with the length of the intermediate dark periods over the course of a day - produced an equal number of photochemical processes in the short time they were exposed to light. Chlorophyll pigments, stomatal conductance, transpiration rate, and various physiological indices, measured daily in all three treatments, showed that basil plants can grow sufficiently during the hours when the price of electricity for lighting is lowest, even if they do not follow a normal distributed intermittent pattern in hourly light sequence. Finally, NDVI index, post-harvest measurements and especially the amount of shoot biomass showed a significant increase under the two discontinued lighting treatments. This indicates that basil plants, even with a significantly lower energy requirement, can form more leaves, and thereby energy savings of approx. 18 €/day. This article therefore, confirms the basic hypothesis that plants can grow efficiently and in a sustainable way by continuously monitoring them and using a flexible lighting system with short light intervals, where energy consumption is adapted to the fluctuating electricity prices in the market.

The sixth and final research article *(Reduction of Energy Costs in Indoor Farms for Artificial Lighting by Shifted Energy Demand Response)* in this dissertation answers Research Question 3 *("What impact does the application of interrupted photoperiodic lighting have on the climate footprint and growth of plants grown in an indoor vertical agriculture in a Nordic context? ")* by collecting all applied studies and results from previous research in an advanced techno-economic analysis (in Denmark), evaluates the economic significance of the energy savings that follow from the above experimental research. This article presents a flow chart based on a smart-decision model, which was made to examine the growth stages of plants as well as the market price of electricity, including the use of on/off artificial lighting in IVFs. This model focuses on the Danish energy market and enables farmers to decide whether it is important for plants to receive light at a specific time of day. It is possible to transfer this energy optimisation model to other countries, which also use flexible energy consumption and create a balance between supply and demand, so that users can take advantage of the power grid's opportunities in their production.

This article calculates the potential energy costs from a case study of an indoor vertical production plant using this energy optimisation model and compares them with a similar vertical farm where the plants get light at night - with the cheap electricity. In this way, the model finds the cheapest and most effective way to give the plants light, and by combining this knowledge with the data collection and analysis of the plants' physiology and phenology, is offered an energy-based system that can be used in IVFs for reducing lighting costs (OPEX) while increasing production. A comparison of the results shows that the study using the energy optimisation model can reduce the monthly lighting costs by up to 22%, which corresponds to a saving of approx. 5.6 €/m^2/month. To examine the benefits and costs of an energy model with intermittent light, this article describes nine cash flow scenarios based on the Danish electricity grid according to different schemes of equity, loans, subsidies and wholesale price of basil plants. The study of the scenarios indicates that the payback time when investing in most cases is reduced from 3 to 1 year for most of the financial schemes, with higher IRR and NPV values compared to vertical farms that do not use a flexible energy consumption. Thus, the model with intermittent light in indoor agriculture allows flexible adaptations in order to avoid unnecessary production, reduce production costs and ultimately promote sustainable urban environments. Thus, this article examines the systemic effects of introducing IVFs as well as the application of a lighting system with a flexible electricity consumption, thereby reflecting the potentials for the mass deployment of vertical farms.

Similarly, another techno-economic research article *(Mass Deployment of Plant Factories as a Source of Load Flexibility in the Grid under an Energy-Food Nexus. A Technoeconomics-Based Comparison)* answers Research Question 3 by examining the importance of IVFs' mass distribution using flexible electricity consumption, under an Energy-Food nexus. The increasing urbanisation in recent and coming years has led to increased CO_2 emissions and waste/curtailed energy resources that require further optimisation, especially in urban areas. With the knowledge that greater efficiency and sustainability will be achieved by dividing energy systems into sub-units, it will be possible to promote the growth and development of small and medium-sized indoor vertical farms, which could act as flexible units using discarded or curtailed energy. Investments in renewable energy in Denmark and elsewhere in the world are under pressure as a result of the restrictions and down-regulations that are being introduced on an ongoing basis, which entails a reduction of approximately 30% in wind turbines' expected operating time and a lower wholesale price for electricity from wind turbines (more than 10% lower than the wholesale price on the Danish electricity market). This article examines and proposes a crucial solution by looking at the possibilities for the prevalence of energy-flexible IVFs in urban areas to support the electricity grid while producing local, fresh and nutritious vegetables. Thus, this type of agriculture could be implemented as a hybrid system solution that could reduce energy losses in big cities and suburbs. Various cash flow scenarios were examined and showed that investors of such hybrid systems can get their investment back within 4 to 15 years depending on 1) the capacity of the wind farm, 2) the price of electricity offered to IVFs and 3) the price of electricity offered to the market. The mass deployment of IVFs could save in cities from all over the world millions of tons of CO_2 while supporting the energy system, creating business opportunities for vertical farming producers, network operators, energy consultants and private producers of electricity by working towards a new holistic approach.

In conclusion, the three research questions in the current PhD dissertation have been answered by using qualitative and quantitative data collection methods that ensures a high validity in the holistic and interdisciplinary approach to the techno-economic challenges regarding artificial lighting in indoor agriculture. The proposed solution primarily aims the countries with modern energy networks, where the price of electricity fluctuates from hour to hour, ie. in the Nordic countries and primarily in Denmark. This dissertation examines the influence of interrupted photoperiod on basil plants and the impact of a load-shifted energy demand response on the energy efficiency, productivity and profitability of IVFs. Finally, the dissertation elaborates and concludes with the proposal of a smart-decision optimisation model for artificially-lighted farms, where a specific light supply combined with monitoring of the crops and cultivation area is proposed. A wider diffusion of IVFs in society, could possibly promote and enhance the urban sustainability, decarbonisation and local food production.

Danish Summary

Indendørs vertikalt landbrug eller såkaldt *indoor vertical farms* (IVFs) er et nyt begreb inden for landbrug, som anvender de mest avancerede og lovende teknologier i nyere tid til at producere fødevarer lokalt. IVF-projekter vinder indpas rundt omkring i verden for at imødekomme efterspørgslen på mad i tætbefolkede byområder og samtidig reducere CO_2-udledningen fra lastbiler, der dagligt leverer friske og nærende grøntsager, frugt og krydderurter til byerne. IVFs-produktionsanlæg muliggør dyrkningen af fødevarer i et isoleret og næsten lufttæt miljø, hvor planterne dyrkes i vandrette (og lodrette) lag, mens kunstige lyskilder på hvert hyldelag sørger for det optimale lys til planternes vækst og udvikling. Afgrødernes vækstmiljø kontrolleres og overvåges hele tiden af avanceret hardware og software, mens nødvendigt udstyr såsom klimaanlæg, ventilatorer til luftcirkulation, CO_2-forsyningsanlæg, dyrkningsteknikker uden brug af jord samt anlæg til forsyning af næringsstoffer giver planterne de optimale vækstbetingelser. I indendørs vertikale farme højnes kvaliteten af afgrøderne (med bedre smag, aroma, udseende, næringsværdi, holdbarhed og sikkerhed) samtidig med at både kvaliteten og kvantiteten er helt uafhængig af vejr, klimaændringer samt beliggenhed. Men selvom IVFs kan give store energibesparelser og maksimere produktionen med mere end 100 gange på et markant mindre dyrkningsareal sammenlignet med konventionelt landbrug, så er der også høje startomkostninger og driftsudgifter til belysning forbundet med denne form for dyrkning.

Lys er en af de vigtigste faktorer for planters vækst. Naturligt udendørs sollys spænder over et bredt spektrum; fra UV-lys til infrarødt lys. Grønt lys reflekteres og transmitteres fra plantebladene, mens rødt og blåt lys absorberes mere effektivt og nyttiggøres i fotosyntesen. Lys fungerer som et signal til planterne, der får dem til at udvikle sig på en bestemt måde, såsom at danne en større bladmasse, et større bladareal, udvikle længere stilke eller øge blomstringen. Her er lys afgørende for at maksimere vækst, manipulere med farve eller forkorte planters vækstperiode fra såning til høst. I indendørs vertikale farme belyses planterne normalt mellem 15 til 24 timer i døgnet, for at de kan lave fotosyntese samt for at maksimere og optimere afgrødernes kvalitet og kvantitet. Dette medfører høje driftsomkostninger til dækning af lysbehovet i indendørs fødevareproduktion. Samtidig kan virksomheder i Nordeuropa via Nordpool-samarbejdet omkring en fælles elbørs drage fordel af et fleksibelt elforbrug. Især Danmark, som er førende inden for vindenergi, hvad angår bruttoenergiproduktion, producerer bæredygtig og grøn fra vindmøller.

Så trods de store teknologiske fremskrift er overgangen til et mere energivenligt og grønt miljø af afgørende betydning for IVFs. Dette skyldes for det første den store effekt, lys har på kvaliteten og kvantiteten af fødevareproduktion, men også det høje elforbrug, der er forbundet med vertikale landbrug. Udfordringerne ved driften af belysningsteknologien er veldokumenteret, især inden for gartneriområdet, bl.a. i form af undersøgelser af lysets indvirkning på planters fysiologi og vækst samt teknoøkonomiske undersøgelser af f.eks. kapital- og driftsomkostninger sammenlignet med andre typer af landbrugsanlæg, der delvist (eller slet ikke) anvender kunstig belysning. Men hvis IVFs kan bruges til at reducere CO_2-udledningen i byer og fødevareanlæg, er det nødvendigt at forstå og undersøge deres indvirkning på tværs af forskellige systemniveauer samt vurdere, identificere og foreslå måder til at fremme deres bæredygtighed og effektivitet. Det skal nævnes, at hastigheden af de teknologiske fremskridt hele tiden

fremmer udviklingen på IVFs-markedet; således er IVFs gået fra at være et pilotprojekt eller eksperimentelle modeller til at skyde op over hele verden med en konstant stigende markedsandel, der forventes at beløbe sig til 7,3 mia. dollars i 2025 sammenlignet med 2,9 mia. dollars i 2020.

Indeværende forskning fokuserer på de risici, der er forbundet med driften af belysning i IVFs. Til dette formål undersøges en alternativ metode med en daglig lysperiode, der kan tilsluttes et moderne elnet. Ved at anvende et fleksibelt belysningssystem optimeres både bæredygtighed og lyseffektivitet til forbedring af planternes vækst og udviklingshastighed. For at undersøge IVF-potentialet og muligheden for et fleksibelt elforbrug til belysning, foreslår denne ph.d.-afhandling tre forskningsspørgsmål. Med udgangspunkt i peer-reviewede artikler skal disse spørgsmål undersøge teknologiske specifikationer inden for IVFs-området og identificere de vigtigste flaskehalse med henblik på at udvikle og foreslå en optimeringsmetode, der kan anvendes til at forbedre bæredygtighed og energieffektivisering i indendørs landbrug samtidig med at opretholde eller endda optimere planternes udviklingshastighed. Forskningsspørgsmålene er:

- **Forskningsspørgsmål 1**: Hvad er fordelene og udfordringerne ved indendørs vertikalt landbrug?
- **Forskningsspørgsmål 2**: Hvordan kan man begrænse de risici, der er forbundet med varigheden af kunstig belysning til indendørs fødevareproduktion?
- **Forskningsspørgsmål 3**: Hvilken indvirkning har anvendelsen af en afbrudt fotoperiodisk belysning på klimaaftrykket og væksten af planter dyrket i et indendørs vertikalt landbrug i en nordisk kontekst?

For at besvare disse forskningsspørgsmål er ni forskningsartikler blevet indsendt, hvoraf seks af disse er beskrevet i indeværende afhandling. Forskningsspørgsmål 1 er indeholdt i to artikler med titlerne: 1) *How energy innovation in indoor vertical farming can improve food security, sustainability, and food safety* og 2) *Indoor Vertical Farming in the Urban Nexus Context: Business Growth and Resources Savings*. Forskningsspørgsmål 2 inkluderer to publicerede tidsskriftsartikler: 3) *Optimisation of Photoperiod and Quality Assessment of Basil Plants Grown in a Small-Scale Indoor Cultivation System for Reduction of Energy Demand* og 4) *Basil Grown under Intermittent Light Stress in a Small-Scale Indoor Environment: Introducing Energy Demand Reduction Intelligent Technologies.* Forskningsspørgsmål 3 omfatter to tidsskriftartikler med titlerne: 5) *Minimising the energy footprint of indoor food production while maintaining a high growth rate: Introducing disruptive cultivation protocols* og 6) *Reduction of Energy Costs in Indoor Farms for Artificial Lighting by Shifted Energy Demand Response.*

Forskningsspørgsmålene og artiklerne anvender en forskningsstrategi med forskellige metoder til at dække kompleksiteten af teknoøkonomiske studier og landbrugsstudier. De tværfaglige krav til at kombinere landbrugsteknisk videnskab med økonomiske analyser har resulteret i et holistisk udbytte til gavn for interessenter inden for IVFs og den akademiske verden. Samtidig forventes resultaterne og anbefalingerne grundet projektets tværfaglige karakter at kunne bruges til risikostyring inden for IVFs i de nordiske lande. Helt konkret så vil resultaterne af dette projekt, selvom det fokuserer på det danske elmarked, også let kunne overføres til andre lande, der drager fordel af et fleksibelt energiforbrug, herunder Sverige, Finland, Norge, Tyskland, Holland og mange flere. Resultaterne af og indsigterne fra dette forskningsprojekt er derfor ikke kun anvendelige på specifikke geografiske områder, men også på andre teknologier, f.eks. batterier til energiladning samt vedvarende teknologier til udbredelsen af IVF. Sidst men ikke mindst har denne ph.d.-afhandling til formål undersøge potentialet for energioptimering inden for IVF og anvendelsen af et fleksibelt elforbrug (både i Norden og internationalt) samt kortlægge udviklingen af belysning og den nuværende udbredelse.

Den første artikel (*How Energy Innovation in Indoor Vertical Farming can Improve Food Security, Sustainability and Food Safety*) fokuserer på forskningsspørgsmål 1 (”*Hvad er fordelene og udfordringerne ved indendørs vertikalt landbrug?”)* ved at undersøge effektiviteten i udnyttelsen af ressourcer i IVF-produktionsanlæg og sammenligne den med effektiviteten i udnyttelsen af ressourcer i konventionelle landbrug og gartnerier. Undersøgelsen udforsker de metoder, teknologier og landbrugsteknikker, der anvendes til den massive produktion af fødevarer verden over. Derfor analyserer artiklen både de forskellige ressourceinput, der er vigtige for afgrødernes vækst og udvikling, samt fødevaresikkerheden for hver af de tre landbrug. Desuden identificeres de flaskehalse, der eksisterer på tværs af forsyningskæden inden for vertikal fødevareproduktion, og som hæmmer udbredelsen af IVFs i samfundet og hos forbrugerne. Undersøgelsen anvender en multiteoretisk tilgang baseret på peer-reviewede publikationer, rapporter og bogkapitler for dermed at sikre et reelt sammenligningsgrundlag, der giver en detaljeret beskrivelse af effektiviteten i udnyttelsen af ressourcer for hver komponent. Som noget af det vigtigste undersøger artiklen desuden differentieringen af status på fødevaresikkerheden mellem de tre landbrugstyper, samt hvilke handlinger der kan forbedre og påvirke fødevaresikkerheden. Resultatet viser, at IVFs har en betydelig højere effektivitet med hensyn til udnyttelse af vand sammenlignet med gartnerier og konventionelle landbrug, da vandforbruget kan reduceres med op til 95 % ved at anvende dyrkningsteknikker uden brug af jord, f.eks. lukkede hydroponiske og aeroponiske systemer med konstant vand- og næringstilførsel, der genanvendes. Derudover reduceres mængden af kunstgødning i lukkede systemer kraftigt; faktisk med op til 50 %, da næringsstofferne recirkuleres ved dyrkningsområdet og kun den nødvendige mængde gødning, der skal til, for at planterne kan gro, tilsættes. CO_2-udledningen falder med 40-75 % sammenlignet med gartnerier og konventionelle landbrug. Dette som følge af det høje effektivitetsniveau, der kan opnås med de lufttætte systemer, mængden af CO_2, der returneres til atmosfæren, den øgede luftudveksling samt forskellen i CO_2-koncentrationen i et indendørs dyrkningsmiljø i modsætning til et udendørs. Vertikale landbrug anvender ikke pesticider og kemikalier, da de holdes rene og fri for insekter. Det skal desuden nævnes, at arealudnyttelsen i IVF er optimeret markant (ca. 95 %), samtidig med at udbyttet er væsentligt højere (60-95 %) i forhold til de andre to landbrugsmetoder. Endelig identificerer denne artikel også risiciene ved IVFs samt effektiviteten i udnyttelsen af ressourcer, da energiforbruget forbundet med denne landbrugstype hovedsageligt skyldes det store behov for kunstigt lys. Da kunstigt lys er den eneste lysenergi i dyrkningskammeret, er det nødvendigt at anvende mange LED-lamper for at sætte gang i fotosyntesen, så planterne kan vokse og gro. Resultaterne af denne forskning viser, at energiforbruget i IVFs stiger med op til 40-300 % sammenlignet med henholdsvis gartnerier og konventionelle landbrug, der anvender supplerende belysning eller ikke producerer fødevarer. Med denne artikel giver indeværende afhandling en status på bæredygtighed og effektivitet i vertikale landbrug, både hvad angår fremtidsudsigterne og udfordringerne ved dyrke fødevarer indendørs i byerne.

Den anden artikel (*Indoor Vertical Farming in the Urban Nexus Context: Business Growth and Resources Savings*) fokuserer også på at besvare forskningsspørgsmål 1 (*"Hvad er fordelene og udfordringerne ved indendørs vertikalt landbrug*?") ved at undersøge og kvantificere drifts- og kapitalomkostningerne ved IFVs sammenlignet med drivhuse for derved at undersøge, om det er rentabelt at investere i IVFs. Når man tager i betragtning, at IVF-udbredelsen kun er i sin spæde begyndelse i Europa, er det vigtigt at se på en datamodel, der kan vise, om denne type landbrug er økonomisk fordelagtigt samt vurdere belysning som en af de væsentligste udfordringer ved indendørs fødevareproduktion. Derfor præsenterer denne artikel en økonomisk ramme, der skal undersøge et IVF-projekt og forretningsmulighederne ved vertikalt landbrug i Danmark under forskellige cash flow-scenarier.

Til dette formål anvender undersøgelsen data fra en teknoøkonomisk model, der blev udviklet til en case study, og sammenligner de økonomiske værdier ved en kapitalinvestering (CAPEX), ressourcestrømme samt driftsudgifter (OPEX), der er nødvendige for fødevareproduktion i en indendørs vertikal farm og et drivhus. Hvad angår CAPEX, viste resultatet af denne case study, at startomkostningerne til IVF er ca. 40 % højere end for drivhuse, hvilket skyldes de avancerede teknologikrav, diverse materiel samt de adskillige LED-lys, der skal installeres i hvert dyrkningslag. Derudover påpegede modellen, at IVF stort set har den samme OPEX som drivhuse som følge af den modvægt, der opnås mellem kunstig belysning, vandforbrug, varmeudgifter og husleje. Alligevel kan lys være en væsentligt barriere for udbredelsen af IVFs i Europa, da det ikke umiddelbart er en overskudsforretning. Denne flerdimensionelle tilgang til at lave sammenlignende undersøgelser af forskellige forretningsmodeller inden for landbrug efterfølges af undersøgelsen af forskellige cash flow-scenarier. Forskningsresultaterne indikerer, at Danmark som følge af voksende byområder, den høje efterspørgsel efter friske frugter og grøntsager samt (og også vigtigst) den store produktion af vedvarende energi kan opnå bedre økonomiske gevinster med IVF end drivhuse. Med andre ord viser et IVF-cash flow-scenarie, at investorer kan få deres investering igen inden for 3 til 6 år, når engrosprisen på basilikum er > 6,36 €/kg (lignende pris for økologiske produkter). Endelig viser analysen, at IVF stadig udgør en lav andel af producerede fødevarer, hvilket skyldes de høje drifts- og kapitalomkostninger, der er ved LED-belysning. På baggrund af konklusionen i artiklen undersøger indeværende afhandling belysningsproblematikken samt mulighederne for en fleksibel belysning, så den optimale fotosyntese opnås, samtidig med at man udnytter det fleksible elmarked, dvs. de timer, hvor elprisen er lav, og som de nordiske og baltiske lande kan drage fordel af.

Den tredje artikel (Optimisation of Photoperiod and Quality Assessment of Basil Plants Grown in a Small-Scale Indoor Cultivation System for Reduction of Energy Demand) undersøger forskningsspørgsmål 2 ("Hvordan kan man begrænse de risici, der er forbundet med varigheden af kunstig belysning til indendørs fødevareproduktion?") ved at se på, hvordan forskellige fotoperioder påvirker basilikumplanters vækst og udviklingshastighed. Målet er at evaluere på effekten af en reduceret fotoperiode på en langdagsplante (Ocimum basilicum), som er en af de vigtigste og mest dyrkede arter inden for IVF. Artiklen tager udgangspunkt i forsøg, der fandt sted i et lille dyrkningskammer i kemilab på Institut for Forretningsudvikling og Teknologi (BTECH), Aarhus Universitet. Primær dataindsamling, statistisk analyse og peer-reviewet litteratur er blevet anvendt til at forklare resultaterne af planternes respons i forhold til deres fysiologiske udvikling samt udbytte. De kvantitative resultater viste først og fremmest, at de basilikumplanter, der blev dyrket under en tre-timers reduceret fotoperiode (P11D13L), voksede og udviklede sig langsommere end de planter, der blev dyrket under en kontrolleret behandling med 16-timers kontinuerligt dagslys (P8D16L). En reduceret lysenergi påvirkede både planternes klorofylindhold og deres fysiologiske indeks såsom blad- og substrattemperatur samt den høstede biomasse, hvilket indikerer, at basilikumplanterne ikke i tilstrækkelig grad kunne stimulere deres fotosyntetiske aktivitet og optage den begrænsede absorberede lysenergi. Derimod havde en reduceret fotoperiode på to timer, dvs. en fotoperiode med 14-timers kontinuerligt dagslys (P10D14L), en positiv effekt på planternes vækst og udviklingshastighed sammenlignet med kontrolbehandlingen med de 16-timers kontinuerligt dagslys (P8D16L), bl.a. med et højere klorofylindhold og andre fysiologiske indeks. Derudover viste en undersøgelse af planternes tørre biomasse mellem hhv. P8D16L og P10D14L en større produktionsvolumen, som dog ikke var statistisk signifikant. Derfor bekræfter denne artikel ikke kun vigtigheden af lysenergi for planters vækst og udvikling; den definerer også den første del af en energioptimeringsstrategi, der potentielt kan gøre IVF mere bæredygtig, særligt når det kommer til stordrift. Den tredje artikel påviste, at selvom belysning udgør en risiko i forbindelse med IVF-udvikling, så kan man med nøje overvågning og kontrol af miljøforholdene i hvert dyrkningsområde reducere energiforbruget yderligere. Men i stedet for en reduceret fotoperiode, der ikke viste en synlig forskel i basilikumplanternes vækst og udviklingshastighed, kunne man i stedet gøre brug af et mere fleksibelt belysningssystem med kortere lysintervaller, der kunne give landmænd mulighed for at slukke lyset i timerne med høje elpriser og tænde lyset på de tidspunkter, hvor strømmen er billigst.

Derfor fokuserer den fjerde artikel i indeværende afhandling (Basil Grown under Intermittent Light Stress in a Small-Scale Indoor Environment: Introducing Energy Demand Reduction Intelligent Technologies) på forskningsspørgsmål 2 (”Hvordan kan man begrænse de risici, der er forbundet med varigheden af kunstig belysning til indendørs fødevareproduktion?”) og undersøger, hvordan afbrudte lysintervaller kan påvirke basilikumplanters vækst og udviklingshastighed. Trods de umiddelbare besparelser ved IVFs, som man (som beskrevet i den tredje artikel) kan opnå ved at reducere basilikumplanters daglige fotoperiode med to timer, så kræver det stadig mange timers kontinuerligt lys, hvilket begrænser landmænds mulighed for at udnytte de lave timepriser på el. Denne artikel introducerer en ny metode, der anvender afbrudte lysintervaller med korte lysperioder à 10 minutters varighed efterfulgt af 50-minutters mørke. Den samlede mængde dagslys er stadig 14 timer, men lystilførslen er opdelt i et normalt interval, så der er mulighed for at flytte energiforbruget til tidspunkter, hvor strømmen er billigst. Denne artikel tager udgangspunkt i en eksperimentel protokol til dataindsamling, der fandt sted i et der fandt sted i et lille dyrkningskammer i kemilab på Institut for Forretningsudvikling og Teknologi (BTECH), Aarhus Universitet i Herning. Primær dataindsamling efterfulgt af en statistisk analyse med det formål at få viden om planters påvirkning under forskelle lysbehandlinger samt peer-reviewet litteratur blev anvendt til at forklare og analysere resultaterne.

Forsøgets kvantitative resultater viste en positiv effekt på basilikumplanternes vækst, udvikling og biomasseproduktion for de planter, der modtog den reducerede og afbrudte lysbehandling (I10D14L) sammenlignet med de planter, der fik kontinuerligt dagslys (C8D16L). Målinger af fotosyntesehastigheden indikerede, at basilikumplanterne under I10D14L-behandlingen med korte lysperioder à 10 minutters varighed til sammenligning med C8D16L-behandlingen begyndte at vise tegn på stress på den 19. dag af forsøget (planterne blev høstet den 25. dag af forsøget), hvilket havde indvirkning på den samlede fotosyntese pr. døgn. Under hele forsøget viste planterne imidlertid ingen signifikante forskelle under en lysperiode på fire timer med I10D14L-behandlingen sammenlignet med kontrolbehandlingen, hvilket indikerer, at bladcellerne var i stand til at absorbere nok lysenergi til fotosyntesen uden at påvirke deres primære produktion. Resultaterne af planternes evne til at regulere (åbne og lukke) deres stomata (spalteåbninger), deres klorofylindhold samt forskellige pigmenter på plantebladene viste ingen betydelige forskelle mellem de to behandlinger, hvilket indikerer en stabil transpirationshastighed samt en fin CO_2-optagelse i planternes blade. Endelig viste målinger af biomasseproduktion, bladareal og bladhøjde en lille, men ubetydelig stigning hos de planter, der blev dyrket under en reduceret og afbrudt fotoperiode, men med et lavere elforbrug på næsten 13 kW/h sammenlignet med C8D16L-behandlingen, hvilket resulterede i en besparelse på strøm til belysning på ca. 9,5 €/m^2/dag. Denne artikel undersøger derfor nødvendigheden af at anvende nye belysningssystemer i IVFs, der kan udnytte det fleksible elmarked optimalt, og introducerer desuden systemeffekterne af afbrudte lysperioder på planters udvikling og vækst samt udvikler en ny tværfaglig tilgang, der skal undersøges nærmere.

Den femte artikel (*Minimising the energy footprint of indoor food production while maintaining a high growth rate: Introducing disruptive cultivation protocols*) besvarer forskningsspørgsmål 3 (”Hvilken indvirkning har anvendelsen af en afbrudt fotoperiodisk belysning på klimaaftrykket og væksten af planter dyrket i et indendørs vertikalt landbrug i en nordisk kontekst?”) ved at undersøge, om basilikumplanters vækst og udviklingshastighed påvirkes af en belysningstid med afbrudt lys under normale forhold og en belysningstid med afbrudt lys baseret på et fleksibelt elforbrug. Metoden blev anvendt i et forsøg med tre identiske dyrkningskamre installeret i ’Kyritsis’, et laboratorium ved *Department of Natural Resources Management & Agricultural Engineering, Agricultural University of Athens*, Grækenland. Artiklen anvender den samme metode som den fjerde artikel, dvs. kontrolbehandlingen med 16 timers kontinuerligt dagslys (C8D16L) og behandlingen under normale forhold med afbrudt lys (I10D14L). Derudover blev en tredje behandling med en reduceret og afbrudt fotoperiode baseret på et fleksibelt elforbrug tilføjet (I10D14Ls). Forsøget skulle undersøge, om afbrudte lysintervaller, som simulerer de svingende elpriser, har en indvirkning på basilikumplanters vækst og udviklingshastighed. Artiklen konkluderer, at afbrudt lys baseret på et fleksibelt elforbrug har en positiv indflydelse på planternes fotoperiodiske hastighed, da der ikke er væsentlig forskel på de to afbrudte behandlinger og kontrolbehandlingen, når det kommer til lysintervallerne à 10-minutters varighed, hvilket dermed ikke har nogen indvirkning på den samlede middelværdi. Vi kan derfor konkluderer, at basilikumplanter – uanset længden af de mellemliggende mørkeperioder i løbet af et døgn – producerede lige mange fotokemiske processer i den korte tid, de blev udsat for lys. Klorofylpigmenter, spalteåbninger, transpirationshastighed og forskellige fysiologiske indekser, der blev målt dagligt i alle tre behandlinger, viste, at basilikumplanter kan vokse og gro tilstrækkeligt i de timer, hvor prisen på strøm til belysning er lavest. Endelig viste NDVI indeks, måling efter høst og især mængden af skudbiomasse en betydelig stigning under de to afbrudte behandlinger. Dette indikerer, at basilikumplanter selv med et betydeligt lavere energibehov kan danne flere blade, og derved kan man opnå energibesparelser på ca. 22 €/m^2/dag. Denne artikel bekræfter således den grundlæggende hypotese om, at planter kan vokse effektivt og på en bæredygtig måde ved kontinuerligt at overvåge dem og anvende et fleksibelt belysningssystem med korte lysintervaller, hvor energiforbruget tilpasses de svingende elpriser på markedet.

Den sjette og sidste forskningsartikel (*Reduction of Energy Costs in Indoor Farms for Artificial Lighting by Shifted Energy Demand Response*) i indeværende afhandling besvarer forskningsspørgsmål 3 ("Hvilken indvirkning har anvendelsen af en afbrudt fotoperiodisk belysning på klimaaftrykket og væksten af planter dyrket i et indendørs vertikalt landbrug i en nordisk kontekst?") ved at samle alle anvendte undersøgelser og resultater fra tidligere forskning i en avanceret teknoøkonomisk analyse (i Danmark) og evaluere den økonomiske betydning af de energibesparelser, der følger af ovenstående eksperimentelle forskning. Denne artikel præsenterer et flowdiagram med udgangspunkt i en *smart-decision*-model, som blev lavet til at undersøge planters vækststadier samt markedsprisen på el, herunder anvendelsen af tændt/slukket kunstig belysning i IVFs. Denne model fokuserer på det danske energimarked og gør det muligt for forbrugerne at afgøre, om det er vigtigt for planter, at de får lys på et bestemt tidspunkt på dagen. Det er muligt at overføre denne energioptimeringsmodel til andre lander, der også anvender et fleksibelt energiforbrug og skaber balance mellem udbud og efterspørgsel, så brugerne kan udnytte elnettets muligheder i deres produktion.

Denne artikel beregner de potentielle energiomkostninger fra et case study af et indendørs vertikalt produktionsanlæg, der anvender denne energioptimeringsmodel, og sammenligner dem med et tilsvarende vertikalt landbrug, hvor planterne får lys om natten – med den billige strøm. På den måde finder modellen frem til den billigste og mest effektive måde at give planterne lys, og ved at kombinere denne viden med dataindsamlingen og analysen af planternes fysiologi og fænologi gives et bud på et energibaseret system, der kan bruges inden for IVFs til at reducere belysningsomkostninger (OPEX) samtidig med at produktionen øges. En sammenligning af resultaterne viser, at undersøgelsen, der anvender energioptimeringsmodellen kan reducere de månedlige belysningsudgifter med op til 22 %, hvilket svarer til en besparelse på ca. 5.6 €/m^2/mdr. For at undersøge fordelene ved og udgifterne til en energimodel med afbrudt lys beskriver denne artikel ni cash flow-scenarier, der med afsæt i det danske elnet tager udgangspunkt i egenkapital, lån, tilskud og engrosprisen på basilikumplanter. Undersøgelsen af scenarierne indikerer, at tilbagebetalingstiden ved investering i de fleste tilfælde reduceres fra 3 til 1 år med højere IRR- og NPV-værdier sammenlignet med vertikale landbrug, der ikke anvender et fleksibelt energiforbrug. Dermed giver modellen med afbrudt lys i indendørs landbrug mulighed for fleksible tilpasninger med henblik på at undgå unødvendig produktion, reducere produktionsomkostninger og i sidste ende fremme bæredygtige bymiljøer. Denne artikel undersøger således systemeffekterne af at introducere IVF samt anvendelsen af et belysningssystem med et fleksibelt elforbrug, hvorved potentialerne for masseudbredelsen af vertikale landbrug belyses.

Ligeledes besvarer en anden teknoøkonomisk forskningsartikel (*Mass Deployment of Plant Factories as a Source of Load Flexibility in the Grid under an Energy-Food Nexus. A Technoeconomics-Based Comparison*) forskningsspørgsmål 3 ved at undersøge betydningen af masseudbredelse af IVFs, der anvender et fleksibelt elforbrug, i et energi-fødevare-neksus. Den stigende urbanisering i de seneste og kommende år har medført en øget CO_2-udledning og spild/begrænsede energiressourcer, der kræver yderligere optimering, særligt i byområder. Med den viden, der foreligger om, at man vil kunne opnå større effektivitet og bæredygtighed ved at opdele energisystemer i underenheder, vil man kunne fremme væksten og udviklingen af små og mellemstore indendørs vertikale landbrug, som kunne fungere som fleksible enheder, der anvender kasseret eller begrænset energi. Investeringer i vedvarende energi i Danmark og andre steder i verden er under pres som følge af de begrænsninger og nedreguleringer, der løbende indføres, hvilket medfører en reduktion på ca. 30 % i vindmøllers forventede driftstid og en lavere engrospris på elektricitet fra vindmøller (mere end 10 % lavere end engrosprisen på det danske elmarked). Denne artikel undersøger og forslår en afgørende løsning ved at se på mulighederne for udbredelsen af energifleksible indendørs vertikale landbrug i byområder, der skal understøtte elnettet, samtidig med at de producerer lokale, friske og nærende grøntsager. Her kunne denne type landbrug implementeres som en hybrid systemløsning, der kunne reducere energitab i storbyer og forstæder. Forskellige cash flow-scenarier blev undersøgt og viste, at investorer af sådanne hybride systemer kan få deres investering igen inden for 4 til 15 år afhængig af 1) vindmølleparkens kapacitet, 2) elprisen på IVF-markedet og 3) elprisen på det frie marked. Masseudrulningen af IVF vil kunne spare byer rundt omkring i verden for millioner af tons CO_2 parallelt med at støtte energisystemet, samtidig med at det skaber forretningsmuligheder for IVF-producenter, netoperatører, energikonsulenter og private producenter af el ved at arbejde hen imod en ny holistisk tilgang.

Konkluderende er de tre forskningsspørgsmål i indeværende ph.d.-afhandling blevet besvaret ved at anvende en kvalitativ og kvantitativ dataindsamlingsmetode, der sikrer en høj validitet i den holistiske og tværfaglige tilgang til de teknoøkonomiske udfordringer vedrørende kunstig belysning, som IVF står overfor. Løsningen på problematikken er primært rettet lande med moderne energinet, hvor elprisen svinger fra time til time, dvs. i de nordiske lande og primært i Danmark. Indeværende afhandling undersøger derfor lysets påvirkning på basilikumplanter ved brug af korte og afbrudte lysintervaller i indendørs fødevareproduktion, hvilket giver en mere effektiv og bæredygtig belysningsløsning, der kan medføre betydelige besparelser på elregningen og optimere planternes salgbare udbytte ved høst. Afhandlingen uddybes og afsluttes med en *smart-decision*-model til anvendelse af kunstig belysning i indendørs vertikale landbrug, hvor en specifik lysforsyning kombineret med overvågning af plante- og dyrkningsarealet foreslås. Ved at udbrede IVFs i samfundet vil man kunne fremme, muliggøre samt effektivisere bæredygtighed, dekarbonisering og lokal fødevareproduktion.

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List of Abbreviations

IVFs – Indoor Vertical Farms

GHs - Greenhouses

LEDs – Light-Emitted Diodes

PAR – Photosynthetic active radiation

PPFD – Photosynthetic Photon flux density

RUE – Resource use efficiency

WUE – Water use efficiency

CUE – CO_2 use efficiency

LUE – Light energy use efficiency

LUE_L – Light energy use efficiency of lamps

LUE_P – Light energy use efficiency of plants

FUE – Fertiliser use efficiency

EUE – Electrical energy use efficiency

EUE_L – Energy use efficiency of lamps

EUE_C – Energy use efficiency for cooling

NPV – Net Present Value

IRR – Internal Rate of Return

OCF – Operating cash flow

IL – Intermittent light

LSEDR – Load-shifted energy demand response

NDVI – Normalised Difference vegetation index

1. Introduction

The first chapter provides the structure and framework of the research and introduces the remaining thesis by presenting a general overview of the dissertation with the subject areas of the study. The first part presents the motivation for this research project and the second part defines the research questions including an introduction on the research papers that were used to answer thoroughly these questions. The third part presents an overview of the content and the methodological approaches of the research papers that are included in this dissertation. At the end, this chapter presents significant elements such as the philosophy and design, followed by the contribution and novelty of the research that is presented in this PhD dissertation.

1.1. Dissertation structure

This PhD dissertation is structured based on the three research questions and the research papers that by creating a sequence link seek answer them. The three research elements are designed according to the taxonomy described by Bloom (1956) and follow successive steps that target to investigate indoor vertical farming systems for food production in terms of conceptualisation, applied technology, system challenges and energy demand. The structure and stages of the three research questions primarily sought to understand and define vertical farming as an agricultural cultivation technique, and thereafter analyse the operation and the challenges that vertical farms confront. Finally, develops, frames and evaluates new methodological approaches that could control and reduce the risk while optimising the profitability of vertical farms. To provide sufficient answers on how Indoor Vertical Farms (IVFs) currently operate and how they could be further optimised to continue penetrating into the global market, this dissertation presents six scientific articles that report a combination of different research outputs that pursue to answer the research questions. Table 1 introduces the structure and the connections between the three research questions and the selected six journal articles.

Table 1. Applied scientific articles of this PhD Dissertation.

Research Question	Article Title	Authors	Journal	Year
RQ1: What are the benefits and challenges of indoor vertical farms?	(1) How energy Innovation in Indoor Vertical Farming can Improve Food Security, Sustainability and Food Safety.	Avgoustaki D. D. & Xydis G.	Elsevier (book chapter)	2020
	(2) Indoor Vertical Farming in the Urban Nexus Context: Business Growth and Resources Savings.	Avgoustaki D. D. & Xydis G.	Sustainability	2020

RQ2: How can the risks associated with the artificial light operation in indoor food production be limited?	(3) Optimisation of Photoperiod and Quality Assessment of Basil Plants Grown in a Small-Scale Indoor Cultivation System for Reduction of Energy Demand.	Avgoustaki D. D.	Energies	2019
	(4) Basil Grown under Intermittent Light Stress in a Small-Scale Indoor Environment: Introducing Energy Demand Reduction Intelligent Technologies.	Avgoustaki D. D., Li J. & Xydis G.	Food Control	2020
RQ3: What is the impact of intermittent light application on the energy footprint and the growth of plants in IVFs in the Nordic context?	(5) Minimising the energy footprint of indoor food production while maintaining a high growth rate: Introducing disruptive cultivation protocols.	Avgoustaki D. D., Bartzanas T. & Xydis G.		Submitted
	(6) Reduction of Energy Costs in Indoor Farms for Artificial Lighting by Shifted Energy Demand Response.	Avgoustaki D. D. & Xydis G.		Submitted

In Table 1, the presented journal articles target to answer thoroughly the three research questions. For this reason, this dissertation is divided in chapters, one for each research question and each chapter includes two scientific articles. The last section of this dissertation includes a discussion chapter that aims to elaborate and conclude this research project by synthesising the multiple findings and conclusions from each chapter but also from supplementary research papers that were performed during the three PhD years and bring clarity to further exploration of the topic. Figure 1 below presents the flow chart of the dissertation's structure.

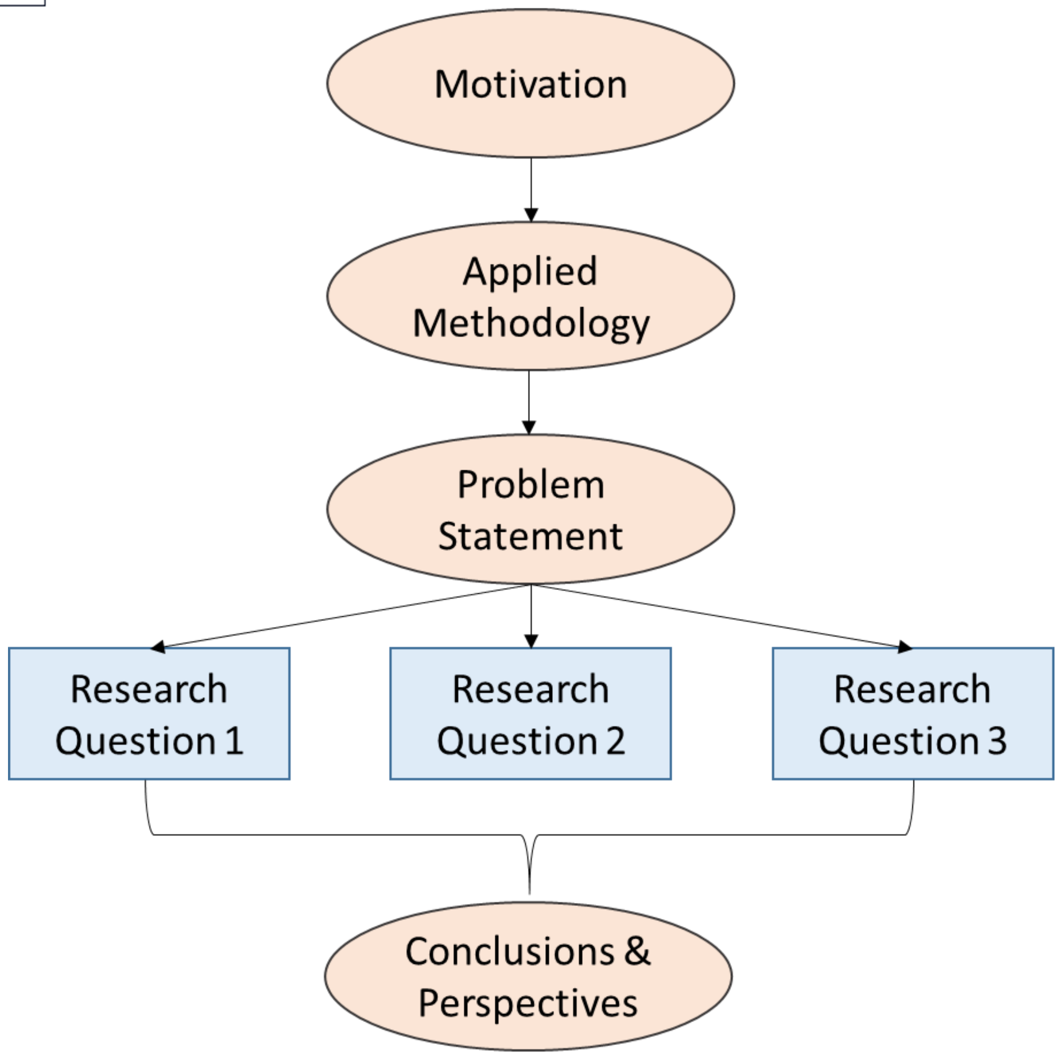

Figure 1. PhD dissertation structure.

This dissertation also contains information from a pool of supplementary published material that have not been included as argumentation articles in this thesis, due to the limited correlation influence on the research questions in comparison with the main six selected scientific articles. However, they will be used as supplementary and complementary arguments to support and provide the necessary insight to the relevant research questions. The supplementary pool of articles can be found in the Appendix 6.1 of this PhD thesis.

In order of this dissertation to organise the examination and answer the above-described research questions, 7 different tasks were completed in a 3-year period.

<u>Task 1:</u> Review of existing publications that focus on indoor urban farming in terms of design, engineering, agriculture techniques and resource use efficiency – Overall organisation of the PhD plan. (publication 1)

Task 2: Analysis and evaluation of the advantages and opportunities but also the challenges and risks that are associated with the existing vertical farming market – What are the elements that require further optimisation in order to increase the efficiency, sustainability and profitability of indoor urban farms? (publication 2)

Task 3: Installation and set-up of the lab experimental unit. Development of sequential experimental protocols aiming to reduce the energy footprint for indoor cultivation and highly link it with the dynamic electricity pricing to maximise the renewable energy sources integration.

Task 4: Final set-up of the growth chamber and controllers - Light optimisation, monitoring and evaluation of growth rate of basil plants under different photoperiodic treatments. (publication 3)

Task 5: Development of intermittent lighting schedule model (publication 4 & 5)

Task 6: Examination and interpretation of model application at the profitability and sustainability status of indoor agriculture. (publication 6)

Task 7: Development of a smart decision tool that provides a distance control and monitor of indoor growing area that allow farmers to compare electricity prices with the electricity demand of the farm.

Task 8: Writing phase, conclusions, and proposals for future work.

1.2. Motivation

Climate is a fundamental determinant of agricultural productivity. As agriculture has a primary role in human welfare and health, it has become a global concern the last decade and expressed by federal agencies the essential need to research and reduce the potential effects of climate change to agricultural productivity and use of resources. The global interest on climate change has given substantial motivation to researchers to investigate and develop novel agricultural techniques that could adapt to climate change and reduce the impact of agriculture to the environment. At the same time, the need of giving the environment the essential time to recover and repair from all the unsustainable agricultural techniques that we continuously practice for sufficient food production is prioritised.

As Earth's population keeps growing and people tend to gather in urban areas, one question still remains; do we need to cut more trees and forests for creating more farmland that produces enough food for all the humanity? This is not necessarily the path that we have to follow considering the technological improvement of the last years and all the promising growing strategies that could still help us preserve our biodiversity and reduce our carbon footprint. Indoor vertical farming is one of the most promising solutions that can grow fresh food without soil requirements in indoor spaces under specially modified and constructed buildings.

Urbanisation and extremely rapid growing population continuously change the urban features and convert them into chaotic mazes. Taking into consideration that the global population already numbers 7.6 billion and is projected to reach almost 9.5 billion people until 2050, it becomes of vital importance the optimisation of our agricultural footprint for year-round crop cultivation (Langelaan et al., 2013). According to Carey et al. (2016), as the global population is so rapidly growing, at least 60% more food production will be required to meet the global demand. Over the last decades the constant mitigation into urban and peri-urban areas results in high air, noise and water pollution levels. Simultaneously, agriculture consumes around 70% of the global fresh water to cover the irrigation demand, making it inappropriate for drinking, due to the high pollution from chemical overconsumption such as pesticides, herbicides and other agrochemicals. Furthermore, the continuous increase of global population and the growing demand for more arable land, leads to further cutting down of forests (mainly hardwood forests) and constantly decreasing amounts of carbon can be absorbed from the atmosphere and higher amounts of air-pollution (Despommier, 2010). Land degradation is the effect resulting from intense human activities that cause high dilapidation of the biophysical environment on the land, resulting in limited capability of land to provide productivity of crops and storing carbon and nitrous oxide in the soil (Franzluebbers & Doraiswamy, 2007). According to the European Commission (2002), the most recognised degradation processes in the European soil is erosion, organic matter decline, salinisation, soil biodiversity loss, contamination, flooding, sealing and finally landslides, that directly cause loss of arable land, increased flooding and low food security, and indirect effects of land degradation are loss of local culture and traditions. Land degradation causes land clearance, agricultural depletion of soil nutrients through poor farming practices, inappropriate irrigation and over-drafting, economies of scale, necessity of heavy equipment for accomplishing agricultural processes, monoculture, and non-biodegradable waste, acidification and loss of soil carbon (Xydis et al., 2020). Currently, more than 30% of the world's land area is under heavy degradation (Nkonya et al., 2016). It becomes clear now more than ever the necessity to develop adaptable and pioneering growing methods that perform higher resource use efficiency in respect to environment and biodiversity, allowing it to repair and regain its lost productivity.

Another problem that modern food supply faces is the significant matter of food waste. Currently, at least 30% of the food that is produced for human consumption is either lost or wasted at the end. Food losses can result from various stages of food supply chain, such as losses due to inefficient agricultural practices during the harvest, process and packaging distribution and even in the final consumption phase. Based on various studies (Lipinski et al., 2013; Reynolds et al.,2016), 23% of oil crops and beans, 28% of grains, 47% of fruits and vegetables, 37% of fish and 21% of meat that are produced for consumption, do never reach the final consumer and are wasted in all the in between processes (Figure 2).

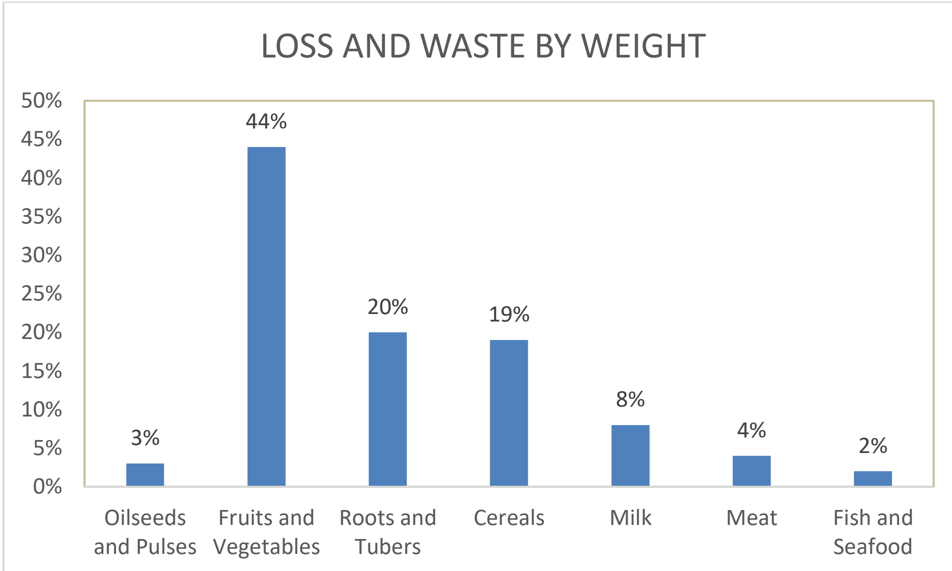

Figure 2. Global food losses and food waste (Lipinski et al., 2013).

Vertical farming is a topic of significant study with more than 650,000 hits in Google Scholar considering also that Dr. Dickson Despommier first introduced this technology approximately 10 years ago (Despommier D. 2010). Vertical farming is a multidisciplinary synergy of pioneering engineering, agronomy and architecture design. The idea is originated by bringing food production into the cities, by moving the farms from the farmland to specially constructed buildings that are located in the urban and peri-urban areas and consequently close to the consumers. The concept of growing crops in indoor spaces might sound strange at the beginning and the first appearance of vertical farms. However, for many decades we grow our commercially viable crops like tomatoes, cucumbers, peppers, strawberries, herbs and flowers at commercial greenhouses that produce year-round crops and protect crops from outdoor climate conditions. Indoor vertical farms are not in a mission of replacing traditional farming and greenhouses but rather provide a supporting method for growing fresh and nutritious fruits, vegetables and greeneries and are close to the consumers under more sustainable and efficient way.

Vertical farming is a technology that aims to maximise crop production per growing area in order to remove the pressure from open-field agricultural production. Indoor vertical farms (IVFs) utilise protected and insulated horticultural systems with controlled environmental factors (temperature, humidity, air quality, quantity and speed) and are installed in multiple layers in horizontal or vertical arrangement to provide maximisation of the growing surface areas and production surfaces are connected in close-loops to increase the efficiency use of resources. Indoor vertical farms apply soilless cultivation techniques such as hydroponic, aeroponic systems or even aquaponics when they are combined with indoor fish production, where plants grow in aqueous nutrient solution. Apart from water, nutrient and growing substrate, light is another of the most crucial environmental factors that highly influence plant development and growth. Light plays a significant role in the process of photosynthesis, since the higher parts of plants capture the light energy and synthesise carbohydrates from CO_2 and water. The selection of light quantity, quality and duration are the three main dimensions that can highly influence the responses of plants at physiological, anatomical and biochemical levels and therefore influence their morphological and phenological development (Zheng L. and He H, 2019). The continuous development and research on optimised LED technology has given a big boost in indoor cultivation by offering the possibility to optimise the photosynthetic rate and the physiology of plants by manipulating different light characteristics and specifications. For this reason, light has because a very popular research topic among the different institutions, universities and industry companies. Only the last decade there are more than 260,000 publications appear in Google Scholar focusing on light optimisation for indoor (Figure 3).

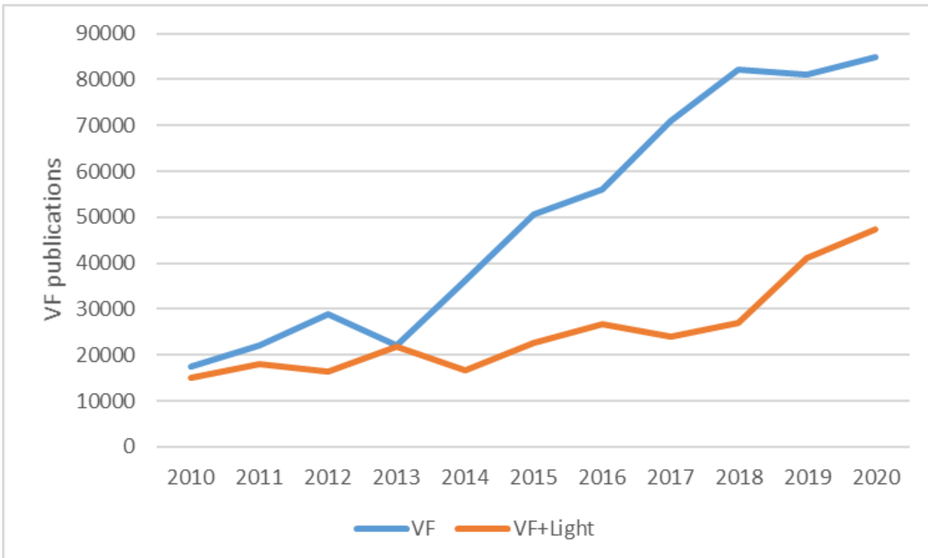

Figure 3. Number of vertical farming (VF) and vertical farming and lighting technology (VF+Light) publications since 2010). Note: Constructed by Author based on Google Scholar outputs.

From a scientific and academic point of view, the growing study and role of artificial light in indoor horticulture across the last ten years and the increasing publication numbers in this topic have significantly promoted the development of vertical farming projects indicating an increasing necessity of IVFs for advance knowledge and data interpretation for improved cultivation management. Vertical farming publications have increased more than 350% in the last decade (from 2010 till 2020) and almost half of them focus on the importance of light in horticulture with around 15,000 at 2010 to more than 40,000 new publications on 2020.

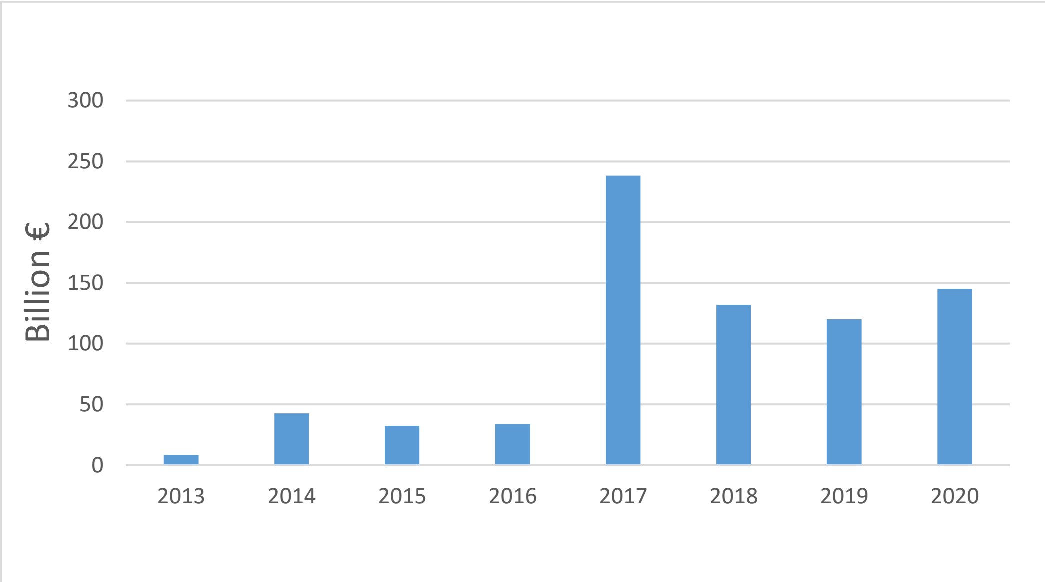

Figure 4. Vertical farming market in a global scale (Note: Constructed by Author based on data from AgFunder, 2019)

In Figure 4, the graph clearly shows a large increase in the market size and investments in the field of vertical farming the last seven years, with a strong activity from 2017 and after. Additionally, figure 5 shows the distribution of publications related to vertical farming from under different regions. We could observe that for example in Asia, US possibly due to the high density of population and the limited space in urban areas, there is a high demand for IVFs. Furthermore, the global growing demand for locally produced food with less CO_2 emissions that can grow irrelevantly from the outdoor climate conditions makes vertical farming a very interesting case for further investigation.

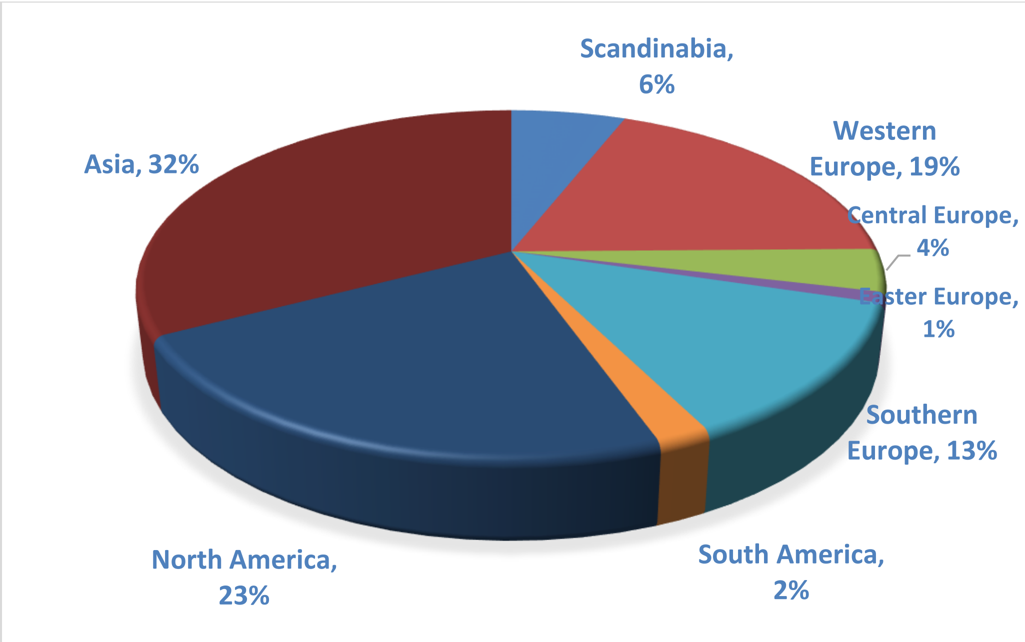

Figure 5. Market size of Vertical Farming by region (Note: Constructed by Author based on data from Horticulture Lighting Market, 2018)

Table 2. Statistics in Nordic Countries. Note: constructed by author with data from Central Intelligence Agency (Adenaueuer L., 2014).

Country	GDP per Capita	Population	Market Potential
Denmark	€ 31,707	5,806,000	55
Norway	€ 45,635	5,433,000	50
Sweden	€ 34,474	10,230,000	94
Finland	€ 42,118	5,518,000	54
Iceland	€ 32,483	364,134	3

Nordic countries due to the cold and dark climate conditions, do not present the most suitable environment for year-round agriculture. The severe weather conditions with low temperatures and limited solar radiation mainly during winter restrain Nordic countries on vegetables and greeneries production for their consumers. To meet the high vegetable demand Denmark mainly imports fresh vegetables mainly from the Netherlands, Germany and Spain that valued almost €3.5 Million on 2018 resulting in significant CO_2 equivalents from food miles, making transportation contributing up to 50% on the climate impact of vegetables (Edjabou & Smed, 2013; WITS, 2018). However, Nordic countries due to the abundance of renewable energy in the form of off-shore and on-shore wind power and hydro and geothermal energy, as also the implementation of a Nordic Energy Exchange Energy Pool (NordPool) as the leading European market among nine Northern European countries, provide the advantage of electricity trading that affects the power price as is determined by the supply and demand. Under this scope, prices of energy fluctuate on different values according to the exchanges between consumers and energy generators but also the 36-hour prognosis of electricity prices, provide the opportunity to consumers to schedule their energy usage in order to limit their electricity costs by adapting to an hourly pricing scheme. Table 2 gives an overview of the development capacity and potential dynamic of vertical farming projects in the region of Scandinavia. Denmark with such high wind energy production provides a great case for installation of large-scale vertical farming facilities that could be partially or even entirely powered with green energy. According to Adenaueuer (2014) assuming that 2 pilot projects of vertical farming start per nation, then in short term 12 IVFs would be constructed, reflecting the high impact and engagement that offers in local communities for seasonal and locally produced food with low carbon footprint.

The development of IVFs in a global scale is highly related with the necessity for innovative and advanced technologies that can support growing crops in an indoor environment with fully automated systems. The role and application of artificial light in horticulture, the soilless cultivation techniques, the climate control and the sensors are some of the most significant elements that give motivation to both academia and industry for further research, evaluation and optimisation to improve the efficiency and productivity in vertical farming systems. The importance for further research and design of high performance and effectiveness technology in agricultural systems, can highly influence the overall productivity and profitability of IVFs by increasing the production per cultivation unit area.

Light can considerably affect plant growth rate, while due to the Increased amount of lamps in IVFs and the multiple hourly operation every day for optimal plant growing, the electricity demand of the farms can highly affected. Last years, the field of research on artificial lighting in horticulture has yielded to advanced knowledge and development of novel technologies that make artificial light sources more energetically efficient and versatile as lighting systems. In the market, there are many light sources with variations at their characteristic, such as Standard Incandescent lamps, Fluorescent lamps, High Pressure Sodium (HPS) lamps and Light- Emitting Diodes (LEDs) lamps. LEDs are known as the fourth generation of artificial lighting sources with a history of almost 60 years since they first appeared in 1961 (Tian, 2016). Martineau et al., (2012), mentions that HPS lamps even if they produce more moles of light compared with LEDs and both present the same yield per mole of light, on the contrary LEDs consume 70% less energy compared with HPS lamps. The total cost of the lighting system in an IVF depends on the purchase price of lighting sources, the cost of electricity consumption and the service and/or replacement cost of the lamps. Lighting expenditures are prioritised as one of the most costly in vertical farming operation, since they reflect almost 40% of the total production cost (Figure 6).

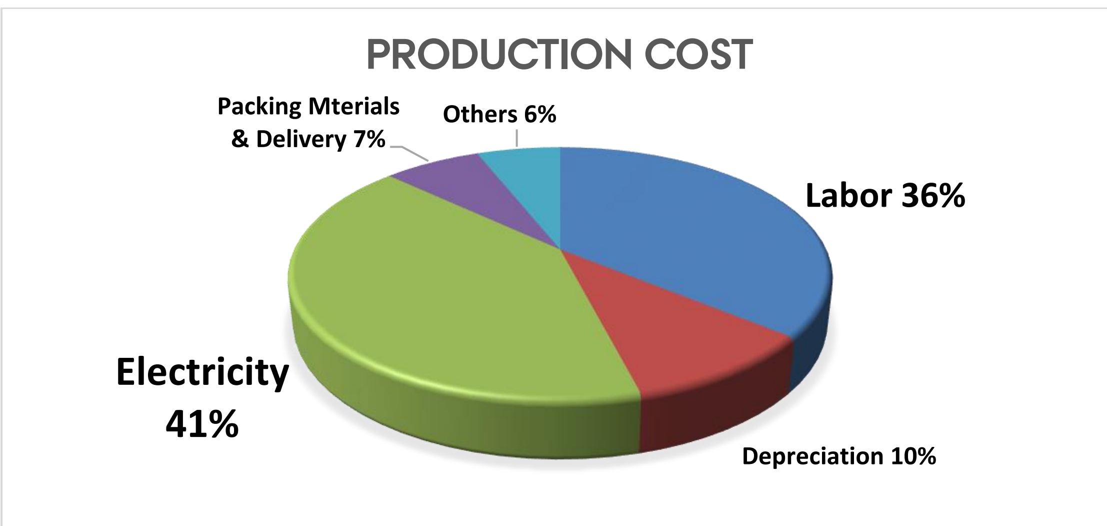

Figure 6. Percentage of cost distribution according to the multiple operational expenses (OPEX) for a VF (Avgoustaki D. D. and Xydis G., 2020)

The main motivation of this PhD research project was to provide a holistic solution that will improve the energy footprint of IVFs, contributing in the high global necessity to adopt more sustainable and efficient fresh food production systems for urban consumers that can benefit the environment with urban decarbonisation and alleviation of climate change. The whole PhD dissertation focuses on the energy demand reduction and development of flexible-load energy systems that IVFs can implement to optimising the lighting operation.

Nordic countries are considered among the most ideal cases for indoor farming application due to the significant lack of natural solar radiation (during the winter months). In 2017, Denmark imported fruits and vegetables that valued roughly DKK 11.2 billion, which is equals with a rise of 22.81% over the last 10 years (FAO, 2011). In other words, Denmark imports approximately 25,000 to 28,000 tons of fresh fruits and vegetables every year. At the same time, Denmark has almost 56% contribution of renewables to the electricity grid, while almost 43% of wind power was used in 2017 (Danish Ministry of Energy, Utilities and Climate, 2017). Denmark targets to become total independent of fossil fuels by 2050 and gradually abolish coal use by 2030. For this reason, the Denmark provides the perfect setting for research conduction and further investigation for renewable-energy-based opportunities and multidisciplinary solutions that can improve the lighting operation in indoor horticulture. Even if Denmark is considered the case study of this research; the proposed methodology could be extrapolated to other countries and markets that perform similar dynamic electricity systems that are characterised with high flexibility, integration of renewable energy sources and energy planning. This PhD dissertation offers a road map of the model of indoor farming, answers will be given concerning the vision, the concept, the basic technology with more focus on lighting technology and the proposed methodology of lighting optimisation. Finally, the calculation and analysis of the business opportunities, the resource use efficiency and the challenges of IVFs have been researched in order to explore and present the status of the market, identify and quantify the initial and operating expenses as also explore potential market opportunities for this technology. The lessons of this research project can be translated and adjusted to other countries, different technological settings and cultivar species contributing in a global Energy-Food Nexus.

1.3. Research Questions

The main thematic basis in this PhD dissertation is to research the concept of IVFs for indoor food production, research the business engagement and market potential of the technology and examine the influence of an optimised energy methodology that can enhance the profit margin of vertical farms by reducing their energy footprint and taking advantage of the electricity fluctuations of modern grids. This research intends to capture knowledge-creation processes and results that could develop the value-creation and impact on academia and simultaneously suggest solutions that could add value in the industry, the consumers and system integrators. According to the academic and industrial motivation, the following main research questions were formulated to frame and support the main research question of this research:

“What are the techno-economic benefits, risks and potential of indoor vertical farms under a Food-Energy Nexus in the Nordic context?”

This main research question intends to find a technical and system-based approach of agricultural practices that could enhance the penetration of IVFs as alternative systems that supply food into cities sustainably. In order to exploit holistically the above question, a number of related research questions needs to further exploration.

Research Question 1: *What are the benefits and challenges of indoor vertical farms?*

In order to answer this question, a firm descriptive exploration of what defines an indoor vertical farm has been proceeded. It primarily presents a detailed explanation of the technical requirements for successful vertical farming followed by a performance comparison between open field agriculture, greenhouse constructions and indoor vertical farms regarding resources input, efficiency and sustainability as well as food safety. Furthermore, it was considered important to establish an overview of how IVFs contribute on limiting food production risks concerning the shortage of resources, the unstable food supply and the degradation of the environment. The focal point is to understand the advantages and drawbacks that are correlated with vertical farming and how the maximisation of crop production and the energy efficiency can reduce the production costs and lead to successful commercial agricultural production for urban areas. Continuously, the research further detects and analyses the major risks that are highly correlated with the capital, operational expenditures of IVFs and how they can influence the investments and profitability of vertical farming units. To reach valid conclusions this part of dissertation compares and analyses the capital and operating expenses of under-coverage agricultural cultivation techniques. Specifically, a systematic and extensive cash flow analysis has been performed to assess the production economics between greenhouses and IVFs. Based on the economic results and the evaluation of the main financial challenges behind IVFs, the main focus of research is addressed to the importance of artificial light operation as one of the key factors of the optimal plant growth and development in indoor environments and due to the high participation in the production costs of indoor farms.

Research Question 2: *How can the risks associated with artificial light operation in indoor production be limited?*

The second research question targets to examine the importance and influence of light photoperiod on the development and growth of indoor crops. Under this scope, the dissertation not only reflects the current academic literature but at the same time is looking to develop a new methodology via experimental applications, in order to examine the opportunities for a more sustainable and efficient light operation for IVFs that maintains a high-quality and quantity salable product while reduces the electricity demand of the farm. An intermittent lighting protocol is introduced that aims to enhance the flexibility and resilience of lighting operation in order to allow indoor farmers operate their lighting equipment under demand response opportunities while preserving the required quality and quantity status of the growing crops.

Research Question 3: *What is the impact of intermittent light application on the energy footprint and the growth of plants in IVFs in the Nordic context?*

To research this question, this PhD dissertation examines if intermittent lighting method could help IVFs decrease the risk associated with the high electricity demand due to the long light operation demand of the cultivated crops. In this direction, this question investigates the influence of intermittent lighting operation on basil plants, and how this methodology can transform the existing lighting applications by creating an interdisciplinary nexus between power grids and food production systems. Therefore, this question reflects the influence of intermittent lighting operation on the energy demand of IVFs, firstly, by examining and evaluating its impact on the development and growth rate of plants. Secondly, this dissertation focuses on developing a new lighting model that enables the hourly electricity price comparison and selection, and by synchronizing it with the growth status of cultivated plants, provides a hybrid system, where IVFs are energy-assisted under the cheapest daily prices. Furthermore, this research evaluates the resulted energy cost savings from the intermittent light operational in an IVF case, followed by systematic and extensive cash flow analysis that assesses the production economics for flexible-load lighting.

With the electricity markets liberalisation in the EU and the established power exchange in Denmark, this dissertation is looking for researching a new methodological approach that enables the synchronisation between demand and supply for food production. The PhD dissertation focuses on Nordic region electricity market and evaluates the opportunities and dynamic of hourly fluctuating pricing in a wind-based electricity system in creating an Energy-Food Nexus.

1.4. Methodology

In this section, the dissertation introduces the research design and the applied methodological approaches that were used to research and study the above-described questions. Firstly, it provides an overview and discusses the research philosophy and the framing of the methodology design. Continuously, follows an introduction for all the six selected article studies, the research design and methodology behind each one of them.

1.4.1. Research Philosophy

After establishing the problem statement and the research questions, the following step is to define the research strategy, the techniques for data collection and the process of analysis (Saunders et al. 2009). The type of strategy and the approach steps of investigation have to follow a specific framing that reflects the overall research philosophy of this dissertation. However, in the scientific community there is no specific pathway that defines which are the most appropriate frames. At the same time, Creswell (2014) states that different research paradigms (the fundamental set of beliefs and actions) can follow different methodological approached within the same research project, meaning whether qualitative, quantitative or mixed methods. . In addition, he mentions that research should primarily follow one of the four specific positions of post-positivism, constructivism, transformative and pragmatism that will guide the researcher to develop specific methodological approaches, tools and practices that reflect the reality and guide the process of decision-making and data evaluation.

The interdisciplinary context of the risks associated with lighting operation in indoor agricultural systems indicates the apparent need for mixed methods use. Howe (1988) states that pragmatism endorses the use of mixed methods, where various multiple methods and data inputs are necessary to explore a complicated research problem that contains objective and subjective knowledge. However, pragmatism can be easily influenced by unexpected results as also the unstructured connections of mixed methods, where researchers can liberally provide reasoning from qualitative and/or qualitative hypotheses in order to reach subjective results (Creswell, 2014).

Instead, postpositivism position reflects the deterministic sceptical, critical and challenging position that a researcher should stand on traditional claims while studying the behaviour and actions of living organisms (humans, plants, animals) (Avenier, 2015). Therefore, based on Howell (2013) the creation and implementation of experimental processes that determine to seek all the cause-and-effect results are carried out with quantitative scientific methodological approaches. The research develops theory followed by data collection that tend to accept or refuse the theory and consequently developing the necessary revisions for future investigation. Yet, Saunders (2009) suggests that the different assumptions that are investigated in every stage of the research have to provide answers about the epistemological, ontological and methodological questions of the object that is studied. At first, the ontological question focuses on reflecting the nature of reality by researching on the existing object and always has the goal to fully reveal the reality. Under this scope, this dissertation defines a critical realism that allows observation and examination of all the possible causes that reflect the true reality, including detailed literature and bibliographic reviews, data collection from valid sources and careful model development based on true statements and hypotheses formulation. Continuously, the epistemological question defines the relationship between the researcher and the nature of the studied object. The use of quantitative data from true experimental designs and model-based approaches seek to give unbiased answers by observing and measuring the objective reality that exists and therefore, by creating connections between the researcher and the data, manages to answer the research questions of this dissertation. Every research question in order to be answered has been confirmed by various approaches and has been examined under different experimental set-ups and multiple inputs of data. Finally, the methodological questions focus on answering how the researcher can reveal the knowledge that defines the nature of reality. For this reason, triangulation of data and research inputs and analysis has been subjected to multiple criticism, and multiple experimental protocols have been applied to ensure the validity and reliability of the data outputs. The followed experimental approaches and protocols enable the access and usage of quantitative measurements targeting the examination and evaluation of the hypotheses and the exploration of the reality. As has been previously mentioned by Creswell (2014), the combination and integration of mixed qualitative and quantitative research design methods provide a more holistic overview on discovering new findings by enriching the post-positivism research design process that has been the case of the scientific articles of this dissertation.

1.4.2. Mixed Methods Design: A Requirement for Techno-Economic Studies

This dissertation is based on a techno-economic approach with multiple experiments and comparative case studies that seek to present the impact and performance of load-shifted lighting operation for indoor climate-controlled agriculture in the Nordic areas by operating under a nexus of energy and food production systems. This dissertation contains a multi-dimensional project with high level of interaction between the different systems and how they influence the economics of vertical farms and the conditions of crop production; therefore, the learnings from different categories are key to understand the connections and the influence within various elements of this techno-economic system (Cherp et al.

2018). For such an accomplishment, this dissertation uses the mixed methods approach to research the techno-economical system in which artificial light for indoor food production operates, develops, interacts and evolves.

Mixed methods due to the application of combined qualitative and quantitative methods, provide sufficient and multi-dimensional reasoning to answer the research questions. Primarily, the subject's exploitation begins with qualitative data collection and analysis that perform open-end and non-previously determined responses and seek to provide the logic reasoning that reveals the truth and help the researcher understand the design and the working challenges of the system (Creswell and Clark, 2011). Subsequently, quantitative data of this dissertation provide a more meaningful analysis and outputs that after analysis and assessment lead to behavioural patterns, influences and explanations (Blaikie, 2003). The mixed methods approach endorses data validity via triangulation, revealing unique learnings, creating better measuring protocols and creating new databases. (Creswell, 2014)

The analysis of a techno-economic model in this project is relevant in terms that it explores economically the innovation of vertical farming, which is not considered one of the dominants of agricultural cultivation techniques. In order to proceed with this assessment, firstly, evaluates the economic status of vertical farms by investigating different cash flow scenarios with secondary data sources, such as scientific journal papers and industry reports (Lauer, 2020). Continuously, embedded mixed methods are applied for extraction and evaluation of qualitative data within a larger experimental design that focuses on investigating the lighting operation in indoor farming system by analysing and evaluating how it operates, interacts, evolves and how it can be further optimised.

This dissertation specifically includes secondary data methods based on peer-reviewed bibliography, market reports and business cash flow models. Subsequently, primary methods were utilised for data collection including the multiple experimental datasets under different indoor growing installation areas. Theory has been used inductively to provide explanations and definitions on the experimental outcomes. The application of mixed methods often presents subjective biased results, when the followed methods are in an unstructured and misleading way. Subjectivity was avoided by systematic searching of conceptual patterns and trends in the literature in order to understand the nature, the size and the dynamic of the problem followed by experimental designs that will thereafter be questioned and researched further with the use of qualitative data.

To summarise, this PhD dissertation follows an exploratory sequential mixed method approach. The first phase of the research focuses on the qualitative exploration of the study by identifying and defining the topic and the technology as also informing the researcher concerning the most suitable instruments, protocols and variables for the following experimentation process. The second part of the research consist of the quantitative phase that examines the relationship between the variables, and by applying statistical processes validates the significance of the results between the different treatments (Creswell, 2014). Therefore, this research dissertation uses both data format elements in order to investigate the roadmap of vertical farming and the connections and dependence on lighting operation for further efficiency of the farming system, focusing mainly in the Nordic area. Particularly, the six different articles that are presented in this dissertation follow specific methodology and approach to answer the different elements that overall answer the three research questions. Subsequently, the three main research strategies that this dissertation uses are presented and continuously is further explained and described how each methodology elaborates in each paper (1.4.3. Research Design).

1) Systematic literature review

Systematic bibliographic reviews is the method that was used to classify, select and critically evaluate the vertical farming concept. Furthermore, systematic review followed specific framing and criteria that clearly defined the information searched in this dissertation. The planning strategy was predefined in order to identify the keyword terms that were used, the search criteria (regional database, dates and technical specifications), the accessibility as also the limits that would structure the research in the most transparent and comprehensive way (Tranfield, 2003; Grant, 2009). This dissertation uses the methodology of systematic literature reviews in order to map an overview of vertical farming and establish the foundations among the various technical procedures that interconnect with each other for indoor food production. Afterwards, systematic literature review provides the reflection of the innovations and the challenges that are correlated with energy footprint of IVFs. This methodology provides the necessary pre-existing evidence that are associated with IVFs and will promote the development of robust (valid and reliable) and applicable hypotheses to be formed in the continuation of this project.

2) Experimental Testing

Experimental design is the most widely applied methodology in the agricultural field that allows researchers to develop and implement an ongoing research project that observes and measures various elements with purpose to answer the research questions, the objectives and the formulated hypothesis. Experimental design is a tool for identifying and isolating the effects of variation and determine whether the differences between various practices (treatments) are significant under specific levels of probability. When experiments are sufficiently structured, they can explore the special variability of crop responses under different treatments (Alesso, 2019). In this direction, true experiments develop and generalise agronomic recommendations as well as improve and make more precise the estimations of the treatment's effects. The design, robustness, structure and organisation of the experiment are significant parameters in the data collection and data analysis process, due to the ability of providing valuable and unbiased information for the estimation of the true effects in the research. In this PhD project, different true experiments were performed within and between-subject design, with observation of multiple dependent variables under the effect of one independent variable and the evolution of the independent variables during the time (Vogt, 2011). Detailed description of the conducted protocols of the experiments are included in all the submitted experimental papers that are selected for this PhD dissertation.

3) Case Study – Techno-economic Cash Flow

Case study is one research strategy that uses an empirical examination to investigate an existing phenomenon as is defined in the real-life context (Wedawatta, 2011). The case study of this dissertation aims to analyse, provide insights and information on the profitability and the viability of IVFs, and define the conditions, benefits, risks and solutions that could benefit the implementation of IVFs in the Nordic areas. The operational and capital expenditures as also cash flows analysis are significant inputs for evaluation of the market promises of IVFs. The economic assessment as one of the most comprehensive analysis, can provide valuable information about the progress, the potentials, the risks and the limitations linked with vertical farming. Additionally, the connection between capital and operating expenditures can define the return period of investment for a project and is used as a tool for improving the cost-effective balance of the business. Such type of models can be very complex due to the cost estimation phase that consist of advanced connections and mathematical approaches or due to limited information. Cash flow management models reflect the balance of received and spent cash on an industry project over a specific time duration (Zayed & Liu, 2014). Under this scope, this PhD dissertation investigates and studies the profit margin of IVFs and accurately manages the financial aspects in order to extract knowledge on the profitability status and the barriers of IVFs.

1.4.3. Research Design

In this PhD dissertation, comparative case studies carried out, seeking to develop a lighting model that can be generalised for the improvement of lighting operation of IVFs and can influence the implementation of IVFs in the Nordics as a source of flexible-load in the power grid. The design of this project follows multi-method approaches in order to provide knowledge and information by researching in depth the techno-economic variables that define the operations, methodology and the role of IVFs in a multidisciplinary framework. In this content, even if the goal is to develop generic patterns for indoor lighting operation, additionally individual information can be obtained for each case study that afterwards can be used to provide new literature information in the field. For example, Research Question 3 targets to develop a new lighting methodology for indoor farming in the Nordic areas, therefore, multiple experimental cases needed to be developed in order to validate the research outputs but also to isolate the different environmental factors that influence the enhancement or reduction of plant growth and development in indoor growing areas (Baxter & Jack, 2008). All the results of this research, are explained and discussed under the existing scientific literature in order to reach critical conclusions, as one of the main characteristics of post-positivism research methodology (Eisenhardt, 1989). In this direction, the selected and applied methodology design is matched to fulfil and complete the desired objectives of each research question. Below, follows the research design that have been applied specifically in each research article and is submitted in this dissertation in order to provide valid answers at the research questions.

The first article studies the sustainability and efficiency status of agriculture under three different cultivation techniques in terms of use efficiency of resources and food safety. The design of this research approach is based on a convergent parallel mixed method where both quantitative and qualitative data have been collected, researched and presented at the same time (Creswell, 2014). The goal of this article is to provide necessary evidence and information that will interpret the findings and will allow all the possible integrations for mapping the sustainability status in agriculture, the innovations and the challenges. The methodological approach of this study consists of a comparative performance analysis between open-field farming, greenhouses and vertical farms. In order to result in concrete conclusions about the sustainability level and reveal of challenges and the risks of each farming type, a thorough and systematic analysis has been conducted towards the resources use efficiency, yield production and cultivation techniques. The purpose of this comparative research is to ensure the equivalence status among the three different agriculture methodologies by collecting valid and unbiased data from literature that can formulated in a comparative way in order to reveal strong arguments on the sustainability and safety levels of food production (Esser F. & Vliegenthart R., 2017). In this research article, secondary data were mainly used including information from peer-reviewed literature and company reports, to examine and describe the cultivation characteristics that define and influence the resources use efficiency under each agricultural method, to investigate the level of variation among them and finally, to compare the three cases based on their similarities and differences.

The second research paper of this dissertation is a case study that performs a techno-economic evaluation, performance analysis and comparison of the operating and capital expenditures between greenhouses and IVFs. To this goal, two case study of a vertical farm and a greenhouse unit located in the city of Aarhus in Denmark were developed and the two cases were examined for their volumes of capital and operational expenses according to their different inputs, outputs and installation requirements. For the analysis and comparison between the two types of farming, two different simulation models were developed, following the same format but adjusted to each typology and installation requirements. Continuously, different cash flow scenarios for both the vertical farm and the greenhouse unit were developed while the internal rate of return (IRR) and the net present value (NPV) indices were used to compare the two farm facilities. The objectives of this study were to investigate the optimal conditions and solutions of vertical farming applications that could be implemented in the Danish society for local food production, provide sufficient and critical comparison between the two under-coverage agricultural methods under resource-conserving perspective and identify the components and challenges that need further improvement (Yin, 2003). This research uses both qualitative and quantitative data to obtain in-depth knowledge, in regard to provide rich mix data for the study of the profitability and the economic efficiency between the two different types of farming.

The third, fourth and fifth research articles that follow in this thesis present three true experiments that evaluate different growth indices of plants (dependent variables) by manipulating a specific variable as treatment (independent variable) and introduces a compilation of results that assess the impact and influence of the outcome (Creswell, 2014). The objective of these studies is to explore different parameters by pairwise comparison in order to provide the relative effect and significance of the treatment factor on the examined indices. These scientific papers provide a multidimensional reveal of the influence value of the treatment as they perform comparisons both between-groups and within-groups designs among different and various parameters. The dependent variables have methodologically selected and derived from the existing literature and also reviewed and evaluated using such literature, following the principles of deductive reasoning for hypothesis and patterns' development while maintaining the validity of the outcomes. Subsequently, the samples' populations that were selected for examination in all the experimental sessions were defined by inductive reasoning in order to reflect the conclusions for a larger population. Conclusions were precautious driven, leading to some significant findings that can be used for future research and development in indoor farms.

The sixth and final research article that is submitted in this PhD thesis is a paper that develops a case study analysis and comparison of a medium-scale vertical farming system that is simulated once without the energy optimisation model and after the energy optimisation model. The case model of the farm follows the same assumptions that were developed in the second paper, while the only differentiation comes from the different lighting protocol application and finally, presents the significance of the comparison results. This paper uses also secondary data sources from the experimental papers and the Energinet and peer-reviewed literature to proceed with the analysis and the assessment of energy optimisation in indoor farms. More specifically, this case study analyses and examines the possibilities, the potentials and the gained value that results by applying load-shifted energy demand response for fresh food production in countries with dynamic electricity market pricing. Denmark is the selected case country of application due to the participation at the Nordpool exchange power market that offers day-ahead and intraday markets to the consumers. Data fed into MATLAB to develop an electricity optimisation model that synchronises plants' lighting demand and hourly electricity prices to provide a smart decision tool for lighting in horticulture. The purpose of this paper is to combine the extracted knowledge and the results of the true experimental research methods and translate them into the Danish market and economy, in order to provide insights and propose an optimisation method that can support indoor food production both technically and economically.

The following Table 3 summarises the research design of each scientific paper that is submitted in this dissertation. Comprehensive description for each applied research design is presented in each and every research article submitted in this thesis.

Table 3. Introduction on the applied research designs.

Research Question	Article	Research Subject	Data Collection	Research Analysis
RQ1: What are the benefits and challenges of indoor vertical farms?	1	The different performances and resources use efficiency between open field agriculture, greenhouses and IVFs. The technical specification and the challenges that risk the sustainability and safety status of IVFs	• Peer-reviewed literature • Market report • Performance data	Collection of secondary data, qualitative and quantitative coding and comparative analysis, which focus on 10 different resources and values of farming
	2	Techno-economic analysis of a case study and economic	• Peer-reviewed literature • Market reports	Qualitative and quantitative secondary data

		comparison between IVFs and greenhouses systems followed by cash flow analysis to assess the financial opportunities and challenges in Denmark	• OPEX and CAPEX model • Cash Flow Model	are structured to reflect the operating and capital expenditures in under-coverage farming. Development and analysis of cash flow scenarios reflects the profitability and investment opportunities in greenhouses and IVFs
RQ2: How can the risks associated with the artificial light operation in indoor food production be limited?	3	Experimentation and evaluation of the photoperiodic requirements' of basil plants grown in indoor cultivation	• Experimental set-up at BTECH Department • Sensors • Data loggers • Statistical Analysis • Peer-reviewed literature	Quantitative coding and statistical analysis using SPSS. Descriptive statistics Analysis of variance
	4	Experimentation and evaluation of intermittent lighting intervals for basil plants grown in indoor cultivation	• Experimental set-up at BTECH Department • Sensors • Data loggers • Statistical Analysis • Peer-reviewed literature	Quantitative coding and statistical analysis using SPSS. Descriptive statistics Analysis of variance
RQ3: What is the impact of intermittent light application on the energy footprint and the growth of plants in IVFs in the Nordic context?	5	Experimentation, documentation and evaluation of load-shifted lighting protocols in indoor growing basil crops	• Experimental set-up at Department of Natural Resources and Agricultural Engineering, Agricultural University of Athens (AUA) • Sensors	Quantitative coding and statistical analysis using SPSS Descriptive statistics Analysis of Variance

			• Data loggers • Statistical Analysis • Peer-reviewed literature	
	6	Development of a dynamic energy model and assess the impact of load-shifted lighting photoperiod for IVFs in the Nordics	• Algorithm Development Data (MATLAB) • Market reports • Peer-reviewed literature • OPEX • Cash flow Model	Cost-optimisation model MATLAB Descriptive data and analysis

1.5. Contribution and Novelty

This PhD dissertation and the articles that are presented contribute on answering the fundamental research questions of this research and are analysed based on the notions of novelty, uniqueness and value that they add on the agriculture and energy sector (Sovacool A. et al., 2018). Research can be novel under the scope of three critical factors: first of all, the theoretical contribution that aims to develop, examine, critise and revise the subjected concepts and contribute on structure and theory development. Secondly, the methodological contribution of this research further explores and develops the appropriate research methods that reflect the objectives and the analysis of data inputs. Finally, the empirical contribution of the research focuses on inserting new applications in the already existing methods and theories as well as provide further analysis of new applications, evidences and data.

Based on literature, this dissertation provides novelty and contribution in the following ways. First, the methodological approach includes mixed methods approaches that implement and manipulate both qualitative and quantitative methods of primary and secondary data sources that answer the research questions, under three different distinct methods (1.4.2. Section). The novel methodological contribution applies various approaches that provide answers and insight on the complex defined questions, such as the techno-economic analysis of vertical farming systems. Additionally, this dissertation includes innovative research methods, by defining and experimenting on intermittent photoperiodic intervals for indoor cultivation. The value of this methodology was validated by the impact and interest of this research output beyond the academic cycles but also being disseminated and communicated in entrepreneurial, industrial, social and supply chain cycles.

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2. What are the benefits and challenges of indoor vertical farms?

The first research question is answered by introducing the following two research publications:

1. Avgoustaki, D. D. & Xydis, G. (2020). How energy Innovation in Indoor Vertical Farming can Improve Food Security, Sustainability and Food Safety. Elsevier. Chapter One. 5, pp. 1-51. https://doi.org/10.1016/bs.af2s.2020.08.002.
2. Avgoustaki, D. D. & Xydis, G. (2020). Indoor Vertical Farming in the Urban Nexus Context: Business Growth and Resources Savings. Sustainability; 12, 1-18. https://doi.org/10.3390/su12051965.

The two articles (one book chapter and a journal article) aim to reveal the specifications, technicalities and flows and efficiency of resource for IVFs, starting more broadly and worldwide and in continue focusing more on the Danish reality and market. More specifically, the first article, examines the performance of three different agricultural methodologies (open field agriculture, greenhouses and IVFs) in terms of resource use efficiency, food safety and sustainability of the methods. Continuously, the second article, focuses mainly in the installation, operation, profitability and return of investment of an IVF case scenario. Under this scope, examines, compares and analyses the operational and capital expenditures of a greenhouse facility and an IVF in the Nordic area, and also quantifies the risks and the challenges that are correlated with indoor farming operation and the significant role of artificial light.

2.1. How energy Innovation in Indoor Vertical Farming can Improve Food Security, Sustainability and Food Safety.

The first scientific article that is submitted in this dissertation examines and presents the performance of three different farming techniques: open-field farming, greenhouses and IVFs. The ankle of comparison includes the input of resources for each agricultural method, the final harvested quality and quantity of products, as also evaluates the safety and the self-life of the products in terms of fresh and nutrient status. This scientific article is based on an extensive synthesis of more than 60 peer-reviewed studies, company reports and European commission reports that seek to explore, categorise and quantify the resources' inputs and outputs under different food production methods. This article describes the characteristics and principal components of IVFs with artificial light, which consist one of the most sophisticated types of closed plant production systems (CPPS). The characteristics of IVFs are compared with those of greenhouses and traditional farming from a viewpoint of resource use efficiency (RUE). More specifically, the comparison criteria include the vital elements on plant grow and development such as water, CO_2, light, nutrients, electricity and heating/cooling. Consequently, this study contributes to the indoor farming industry in terms of reflecting the improvements that are required in the light and electrical energy use efficiencies of IVFs that can enhance the profitability by reducing the production costs. Furthermore, the challenges that are highly connected in IVFs are further discussed in order to provide the necessary background of the ultimate goals of indoor cultivation for optimal operation, which are:

a) the maximisation of the amount of usable and salable part of the crops by using the minimum amount of resources,

b) the preservation of the highest possible RUE,

c) the elimination of environmental pollutants and

d) the minimisation of the costs while achieving the upper goals (Kozai, 2007; Kozai et al., 2016).

Among the various resources that are comparatively analysed, a considerable amount of electrical energy is required to cover the lighting demand of indoor cultivation. Thus, electrical energy and light energy are concluded to be the most important resources that are associated with high risk in IVFs and have increasing necessity for further improvement in terms of RUE in indoor food production systems.

2.1.1. Introduction

Sustainability of resources and safety in the food production line is a major issue globally. By 2050, it is expected that the global population will reach almost 10 billion people, 2.4 billion people more that need to be fed with nutritious food sources (United Nations, Department of Economic and Social Affairs, 2015). Today, agriculture occupies land equal to the size of South America in order to cover the demand of the global population (FAO, 2019). Based on the assumption that the minimum daily demand of a single person is minimum 2000 kcal, if we maintain the same agricultural practices for food production, we will need additional land equal to the size of Brazil (2.1 billion acres) to cover the global food demand (Despommier, 2009). On the other hand, according to Lotze-Campen et al. (2008), part of the land used for agriculture is projected to be transformed for other purposes such as urbanisation, energy production, or infrastructure growth. It is worth to mention, that another crucial challenge that will significantly affect agricultural production in the upcoming years is the rapid increase of the global temperature, as per each degree of temperature rise, 10% of existing agricultural land will be lost (Despommier, 2010). Nowadays, climate change is a huge issue since it is expected that the upcoming 50 years will outstandingly affect the agricultural process. The significant increase of the carbon dioxide emission levels from a global perspective—since it constitutes an important impact factor of agricultural productivity—can influence the global economy via the effects on the agriculture's total production rate. In specific, based on Mulatu's et al. (2016) research conducted for Ethiopia, indicates that the impact of CO_2 emissions will decrease 3.5% to 4.5% of the real agricultural GDP (Gross Domestic Product), since it will lead to lower the agricultural productivity and subsequently reduce the amount of traded and non-traded crops. Such population increase certainly indicates a significant rise in the required food production, raising concerns on the deficiency, the quantity, and the quality of future food products. We should also take into account the fact that nowadays food travels daily thousands of miles from the production areas to the urban consumers, in order to meet the demand, releasing huge amounts of CO_2, jeopardising the sustainability and the quality status of products (Kemp et al., 2010).

Less developed countries such as Ethiopia, Niger and Mali that were mentioned above, apart from global climate change will have to face and other enlarged problems concerning food safety and extreme hunger. For example, human excrements that are used as fertilisers (estimation of 50% of the global farming) can cause diseases such as cholera, typhoid fever and numerous parasitic infections (Despommier, 2010). Nowadays, even the more developed counties have to face food safety and security problems even if this kind of infectious diseases have been eliminated. It is worth to mention the pandemic of our age, COVID-19 caused by virus SARS-CoV-2 that was initially reported in the province of Hubei, Wuhan in China. The disease is estimated to have originated from a seafood market in Wuhan where wild animals were traded such as marmots, bats, snakes and birds (Zhou et al., 2020). The specific family of viruses, coronaviruses, are known to be transferred from animal to humans. According to Zhou et al. (2020), it is mentioned that 96% of the genetic makeup of COVID-19 is matched with the coronavirus found in bats. The uncertainty that is caused globally via COVID-19 has caused apart from multiple deaths and lockdowns to almost all the countries, will affect significantly the economy and will cost trillions of dollars in the global economy, during 2020 and beyond (UNCTAD, 2020).

Food safety is a major issue of our era, as there are multiple reports of cases worldwide over the last years that have caused food recalls due to bacterial infectious diseases leading to loss of billion dollars. Why do we seem to have so many outbreaks concerning food production these days? Only in the US, despite the attempts to provide a safe food supply, every year are recorded 48 million foodborne illnesses, 128,000 hospitalisations and 3000 deaths (CDC, 2013). In 2017–18, E.coli O157: H7 outbreak in the US caused sudden eruption linked to consumption of leafy greens and the romaine lettuce. The pathogen was mainly reported in the regions Yuma, AZ and Salinas, California, where greenhouse installations that produce more than 90% of the leafy vegetables and greens in the United States are based. E.coli contamination in the production line almost all the times originates from the irrigation water used in the fields. Additionally, further risk in the contamination process from various bacteria and pathogens comes from the washing of field-grown products after they are harvested, while this step can spread contamination to the whole production (Mishra, 2008). The most regular technique that outdoor farming applies after harvest is dunking lettuce heads in water tanks from rainfall or irrigation while most greenhouses apply triple washes with running water from the local network (Nerín et al., 2016).

Vertical farms are a novel type of farming in a controlled-environment with a total replacement of solar radiation with artificial lighting that provides the necessary nanometres of the spectrum for the growth and development of plants. In vertical farms, plants grow in soilless cultivation systems such as hydroponic (roots are immersed in multiple substrates, i.e., perlite, rock wool enriched water with nutrient solution), aeroponic (soilless air/mist solution) or even aquaponic (co-cultivation of fish and hydroponic/aeroponic plants) systems that allow stacking multiple layers or columns of plants horizontally or vertically. Vertical farms are located in completely isolated spaces from outdoor environment with thermally insulated installations (especially when at the top floor of the building) and airtight structures that give the opportunity to the farmers to control the environment in terms of temperature, humidity and CO_2 (Avgoustaki & Xydis, 2019). Since vertical farms can theoretically be placed anywhere in the urban network, they allow local, nutritious and fresh consumption for consumers. In specific, a study conducted by Jill (2008), mentioned that food sourced from conventional farming uses 4 to 17 times more fuel compared to locally grown food and emits 5 to 17 times more CO_2. Meanwhile, vertical farms may be able to increase the productivity rate in highly urbanised areas that can lead to improvements in the food security of the community.

The purpose of the following subchapter is to compare the different farming techniques of open-field farming, greenhouses and indoor vertical farms in between them in terms of input of resources, the final product in terms of safety and the shelf life of the products in terms of nutrient status and freshness. Additionally, we will examine the above criteria for lettuce, which is one of the most importantly cultivated species in vertical farms and will give us access to multiple data. Lettuce belongs to the basic daily diet products; its nature is fragile and can be easily contaminated and spread diseases among the population.

2.1.2. Comparison in resources input and sustainability between different farming types

To make more understandable the concept of RUE, in Fig. 7 the essential resources for growing plants under various farming types are shown. The most vital for plant growth is water, CO_2, light, nutrients, electricity (for ventilation purposes) and heating.

As shown in Fig. 7, the definition of RUE is given by the ratio of the final plants production to the total input. In order to calculate the total input of a system, we have to summarise the input of resources, the environmental pollutants and the production system.

To evaluate the sustainability and efficiency of a production system in the food industry, we have to assess three key directions of the system.

• RUE: the amount of necessary resources to produce.

• The cost performance: the ratio of the sales amount to the production cost.

• The vulnerability of the system, meaning the deviation of the yield production per year and the quality value per product unit.

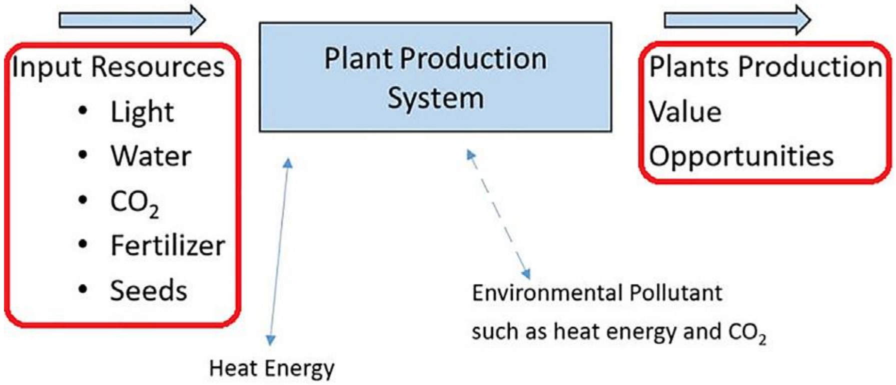

Figure 7. RUE concept of a plant production system.

Water is absolutely necessary for all food production such as vegetables, fruits, grains, meat etc. Based on Nederhoff and Stanghellini (2010), the water use for the global food production reaches at 5400km^3 and has a rapid increasing rate. The irrigation water-use efficiency (WUE) can be researched under different scopes and multiple concepts such as storage, delivery distribution of the water to the farm or out of the farm. Additional systems that can affect WUE is the ratio of water that is delivered for irrigation and the water that supplies the system. There are various ways we can calculate WUE as one of the major resource inputs in food production that can be accomplished with agronomic ways, engineering or even economic approaches. More analytically, irrigation efficiency estimates the ratio between the diverted water and the consumed water by the cultivation; thus it provides water-use measurements that estimate the performance of the irrigation system. On the other hand, WUE is considered an economic concept that traditionally evaluates the farm, as it is calculated by the crop yield unit of water diverted (kg/m^3).

In terms of energy consumption, greenhouse gas emissions (GHGs) it is one of the reasons that contribute significantly at the rising global warming. The main gases released by agricultural production are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Since the global policymakers, organisations, researchers, retailers and producers try to propose and implement novel techniques that identify and reduce GHGs, it is necessary that we will focus and refer to the status of emissions under each farming type and propose mitigation measures in the sector.

To describe sustainability in agriculture, it is not enough to relate sustainability with the field only from the resources' perspective. Understanding and evaluating what constitutes a sustainable farming system, it is of vital importance, to furthermore understand the economic and social terms that influence the contemporary issues, values and potentials of a unique system. Economic efficiency reflects to the value that is relative to the cost. In order a resource to reflect an economic value, has to be rare and difficult to obtain, for the market prices to allocate the use of this resource for competitive purposes. For example, even if air and water are essential resources for life giving them high "intrinsic" value, nevertheless under most circumstances they have no economic value due to their sufficiency levels in the environment (Ikert, 2001). They only obtain an economic value in cases of scarcity due to, e.g., high levels of pollution or drought.

2.1.2.1. Open-field farming

2.1.2.1.1. Status of resource use efficiency

Traditional farming is the type of agriculture where plants are shown and grown in the land field in soil. Even if is the most ancient way that people use land, over the last decades with the technological breakthroughs and the numerous innovations introduced, outdoor farming has changed. Sensors, satellites and advanced machinery allow farmers to apply more targeted (and precision) agriculture to treat the fields individually according to the needs of the crop and the soil, by dividing it in smaller parts in order to take into consideration the variability level of each unit. To complete the whole picture of climate change issues, an additional evolution process that crucially reduce the growth rate of plants is soil degradation due to excessive floods and droughts.

Open-field food production systems offer food solutions to people from the beginning of human history. Over time, additional innovative techniques were applied in traditional farming to rise the productivity rate and reduce the cost and the crops overall footprint. In terms of resources, conventional farming seems to have an increase demand for water use, as traditional agriculture uses almost 70% of the available fresh water globally (Table 4). Furthermore, a very common problem in terms of sustainability in WUE of conventional farming is the limited soil water-holding capacity that results from the limited mulching of the soil and the consistency in the same fertilisers/soil-preparation practices. Scientific results (Pimentel et al., 2005) have shown that this maintenance of these practices lead to low soil moisture status and low conservation levels of conventional farming systems.

The most used approach for conventional farms is the irrigation efficiency and the WUE. It is worth to mention that the more water applications are applied in a crop, the higher the water delivery losses are. In order to improve the WUE, many farmers apply a combination of hydroponic systems with drip irrigation and smart scheduling of water distribution. Hydroponics successfully address the challenge of soil drought and salinity that reduces both yield and crop quality. It should be noted that a decisive factor for the selection of hydroponic systems is the high irrigation water needs that renders the requirement for recirculating water. It becomes apparent that a combination of water–saving technologies with limited-water application technologies (such as close-loop hydroponics, drip irrigation, mulching and smart scheduling of water supply) are the most effective solutions for optimising WUE.

Table 4. Summary of annual data for outdoor farming.

Resources Efficiency	Traditional Farming (lettuce)	Citation
Water Use Efficiency	250 L/ kg lettuce/ year	Barbosa et al. (2015)
Water Use	Irrigation and rainfall Approx. 250 L/m^2	Coyle & Ellison (2017)
Energy Use	0.3 kWh/kg/year	Barbosa et al. (2015)
CO_2 emissions	540 kg/tons of lettuce	Gerecsey (2018)
Light source	Solar radiation	

Pest control use	EPA-approved pesticides, herbicides and fungicides as also traditional methods as plowing, weeding and mulching	
Yield	3.9 kg/m^2/year	Coyle & Ellison (2017)
Land Use	275 days/year	Coyle & Ellison (2017)
Land Use Efficiency	93 m^2 for 1 kg lettuce /day	
Harvests per year	2 per year	Coyle & Ellison (2017)
Food miles	3200 km	

Regarding land use, growing and producing food to respond to the expanding demand of the world has led agriculture production and food scarcity that can be difficulty bridged. Today's farmlands, occupy almost 50% of the global habitable land (ourworldindata.org). We gathered the footprint of the various resources that meet the demand for lettuce production via traditional farming techniques. Worth noticing that deforestation is a major problem, since forests are continuously sacrificed against farmland that leads to climate change acceleration and soil inability to maintain water at lower levels. Depending on the cultivated variety, the techniques and the season, traditional farmed lettuce has a cultivation cycle between 1.5 and 2.5 months. Therefore, farmers have the ability to grow multiple successive crops in the same field throughout a yearly cultivation period in order to increase their yield and income. Additional techniques that open-field farmers follow in order to increase their yield and income per hectare (ha) of cultivated land is the density of planting, fertigation (combination of fertilisation with irrigation) application and the use of healthy transplants grown in nurseries. Assuming that romaine lettuce growing in the Mediterranean is planted in distances of 30–50 cm between the rows and 20–35 cm between the plants, then the resulted yield reaches at 75,000–220,000 plants per ha (Savvas et al., 2015). By increasing the planting distance per row by 1 cm, it can lead to a 76% reduction of the total production. Harvest period varies depending on the type or the variety of the cultivated crop. For the romaine lettuce grown outdoors, the harvest period is between 55 and 70 days with a typical yield of 25–30 tons/ha.

The energy use in outdoor farming is mainly linked to fossil fuels for operations such as soil plowing, sowing, fertilisation, harvesting etc. Additionally, further electricity is required for pumping (water irrigation), which in developed countries can reach up to 20% of the total fossil fuel usage (Despommier, 2010).

Conventional farming, unfortunately, is associated to higher emissions in comparison to other types of farming. The majority of the emissions is directly linked to the transportation of the products, also known as food miles. The amount of miles that is required in order for food to travel from the producer to the consumers could release between 11 to 666 kg of CO_2 emission depending on the location of the farm (Gerecsey, 2018). Since farmlands are often located many kilometres away from the urban centres, where the majority of the end-user is located. Food miles emissions represent on average 62% of the total emissions released throughout traditional farming. Another important source of CO_2 emissions that is linked to traditional farming is the significant amounts of food waste. Even if food waste is not only linked to traditional farming, maladministration and mismanagement on-farm losses, and non-marketable crops put traditional farming under the spotlight of high shares of carbon footprint. For the estimation and assessment of the economic efficiency of farming, a significant role in the calculation, the resources that bear an "economic" value have played a role. In traditional farming, there is limited capability to protect and evaluate the quality, use and maintenance of water, air, solar radiation and in some cases even soil fertility and productivity. The costs of a farm can vary between two main categories: the variable costs (operational expenses-OPEX) and the fix costs (capital expenses- CAPEX). In the category of variable costs, all the expenses that cover particular farming actions in a specific period of time such as seeds, fertilisers, chemicals, equipment operation and labour are included. On the other hand, in the fix cost category, all the expenses that will be incurred regardless the process and status of production, building expenses (rent, installations, land) and equipment installation (irrigation system, machinery) are included. Thus, the economic efficiency consists from a combination of technical and other components. Based on Aurangzeb et al. (2007) and research that conducted to compare the economic efficiency between traditional farming and mechanised farming systems, it is pointed out that the net income in mechanised farms is significantly higher due to the higher yields/ha than the one of traditional farms. This effect of traditional farms could be explained by the longer time periods in soil preparation, limited tillage practices as well as the high-cost requirements of labour expenses (specifically in seasonal workers during harvesting and sowing) in comparison to the high technology and mechanisation farming systems. Last, another factor that highly affects the final quantity of production is biodiversity. For this reason, the selection and maintenance of mono-cropping techniques that provide a uniformity in the applied practices, can reduce the labour costs and make harvesting easier. However, by cultivating only one crop's species in the entire field, it can highly influence the biodiversity and make crops more susceptible to pathogen infections. To avoid this effect, traditional farmers apply chemicals and genetically modified organisms to maintain a simple farming system. This practice, though, requires a lot of continuous input of resources and energy (cost).

2.2.2.1.2 Solution for increasing sustainability

The innovative and high-quality mechanisation and technological innovation can lead to the increase in production and hence income. Multiple practices become more and more vital in traditional farming, as they improve the efficiency use of resources in general and can overall enhance sustainability. Concerning the water usage, there are several approaches that new farms bring along in the field and can optimise the existing severe water waste situation. Common agronomic measures such as improved crop husbandry and changed crop mix driven by the crop selection, can have a huge impact in improvement of water usage. Furthermore, there are various cultivation techniques such as modification of the irrigation infrastructure, which can also influence positively the WUE. Last, management actions such as optimal irrigation planning and frequent maintenance irrigation system scheduled maintenance can also influence positively the system's efficiency (Wheeler et al., 2015).

2.1.2.2. Greenhouses

Due to the growing population, farming has shifted to technologies that enhance significant scale-up of the production via innovative technologies. Greenhouses are types of installations, designed to protect and enlarge the cultivation season of various crops. Plants growing under greenhouses can grow protected from severe weather conditions such as hail, snow, extreme low temperatures or excessive heat while at the same time can allow cultivations of out-of-season species. Greenhouses first introduced in the 17th century but only on the 19th century were commercially applied in the global market. According to their installed area, greenhouses can be presented with various coverage materials such as plastic, glass, polyethylene and rigid that protect crops from the variability of the outdoor conditions, diffuses solar radiation and traps moisture, which contributes to increased plant growth. The coverage system allows farmers to control the cultivation environment according to each crop preference, as they can apply different methods that will maintain the heating and the cooling requirements to the desired levels. This way, inside the greenhouses, farmers can develop and maintain the desired microclimate and create a more predictable environment that enhances the final plant yield, achieving higher quality and reduced water consumption compared to open-field crops.

There are different greenhouse systems that are diversified according to the energy flow inside the greenhouse and the resources flow in the production line. In more details, open greenhouses refer to the structure of the irrigation system, meaning that they do not collect the drained water of the crops for reuse (usually have soil-based crops). These systems seem to have low level of water usage efficiency as they are affected by water losses due to soil depletion and constant water drainage, which drains the excess amount of water with fertilisers. This waste of resources causes significant problems to the environment. Usually growers can control the amount of drain as part of the management strategy of resources they follow. The percentage of drain can number between 5% and 50% of the water supply, but can be improved by reusing this drain in the irrigation system. Additionally, open greenhouses use window openings as the only mean of dehumidification and cooling technique.

There are also the semi-closed systems of greenhouses that have a smaller cooling capacity and window openings, combined with mechanical ventilation of air-cooling systems. The combination use of mechanical systems and window openings depend on the cooling demand. Concerning the irrigation systems, semi-closed greenhouses reuse the drained nutrient solution by collecting it to a tank that is constantly topped-up with fresh water. In some cases is followed water disinfection in order the collected drain water to be purified for avoiding diseases spread in the crop. To avoid imbalances in the nutrient solution, farmers use various techniques such as bleeding or dumping. In specific, bleeding techniques remove constantly 10% of the drain water, while in the dumping technique the mixing tank gets completely emptied and refilled with fresh water enriched with nutrient solution (Savvas, 2015) .

Finally, closed-systems refer to absolute mechanical support of the cooling and dehumidification system by air treatment units. The air treatment unit consists of a heat exchanger that is connected to a ventilator. The purpose of the ventilator is to withdraw air from the interior of the greenhouse, cool it, dehumidify it, and then distribute it back into the greenhouse. Furthermore, in closed-systems water usually follows a close loop that allows the collection, recycle and re-distribution of the irrigation water both for irrigation purposes but also for cooling and heating purposes from inside the distribution pipes between the plant lines (Qian, 2017). Concerning the irrigation system in closed-systems of greenhouses, the water does not follow the procedures of bleeding or dumping that are followed in semi-closed systems. On the other hand, the water is constantly recirculated in the mixed tank as it is automatically topped up with the correct and precise amounts of fresh water and each nutrient element. The growers are aware of the status of each nutrient element and can adjust it precisely in order not to disrupt the nutrient balance. This process becomes possible because of the high evolvement of automations, sensoring and programming in close greenhouse systems and achieve a 10–50% better water use compared with open greenhouse systems (Nederhoff and Stanghellini, 2010).

Table 5. Summary of annual data for a hydroponic greenhouse plant.

Resources Efficiency	Greenhouses (lettuce)	Citation
Water Use Efficiency	20 L/ kg lettuce/ year	Barbosa et al. (2015)
Water Use	hydroponics or soil 200 L/ m^2 or 400L/m^2 respectively	Coyle and Ellison (2017) and Ntinas et al. (2016)
Energy Use	60-180 kWh/kg/year	Graamans et al. (2017)
CO_2 emissions	352 kg/ ton of lettuce	Gerecsey (2018)
Light source	Solar radiation and artificial light that operate 2-4 hours/day	
Pest control use	Indoor environment Fermont traps	
Yield	41 kg/m^2/year	Coyle and Ellison (2017)
Land Use	365 days/year	Coyle and Ellison (2017)
Land Use Efficiency	9 m^2 for 1 kg lettuce /day	
Harvests per year	6-7 per year	Coyle and Ellison (2017)
Food miles	800-1600 km	

2.1.2.2.1 Water use in greenhouses

Greenhouses have different techniques for irrigation and water collection and highly depend on if greenhouses use soil-based techniques or soilless for crop production. Another factor that highly influences the final water use and WUE is the type of the system, meaning it can be an open system, a semi-open system or a closed-system. However, as can be retrieved from Tables 4 and 5 the big difference in WUE can be explained primarily because of the higher production accomplished in greenhouses compared to open-field farming but also because of the lower transpiration in greenhouses. Transpiration is the most important factor that influences the water uptake by 90%, therefore the control and reduction of transpiration rate can have a huge impact on the final water use. Transpiration is highly affected by the status of humidity and the irradiation levels inside the greenhouse. The higher the humidity inside the greenhouse the lower the transpiration levels are. If growers manage to control these two factors in the optimal levels for each crop, then there is reduced transpiration level per m^2, which means lower water usage and therefore better water efficiency (Lake & Woodward, 2008).

The selection of the applied irrigation system, has also a significant influence. Drip irrigation is one of the most popular irrigation techniques in greenhouses. Water is located beneath each plant with the use of a pipe. Drip irrigation has the advantage of saving large water amounts and also can control and maintain the humidity levels of the soil or the hydroponic substrate in constant levels. In that way, water stagnation and puddling of the selected substrate mean can easily be avoided. Finally, drip irrigation allows the targeted and limited fertilisation being dissolved, in the watering system.

Other irrigation systems are the micro sprinklers that spray water in a range around two meters according to the pressure of the selected nozzle type. This system is mainly used in soil-based greenhouses with sandy soil texture. Another very commonly used system is the irrigation with diffusers and is mainly used in narrower areas and the pressure of the diffuser depends on the nozzle that regulates the water supply and flow. Finally, other irrigation systems applied in greenhouses are the irrigation with hose and underground irrigation mainly found in soil-based greenhouses and present low level of water efficiency.

2.1.2.2.1.1 Hydroponic systems

Most of the modern greenhouses apply hydroponic solutions that allow plants to grow without soil. In more detail, the word hydroponic comes from the Greek words “Ύδωρ + Πονέω” translated as “Water + Cultivate,” meaning that plants do not grow in soil but in mineral nutrient solutions in water solvent. Various substrates in the market replace soil such as perlite, rock wool and zeolite. Because of the nature of this technology, plants are permitted to dip directly in their roots into the nutrient-rich solution and subsequently plants can absorb faster the nutrients and in an easier way in comparison with soil-based crops. Because of this process plants grown in hydroponics with smaller root system and can divert more energy for growing their leaves and stems. Additionally, smaller root allows more plants in the same area to be grown and harvest higher quantities in comparison to the outdoor farming. The above-described capacity of hydroponic systems, boosts the ability of growing food in limited areas as greenhouses can be. Hydroponics consist of a total automated system that water-pumps, and pipe-system can be completely auto-controlled. Under various handling and monitoring of every aspect that can be practised in hydroponic systems, the growers can result into optimal food production results. More specifically, this process gives the opportunity to farmers to control the whole irrigation process of the crops according to the demand of each species and the seasonality. In addition, they can have access to data that can optimise the development rate and the resource footprint of the plants such as (a) the quantity of water that is distributed in each plant, and (b) the amount of nutrient solution that was given to the plants.

Hydroponics offer a big advantage as they are usually installed in close or semi-close loops that return the excessive water with the enriched nutrient solution back to a collective tank in order to re-distribute it back to the cultivation area. In contrast to the hydroponic solutions, traditional farming experiences huge amounts of resource and water waste as farmlands face the negative effects of soil degradation and the harmful effect of eutrophication (when nutrients from agricultural land create massive increase in phytoplankton populations leading to reduction of oxygen and nutrient reduction of from water and suffocation of multicellular water organisms). Unfortunately, in open-field agriculture, excess supply of phosphates and nitrates in the soil can cause nutrient run/off and leaches. Furthermore, the close or semi-closed loop of hydroponics categorises them as more efficient in terms of sustainability process for water efficiency in comparison with traditional farming where most of the water is drained to lower levels of soil that plants cannot access.

2.1.2.2.2 Indoor air control

Greenhouses consist of air-sealed cultivation rooms where are installed various automations and technologies that can control and provide the optimal environmental conditions for each crop. According to factors such as location, size of installation, height, outdoor climate conditions, greenhouses use different technologies that can properly adjust the indoor environment to the ideal air conditions.

2.1.2.2.2.1 Heating

Heating is one of the most important processes for space heating inside the growing room, when the outdoor conditions and too hostile for the plants' growth. For heating purposes, the technologies that are usually used vary according to the demand of each case. In general, heating systems use the interior hot air of the greenhouse to transfer heat through a heat exchanger to the stored water that is used as a thermal storage medium. A very common and cheap technique is using water heating systems that consist from plastic bags and ground tubes filled with water placed inside and between the rows of the plants. During daytime, this system absorbs and traps the solar irradiation and during nighttime, the stored heat is transferred in the interior of the greenhouse by releasing heat (Sethi and Sharma, 2008). Electric heaters operate via a thermostat or an automatic timer in order to rise the inside temperature to the desired levels. Additional techniques used for heating are rock bed storages, movable insulation and ground air collectors (Savvas, 2016).

2.1.2.2.2.2 Cooling

Cooling is a technique of similar importance with heating as it enables to reduce the thermal energy inside a greenhouse and maintain the optimum temperature in each growing stage of the crop. Various techniques are used around the world according to the specific climatic conditions, the size and the demand of each case. Such techniques can be natural or forced ventilation, fogging and misting, roof cooling and fan-pad systems, as well as shading and reflection systems. The most successful systems are the composite systems since they are giving the opportunity for both heating during the winter period and cooling during the summer period. According to Sethi and Sharma (2008), the most promising composite system is the earth-to-air-heat exchanger system (EAHES) that operates with the underground constant temperature of Earth mass and utilise it to transfer or dissipate heat from or to the greenhouse.

2.1.2.2.3 Light proofing

According to botanists plants are diversified to "long day" plants and "short day" plants based on the photoperiodism needs—meaning on how many hours of light they have to be exposed during the day to grow. Artificial lighting is a technique that provides greenhouses supplementary lighting in case that the solar radiation does not completely meet the photosynthetic demand of each plant species for optimal growth and development. Efficient and proper use of lights in horticulture and with additional boost of reflectors can provide apart from the optimal levels that are required for photosynthesis also can benefit the greenhouses with additional heating (Fig. 8). Heat and energy loss is a common issue in greenhouses with artificial lighting. The latter can become an effective solution that mitigates these losses and add a value on the required lighting solutions. The most common types of lamps that are used in greenhouses are high-pressure sodium lamps, lighting emitting diodes (LEDs) lamps and ceramic metal halide lamps.

2.1.2.2.4 Energy use

Energy use into a hydroponic production line is mainly meeting the demand of artificial lighting, heating and cooling loads as well as water pumps. The energy that meets the water pumping needs in a hydroponic system for lettuce is estimated by the average pumping time that is needed to irrigate the plants and the corresponding nominal power of the pump. Based on the calculations of Kublic et al. (2015) it was estimated that the average irrigation duration for lettuce is four and a half hours of total pumping daily.

Figure 8. Indoor farming small-scale unit with additional reflectors.

The energy related to the heating and the cooling loads in a lettuce production greenhouse is estimated by using the following equation

$$Q= U*A\ (T_{in} – T_{out}) \qquad [1]$$

where

- Q = Heat that is lost or gained due to the outdoor temperature ($kJ * h^{-1}$)

- U = Total heat transfer coefficient ($kJ* h^{-1} *m^{-2} *^{o}C^{-1}$)

- A = Surface area of greenhouse (m^2)

- T_{in} = Temperature inside the greenhouse

- T_{out} = Temperature outside the greenhouse

The heat transfer coefficient depends on the coverage material of each greenhouse, while the efficiency of cooling and heating systems depends on the height of the greenhouse ceiling. The loss of heat depends on the external climatic conditions, and it is a decisive factor of the air technique modification to be used.

Artificial lighting usage depends on the photoperiod necessary for each species and the active hours of sunlight that plants can absorb for photosynthesis purposes. The active time that lamps have to operate is highly relevant with the location of the greenhouse, meaning that greenhouse areas with limited solar irradiation hours (North part of Europe, i.e., Netherlands, Denmark) have higher demand on artificial lighting in comparison with areas under sunshine (southern part of Europe, i.e., Spain, Greece, Italy). Furthermore, the duration of the supplementary lighting depends on the nature of the cultivated plants in photoperiodism (if they belong to "long day" or "short day" plants as we mentioned before) (Avgoustaki et al., 2020). This characteristic can differentiate the need of the plants in total daily radiation and according to the outdoor sunlight; the extra hours that artificial lamps need to operate should be estimated based on the required Daily Light Integral (DLI) that describes the number of photosynthetically active photons that reach the canopy area in a daily period. The ultimate purpose of artificial radiation is to provide to the crop the indispensable Photosynthetic Active Radiation (PAR) in mole/m^2/day for optimal yield production. To calculate the energy of a mole of photons that reach the canopy the following equation is used:

$$E = \frac{h*c}{\lambda} + \frac{L}{mol} \quad [2]$$

where

- E = the energy per mol of photons (J / mol)

- h = Planck's constant ($6.626*10^{-34}$ J*s)

- c = Speed of light ($2.998*10^{8}$ m/s)

- λ = Wavelength of light (m)

- L = Avogadro constant ($6.022 * 10^{23}$ mol^{-1})

The result value of the above calculation of the energy demand of artificial lighting in the greenhouse is in [kJ/kg/year].

2.1.2.2.5 Carbon footprint

Food production and consumption is constantly rising, having a significant environmental impact making the implementation of more sustainable practices in food production necessary. In order consumers to satisfy their demand for off-season vegetables and fruits, the necessity of heated greenhouses for production is continually increasing. As it is mentioned in the traditional farming section, food transportation causes huge amounts of GHG emissions. However, this number is lower in comparison to the GHG emissions corresponding to heating hydroponic greenhouses in cold climate areas (Ntinas et al., 2016) that try to meet high yields in order to meet customers demand. When heating of greenhouses is achieved with the use of natural gas, the consumed energy can reach the 31.6MJ with 2.02 kg of CO_2 for the production of 1 kg of tomatoes. Since the majority of greenhouses uses fossil fuels to meet their heating demand such as natural gas, diesel, fossil fuel and liquid petroleum gas, it is of vital importance to strongly limit the greenhouses heat losses, upgrade the heating systems and to shift in utilisation of renewable energy sources (Xydis et al., 2020). Heat losses can be minimised with the use of double glazing coverage material or with the use of multiple screens. The upper goal of these measures is to increase the environmental sustainability of greenhouse production lines.

2.1.2.2.6 Renewable energy

As it has already been mentioned, greenhouses combine different energy technologies, automations and digitalisation for plants' monitoring, controlling and harvesting. Greenhouse is a type of farming that can provide the option to connect with renewable energy resources in order to increase the sustainability of such systems and the energy efficiency of the various treatments that are necessary for mass food production (Manos and Xydis, 2019). Different types of renewable energy sources such as solar, wind, geothermal, hydroelectric, biofuels, biomass etc., are found all over the world bringing the possibility to greenhouse plants to produce yields under a more sustainable, economical and cost-efficient way (Xydis, 2015a). Energy policy strategies in a national and a global level, have as a high priority the support of electricity generation and heating from renewable energy and biofuels (Xydis, 2015b). Over the last decades significant improvements in a big variety of significant renewable energy systems, which are ground source-based, solar-based energy systems and wind-based energy systems have been made (Koroneos et al., 2009, 2017). These can be for example electricity-driven heat pumps instead of traditional combustion-based heating systems consumes 25–65% less energy in comparison to a conventional fuel heater (Avgoustaki and Xydis, 2019). Another advantage that heat pumps present 1.3 2.6 times higher energy efficiency compared to fossil fuel heaters as also 56% -79% reduced CO_2 emissions in the cultivation area in comparison with the conventional. There are also examples of greenhouses that use several solar systems that store energy or other photovoltaic systems (PV) that undertake the conversion of solar energy to electricity that meets the heating and cooling needs of greenhouses. Based on research conducted by Ntinas et al. (2016), greenhouses that utilise renewable biofuel (wood pellet) present 3–5 times lower global warming potential in comparison with a greenhouse that use fossil fuels for heating purposes (0.4–0.7 kg of CO_2 per 1 kg of harvested tomatoes), even when the required energy is the same for both cases.

2.1.2.2.7 Land use efficiency – Labour

Greenhouses in the Netherlands use complex technology for production of various cultivars that gather multiple operation during the production such are nurseries, growing bedding plants and transplants. These systems are highly automated and occupy land approximately 10ha or more (Kozai et al., 2016). Even if these machineries occupy a lot of potential cultivated space, they reduce the labour cost and therefore the production cost. Without the use of highly automated technology, the average work force required in greenhouses for cultivating purposes is estimated at approximately 8 workers per a 500 m^2

production area. According to Penissi et al. (2019), greenhouses produce 112g of fresh weight of romaine lettuce per m^2 daily, while traditional farming produce 10g of fresh weight of romaine lettuce per m^2 per day. As it can be retrieved from Table 5, the required land use for obtaining 1kg of fresh romaine lettuce daily is 9m^2 presenting almost 90% of decreased land usage in comparison to traditional farming.

2.1.2.2.8 Cost efficiency

In greenhouses there are different variables that based on their priority that can offer different benefits to the farmers. These could be the location of the greenhouse, the product type, the access to capital, the required workforce and other requirements. High significance in the cost efficiency is also the upfront cost and the ongoing growing cost of the greenhouse that can also lead to higher cost depreciation and development rates of the production unit. Based on a comparative study conducted by Avgoustaki and Xydis (2020), a greenhouse farm consisting of a semi-closed system in Denmark, the OPEX and CAPEX related with the farm were analysed. Their results showed that by assuming that the wholesale price of greenhouse produced greeneries reached at 7.37€/kg, the annual yield production of harvested products reaches at 25 kg/m^2/year. It is also presented that the capital expenses for the installation of the greenhouses was calculated at 320 €/m^2 including the hydroponic system and grow unit racks, natural gas, heating and ventilation system, light connection (for supplementary radiation), and electricity distribution. Additionally, for the operational expenses the total amount of expenses rises to an annual cost of 225 €/m^2, including the leasing costs, the electricity demand costs (lighting, ventilation), the natural gas heating cost, the water demand, the labour requirements, the packaging expenses and finally the use of organic material (seeds and nutrients). Different greenhouse scenarios were presented and a cash flow analysis in a 20-year projection, indicated that the cumulative gross profit increased in parallel with the increasing wholesale price of greeneries. More specifically, the payback period was calculated much longer than the operational period of the 20 years resulting in negative prices of the Net Present Value (NPV), unless the wholesale price of greens increases to 10.37 €/kg or more. More analytically these numbers will be examined in the next research paper (2.2 Chapter).

2.1.2.3. Indoor vertical farms

Indoor vertical farming is an innovative type of closed plant production system that provides the opportunity for controlled-environment agriculture, which can be controlled according to the crop regardless of the weather conditions. IVFs use artificial lighting as the only radiation source to cover the demand of plants for growth and development via photosynthesis. Vertical farms are based in soilless cultivation techniques such as hydroponics, aeroponics or aquaponics.

In addition to the hydroponic systems that recirculate the nutrient solution and benefit greenhouse cultivations, vertical farms use systems that condense and collect the water that is transpired by plants at the cooling panel of the air conditioners and continuously recycle and reuse it for irrigation.

Some principles concerning the structure elements permeate closed systems of vertical farms. More specifically, vertical farms are thermally well-insulated and nearly airtight structures that are covered with opaque walls. This characteristic makes the farms capable to totally protect the inside crops from the outdoor climatic conditions and make them able to maintain the indoor climate conditions at desired levels without having thermal losses. Another characteristic that differentiate vertical farms from greenhouses is the multiple layers of stacked plants in the vertical racks or horizontal columns. This way, the construction provides maximisation on the possible yield per unit of land in comparison to both greenhouses and open-field farming. More specifically, vertical farms, according to the size on the installation, have a multilayer system mostly between 4 and 16 rows or columns with approximately 40cm of distance between the layers (can slightly vary according to the selected cultivated crop). Inside vertical farms air conditioners or heat pumps, which principally are used to reduce the heat generated from the lamps and provide cooling and dehumidification for the crop are installed. Furthermore, air-conditioners help to eliminate the water vapour that plants transpire in the cultivation area. Installed fans circulate the air in the culture room; at first to achieve a constant and stable spatial air distribution and secondly to improve the photosynthesis and transpiration status of the plants. Key factor in the optimal operation of vertical farms is the CO_2 delivery units that stabilise the CO_2 levels in the cultivation area at around 1000ppm during photoperiod (when lamps are on) in order to increase the level that plants photosynthesise (Kozai, 2018). An important characteristic of vertical farms is the nutrient solution unit that distributes the nutrients to the crops, the electrical conductivity control unit (EC) and the pH controller that monitors the level of the nutrient solution.

Last, it is critical to analyse the radiation systems inside vertical farms as part of the total structure essentials. As mentioned above, vertical farms are equipped with artificial lighting due to absolute lack of solar radiation. Lighting is a key factor in plants development and depending on the selected lighting solution, plants can present differentiations in morphology, flowering and biomass production. Light is electromagnetic energy that includes visible as also invisible wavelengths. Sunlight is a free resource input that provides plants the whole spectrum of several wavelengths, 97% of it is within the range of 280-2800 nm (Kozai et al., 2016). However, according to a number of researchers over the last decades (Hogewoning et al., 2010; Kim et al., 2004; Lin et al., 2013; Liu et al., 2011), it is reported that the most important wavelengths for photosynthesis, morphology of plants and flowering are the wavelengths in the visible (400–700 nm) and the infrared (700–800 nm) spectrum. Lighting emitting diodes (LEDs) offer advantages in comparison with other types of lamps such as fluorescent, incandescent, high-pressure sodium (HPS) or high-intensity discharge (HID) lamps. These advantages are the robustness, as they produce a stable output that is immediately activated after the electric current flow, they have long life (approximately 100,000 h) and the opportunity of controlling the light output etc. For this reason, vertical farms focus on applying lighting recipes that combine different nanometres and can promote plants' growth. Apart from the spectrum selection of the lamps crucial factors for plants are the dimensions of light, meaning the intensity of light during light provision and the duration that lights operate.

Table 6. Basic units for indoor vertical farms

No.	**Basic units for plant cultivation**
1	Well thermally insulated, airtight and clean cultivation area
2	Horizontal or vertical multi-tiers of racks inside the growing area. Hydroponic systems where plants are placed on the surface of each tier – Lighting sources (with reflectors) are located on the upper limit of each tier

3	Air-conditioning, fans and dehumidifying units that mix the air, filter and provide the required air flow
4	CO_2 supply unit is composed by a pure CO_2 tanks, gas valves and pipelines
5	Consists of the unit that delivers and circulates the nutrient solution for the cultivation beds, and is composed by water pumps, tank with nutrient solution, tank with stock nutrient solution, pipelines and nutrient solution sterilizer with filters
6	Data collection and control unit for monitoring and controlling all the variables in the cultivation area
Main elements for crop and equipment handling and employee welfare	
Machinery and/or robots and/or spaces that are used for seeding, transplanting, transporting, trimming harvesting, weighting, packaging, storing and shipping processes that a farm arranges	
Rooms for entrance of human in the cultivation room, air showers, handwashing that ensure food safety but also other spaces for various operations (storage, meeting, etc.)	

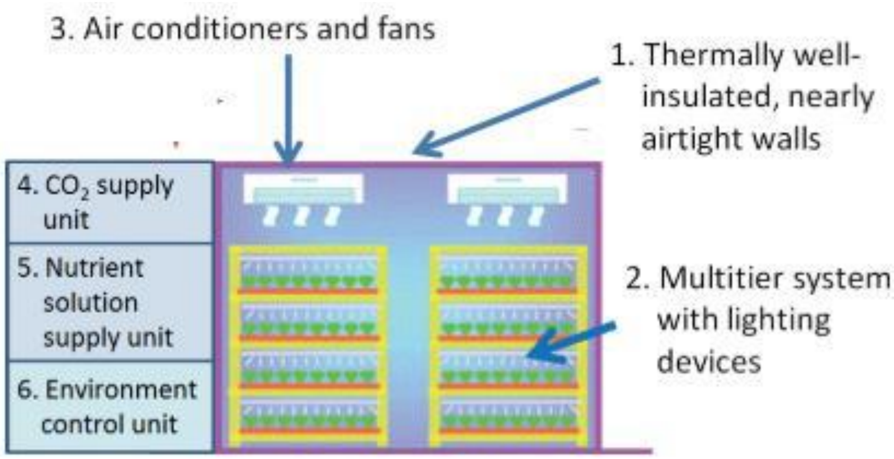

Figure 9. Configuration of the cultivation area in an indoor vertical farm with artificial lighting, containing six main units (Kozai, 2018).

Outdoor farming techniques in order to maximise their yield usually irrigate almost every plant with extra water than the amount that the water they only obtain from rain events. Due to the extensive application of soil improvements, herbicides, pesticides and fertilisers the run-offs usually end up in rivers, lakes and the underground aquifer. When run-offs reach the aquatic environment, the nitrogen portion of fertiliser captures oxygen from water and neutralises all the living organisms. On the contrary, indoor vertical farms can prevent run-off damage due to the hydroponic systems they use that provide water enriched with nutrients to crops and are installed in close loops that allow recirculation and reuse of both water and nutrients (replace at the same with plants absorbance rate).

2.1.2.3.1. Water use efficiency

Indoor vertical farms have thermally insulated walls and high level of airtightness that allow better cooling conditions by air-conditioners performance during the time that lights operate. This process is functioning even during cold winter nights, as the interior temperature can be increased due to the operating lamps that constantly generate heat in the cultivation rooms. The ultimate goal of air-conditioners is to maintain the indoor temperature at the desired levels. However, during the cooling process, a lot of the water portion is lost due to evaporation of plants or evapotranspiration. Indoor vertical farms have heat pumps with cooling panels, which can condense and collect this water, recycle it and via the close irrigation loop, reuse it for watering the plants. According to Kozai et al. (2016), only a small part of the irrigated mass water is getting lost to the outside because of the high level of airtightness inside the vertical farm. It is also pointed out in this research, that the airtightness level of vertical farms should not exceed the $0.02h^{-1}$. This is suggested because this level of airtightness helps to reduce the CO_2 losses to the outside environment and at the same time to maintain that sanitise level inside the farm by preventing pathogens, bacteria, dust or insects to enter the area of cultivation.

Greenhouses compared to indoor vertical farms, do not provide the opportunity of collection, reuse and recycle of the water masses from the evapotranspiration of plants, because the majority of the water is lost via the ventilation process to the outside area and furthermore most of the water vapour of greenhouses is mainly condensed at the inner walls, making impossible its collection process.

Another remarkable point that influences the resulted transpiration in indoor vertical farms is the operation of the artificial lighting. More specifically, when lamps do not function, the relative humidity of the room can reach up to 100% (little transpiration in the culture room), and cause physiological and morphological disorders to the plants. In order to solve this issue, farmers operate the lamps in rotation after dividing them in groups (two or three) and each group operates for 12–16h per day. With this action, a constant heat generation during the day from the lamps that aligns with the 24-h function of the heat pumps that dehumidificate and cool the air in the culture room can be achieved.

In order to calculate the WUE in indoor vertical farms the following equation is used:

$$WUE = \frac{Wc+Wp}{Ws}, \qquad [3]$$

where

- *Wc* is the water mass (or weight) that is collected in the cooling panel of the air conditioners for recycling purposes ($kg*m^{-2}*h^{-1}$),

- *Wp* is the alteration in the water mass that is detained by plants and hydroponic

substrates ($kg*m^{-2}*h^{-1}$) and

- *Ws* is the irrigated (or supplied) water mass to the indoor vertical farm.

2.1.2.3.2. CO_2 use efficiency (CUE)

In general, CUE in indoor vertical farms is around 0.87–0.89 (when the level of airtightness is between 0.01 and $0.02h^{-1}$) and the concentration is around 1000ppm—unlike greenhouses which achieve approximately a 0.5 CUE with closed ventilation system and airtightness level of $0.01h^{-1}$ and CO_2 concentration level at 700ppm (Yoshinaga et al., 2000). Based on these data we can estimate that the CUE of indoor vertical farms is 0.88/0.5 = 1.8 times higher compared to the greenhouses that do not operate the ventilators and provide CO_2 enrichment in the culture room. This phenomenon can be explained because of the amount of CO_2 that is released to the outside area from the culture room and keeps increasing with the level of airtightness but also with the difference between the CO_2 levels inside and outside. The fact that the CO_2 concentration for enrichment in an indoor vertical farm is usually around 1000–2000ppm in comparison to the greenhouses that have around 700–1000ppm can be explained based on that.

In order to calculate the CUE the following equation is used:

$$\text{CUE} = \frac{Cp}{Cs+Cr} \quad [4]$$

where

- *Cp* is the net photosynthetic rate (μmol m^{-2} h^{-1}),

- *Cs* is the enrichment rate of CO_2 (μmol m^{-2} h^{-1}) and

- *Cr* is the rate of respiration of the workers (if there are) in the culture room (μmol m^{-2} h^{-1})

2.1.2.3.3. Light energy use efficiency (LUE)

Light is electromagnetic energy or also defined as electromagnetic radiation that includes both visible and invisible wavelengths in the spectrum. The longer the wavelengths, the less the energy and vice versa (Figure 10). The visible range of wavelengths is between approximately 380 nm to 780 nm and is what the human eye can perceive and process. Visible light is very important also for the plants as it concurs with the radiation that they use for activating and accomplishing the process of photosynthesis (Photosynthetically Active Radiation, PAR, 400-700 nm). 97% of solar radiation is within the range of 280-2800 nm, and 43% out of it consists of visible light that is useful for plant development, 53% is infrared that produces heat and 4% is ultraviolet. Light is characterised by two conflicting properties as it can be observed as a wave phenomenon but at the same time, it performs as discrete particles that are called photons. A photon constitutes the smallest particle of light or a single quantum of light. On the contrary with other environmental factors such as temperature, humidity and CO_2 concentration, light diversifies in at least three dimensions; quality, quantity and duration.

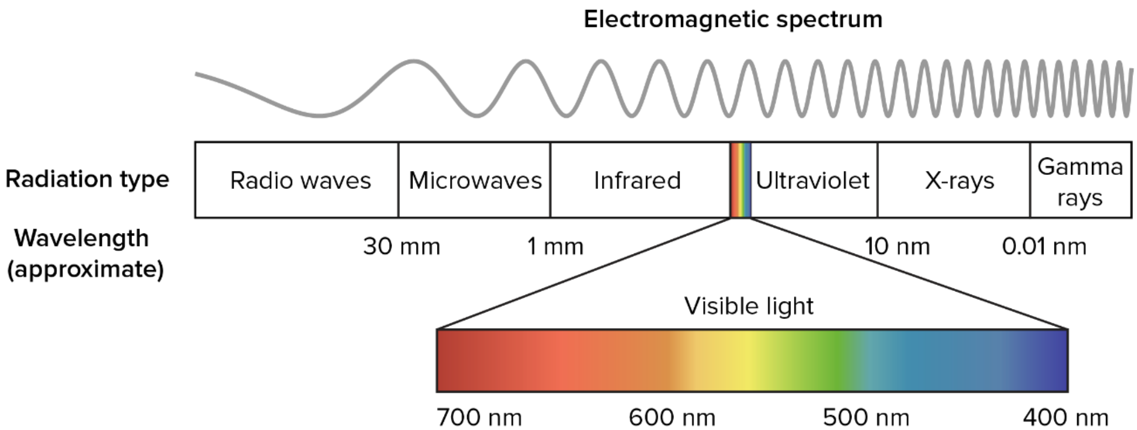

Figure 10. The electromagnetic spectrum

Plant productivity is influenced by the three dimensions of light that we provide to the crops; light quality (the qualitative characteristics meaning the multiple light spectra that are provided by lamps for horticultural production). More specifically, the light quantity (the intensity of the lamp, meaning the amount of photosynthetically active photons that leave from a light source and arrive at the growing area) and the light duration (the photoperiod that crops are exposed to light operation during a day) are the three parameters of light that can strongly influence plant growth, morphology, physiology and phytochemical accumulations (Zheng et al., 2019). Various studies have already focus on the qualitative characteristics of light in horticulture in order to identify the most useful spectral combinations that can enhance the absorption of photosynthetic pigments. Under this scope the below Table 7 summarises the influence effects on plants' growth and development under the exposure in different spectrum bands (Danila & Lucache, 2013).

Table 7. Influence of plants under different light wavelengths.

Wavelength of the Spectrum	Plant Characteristics
280-320nm (Ultraviolet –B)	The effects of UV-B radiation is in general harmful for pant growth and development
320-400nm (Ultraviolet-A)	Show positive results in plants when they are combined with blue parts of the spectrum
400-500nm (Blue)	Highly influences plants' and leaves' elongation and can increase the height of plants. Promote chlorophyll's accumulation
500-600nm (Green)	Not the major band for photosynthesis process but contributes to photosynthesis and is included as a significant

	component in the majority of artificial radiation sources
600-700nm (Red)	Significantly optimises the maximal photosynthetic capacity of plants. However, monochromatic red radiation sources can cause abnormal development in most of the species
700-750nm (Far-red)	Increase of flowering, stem elongation etc. of some species (as a function of red/far-red ratio) with the quantity of photons centered at 725nm to be equal or higher than the quantity of photons centered at 660nm

The light energy of lamps that is sent in the canopy aims to provide the necessary energy that plants need to grow and photosynthesise. However, the salable part of plants can only fix maximum 1–2% of the electrical energy as chemical energy. The remaining 98–99% of the electrical energy that is not absorbed by plants is converted to heat energy into the culture room and the remaining is removed by air-conditioners to the outside area (Avgoustaki, 2019). The above-described effect can also explain the negligible heating costs in well thermally insulated indoor vertical farms even in the winter cold nights. At the same time, light acts as an information medium as is involved in the regulation of multiple growth and development processes such as photoperiodism and photomorphogenesis. For this reason, plants develop photoreceptors, which consist the light sensors of plants that provide the necessary and important information to plants on subtle changes of light configuration of the cultivation area and influence the physiological and morphological responses of plants.

Nevertheless, indoor vertical farms are based in automations and precision agriculture and all the input resources are measured and validated in order to provide the optimal results in the cultivated crop. For this reason, all farms focus on measurements and optimisation of the LUE both of the lamps and of the plant community. What is important for these measurements is the definition and estimation of the PAR, which in other words, is the wavelengths of light that are in the visible spectrum of the 400–700 nm and are the ones that drive photosynthesis. PAR is not a measurement of light; rather it defines the type of light that is necessary for plants to photosynthesise. Apart from the type of light, farmers need to know and further metrics of light such as the amount and the spectral quality of PAR.

In order to estimate the light energy use efficiency of lamps (LUE_L) we use the following equation:

$$LUEL = \frac{f\mathrm{D}}{PARL}, \qquad [5]$$

where

- f is the convention factor from dry mass to chemical energy that is fixed in dry mass (around 20 MJ kg^{-1})

- D is the increase rate of dry mass of the whole unit of plants or only the salable part of plants in the indoor vertical farm (kg m^{-2} h^{-1}) and

- PAR_L is the photosynthetic active radiation emitted by the lamps (MJ m^{-2} h^{-1})

Respectively, in order to estimate the light energy use efficiency of the plant community (LUE_P) is provided by the following equation:

$$LUEp = \frac{f\mathrm{D}}{PARp} \qquad [6]$$

where:

- PAR_P is the photosynthetic active radiation that is received at the surface area of the cultivation.

Based on the calculations and experiments conducted by Yokoi et al., 2003, it is shown that indoor vertical farms have 1.9 to 2.5 times higher LUE_P in comparison to the greenhouses. Only 1% of the light energy is actually converted into salable portion of plants. Nevertheless, there are different techniques which can be applied and improve the conversion factor to 3% or a little higher. A simple technique that can be followed is the application of interplant lighting, upward lighting, and use of reflectors (Fig. 11). Traditional lighting that is located only on top of the crop can cause undesirable shading in dense crops by uneven light distribution and lead to senescence of the leaves that are in lower levels. On the contrary, the application of interplant lighting can provide access of light also in the lower levels of the plants, improve the distribution of light and therefore improve the photosynthetic rate of the crop.

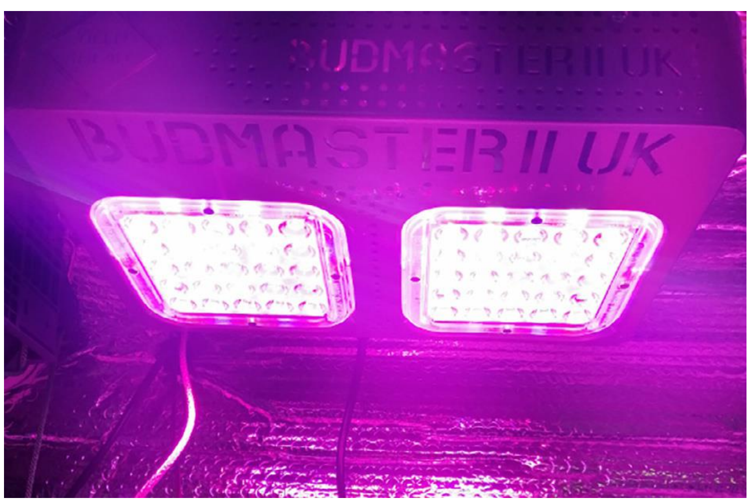

Figure 11. Upward lighting and use of reflectors in a small-scale experimental unit.

According to Dueck et al. (2006), the photosynthetic rate of leaves in low levels is usually negative or nearly zero, but the application of interplant light can increase it in positive values. Well-designed reflectors can significantly enhance the LUEL as they can reduce the vertical distance between the canopy and the lamps and increase the distance between the plants or the density, since plants constantly grow. The same positive results by interplant lighting have been reported also in greenhouse canopies. The most suitable lamp selection for interplant lighting technique is LEDs as they have small volume, and they perform lower surface temperatures in comparison to fluorescent and other types of light sources. LEDs have been proven beneficial for reducing the EUE_L also due to the higher conversion coefficient from electrical energy (0.4) compared to the fluorescent lamps (0.25) (Yokoi et al., 2005). Although the capital cost of LEDs is generally higher than the cost of fluorescent lamps, LEDs have longer operational life and the prices have considerably decreased over the last couple of decades and is expected to continue decreasing.

Apart from the lighting adjustments, other modifications can improve the LUE_L such as the control of the environmental conditions. The environment of plants and the physiological status of plants can be enhanced by the optimal selection of air temperature, CO_2 concentration, water vapour pressure deficit (VPD), air current speed as well as the combination of pH, electric conductivity (EC) of nutrient solution. These parameters have to be set according to the selected cultivated species.

Another way to improve the LUE_L as well as the EUE_L of the salable part of plants, is to reduce the dry mass of the nonsalable parts of the plants. In indoor vertical farms, the most frequently selected crops for cultivation are leafy vegetables such as lettuce, small fruits and herbs, and it is important to limit the percentage of the root mass into less than 10% of the total mass of the plant (Kozai et al., 2016). Due to of the cultivation technologies used in indoor vertical farms this is an achievable measure only by minimising the water stress of plants by controlling the water vapour pressure deficit of the room. If the selected crop is root species, then we can significantly increase the salable portion by harvesting earlier than usual in order to have an edible aerial part. Finally, other factors that can also help in increasing the relative annual production capacity (per unit land area) of indoor vertical farms are:

- Limitation of the culture period between transplanting and harvesting by optimal monitoring and controlling of the environmental conditions
- Increase of the ratio of cultivation area under each farming type (field, tier, floor, culture bed)
- Increase of the salable part of plants as also the percentage of salable plants.

According to Kozai et al. (2016), it is stated that by applying the above described techniques, the relative production capacity per land area unit in an indoor vertical farm of 10 layers can raise up to 200–250 times higher compared to outdoor farming, considering that indoor vertical farms already produce 100–150 times more yield than traditional farming (Table 8). In practice, those techniques could double the efficiency of the whole system.

Table 8. Summary of annual data for an indoor vertical farm.

Resources Efficiency	Indoor Vertical Farms (10 layers - lettuce)	Citation
Water Use Efficiency	1 L/ kg lettuce/ year	Barbosa et al. (2015)
Water Use	Usually hydroponics or aeroponics Approx. 11 L/head	Coyle and Ellison (2017)

Energy Use	250 kWh/kg/year	Graamans et al. (2017)
CO_2 emissions	158 kg/ton of lettuce	Gerecsey (2018)
Light source	artificial light that operate 10-24 h/day	Kozai, 2016
Pest control use	Indoor cultivation Sterilised environment	
Yield	80-120 kg/m^2/year	Coyle and Ellison (2017)
Land Use	365 days/year	Coyle and Ellison (2017)
Land Use Efficiency	0.3 m^2 for 1 kg lettuce /day	
Harvests per year	8-12 per year	Coyle and Ellison (2017)
Food miles	43 km	

2.1.2.3.4. Fertiliser Use Efficiency (FUE)

Indoor vertical farms use culture beds that are isolated from soil usage and the nutrient solution that enriches the irrigation water is distributed through pumping to the plants. Because of the high-automated process of irrigation, the nutrient solution is drained from the culture beds that plants are growing, and it follows a close loop by returning to the central nutrient solution tank for recycle and reuse. In order this process to be achieved, nutrient solution is rarely removed to the outside area. This process usually takes place once or twice per year when the level of certain ions such as Na^+ and Cl^- are not well absorbed by plants and the percentage in the culture beds exceeds the normal levels, requiring discharge. In order this measure to be implemented, the supply of fertilisation closes for some days and plants already planted can absorb the nutrient elements existing in the culture beds (Kozai et al., 2016). On the contrary, the FUE of greenhouses and of fields in traditional farming is relatively low and occasionally can cause on the soil, surface salt accumulation.

In order to calculate the FUE the following equation is followed:

$$FUE = \frac{Iu}{Is} \qquad [7]$$

where:

- I_U is the absorption rate of plants of ion element I that are in the organic fertiliser and

- I_S is the supply rate of ion element I into the indoor vertical farm.

It is worth to be mentioned that the ion element includes the basic elements of fertilisation solutions such as nitrogen (NO_3^- and NO_4^+), phosphorus (PO_4^-) and potassium (K^+).

2.1.2.3.5. Electrical energy use efficiency (EUE)

Artificial lighting apart from a key element in the growth of plants indoor, it does increase the energy consumption of vertical farms. Shamshiri et al. (2018), noted that three major expenses in a vertical farm are the electricity cost with 25-30% of the total production cost, the operational costs (OPEX) with 27% of the total cost and the capital expenditures (CAPEX) with 18–20% of the total cost. Indeed, energy consumption is a significant cost of indoor vertical farms and can be used as a measure for their sustainability levels. Many research groups and institutes focus on developing innovative technologies and optimising the lighting recipes in order to reduce the energy footprint of vertical farms and create a more sustainable and cost-efficient type of farming. Even if the demand for purchased energy is much higher in indoor vertical farms than in greenhouses, the energy efficiency of the former is significantly higher (Graamans et al., 2017). Indoor vertical farms, since are in absolute controlled systems face high efficiency when operating with renewable energy (Xydis et al., 2020). There are multiple examples of vertical farms that are operating under smart grid systems that generate energy for the demands of the farm via wind turbines or solar panels or even geothermal energy. Additional roles in the vertical farm systems towards increasing their efficiency have the connectivity with resourceful batteries that provide the opportunity for smart use of cheap stored-electricity from the hours that the electricity prices are lower. An approach gaining constantly more and more attention also under the dynamic pricing concept, where also accurate forecasting plays a crucial role (Karabiber & Xydis, 2019).

In order to calculate the energy use efficiency for the lamps (EUE_L) is followed the below equation

$$EUEL = \frac{f * h * D}{PARL} \qquad [8]$$

where:

- *h* is the conversion coefficient of electrical energy to energy of photosynthetic active radiation that is emitted by lamps. For the latest technology of LEDs this number reaches the 0.3–0.4 (Kozai et al., 2016).

Apart from the energy that is consumed in order to meet the lighting demands, the energy demand of the heat pumps for the cooling (or heating) processes in the indoor vertical farms should be added to the equation. This type of efficiency is often referred in literature as coefficient of performance of heat pumps for cooling purposes. The coefficient of performance of the heat pumps, in a specific room, increases when the outside temperature decreases. The electrical energy use efficiency for cooling by heat pumps (EUE_C) is calculated by the following type:

$$EUEc = \frac{H}{A} \qquad [9]$$

where:

- *H* is the heat energy that the heat pumps remove from the cultivation area (MJ * m^{-2}*h^{-1}) and

- *A* is the consumption of electrical energy by the heat pumps (air conditioners) (MJ * m^{-2}*h^{-1}).

It is worth to mention that the total energy consumption of indoor vertical farms is defined by the sum of the energy consumption of the lamps, the heat pumps/air-conditioners and the electricity demand of other equipment used for the optimal function of the farms such as nutrient solution pumps and air circulation fans. If we focus only in the electricity cost demand of indoor vertical farms, lighting can reach up to approx. 80% of the annual electricity energy use (assuming fluorescent lamps of 40W) while the electricity cost demand for air conditioning is around 16% and 4% the electricity demand of the auxiliary electrical equipment (Kozai et al., 2016). Table 6 presents the estimated representative values of resource use efficiencies in an indoor vertical farm that use artificial lighting. It could be concluded (from Table 6) in comparison to Table 4, that the relative production capacity per land area unit in an indoor vertical farm of 10 layers is 76 to 116 times higher compared to traditional farming and 40 to 80 times higher compared to greenhouse production.

2.1.2.3.6. Land use efficiency – Waste management

Indoor vertical farming is a type of farming which by definition is developed to provide enough production in order to meet the local demand in urban areas with continuous increased demand for fresh and nutritious fruits, vegetables and herbs. In general, the most frequently cultivated species are plants that have higher profitability and have a relatively high price. A significant factor on crop selection is the crop to have a short production cycle in order to reduce the required electricity costs for lighting, heating and cooling of the crop and therefore can be harvested as early as possible (Despommier, 2014). Additionally, growers prefer plants that have high harvested yield, meaning a high portion of the crop that can be harvested and sold. For example, in crops like lettuce and herbs, growers can harvest and sell the whole unit of the plant, while in tomatoes or peppers they can sell only the harvested fruit but at the same time. Therefore, the electricity used for the rest of the plant, could be considered as a product waste. Another key issue in crop selection is the height of the plants, meaning that it is way more preferable the crop to have a compact status in order to be able to reduce the growing distance between multiple plants and grow more at the same available area. Plants are also selected according to the perishability level that they present after harvesting and reaching the market. Since indoor vertical farms are mainly located in urban or suburban areas, their goal is to produce crops that can increase their self-life (even of perishable crops), by shortening the harvesting and delivery time to the market. Another parameter considered when selecting crops is the situation in the local market. If, for instance, tomatoes are missing for some reason from the market, then depending on the price they can get, they could be preferred against of another fruit or herb that is abundant and its price cannot climb up. Finally, the most suitable crops are those that have year-round productivity in order to be affordable for the farmers to have a year-round market demand that can be profitable despite the continuous operational expenses (Al-Kodmany, 2018). The constant production in a yearly basis of the same crop selection, allows also maintenance of the same, specific engineering settings of the crop, avoiding the modifications in the automations’ selection that could cause abnormalities from a horticultural perspective.

Due to the concept of indoor vertical farming and the technology used in the cultivation areas, growing in an urban environment do not advantage the crops due to possible shading of the building, non-fertile soils or dormant soils. This fact can also be considered as one of the major drawbacks as the land price in urban areas is relatively high. Concerning this approach, indoor vertical farms are often installed in large warehouses, industrial factories or even abandoned buildings, where the prices are low. According to Kozai et al. (2016), it is stated that indoor vertical farms can produce the same yield of lettuce heads and other leafy greens in only 1% of the land required by traditional farming and 10% compared to a greenhouse construction. Based on Tables 1–3, it can be retrieved that the land use efficiency of indoor vertical farms ($0.3m^2$) required for obtaining 1 kg of fresh romaine lettuce per day is almost 97% reduced compared to greenhouses and 100% compared to outdoor farming. An indoor vertical farm of 10 layers can produce 3110g of fresh weight of romaine lettuce per m^2 per day (112 g FW/m^2/d for greenhouses and 10 g FW/m^2/day for traditional farming). Adenaeuer (2014) mentions that the increase in yield between indoor vertical farms and traditional farming can be increased by 1.5 due to the technology and by 709 due to the technology combined with the stacking ability of the plants. Depending on the stacking area and the volume of harvest, cultivation care and crop preparation techniques, the workforce can highly vary. Avgoustaki and Xydis (2020), state that 35% of the annual operational expenses of the farm covers the labour expenses if 1 worker is necessary per 30,000kg of product (depending on the labour cost in each country). The same workforce is required for a greenhouse production and approximately half of it for an open field farm. More analytically, according to Savvas et al. (2015), in soil-based crops the labour numbers 34,000 €/ha, while a hydroponic greenhouse or indoor vertical farm requires around 64,000 €/ha as production cost. This demand is met by both permanent and by seasonal workers that will be hired for specific labor-intensive operations of the farm (like pruning and harvesting) throughout the year.

Indoor vertical farms have the advantage that allows them to generate bio-waste as bio-product during the process of edible biomass production. According to the cultivation system that plants grow in (hydroponic, aeroponic or aquaponic), the opportunity to farmers to collect easily all the by-products after the harvest period such as leaves, roots with fibres, stems, or even damaged vegetable and fruits and use it as well waste is offered. Based on Adenaeuer (2014), the bio-waste that is collected and used in indoor vertical farms can be 2443 metric tons per year and with daily plant wastes that are collected for the indoor farms of roughly 8.11 tons. Since indoor vertical farms use advanced close loop systems, present also the possibility to convert the daily amounts of bio-waste and after careful processing to useful resources material for the crop as liquid fertiliser or biofuel (Nikas et al., 2018). There are several cases of installation of indoor vertical farms that have designed specific lines of bio-waste management in their production line that only serve this specific purpose.

It should be stressed that indoor vertical farms have the option to implement high-tech equipment for conversion of food waste into energy production via anaerobic digestion. More specifically, this technology is a biogas recovery system that captures methane from food waste and convert it to heat, steam and electricity to meet the energy demands of the farm. This process requires a close-loop system, which creates biogas from organic material by piping it into the turbine generator. The electricity that is finally produced meets the high-energy demand of indoor vertical farms such as the operation of the lamps. Anaerobic digestion is also compatible with aquaponic systems by receiving the organic waste of both fish and plants to produce electricity (AgSTAR, 2020; United States Environmental Protection Agency, 2017).

2.1.2.3.7. Cost efficiency

One of the key factors that influences the selection of the farm system is the selling price of the products. According to Tasgal (2019), traditional farming products are 3 to 5 times cheaper in comparison to greenhouse an indoor vertical farming products. More specifically, traditional farming lettuce price usually costs less than 1€/head, while greenhouses lettuce and indoor vertical farm lettuce cost 2–3 €/head. Additionally, based on the same study, the significant upfront capital requirements of indoor vertical farms can highly limit the pool of market participants. This happens because both the land prices, rents and acquisition of high-technology equipment are significantly higher in comparison with the leasing cost of farmland.

On the other hand, Avgoustaki and Xydis (2020), by conducting a comparative analysis between indoor urban farms and greenhouses presented slightly different results. In more detail, they assumed an indoor vertical farm with the same growing space and wholesale price of the greeneries as in the greenhouse facility, of 675 m^2 and 7.37 €/kg respectively. An interesting point is the massively increased production yield that can be achieved in an indoor vertical farm compared to greenhouses, reaching at 33,750kg of fresh greeneries being annually harvested. The operational expenses of indoor vertical farms according to the examined case reached at 220 €/m^2/year resulting in almost similar numbers with the greenhouse facility. However, the biggest cost of indoor vertical farms noticed were the capital expenditures reaching at 476 €/m^2 of grow unit, with the most costly equipment the lamps and integral connection of lamps, installation of growing unit racks and the electric distribution of electricity. Subsequently, based on their model and the different cash flow analysis, indoor vertical farms present profitable investment opportunities with a high Internal Rate of Return (IRR) and a payback period between 3 and 6 years with a wholesale price equal or more than 6.36 €/kg (further exploration of the topic is presented in 2.2 Chapter).

Another research conducted by Liaros et al. (2016), a case scenario of a small IVF of 100m^2 growing area inside an apartment was presented, showing profitability to smallholders under various scenarios. Worth to mention at this point, micro indoor farming in small growing spaces such as containers, garages or even simple rooms can be profitable depending on the demand and the flexibility to rearrange different cultivation parameters aiming for the optimum result. Similar findings were also supported by Ucal and Xydis (2020). On the other hand, based on a report conducted by Agrilyst (2017) indoor micro-farms can be very costly, nevertheless, there are multiple marketing strategies for optimising the results.

2.1.3. Comparison in food safety issues between different farming types

According to the United Nations (UN) projections, the global population will exceed 9.8 billion until 2050, all requiring to meet their food demand. Additionally, the UN estimates that 80% of the global population will be located in urban areas by that time. In order all this increased food demand to be met, it is necessary to produce 70% more nutritious and fresh food. However, at the same time, land experts such as agronomists and ecologists, already warn of the growing shortages in agricultural land, necessary for sufficient food production (Al-Kodmary, 2018). When it comes to high-quality food, the fact that already food prices are climbing high also due to limited agricultural resource inputs such as water and energy is a matter of great concern. Over the last decade, the increase demand for more farmland in order to meet global food demand it becomes more and more obvious. As an immediate effect a lot of forest areas are substituted by new farmlands in order to supply this demand. At the same time, since cities constantly grow in terms of area they occupy, a lot of farmland is lost due to this expansive urban development. It is important to convert the global production line to a greener form for both human beings but also for the planet. This implies that food production will not sacrifice the attention for the human health against the commercial profit. According to the World Health Organisation, more than half of the farms globally, still use for fertilisation purposes of their crops raw animal waste that can attract insect as flies or contain weed seeds or even diseases which can contaminate the cultivated crops. Subsequently, these techniques can highly affect people's health and can cause diseases.

Nowadays, the majority of the food is produced in large, industrialised farms and is transported, distributed and sold in supermarkets, grocery stores or multinational food outlets. Agronomists, engineers and farmers in order to reduce the production cost and resource footprint of food production and at the same time increase the variety of the available food species for the consumers have developed various techniques. The high centralisation level of food supply can allow the possibility of infection from foodborne pathogens and toxins that can poison large numbers of consumers. Food usually travels thousands of miles every day leaving huge possibilities for contamination threats as it can be infected in one country and develop pollutant populations in another. Because of the high logistic complexity of food supply, it is worth to mention the advantages and drawbacks of each farming type during the whole supply chain. What follows is an exploration of the three subjected farming types, including outdoor farming, greenhouses and indoor vertical farming. We will compare and evaluate products and growing process under the scope of food safety practices.

2.1.3.1. Open-field farming

2.1.3.1.1. Food safety status of traditional farms

Outdoor farming is applied for thousands of years, allowing an unprecedented human development. However, over the past years the continuously increasing demand of the population has led farmers to apply chemical inputs for nourishing of plants, fighting pests, insects and improving soil quality. However, because of its nature, crops growing in the open field are facing all the difficulties from severe weather conditions and the danger of infection from various insects and pathogens. Traditional farming is a type of agriculture that allows to multiple plant pathogens, bacteria and insect pests to affect crops, causing scalable losses in global crop production. After heavily tilled farming applications, severe irrigations and monocropped selections, soil has been seriously affected causing depletion of its nutrients, highly requiring additional nutrient solutions that can improve its fertile condition, making it appropriate for cultivation.

Once crops are harvested, a big after-harvest process and logistic supply has to be followed in order food to be transported from the farmer to customers' table. When we are talking about vegetables and greeneries there is a high level of perishability that needs to be confronted. Crops have to keep cool in order to maintain the high fresh and nutritious status. In order farmers to retain a high value for their products, after harvesting, food is transported from the field to processing facilities that are responsible for the cutting, washing of plants in cold water applying centrifugation methods in order to remove the excess water from the products. After removing the roots and fulfilling the described procedure, products begin to decompose. A common procedure that farmers follow is to treat their production with chlorine compounds and/or antioxidants that expand preservation during and after washing. Continuously, food is usually packaged and stored in refrigerators and very low temperatures in order to remain in inertia status. However, outdoor farmers are not able to perform refrigeration between harvest and transport of the products for water processing, making it more uncertain in pathogens infection. In order groceries to arrive from the processing facilities to the shelves of the markets, they require on average 2000 to 3500km, resulting to 4–6 days in transportation. According to Kublic et al. (2015), every three days, products lose 30% of their nutritious value after being harvested and roots' removal, meaning that consumers finally receive severely influenced vegetables in terms of nutritional value.

Based on the Centres for Disease Control and Prevention, each year, "roughly 48 million people (1 in 6)" are food poisoned in the United States. In terms of food safety what products of outdoor farming face is the severe contamination from improper use of manure, either from human faeces that is used as fertilisation mainly in developing countries or from contaminated Concentrated Animal Feeding Operations (CAFOs). Even if it has been proven by various researchers as a great nutritious source for the crops after proper compostable process, on the other hand the absence of carefulness, targeted application and lack of sanitation can lead to transmission of various types of parasites. A serious parasite that is worth to be mentioned is Geohelminths (hookworm, Ascaris and whipworm), that can survive their eggs in soil for years when they find the right climate conditions, causing diarrheal diseases as well as permanent learning deficit to children (Hotez and Pecoul, 2010). E.coli was a foodborne illness that took high publicity after infecting approximately 265,000 people and causing about 100 deaths, after severe pollution of agricultural water reservoirs in farms of California. To summarise, even if there are multiple technological automations, innovations and outbreaks in outdoor farming over the last decades, the nature of this agricultural type is very open to foodborne illnesses, illnesses extremely difficult to be traced rising the total risks.

2.2.3.1.2. Solutions for safety status improvement for outdoor farming

Because of the importance of food safety and in order to avoid further foodborne illnesses, there are several rules that force outdoor farmers to enhance the safety status of their production for the overall benefit of the population. The strictest and most widely recognised organisation of food control audits is the Global Food Safety Initiatives (GFSI), which was established in 2000 to reduce and control the risks associated with food production as also to streamline and improve the overall food safety while reducing the operating costs. Various certifications are provided to farmers including the Safe Quality Food (SQF) and Hazard Analysis Critical Control Points (HACCP) that set the necessary rules and prerequisites of a high-level food safety status. This includes some of the following rules:

- It is of significant importance the control and validation of the agricultural water. To be more specific, there are rules that prerequisite the testing of the water quality that is applied via irrigation to the crops, but also the water related to the tangential purposes such as hand-washing of the workers during or after harvest, the ice that refrigerates food and the surfaces that food contacts with.
- Biological adjustments are often applied in soil for or particular nutritional uses that replace chemical fertilisation. It is of vital importance that farmers who follow these techniques to follow specific guidelines for the use of raw manure (such as animal and human faeces) as also for the use of stabilisation compost in order to maintain a high level of sanitation.

- There are rules concerning the compliance of domestic and wild animals either they are working in the farm, invade in the farm or graze.
- Finally, there are high requirements in workers' health and hygiene that need to be followed in order to prevent the contamination that may source by humans.

2.2.3.2. Greenhouses

2.2.3.2.1. Food safety status of greenhouses

As has already analysed, there are greenhouses that are soil-based and the more advanced use hydroponic solutions. In hydroponic greenhouses, plants are transported several times according to the growing stage and are monitored throughout the different growing cycles. That give the opportunity to apply the exact resource requirements in every stage, in comparison with soil-based greenhouses and outdoor farms, where the plants remain in the same position until their harvest.

Another significant advantage of greenhouses in relation with outdoor farming is the high geographical flexibility of installation as it allows a significant reduction of the transit time of the products from the harvesting and processing point to the final consumers.

Greenhouse plants is an industry that constantly grows, with today's list accounting half of the tomato production and 1/3 of the global pepper production that are distributed in the fresh market (Brauther, 2010). Greenhouses are a significant driver of national economies of the agricultural sector because of the high profit margin as also the opportunities for high added-value products. Unlike traditional farming products, greenhouse production is highly protected from dangerous elements and various contaminants.

However, the technologies that are applied for monitoring and controlling of the environmental conditions do not guarantee crops free of microbes and pathogens. The management practices applied in greenhouses are these that can conduct to growth, survival and spread of foodborne pathogens. A severe contamination thread could be spread by processing equipment since crates and baskets that are used for transportation of products, from propagation tools or even for surfaces that food contacts with.

Irrigation water is one of the most important food safety risks even in greenhouses as it can be drawn from a wide variety of uncertain sources such as municipality supply, rainwater, underground aquifer, reservoirs or surface water. Greenhouses that use untreated surface water as irrigation source face high contamination risks. For example, in 2013, Salmonella Saintpaul (CDC, 2013) found to have infected cucumber greenhouses in the US that caused the infection of 84 individuals across the country as they consumed imported vegetables with questionable irrigation water status.

2.2.3.2.2. Solutions for safety status improvement for greenhouses

Because of the high risk of infection of consumers, even from more controlled agricultural systems (compared to outdoor farming), regulations for food safety have become stricter by establishing new standards for food production (Produce Rules). The four areas that these standards focus on are the followings:

- Health and hygiene

This practice targets in maintaining hygienic conditions of the personnel that is occupied in the greenhouse factories, involving criteria for personnel cleanliness, hand-washing and use of appropriate gloves. Even if hand-washing is considered one of the simplest and cost-efficient practices, it has been reported that only 22% of greenhouses practice hand-washing before the harvesting process.

- Irrigation water quality and management

Since water quality is one of the most crucial and contentious factors, it seems absolutely necessary the mandatory establishment of rules that control the water baseline quality profile. Greenhouses withdraw water from a big variety of sources such as municipality supply, wells, reservoirs and surface ponds. By checking and understanding the quality of the quality of various water sources can provide important information and reduce the risk of contamination. By regulation, greenhouses have to determine frequently microbiological testing on the water sources. Furthermore, greenhouses that apply hydroponic solutions in semi-close or closed loops that circulate, recycle and reuse water, have to include filtering treatments that remove possible pathogens before re-applying it. Methods that are effective and efficient in water recycling is UV light or disinfectants.

- Animals and waste

Significant measure for the protection of crops from foodborne pathogens is also to eliminate the restriction of domestic and wild animals at growing activities inside the greenhouses as well as in the outside area of the buildings. Practices that contribute in discouraging animal intrusions can be for example the rapid weeding that will minimise rodents' attraction and protection.

- Sanitation of equipment, tools and greenhouse surfaces

Foodborne pathogens are usually found all over the greenhouse environment such as harvesting bins and boxes and trap floor covers of the greenhouse (Ilic et al., 2014). According to Produce Rule, all the tools and equipment that used in the production line should be inspected, cleaned, sanitised and maintain in this condition throughout the whole production, harvesting and post-harvesting process, in order to prevent contamination.

Greenhouses in comparison with traditional farming have the advantage of the three-key elements application that can eliminate contamination risk: innovations, automations and control. In specific, innovations provide to greenhouse farms a more secure food safety support such as water filtration systems, integrated pest management and higher quality control systems. Automations can reduce the danger of contamination or cross contamination as they minimise or decrease the introduction of foreign specimens. Finally, biometric systems provide to growers the ability to detect tracking information concerning the plants. After harvesting, the produce is set up in a traceability system from the greenhouse plant to the customer delivery service.

2.1.3.3. Indoor vertical farms

2.1.3.3.1. Food safety status of indoor vertical farms

Leafy greens, vegetables and herbs are considered of high-risk crops since they are usually not cooked but eaten raw. The usual process of consumers is to rinse their purchased greeneries after purchasing them from their grocery store and then consume them. This is not a particularly effective and protective procedure, since harmful pathogens need interference of chemicals to be detached from plants. Outdoor farming and most of the greenhouses perform triple-wash on the harvested plants in order to mitigate the contamination risk, as a post-harvest process. This process consists of the pre-washing, a saline wash and the final bathing of greeneries in sanitising, choline base solutions. Unfortunately, this method cause quality reduction to greeneries, as is observed loss of flavour and texture along with the concurrent risk of contamination existing and spreading under the possibility of incorrect application.

Greens that grow outdoors follow the triple-wash procedure as a post-harvest measure for increasing their health status. Harvested crops are transported in the processing facility and sorted, rinsed, put in spinners, apply a second rinse, spinner again, third rinse, sorted (again), packed, and then at the end they get delivered at the grocery market. Crops that follow the above washing method bear usually on the packaging labels such as “triple-washed” or “pre-washed”. Even if this method can provide sufficient results in harvested outdoor crops, if the water used for the triple washing process is polluted with pathogens, then this can spread rapidly to the rest of the harvested crop. For this reason, triple washing cannot be categorised as the most effective and guaranteed process.

Indoor vertical farms apply only nutrient elements in the irrigation system and completely avoid using any chemicals during the growing period of plants, excluding all the types of pesticides, herbicides and chemical spaying for fertilisation. The philosophy of indoor farming depends on monitoring and constant controlling of the crops as also of all the resources that come in and out from the farm, and they are isolated from Mother Nature where many threats and contamination sources may appear. For this reason, indoor farmers suggest that their products do not need to be washed before consumption, as they are already clean by a protected and purified growing process and a quick delivery to local grocery stores.

Hermetically sealed environments, inside highly controlled spaces that are designed to offer the highest possible level of food safety particularly for the growing period, surround the cultivation rooms of indoor vertical farms. Since there are no seasons to be followed as in outdoor farming neither humidity, temperature fluctuations nor long gaps on post-harvesting processes and packaging, indoor farmers can dramatically reduce a potential contamination with precise systems. In addition, the hermetically sealed environment protects crops from being exposed to outside elements such as harmful pests, insects, fungi and bacteria.

In one of other type of such systems, aquaponics, co-cultivation of fish with plants is done. This method of cultivation uses very innovative water filtration systems, which extract solids from the fish tanks. Continuously, solid break down to beneficial bacteria that transforms them into nitrates. Then, the nitrate-rich water circulates to the plant culture area where plants absorb the nutrients and purify the water. Since the aquaponic system follows a close-loop, the clean water is circulated and reused into the fish tank.

Plants that grow in soilless systems can travel along their production process giving the opportunity to be inspected for health status. For example, after sowing, seeds are moved to germination rooms with high humidity that boosts their sprouting. Then, seedlings are moved to a propagation room with controlled climatic conditions that promote their development. Next, young plants usually located in the main part of the cultivated room in floating rafts, receiving a nutrient-rich water. After finishing their development and reaching their mature stage, they are daily harvested and shipped. Between every translocation of plants, there is intensive quality check to prevent crops' contamination.

High-precision irrigation systems are used in order to monitor the water that travels throughout the crops. Innovative hydroponic or aeroponic methods usually draw water from filtered and drinkable sources and distribute it at each crop often without even touching the salable part of the plants. This is achieved either by the use of water in liquid form, mist or fog that sprays it only into the root section of the plants and not in the parts consumed.

Extensive sterilisation and supplier are also applied methodologies of indoor vertical farms that control and assure the input resources of the farms such as seeds, nutrients that need to be absolutely safe and clean. Because of control and monitor mechanisms that are carried out indoor, there is clear advantage of indoor farms. They are aware of the cleaning status of plants and maintain it with further regulations during the cultivation period and finally harvest and deliver a healthy and fresh product.

Even if indoor vertical farms produce food safer to consume than the open field grown products, bottlenecks and hazards can still be introduced during the growing process of crops. Such threats can be dirt and bacteria transferred from the workers and dangerous threats in the nutrient medium that include chemical sources, cleanliness and water safety. Further risks can also detected at the post-harvest activities such as trimming, sorting and delivery of the products. Thus, it is of vital importance even for indoor farmers to perform high status and certified systems for detection, monitoring, testing and evaluation as in outdoor farming and greenhouses.

A study conducted by Purdue University (Wang et al., 2019), found that there is also high risk of crops contamination due to pathogen pollution in vegetables grown in hydroponic or aquaponic systems. More specifically, they reported that E.coli O157:H7 was found in fish faeces and because of the circulation that close loops systems, it caused water contamination of the plant root surfaces that were in the aquaponic and the hydroponic systems. Since fish probably were contaminated by the bacteria, it is important to follow a proper and certified handling, cleaning and sanitising process in order to reduce the contamination risk in hydroponic and aquaponics.

2.1.3.3.2. Solutions for safety status improvement for indoor farms

It is a very difficult, time-consuming and α costly process to control all the plants even in an indoor vertical farm for having a 100% safe food product. Indoor vertical farms use controlled environment of humidity and temperature in order to provide plants the most suitable conditions. However, in the case that unpredictable production errors occur, e.g., technical malfunctions with the engineering equipment, temperature and humidity can get out bounds to undesired levels and create a fertile environment for bacteria growth. This incident could be possibly avoided in the case of traditional farming, as the constant natural air circulation and the sunlight could smooth out some of these errors. Bacteria population are not biased, meaning they do not grow or prefer targeted geographic locations, but they are transported to different locations by human activities as they can be brought by clothes, shoes or skin. Furthermore, it should be noted that even if indoor farms consist a safer environment compared to other farming types, if a controlled environment develops for some reason bacterial infection, it will be extremely difficult to eliminate the contamination and protect the rest of the growing crop. For this reason, indoor farms follow high sanity level protocols to avoid the possibility of crops' contamination by human contact that involves all the workers involved with various cultivation processes of the plants. That include strict control by imposing the use of facemasks, hair and beard net, footbaths and clean or single-use suits, which can diminish the risk of contamination.

Another solution for further risk elimination from potential contamination, is the application of innovative technologies that operate extensive integrated pest monitoring. This can be achieved with the use of ultraviolet light outside the farms that detect possible threats as also air curtains that are installed in every door and can control air that enters the cultivation room protecting it from the danger of contamination. Additional solution that can increase the sanitation levels of indoor crops, is the application of certified HVAC filters, in order to perform an extensive pest monitoring.

2.1.4. Customer opinion on indoor vertical farms

Indoor vertical farms belong to a novel type of farming cooperating with innovative technologies in order to provide the safest, higher quality and most fresh and nutritious groceries. Both advocates and critics of this technology seem to recognise that indoor vertical farms under suitable circumstances (mainly of the high demand on electricity loads), could offer a solution to the safety and sustainability problems faced in traditional farming. However, consumers seem to be more sceptical and critical on this technology. A potential explanation of the consumers' scepticism is the uncertainty and lack of trust in other food innovations such as genetically modified crops, food nanotechnology and artificial irradiation that struggled to find acceptance in the market. Nevertheless, the subjective knowledge and awareness level of consumers on the indoor vertical farming is still limited, even with the excessive spread of technology and information globally, it is of vital importance to increase the education of people on this new technology by informing them on the actual growing properties and impugn the unjustified myths and dangers.

Because of the increasing demand of indoor vertical farms and their establishment in the market, many researchers have focused on designing and addressing customer surveys and other research methodologies in order to define the public opinion on this technology and the status of their trust and preference on already existing agricultural production systems. Significant angle on these researches is to explore the existing knowledge and perception of customers between the three different farming systems; traditional farming, greenhouses and indoor vertical farms, in respect of the cultivation techniques, safety, resource sustainability, quality and their willingness to buy products from each category. For this reason, primarily it was of high importance to validate that consumers are able to recognise the different agricultural systems between them in order to provide valid, clarify and comprehensive results.

Different customer studies that investigated customers' opinion on different agricultural methods show a more sceptical belief concerning novel technologies on food production. More specifically, peoples' perception with technological innovations in agriculture are associated with high risks for food production presenting low expectations on the provided benefits of technology used (Sparks et al., 1994). In another research (Coyle and Ellison, 2017) participants rated higher the greenhouses facilities and the outdoor farms compared to the indoor vertical farms in terms of naturalness in the production process and the final product. Concerning the quality status of the final product people also seem to present higher levels of confidence and trust on the greenhouse products and subsequently indoor vertical farms and finally in outdoor farming products. Naturalness seems to be a high influencing indicator for consumers' selection globally as also a critical significant factor on the usefulness of the agricultural system.

According to Jurkenbeck et al. (2019), customers replied that LED lighting is not considered a too artificial tool for horticulture and slightly agreed that they do not consider indoor vertical farming too artificial concerning the overall production system. Even if consumers in general prefer naturally and traditionally produced food, nevertheless the fact that food of indoor vertical farms grow without chemical additives is highly considered.

On the other hand, under a customer research conducted by Jurkenbeck et al. (2019), it is noticed that consumers seem to present a high acceptance on indoor vertical farming concerning the offering sustainability and the high ecological footprint. People seem to select their purchased food based on their concerns on the naturalness, ethics and environmental status. In more details, 95% of the respondents in that research declare that they put an extra effort to select and buy locally grown food because of its high level in freshness, nutrition and reduced food mile emissions compared to traditional farming methods. On the other hand, a significant share of the consumers evaluates indoor vertical farming as an artificial agricultural process in order to trust their footprint outcome. For this reason, it is pointed out that knowledge, information and nutritional awareness can become a solid solution for the higher acceptance of indoor farming and irradiated food products. Respondents of the specific survey showed a strong willing on buying products that were produced in an indoor vertical farm with 46.7% of the total sample, 36.4% partly agreed on that statement, and finally only 16.8% were not willing to purchase these products. However, it should be noted that the perceived behavioural control does not influence the customers' willingness to buy, but it has some influence on the behavioural intension of willingness to purchase the product. Overall, the behavioural intention of customers to purchase products from indoor vertical farms is highly dependent on sustainability.

Under a different analysis, it has become clear that perceived sustainability of indoor vertical farming is the main reason of acceptance. It has been observed that the more positive the resulted sustainability status of the system is, the higher and the customers' acceptance and willingness to purchase the product is. Furthermore, based on the perceived sustainability level of indoor vertical farms it seems that customers increase and their acceptance of this innovative technological food production system. Based on these results, we could indicate that the growing involvement and concern of consumers to select products from agricultural systems that present high environmental performance.

2.1.5. Conclusions

Indoor vertical farming can be very advantageous in terms of resources sustainability since due to application of high technology and the soilless cultivation systems, it consumes way less on natural resources (e.g., water and nutrients). Additionally, indoor vertical farms significantly decrease the CO_2 emissions that are correlated to food transportation from the producers and the processing facilities. In specific, indoor vertical farms can provide 100 times higher productivity per year per unit land area compared to traditional farming due to the zero dependence on weather conditions, seasonality and possible infections from insects, pests and bacteria. Due to the evolution of technology, it is not anymore a prerequisite holding a large area of land for sufficient fresh food production, but the use of multiple layers, optimally controlled (environmental conditions and physiological parameters of the crops and minimum possible loss from crop threats). A significant characteristic of IVFs in terms of sustainability is the minimisation food delivered losses. In addition, significant reductions can be observed in the cooling fuel demand, necessary to cool the production in order to be transported in long distances. This can be achieved since IVFs are usually installed in the urban or suburban areas in shaded and/or abandoned buildings (or even basements) due to the soilless farming techniques and the artificial lighting, providing access to fresh and nutritious greeneries to citizens. Finally, one of the significant benefits that IVFs provide is the ability after proper processing of the use of waste water, crop wastes and excessive CO_2 produced in urban areas, as input resources of water, nutrients and CO_2 in the culture area.

To summarise some of the basic improvements in resource savings provided by IVFs compared to the immediately following high technology cultivation system, the greenhouses are the following:

- Indoor vertical farms save 100% of the pesticide use in their interior by maintaining the culture area clean and insect-free.
- Because of the application of close loop irrigation systems and of the collection, recycle and reuse of the water vapour that plant leaves transpire, indoor vertical farms can reduce up to 95% the water consumption. Furthermore, the use of closed loops can decrease up to 50% the fertiliser usage since it is feasible to recirculate and reuse the nutrient solution.
- Significant land reduction up to 90% can be achieved with the application of indoor vertical farming, due to the important increase (more than 10 times) of the annual productivity of crops per unit land area.
- Yield variation can also be reduced by 90% because of the constant monitoring and control of the crops and the lack of influence from the outdoor environmental conditions.

Food safety and traceability of products is another important factor highly relevant to indoor food production systems. Even if it does not provide a 100% safety for consumers, even though crops grow in a controlled environment protected by wildlife, animals, birds and insects, it upgrades the safety and security feeling of the products than those that grow in the open field. The majority of the selected cultivated crops of indoor vertical farms are among the species with the higher contamination risk when they grow outdoors or unprotected, because they grow very close to the ground level. Furthermore, one of the most crucial factors that greatly affect the possibility of contamination is the water quality that involves during the whole production process, including the irrigation water as also the washing water at the post-harvest processing techniques. Farmers of all categories should follow high standards and criteria for the water sources that channel water into the farms as also frequent control and monitor of the crops for potential threats of contamination.

It is now clear, that IVFs are a high necessity for tackling the challenges concerning the conservation of their resources. Nevertheless, in order to enhance the environmental sustainability and improve the efficiency and sufficiency of food production supplies for our society, it is necessary to develop more diverse, effective and ecological agricultural systems including both the traditional farms and the greenhouses. Further research and experimentation it is absolutely necessary in order both to improve the efficiency of resources in an indoor vertical farm but also to possibly eliminate the possibilities for contamination threats and constantly provide the outmost safe, fresh and nutritious fresh fruits and vegetables to the human population.

Notwithstanding the promising benefits that are linked with indoor vertical farming, there are also important challenges in the further implementation of this farming system in the future. It is of vital importance further improvements on the efficiency and effectiveness of the equipment that will lead to a significant decrease in the energy demand of the systems. By achieving the reduction of energy demand, it will add extra value in the environmental sustainability of the system, but also it would also make it more appealing for the public, the investors and the industry and will increase the viability and profitability. However, it is pointed out by Despommier (2011) that there is the opportunity for energy recovery from the non-salable crops' parts and capture of renewable sources of energy that can create zero energy building for hosting indoor vertical farms. At the same time, the whole system of indoor farming can synchronise and manipulate huge amounts of carbon and simultaneously release into the atmosphere oxygen from plants' respiration. Significant is also the start-up costs that are associated with indoor vertical farms as it is clear that it is more expensive to develop a vertical greenhouse than a normal greenhouse (Fletcher, 2012). As it has been highlighted by many studies one also key barrier that indoor vertical farmers have to confront is the public resistance to these type of products as social masses face difficulty in accepting indoor vertical farms instead of traditional farming ones because of the natural way that food is produced. Additionally, as indoor vertical farms serve the concept of local, fresh food production, and they are mainly installed in urban or peri-urban areas, they have also to salient the issue of affordability because of the expensive land and space use. For this reason, key factor is the productivity rate of indoor vertical farms that can maintain them profitable and keep them prevailed in the future. More specifically, if indoor vertical farms achieve to produce up to 50 times more yield compared to outdoor farming, then they can offset the capital expenditures and the expensive land use. Finally, another drawback that is linked with indoor farming production is the limited variety of crops that can be produced with this technology, such as lettuce, herbs, tomatoes and berries. Even if theoretically, all types of crops could be cultivated indoors, that would not be economically feasible due to the highly increased energy demand. Thus, low-value agricultural crops such as wheat and barley will continue to grow under economically and environmentally unviable conditions. Under these circumstances, IVFs have to face a limited production compared to the “limitless” hectares of traditional farming and a reconsideration of scaling up would be particularly costly and complicated.

The last years that indoor vertical farming gained more recognition and research interest, a plethora of new studies, prototypes and innovation designs have been presented under the academic and industrial scope. Indoor vertical farming presents a high interest and potential to play a critical role in the demanded sustainability in food of urban areas. This becomes even more important by the multiple studies that estimate and analyse the significant increased food demand in urban areas. Indoor vertical farming presents important advantages compared to traditional farming, concerning the required sustainability in our times by focusing in three main categories: environmental, economic and social.

There is a high demand for further development in automation. This will be scaling up the projects in order to create more feasible scenarios both from economic and commercial perspective. Future research is necessary towards a holistic approach via the investigation and the analysis of the full life-cycle of indoor vertical farms and the impact to the environment compared to the traditional farms and greenhouses.

2.1.6. References

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2.2. Indoor Vertical Farming in the Urban Nexus Context: Business Growth and Resources Savings

This journal article reveals the profitability and the cash flows of indoor vertical farms by comparing it with the economics of a greenhouse installation. The purpose of this study is to provide the necessary insights on vertical farming economics from data extracted from peer-reviewed papers, conference papers and company reports and the use of a detailed simulation model to compares the financial viability of the two agricultural methodologies. The comparative analysis performed in this research reveals the strengths, the risks and the challenges that can influence and risk the development of an IVF case study that produces fresh basil year round in the region of Aarhus, Denmark. Additionally, a techno-economic cash flow analysis under different financial schemes between greenhouses (GH) and IVFs, can provide the necessary evidence of the internal rate of return (IRR), the net present value (NPV) and the repayment period of a business plan of an IVF and a GH.

2.2.1. Introduction

In recent years, the phenomenon of urbanisation, i.e., the continuous increase of population in cities and towns, has rapidly increased. Many metropolitan cities require fresh food hotspots to feed their population. According to Angel et al. (2011), urban land cover will increase globally from 300,000 km^2 in 2000 to 770,000 km^2 in 2030 and to 1,200,000 km^2 in 2050. One of the most revealing examples of urbanisation is the case of Lagos in Nigeria, which had about 300,000 inhabitants in 1950, but today, the city has reached 17.5 million inhabitants (Lagos Production, 2019). Land in urban regions must become more efficient and better organised to maximise the space usage. The population increase in megacities (cities with more than 10 million people) is an inevitable fact that academia and businesses need to investigate in order to improve the quality of life overall. The growing need for more food has escalated over the last few years, and as a result, it is of vital importance to adopt more sustainable and efficient food production solutions. In the Food and Agriculture Organisation (FAO) report (UN, 2015), it is stated that the number of agro-businesses must increase up to 70% by 2050 to meet the food demand in megacities. In this context, it is also very important to mention that more sustainable ways of distributing food globally are needed to prevent the massive food waste. In fact, if food waste were a country, it would be the third-largest greenhouse (GH) gas emitter in the world with its four billion tons of food waste annually (Fuldauer et al., 2018). The competition between food and energy commodities due to the limited land and water should also be mentioned (Manos and Xydis, 2019). More than ever, it is crucial to make biofuels more efficient and limit their use. In addition, greater efforts should be made to achieve the sustainable global goals by using energy sources that are not dependent on food biomass but promote energy efficiency in industries and households. Every day, food travels between 100 and 1500 km from the producer to the consumer, accounting for 5%-15% of the energy used just to bring food to the table (Cuesa, 2005). According to research conducted by Blanke (2005), imported fruits demand 27% more energy than those locally grown.

Providing food to urban residents is one of the most complicated procedures in agriculture. A UN report (2018) states that one of the most advantageous farming procedures is organic farming and agroecology. In a study published by George Mason University (2005), it was proven that in African small-scale farms, the yield productivity increased up to 116% using agroecological farming techniques compared to traditional farming. Another solution that can increase food quantity is biodiversity. Li Chengyun (2009) argued that the production yield could be increased from 33.2% to 84.7% by not using monocropping techniques but altering the crop between the years (and the use of legumes). Finally, urban farming is one of the most prosperous ways that food can be provided to urban citizens. Since the population is constantly increasing and the farming areas needed are already equal to the size of South America (FAOSTAT, 2016), the most sustainable option is to include urban areas as part of production schemes. Many cities already reuse abandoned properties as urban farms and cultivate their own fresh vegetables to feed their citizens.

2.2.1.1. The Danish Reality

Since this research focuses on the Danish market, it is worth looking at Denmark's ecological footprint. According to OECD statistics, Denmark emitted approximately 51,620 tons of GH gases in 2016 (OECD, 2019). In fact, according to a WWF report (2014), Denmark's ecological footprint per capita is the fourth largest in the world after Qatar, Kuwait, and the United Arabs Emirates. In 2014, Gitte Seeberg (2019), the secretary general of WWF Denmark, stated in a newspaper that the Danish nation consists of roads, cities, and wheat fields, but one of the main problems is the lack of biodiversity in Denmark. Adding to this, the Danes' high meat consumption is one of the biggest reasons for its large ecological footprint. Finally, Global Footprint Network has calculated that Denmark has a bio-capacity per person of 4.4 global hectares (gha) and an ecological footprint of 6.7 gha per person. Furthermore, it states that until 2014, the ecological footprint versus the bio-capacity in Denmark was 40,246,094 gha. Clearly, there is an immediate need for food production change, distribution, and consumption in the country.

Research conducted by Tropp (2013) shows that demand for fresh, locally grown food was almost $12 billion in 2014, and was to reach $20 billion by 2019. Commercial GHs are the major sources of fresh food production for cities. For this reason, the annual growth rate of these businesses reached 8.8% in 2016, and the market's growth forecast is expected to exceed $29.64 billion by 2020 (Markets and Markets, 2017). GH production is the oldest form of controlled farming, where plants can be cultivated in an isolated environment, which is partly independent of the outdoor weather conditions. GH production is an intensive cultivation method that uses air management techniques as well as cooling and heating processes to produce high crop yields. In recent years, GH growers have started installing artificial lighting in addition to the hydroponic cultivation methods in order to further increase the yield of crops and reduce their water footprint. There are no detailed literature studies linking the need for indoor vertical farming facilities in areas with a lack of solar energy, which is vital for food production (40% average sunshine percentage from April to September and around 20% the rest of the year) (weather-and-climate.com). In 2017, the import value of vegetables and fruits to Denmark amounted to roughly DKK 11.2 billion, which equals a rise of 22.81% over the last 10 years (Statista Denmark, 2019). In other words, Denmark imports between 24,450 and 27,850 tons of fresh fruits and vegetables annually (FAO, 2011).

The country has some of the highest electricity prices in Europe, but at the same time, a very high level of renewable energy (mainly wind energy) connected to the main grid (Xydis et al., 2017). The combination of IVFs with renewable energy and batteries can lead to a radical decrease of system energy costs.

2.2.1.2. Indoor Urban Vertical Farming

Vertical farming is another way of allowing a fresh, locally grown food production, i.e., the possibility of a year-round crop production. The development of GHs has led to today's highly sophisticated, controlled agricultural systems. Vertical farming is the new promising technology that allows us to optimise agricultural production and convert it from traditional farming to an integrated urban network using the most innovative and sustainable technological achievements of our time. In IVFs, plants grow indoors by using hydroponic methods (aeroponic or fogoponic in a few cases) and artificial lighting that simulates solar radiation. An IVF —an intensive type of vertical farming—refers to a massive plant production establishment equipped with thermal insulation. Its structure is completely isolated from the outdoor environment (Kozai, 2013). Unlike traditional agriculture, IVFs resemble a "production line" in a warehouse, where cultivation shelves are stacked several meters high to maximise the utilisation of the vertical space. IVFs include seeding, transplanting, moving cultivation panels, harvesting, pollinating, weight control, packaging, metal inspection, and panel cleaning. Companies that have implemented this type of technology use different methods, numbers, and applications of the above techniques according to their business plan and strategy. IVFs present many advantages that make them very competitive compared to conventional farming, especially for consumers located in the urban network. The use of pioneering systems in IVFs eliminates the use of fertilsers and pesticides in the green production although IVFs consume almost 2% water in comparison with open-field water footprint, as 95% of the water from plant evapotranspiration in this system is compressed in the air conditioning evaporator in the form of liquid water (Kozai, 2013). After this process, water is collected, sterilised, and then returned to the water tank to be reused. The water is enriched with a nutrient solution, and, as a result, the nutrient fluids in the cultivation area can be reused and recycled. Another benefit to be highlighted is that IVFs reduce CO_2 emissions, as they are located in urban or suburban areas, virtually eliminating food transportation and thus the carbon footprints of food. The nutritional value of fresh fruits and vegetables diminishes during the shipping process, even at very low refrigerating temperatures. B-vitamins are very sensitive to freezing with a loss in the transportation process ranging from 20% to 60% (Barrett, 2007). A Japanese study describes how waste heat from fossil fuel power plants is imported to nearby IVFs, thereby reducing CO_2 emissions by 1204 tons per year (Togawa et al., 2014). Some IVFs avoid electricity peaks during the daytime by switching on lights only at night to utilise surplus electricity (Kozai, 2013; Avgoustaki, 2019). The area around industrial factories and mining operations is particularly worrisome with pollution rising significantly to 36.3% (Yang et al., 2019). However, in areas with many job and business opportunities that have a developed industry and a denser population, the likelihood of people eating local crops is high.

2.2.1.2. Food Waste and Management

Food production must remain sufficiently intensive to meet consumer and food demands. Cultivation methods must be made more efficient and sustainable but without further compromising land use and biodiversity. Farming techniques must be optimised, including waste processes. Globally, 40–50% of fruits and vegetables are wasted or lost during the food supply chain (FAO, 2019). In Europe, 39% of food resources such as energy, land, and water are wasted in the manufacturing process (by-products, overproduction, and weather conditions) and almost 42% in the households (over-purchasing and disorganisation). In Denmark, households waste around 260,000 tons while the agriculture/food industry wastes 133,000 tons of the total 700,000 tons of food waste each year (United Against Food Waste, 2019). In Denmark, fruits and vegetables are still part of the wholesale link in the food supply chain and are separate from the retailers' and producers' business strategy (Halloran, 2014). Consolidating businesses in order to reduce food waste are therefore difficult. Furthermore, fruits and vegetables are the largest waste producers in the retail and wholesale markets (Nordic Council of Ministers, 2016). According to Ettrup and Bjørn (2002), farming techniques supported by the retail market create 165-562 kg of food waste for every €130,000 in revenue. In a Danish household, fresh vegetables produce 1.42 kg waste per week of which 77.5% is unprocessed vegetables (Halloran, 2014). The development of farming techniques that will perform under a finite and limited resource base is necessary. The RUE needs to be optimised to reduce fruit and vegetable waste.

Already by definition, IVF have the ability to transform bio-waste into useful by-products that come from crop leaves, damaged fruits and vegetables, stems, and roots. Although IVFs are rapidly developing, they only have a very small share of the overall food market. The high construction start-up costs are directly related to this lack of market exposure. An IVF with 10 tiers costs on average around $4700 per square meter, and only after 5-7 years can the capital be reclaimed. The initial investment is approximately 15 times higher than a normal GH, making the business entry too expensive (Kozai, 2013). Another reason is profitability. Many IVFs prefer to grow market-oriented crops such as lettuce, herbs, and microgreens. However, IVFs as high-tech companies have high start/up costs, reaching up to 26% (Kozai et al., 2016). New indoor vertical farming business are more common in Asian countries such as North Korea, Japan, China, and Singapore. In Japan, 165 IVFs were in operation in 2016 (Kozai et al., 2016), and in China, the forecast shows that the number of IVFs will reach 200 by 2021 (Zhiyan, 2013). Nevertheless, more and more IVF facilities are being installed worldwide, with annual growth rate reaching 24.8%, which is expected to grow to $5.8 billion by 2022 (ReportsnReports, 2019).

This research analyses a case study on the profitability and the financial viability of IVFs, creating a nexus between energy, food, and water in urban areas (Avgoustaki and Xydis, 2020). A techno-economic cash flow analysis for the use of indoor farming in the Central Denmark Region (Region Midtjylland) with two different cultivation techniques, GH and IVF, was evaluated. In both cases, the selected cultivation plant was basil, as this plant responds extremely well in climate-controlled environments, has a short production cycle, and thrives at a high plant density. The purpose was to find the optimal conditions and solutions for using vertical farming to influence the Danish population to consume their own produced products and minimise the cost of imported products. The two techniques are compared against the internal rate of return (IRR), the net present value (NPV), and the repayment period of a business plan for a new IVF. Another objective was to compare the two cultivation methods from a resource-conserving perspective with the aim of developing a case study to act as a guide for private funds, presenting various investments scenarios.

2.2.2. Materials and Methods

The location and the size of the GH and IVF facilities studied were determined. It was decided that the case study should take place in an industrial area in the city of Aarhus, Denmark. The area of Aarhus is about 91 million m^2 and is located on the east cost of the Jutland peninsula. The size of the municipal population is approximately 340,000 citizens. This area was chosen because:

a) Aarhus is the second largest city in Denmark, meaning that a business providing sufficient quantities of fresh fruits and vegetables to the consumers can be a sustainable case.
b) Aarhus is considered one of the major global hubs in the wind energy market. Indeed, Denmark is one of the most energy self-sufficient countries in the world with a rate of 94% and a 28% share of gross energy consumption deriving from renewable energy and waste (Danish Energy Agency, 2019). Denmark is among the NordPool countries that exchange electricity with Swedish, Norwegian, German, and other power grids in an integrated power system.
c) The vegetables available in Aarhus supermarkets and grocery stores are of very high quality. Denmark has one of the highest organic market shares in the world. In fact, more than 11% of the Danes buy organic products, of which vegetables and fruits comprise 33% (€1.8 billion) (Kaad-Hansen, 2019). Customers are familiar with high-quality products, and they are willing to pay more money to buy high-nutrient value and chemical-free products.

We chose not to use Copenhagen as the IVF's case location, as it is the most expensive region in Denmark with real estate prices almost 76% higher than in Jutland (Ritzau, 2019). In order to create a more objective case, actual data from the Danish market were combined based on previous literature studies. However, since a detailed cost analysis of the various vertical farming expenses is presented, some of the numerical data are based on assumptions (all mentioned in the analysis). As previously discussed, the plant used in this research was basil, as it is one of the most frequently cultivated plant species in both IVFs and GHs with high product value. Herbs can be a great crop for market growers and are usually more profitable than leafy greens (Storey, 2019; Liaros et al., 2016).

2.2.3. Basic Assumptions and Resource Analysis

2.2.3.1. Assumptions

1. A semi-closed GH was chosen, as this would reduce costs compared to a closed GH. Semi-closed GHs have vents, which can be used to cool, dehumidify, and control pest infestation. Similarly, plants in IVFs grow in a closed loop with horizontal layers (one above the other). This method cannot be applied in GHs, as lower plants will receive limited sunlight radiation due to shading. For this reason, 5000 LED lamps were installed in the IVF facility at an assumed price of 1.4 €/W^3 (approximately 15€/bulb) to simulate the solar radiation (US Department of Energy, 2015).
2. Assuming that the IVF facility used a closed-loop production system, the waste could be recycled and reused into useful resources, e.g., fertilisers or biofuels. In such systems, water is constantly circulating in closed loops, with wastewater recycled and reused through installing volcanic rock particles in pipes that, through pumping these rock particles, can extract nutrients and reuse them in the nutrient solution. Using this method, bio-waste can be used to create a plant nutrient

solution. According to Adenaeuer (2014) [38], the estimated quantity of nutrients is equal to almost 50% of all the essential nutrients of the plants. Consequently, the estimated nutrient costs can be reduced up to 50%.

3. To make it easier to compare the two farming techniques, it was assumed that both plant factories had a cultivation area of 675 m^2. However, the IVF facility had a smaller unit area of floor space (225 m^2), since the crops are grown in multiple layers. Based upon real estate leasing standards in the Aarhus area, it was estimated that the rent of the IVF facility was 31.5€/m^2/year and 25.8€/m^2/year for the GH.
4. No safety measurements against fungi, different types of bacteria, pests, and diseases were assumed for the design of the building. However, necessary measures to prevent and combat diseases in the IVF facility were needed, but this will be examined further in a future study.
5. To achieve this result, we used the same environmental conditions in the cultivation area, including relative humidity, air temperature, and CO_2. Dou et al. (2018) recommend 14 mole/m^2/day for a 16-hour photoperiod as the optimal daily light integral (DLI) for sweet basil (Beamman et al., 2009). In the GH facility, the artificial lighting was used only as a supplementary lighting and not as the main light source, which was solar radiation. However, adding artificial lighting would be necessary considering that the number of lighting hours in Denmark is very limited, specifically in winter.
6. No calculations were performed on the structural condition of the building. Instead, several estimations were made based on previous literature studies on the building structure and the location of the structural materials of a vertical farm. IVFs are completely isolated from the outdoor environment and have no window openings. For this reason, the ceiling and the walls surrounding them have a better thermal insulation compared to a GH facility. The R-value for both facilities was defined. The R-value expresses how well a building is insulated; the higher the R-value, the better the insulation. We assumed that the IVF facility was installed in the interior space of a warehouse, and thus an R-value of 13 was used (Colorado Energy, 2019), while the GH had an R-value of 0.95, assuming that the coverage material was single-pane glass. It was assumed that the height of the building was the same throughout the building.
7. In terms of construction and equipment, it was assumed that the GH has a heating, cooling, and air-conditioning (HVAC) system that operates primarily with solar radiation for heating purposes and with heating natural gas in a semi-closed system and with natural ventilation for cooling and dehumidification purposes. The heating and cooling costs for the GH case very much depended on the latitude and external climate conditions of the facility, and because of the mean of natural gas we did not convert their energy loads using coefficient of performance. As an alternative, it was assumed that the conversion of natural gas to electricity has the same conversion efficiency as heating. For the GH facility, the CO_2 level was assumed at 800ppm. For the case of the IVF that is a closed system, we assumed a forced circulation system of heating, cooling, and air cooling. The interior climate in the IVF had a limited interaction with the outdoor conditions, making easier and more efficient the energy use for heating, cooling, and lighting purposes. To calculate the energetic loads in the IVF, we converted them to electricity using their respective coefficients of performance sourcing from previous literature (Graamans et al., 2017). It was assumed that the

CO_2 use of the IVF remains stable throughout the whole year, 1000ppm daily, to assure that plants have enough CO_2 to transform into sugars through photosynthesis and continue their optimal growth. In order to define the total electricity demand of the IVF, we proceeded to energy calculation of heating, latent cooling, and sensible cooling. In addition, to control the humidity and cooling of the farm, ventilation fans powered by electricity were used.

8. Finally, it was assumed that the wholesale price of basil was the same for both facilities (7.37 €/kg) and that the distance from the facilities to the consumers was the same. This was assumed due to the floating prices in the real estate; the closer a facility is to the city centre, the higher the rental price per m^2 (Chalabi, 2015). IVFs are located in and around city centers and can provide products that are fresher, more sustainable, and of higher quality. However, the rental price is much higher in urban cities, which is the reason the above assumption was established. Additionally, the number of harvests was different depending on the facilities and the yield per harvest (Table 9). Furthermore, it was assumed that the density of the plants was the same in both facilities.
9. Based on previous literature, it was considered that WUE can reach up to 70% in a closed-loop IVF facility compared to a semi-closed GH (Naus, 2019; Pennisi et al., 2019).
10. It was assumed that the IVF facility consumes 50% less nutrients than the GH, as minerals are added to the irrigation water and supplied to the plants directly at their roots by the hydroponic system (Zhiyan, 2013). Since the IVF facility is based on a closed-loop system, where nutrients are circulated, it is possible to design a circulatory system without nutrient waste in the production line.

2.2.3.2. Real Estate

As stated previously, IVFs are located in the urban network. They are installed indoors in a controlled environment without access to natural lighting. For this reason, the use of LED lamps is necessary to imitate solar radiation, which is essential for plant growth. Therefore, 5000 LEDs were installed based on the size of the building and the intensity of light needed for the plants to grow to their full potential.

Calculations for IVF operation indicate that it requires a full-time employee responsible for harvesting, the application of cultivation techniques, crop management, as well as weeding and chipping of the crops (Department of Primary Industry, Australia, 2020). The possibility of hiring, in the future, a part-time worker for the picking periods or various administrative tasks is also considered. Calculations are based on the average monthly salary in Denmark, and there are two categories: 1) the average monthly salary of agricultural workers (farmers), which is 3600€, and 2) the average monthly salary of engineers, which is 4500€ (Trading Economics, 2019).

Labour costs are one of the largest expenses in vertical farming. In Denmark, the average hourly salary of workers with four years of practical experience and the necessary practical qualifications for working tasks in this environment is approximately 18–19 €/h. For tasks requiring less expertise and qualifications, workers from the second salary group (with at least one year of practical work experience) can be hired with a salary cost between 17–18 €/h. In our analysis, two experienced agricultural workers were employed, one working full-time and the other part-time. Most of the numbers of the basic assumptions in this case study are presented in Table 9.

Table 9. General case study assumptions.

	GH	IVF	Unit	Citation
Real Estate				
Lease	25.76	31.5	€/m^2	https://www.matchoffice.com
Width of Building	18.3	15	m	
Length of Building	91.5	15	m	
Height of Building	4.6	7.5	m	
Growing Space	675	675	m^2	
Grow Levels	1	6		
Grow Unit Size	1.5	1.5	m^2	
Labour				
Labourers/10.000 kg yield	0.18	0.18	person	Dorward A., 2013
Hourly Cost of Labour	43.5	43.5	€/h	Trading Economics, 2019
Electricity				
Electricity Cost (500-2.000 MWh)	0.18823	0.18823	€/kWh	Statista (Tiseo I.), 2019
Electricity Cost (20.000- 70.000)	0.10086	0.10086	€/kWh	Statista (Tiseo I.), 2019
Internal electricity distribution capital cost	0.45	0.45	€/W	Eaves J. and Eaves S., 2018
Electricity Demand Charge	13	13	€/kW	www.hydroquebec.com
Utility electricity distribution capital cost	0.30	0.30	€/W	Eaves J. and Eaves S., 2018
Plants - Basil				
Harvest/Year	5	10		Department of Agriculture: Republic of South Africa, 2012
Yield/Harvest	2	5	Kg/m^2	Raimodi G. et al., 2006 UC Davis WIFSS, 2016
Wholesale price	7.37	7.37	€/kg	www.tridge.com
LED price	1.48	1.48	€	
LED efficacy - Photosynthetic Photon Efficacy (PPE)	4.8	4.8	µmol/J	Runkle E. and Bugbee B., 2017
Heating and Cooling				
Ventilation System	0.986	0.986	€/W	Eaves J. and Eaves S., 2018

Heating system capital cost	0.0208	0.0208	€/W	Eaves J. and Eaves S., 2018

2.2.3.3. Yield/Biomass Production

The calculations used for estimating the harvest, yield, and the biomass production of basil for both the GH and IVF facilities were based on previous literature (Graamans et al., 2017; tridge, 2019; Putievsky and Galambosi, 1999). On average, the annual harvest of basil in a GH is 16,875 kg/year, while in an IVF facility, 33,750 kg of fresh basil are harvested/year. The differences between GH and IVF for basil yields per year are shown in Figure 12.

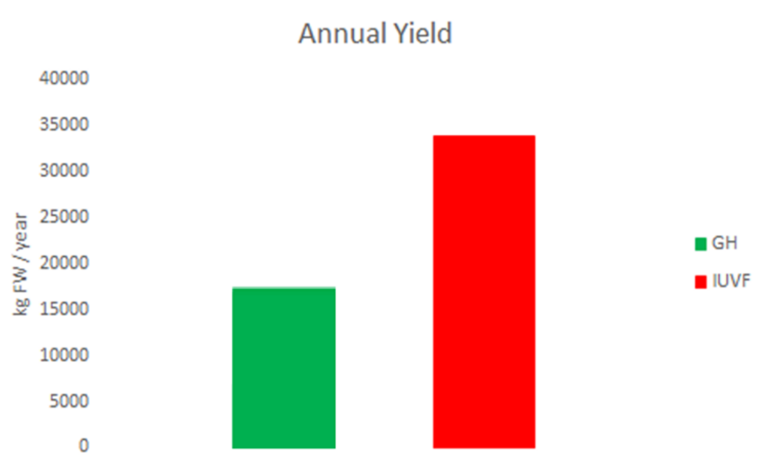

Figure 12. Total annual yield produced under the two cultivation facilities (red: indoor urban vertical farming—IUVF; green: greenhouse—GH) (Chalabi, 2015; Runkle & Bugbee, 2019; Birkby, 2016).

To calculate the operational expenditures (OPEX) and the capital expenditures (CAPEX) of an indoor urban vertical farm, equations from previously published literature were utilised (Eaves & Eaves, 2018). The calculations varied according to the primary plant species used on each farm. The case cultivar that was examined was basil, which constitutes one of the most frequently selected species in IVFs, as it has the ideal properties for indoor cultivation (high density, low height, and high yield).

2.2.3.4. Mobility and Dynamics on OPEX and CAPEX

The key data collected and analysed initially were DLI for Denmark, the annual outside temperature, the annual indoor temperatures, the indoor cooling and heating, the humidity requirements in the IVF unit, and the heat generated by LEDs. These data were collected, and their connections and interactions helped define the CAPEX for an IVF unit and the associated equipment. Additionally, these data determined the OPEX necessary for the optimal function of the facility in order to enhance basil yield.

Tables 10 and 11 provide the results of the average monthly electricity consumption for the acquisition of optimal environmental conditions for each farm facility. Furthermore, they indicate the electricity required for the optimal operation of the IVF facility to reach the optimal performance of the LEDs, the cooling system, and the ventilation system (fans). The waste heat mainly generated from lighting in winter can be beneficial, for heating purposes. In the summer, however, the excess heat (energy) produced by the LEDs must be either stored and redistributed in the system or removed with the ventilation system. Both tables also indicate that in an IVF unit, the system's total electricity demand is around 75,500 kWh/year, while the natural gas (NG) use for heating purposes is around 27,000 m^3.

Table 10. Total monthly electricity consumption used in the GH facility with basil (Eaves & Eaves, 2018).

Month	T_{out} (°C)	T_{in} (°C)	DLI (mol/m^2/d)	NG Heat (m^3)	Electricity (kWh) Ventilation	LEDs lighting	A/C Cooling	Total electricity
Jan	0.0	18.3	25.2	4,738	8	24,517	0	24,524
Feb	1.0	18.3	28.8	3,136	7	14,991	0	14,998
Mar	3.0	18.3	32	3,037	8	7,237	0	7,245
April	6.0	21.1	31.5	2,139	13	0	0	13
May	12.0	21.1	27	1,330	13	0	0	13
June	15.0	21.1	22.5	0	13	0	2,769	2,781
July	17.0	21.1	19.8	0	91	0	2,794	2,886
Aug	17.0	21.1	15.3	0	91	0	3,573	3,665
Sep	14.0	21.1	12.6	386	88	4,913	0	5,002
Oct	10.0	18.3	14.4	1,717	21	11,557	0	11,578
Nov	5.0	18.3	17.7	3,081	20	21,636	0	21,656
Dec	2.0	18.3	21.6	3,782	21	28,837	0	28,858
Total				23,345	396	113,686	9,136	123,218

Table 11. Total monthly electricity consumption in the IVF facility with basil.

Month	T_{out} (°C)	T_{in} (°C)	DLI (mol/m^2/d)	NG Heat (m^3)	Electricity (kWh) Ventilation	LEDs lighting	A/C Cooling	Total electricity
Jan	0.0	18.3	0	3,823	4	59,076	0	59,081
Feb	1.0	18.3	0	4,830	4	53,359	0	53,363
March	3.0	18.3	0	3,296	4	59,076	0	59,081
April	6.0	21.1	0	3,442	4	57,171	0	57,175
May	12.0	21.1	0	2,638	4	59,076	0	59,081
June	15.0	21.1	0	1,942	4	57,171	2,041	59,261
July	17.0	21.1	0	263	29	59,076	1,950	61,055
Aug	17.0	21.1	0	298	29	59,076	3,273	62,378
Sep	14.0	21.1	0	29	28	57,171	0	57,199
Oct	10.0	18.3	0	706	4	59,076	0	59,081
Nov	5.0	18.3	0	1,862	4	57,171	0	57,175
Dec	2.0	18.3	0	3,096	4	59,076	0	59,081
Total				26,225	125	695,576	7,265	702,966

The percentage of electricity consumption for covering the lighting demand of an IVF is approximately 82% of the total energy demand of an IVF. In continuation by air conditioning equipment for heating and cooling purposes of the growing environment is around 13% and finally other electric equipment (such as pumps for the nutrient solution, fans, sterilisation units etc.) is <5% of the total energy demand of the farm (Figure 13).

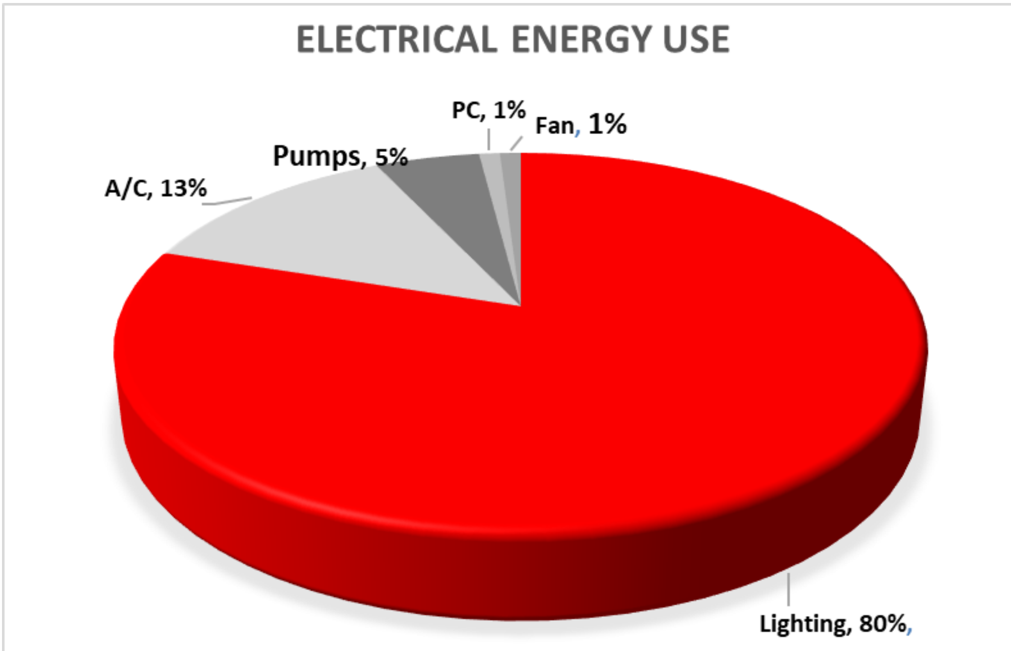

Figure 13. The electrical energy use of the total equipment in a growth are of an IVF.

2.2.3.5. Resource Use Efficiency

According to the model calculation, IVF requires greater amounts of electricity to achieve optimal efficiency and biomass production (Tables 10 and 11). The semi-closed GH facility allows and supports the use of available solar energy. Thus, the GH requires less purchased energy to operate than the IVF; the GH requires 83% more electricity than the IVF facility.

IVFs use their resources more efficiently than GHs. WUE in closed systems (as in IVF) provides higher efficiency in comparison to semi-open production systems (Figure 14) (Graamasns & Baeza, 2017).

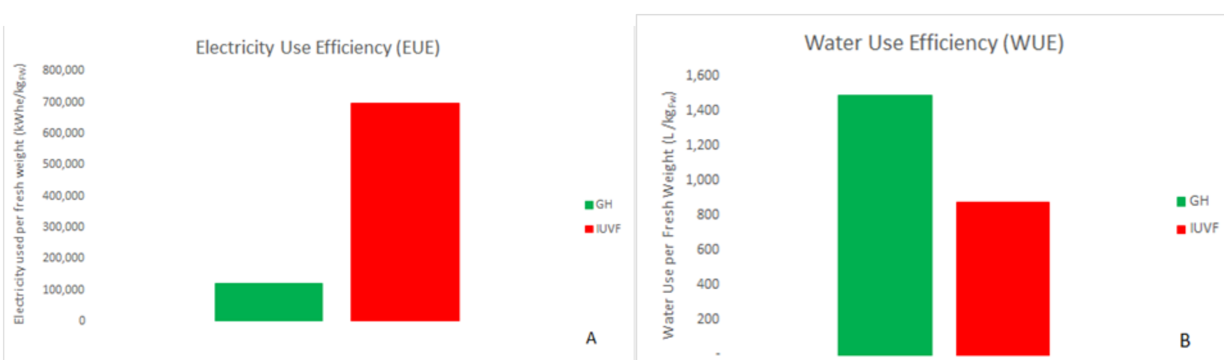

Figure 14. RUE for a) electricity and b) water in a GH and an IVF facility.

2.2.3.6. CAPEX and OPEX

In the Table 12 below, the modeling results for the CAPEX of an indoor urban vertical farm in the Aarhus area are presented. The local rental prices and electricity prices in Denmark have been taken into account. The first column shows the CAPEX cost per grow unit for cultivating basil only, while the second column provides the percentage of each capital expenditure out of the total CAPEX. In table 10, both examines cases of a greenhouse and subsequently the case of vertical farm are presented.

Table 12. Capital expenditures (CAPEX) for GH and IVF basil production.

	GH		IUVF	
	Cost (€) per Grow Unit	**Total in %**	**Cost (€) per Grow Unit**	**Total in %**
Lights	180.87	21.08%	370.55	43.19%
Integral connection of lights etc.	51.67	6.02%	105.87	12.34%
Electric distribution of electricity	36.20	4.22%	74.14	8.64%
Grow unit rack	112.94	13.16%	112.94	13.16%
Hydroponics	98.15	11.44%	98.15	11.44%
Ventilation fan syst.	5.91	0.69%	5.97	0.70%
NG heat syst.	0.24	0.03%	0.08	0.01%
Others	90.34	10.53%	90.34	10.53%
Total CAPEX Facility	216,123		321,763	

One of the major CAPEX related to installing the two vertical farms is the acquisition and wiring of LED lamps. However, the two selected plant species do not have different values, as the desired density and the yield of the plants do not affect the actual installation at the facilities. Table 12 shows that the acquisition and wiring of the LEDs represent 32% of the total CAPEX for the GH, while this number rises up to 65% for the case of the IVF. Table 13 presents the OPEX for the GH and IVF basil production.

Table 13. Operational expenditures (OPEX) for GH and IVF basil production.

	GH		IUVF	
	Annual Cost (€)	**% Total**	**Annual Cost (€)**	**% Total**
Real Estate Lease	43,058	28.4%	7,087	4.7%
Lights electricity	13,443	8.9%	49,290	32.6%
Ventilation electricity	35	0.2%	520	0.3%
Elect. Demand Charge	6,050	4%	13,897	9.2%
Heating Cost (NG)	26,603	17.6%	15,805	10.4%

Water	1,677	1.1%	882	0.6%
Nutrients	1,149	0.8%	574	0.4%
Seeds	7,031	4.6%	7,031	4.6%
Package	556	0.4%	2,511	1.7%
Labor	53,200	35.1%	53,200	35.1%
TOTAL OPEX	152,802		150,800	

Table 13 provides the differences in OPEX between GH and IVF for basil production. In particular, there are significant differences in the quantity of nutrients used at each facility. As mentioned by Birkby (2016) and Xydis et al. (2020), IVFs consume less water and nutrients compared to even hydroponic GHs while at the same time increasing the crop growth. In the presented model, it is assumed that an IVF uses 50% less nutrient solution than a semi-closed GH because it operates in a closed-loop cultivation system with virtually no input wastes. In this environment, the plants constantly obtain minerals for their growth. Therefore, growing and harvesting times of plants in IVFs can be increased up to 10 times annually compared to traditional farming, and 2–3 times annually compared to GHs (Pedersen, 2014).

2.2.4. Cash Flow Analysis: Scenarios Proposed

For the basic scenario, it was assumed that we received a loan from a Danish bank, which would cover the CAPEX listed in Table 12. According to analysts in the Danish agricultural market (Pedersen, 2014), banks and mortgage banks are the most important and vital sources of funding in Denmark. Since there is no government subsidy, the approved loan covering 50% of the total initial investment (the other 50% is equity financing) is only considered in the vertical farm basic scenario. The loan was fully amortised over 10 years, following periodic payments into a sinking fund, depending on the market rules. The loan was used to cover the CAPEX for the two farming facilities. The calculations below were made to estimate the gross profit of these facilities.

The operating cash flow (OCF) was calculated by the following equation:

$$\sum_{yr=1}^{yr=20} OCF = \sum_{yr=1}^{yr=20} \mathrm{To} - \sum_{yr=1}^{yr=20} \mathrm{OPEX} \qquad [10]$$

where, To is the turnover. In the event that extra private equity or a loan has to be fully repaid (depending on the size of the subsidy) from the total investment cost, IC represents the participation rate. In the examined case, the possibility of receiving a private equity was not examined. The unamortised value (UV) was given by the following equation:

$$\sum_{yr=1}^{yr=20} UV = \mathrm{a} * \mathrm{IC} \qquad [11]$$

where, 0.6 <= a <= 0.7 (an equity of 60%-70% of the total IC).

According to Xydis (2013), the depreciation rate A can be calculated using the formula:

$$\sum_{yr=1}^{yr=20} A = 15\% * \sum_{yr=1}^{yr=20} UV \qquad [12]$$

where, 15% represents the declining-balance method of depreciation.

The loan interest rate I is calculated by the following equation:

$$\sum_{yr=1}^{yr=20} I = i * \sum_{yr=1}^{yr=20} \mathrm{L} \qquad [13]$$

Where, *i* is the interest rate. The calculations are updated annually according to the loan balance. The loan amount needed for the payment of the loan L was calculated while it was assumed that the interest rate *i* is given by the equation:

$$\sum_{yr=1}^{yr=10} \mathrm{Do} = \sum_{yr=1}^{yr=10} (L\mathrm{i}) / [1 - (1 + \mathrm{i})^{\mathrm{N}}] \qquad [14]$$

where, *Do* is the monthly loan amount and N equals a 10-year loan repayment period.

From the above equations, the profits before taxes (PBT) were calculated:

$$\sum_{yr=1}^{yr=20} PBT = \sum_{yr=1}^{yr=20} OCF - \sum_{yr=1}^{yr=20} A - \sum_{yr=1}^{yr=10} I \qquad [15]$$

where, *A* is the depreciation rate.

The examined scenario includes the Danish Tax Agency's third and higher taxation category: 74,753 <= Income <= above with a marginal tax rate of 56.5% (including labor market tax). From these data, the profit after tax (PAT) can be calculated by removing the tax factor on the profits before tax (PBT). As a result, the net cash flow (NCF) was calculated as follows:

$$\sum_{yr=1}^{yr=20} NCF = \sum_{yr=1}^{yr=20} PAT + \sum_{yr=1}^{yr=20} A \qquad [16]$$

Moreover, the final net cash flow (FNCF) equaled:

$$\sum_{yr=1}^{yr=20} FNCF = \sum_{yr=1}^{yr=20} NCF - \sum_{yr=1}^{yr=20} NRA \qquad [17]$$

where, NRA is the net repayment amount. Then, the conversion coefficient ratio of the current values (CV*coef*) and the cumulative cash flow (for all 20 years) were calculated with the following equation:

$$CVcoef = \frac{1}{(1+\mathrm{CDR})}\mathrm{yr} \qquad [18]$$

where, CDR is the capital discount rate and *yr* indicates the number of years. Finally, the current value of the final cash flow (CVFCF) was given by the formula:

$$\sum_{yr=1}^{yr=20} CVFCF = \mathrm{CVcoef}* \sum_{\mathrm{yr}=1}^{\mathrm{yr}=20} FNCF \qquad [19]$$

which provides the NPV. Furthermore, the increasing revenues from the project were calculated, and last but not least, the IRR, which is a metric to estimate the viability of the proposed investments, was calculated.

2.2.5. Results

The scenarios examined intended to provide comparisons of two farming methods, GH and IVF facility, for basil production. In all cases, the IVF facility was the most successful in terms of productivity. In the default case examined, the 50-50 (equity/loan) approach was used. The 20-year cumulative gross profit and OPEX were 6,418,265€ and 3,977,610 €, respectively, with a sweet basil price of 7.37 €/kg. The IVF project cost was estimated at 321,764 €, and for the investment, an interest rate of 6.50% was estimated. The NPV was calculated to be 911,317 € and the IRR to 34.74%, with the payback period to four years. In Tables 14 and 15, the results are presented analytically for both the IVF and GH facilities. The “Equity/loan/(subsidy) (price)” for scenario 1 states “50-50”, which means that 50% of the funding comes from equity financing and 50% from a bank loan (0% funding from other sources) at a basil price of 7.37 €/kg. In scenario 4, “20-50-30-8.37”, indicates that 20% of the funding comes equity financing, 50% from a bank loan, and 30% from other sources (e.g., crowdfunding) at a basil price of 8.37 €/kg.

In Tables 14 (part 1 & 2), the results of the cash flow analysis of the IVF facility are presented. The analysis shows that the 20-year cumulative gross profit increases with higher basil wholesale prices but also that the 20-year cumulative OPEX and the total costs of the project remain steady. It is seen that for the 50-50, 40-50-10, and 50-40-10 scenarios (all with a wholesale price of 7.37 €/kg), the differences are small in terms of IRR and NPV, with an equal payback period of four years. It should be noted that even with a wholesale price of 6.37 €/kg, the business is viable (with a payback period of six years) but is not at a lower price. If the wholesale price drops to 5.37 €/kg, the business is no longer profitable, and investors will have their money back in 21 years. Even with a different business plan, the result is the same (e.g., with an equity of 70%, a loan of 30%, and the same wholesale price (of 5.37€/kg)). The project’s IRR is 0.04%.

For Scenario 6 (which has an equity of 25%, a bank loan of 75%, and an interest rate of 6.25%), the results are even better (an IRR of 63.3%) with a three-year payback period. Lastly, in cases where supplementary funding is found (e.g., crowdsourcing or possible state subsidy), the cash flow analysis results show that the business is extremely profitable with a NPV value above 1 million €, an IRR of 97.5%, and a two-year payback period. Figure 15 comparatively illustrates the results of NPV and IRR of different funding scenarios IVFs.

Table 14. Vertical farming scenarios and cash flow analysis (part 1).

VERTICAL FARMING	**SCE_1**	**SCE_2**	**SCE_3**	**SCE_4**	**SCE_5**
Equity-Loan-(Subsidy)-(price)	***50-50***	***40-50-10***	***50-50-5.37***	***50-50-8.37***	***50-50-6.37***
20-years cumulative Gross Profit [€]	6,418,265	6,418,265	4,676,538	7,289,128	5,547,401
20-years cumulative OPEX [€]	3,977,610	3,977,610	3,977,610	3,977,610	3,977,610
sweet basil [Price/kg]	7.37	7.37	5.37	8.37	6.37
Project Cost [€]	321,764	321,764	321,764	321,764	321,764
Subsidy/Alternative Funding	0%	10%	0%	0%	0%
Loan	50%	50%	50%	50%	50%
Equity	50%	40%	50%	50%	50%
Interest Rate	6.50%	5.80%	6.50%	6.50%	6.50%
NPV [€]	911,317	966,881	168,570	1,275,569	547,065
Project IRR (%)	34.74%	45.25%	0.38%	52.24%	17.96%
Period Payback (Yrs)	4	4	21	3	6

Table 14. Vertical farming scenarios and cash flow analysis (part 2).

VERTICAL FARMING	**SCE_6**	**SCE_7**	**SCE_8**	**SCE_9**
Equity-Loan-(Subsidy)-(price)	***25-75***	***50-40-10***	***20-50-30***	***70-30-5.37***
20-years cumulative Gross Profit [€]	6,418,265	6,418,265	6,418,265	4,676,538
20-years cumulative OPEX [€]	3,977,610	3,977,610	3,977,610	3,977,610
sweet basil [Price/kg]	7.37	7.37	7.37	5.37
Project Cost [€]	321,764	321,764	321,764	321,764
Subsidy/Alternative Funding	0%	10%	30%	0%
Loan	75%	40%	50%	30%
Equity	25%	50%	20%	70%
Interest Rate	6.25%	5.90%	4.40%	6.70%
NPV [€]	857,409	988,363	1,095,480	226,049
Project IRR (%)	63.34%	37.49%	97.55%	0.04%
Period Payback (Yrs)	3	4	2	21

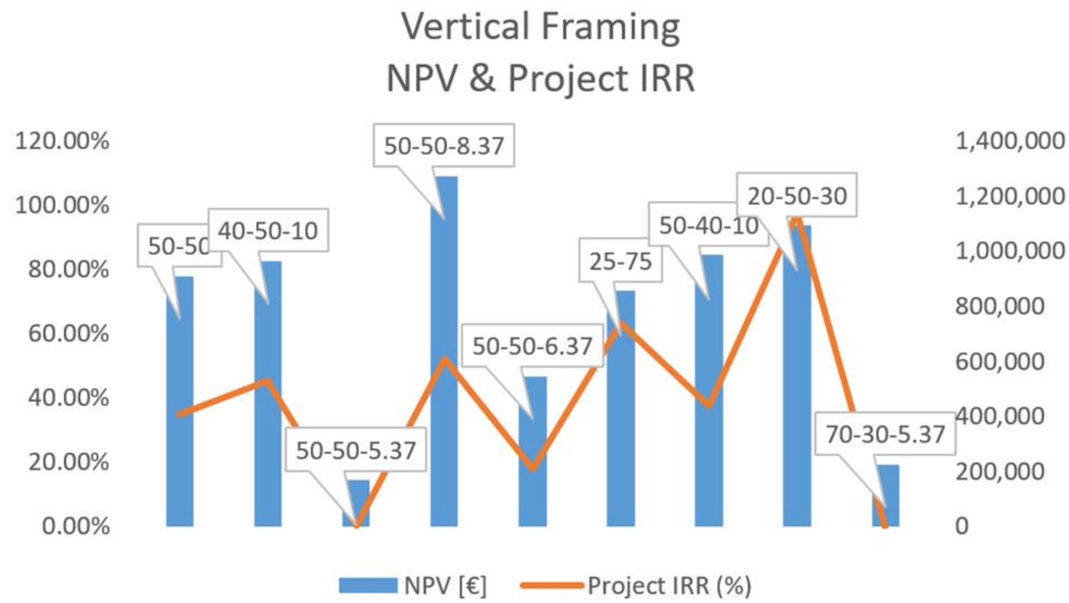

Figure 15. Comparative results of different scenarios of an IVF.

For the GH, the same analysis methodology was followed, similar scenarios were tested, and more scenarios were added compared to the IVF case. In Tables 15 (part 1 & 2), the results are analytically presented and illustrated in Figure 16.

Table 15. GH scenarios and cash flow analysis (part 1).

GREENHOUSE	SCE_1	SCE_2	SCE_3	SCE_4	SCE_5	SCE_6
Equity-Loan-(Subsidy)-(price)	***50-50***	***40-50-10***	***50-50-5.37***	***50-50-8.37***	***50-50-6.37***	***25-75***
20-years cumulative Gross Profit [€]	3,209,132	3,209,132	2,338,269	3,644,564	2,773,701	3,209,132
20-years cumulative OPEX [€]	3,907,011	3,907,011	3,902,743	3,909,146	3,904,877	3,907,011
sweet basil [Price/kg]	7.37	7.37	7.37	7.37	7.37	7.37
Project Cost [€]	216,127	216,127	216,127	216,127	216,127	216,127
Subsidy/Alternative Funding	0%	10%	0%	0%	0%	0%
Loan	50%	50%	50%	50%	50%	75%
Equity	50%	40%	50%	50%	50%	25%
Interest Rate	6.50%	5.80%	6.50%	6.50%	6.50%	6.25%
NPV [€]	-475,965	-503,174	-928,760	-249,568	-702,363	-538,813
Project IRR						
Period Payback (Yrs)	NEVER	NEVER	NEVER	NEVER	NEVER	NEVER

Table 15. GH scenarios and cash flow analysis (part 2).

GREENHOUSE	SCE_7	SCE_8	SCE_9	SCE_10	SCE_11	SCE_12	SCE_13
Equity-Loan-(Subsidy)-(price)	***50-40-10***	***20-50-30***	***50-50-11.37***	***70-30-5.37***	***50-50-9.37***	***50-50-10.37***	***20-50-30-11.37***

20-years cumulative Gross Profit [€]	3,209,132	3,209,132	4,950,860	2,338,269	4,079,996	4,515,428	4,950,860
20-years cumulative OPEX [€]	3,907,011	3,907,011	3,915,549	3,902,743	3,911,280	3,913,414	3,915,549
sweet basil [Price/kg]	7.37	7.37	7.37	7.37	7.37	7.37	7.37
Project Cost [€]	216,127	216,127	216,127	216,127	216,127	216,127	216,127
Subsidy/Alternative Funding	10%	30%	0%	0%	0%	0%	30%
Loan	40%	50%	50%	30%	50%	50%	50%
Equity	50%	20%	50%	70%	50%	50%	20%
Interest Rate	5.90%	4.40%	6.50%	6.70%	6.50%	6.50%	4.40%
NPV [€]	-477,426	-565,282	359,468	-871,795	-26,754	172,630	430,861
Project IRR			17.42%		-12.11%	4.64%	50.22%
Period Payback (Yrs)	NEVER	NEVER	7	NEVER	NEVER	15	3

The analysis for the GH again shows that the 20-year cumulative gross profit increases with higher basil wholesale prices. In all the scenarios with wholesale prices lower than 9.37 €/kg (regardless of financial scheme, i.e., equity/loan/subsidy), the payback period is much longer than the operational duration of the project (more than 20 years). In practice, this means that the investors never get their capital back, and, for example, in the scenario "50-50-9.37", the IRR is still -12.11%.

The NPV only turns positive with wholesale prices greater than or equal to 10.37 €/kg. In the scenario "50-50-10.37", the project's IRR reaches 4.64%, and the payback period is 15 years and is therefore still not considered the best investment option. If the wholesale price rises to 11.37 (shown as Figure 10), the business becomes profitable and the investors will get their money back within 7 or 3 years (the "20-50-30-11.37" and "50-50-11.37" scenarios with an IRR of 17.42% and 50.22%, respectively).

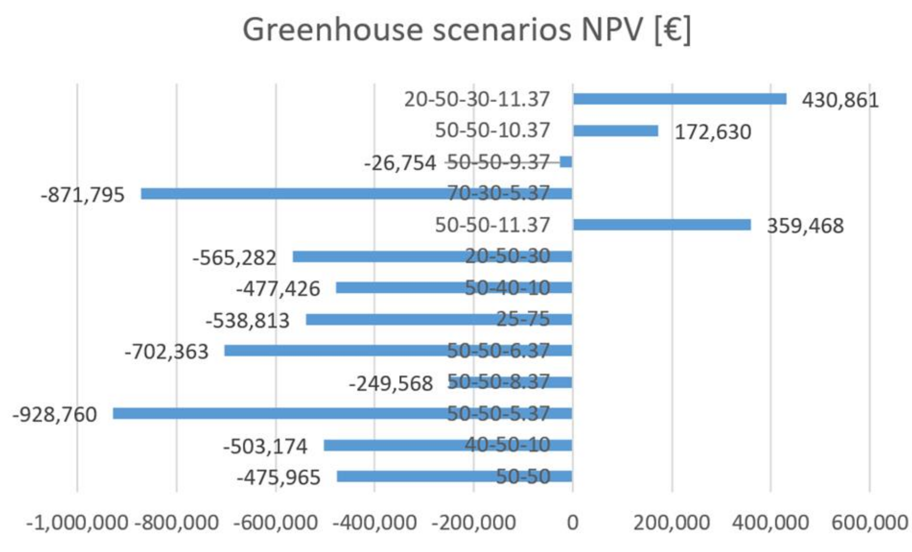

Figure 16. Comparative net present value (NPV) results if the various GH scenarios.

2.2.6. Discussion

Due to growing urban environments throughout the world, the financial opportunities and risks for commercial IVF and GH facilities were compared for basil production in the Midtjylland region of Central Denmark. Due to the high fresh fruit and vegetable demand in Denmark (Growth et al., 2001) and great opportunity to use renewable energy (Xydis et al., 2020), IVFs were shown to provide a greater financial gain compared to GHs. By 2020, 30% of the energy in Denmark will be based on renewable energy sources (Denmark.dk, 2020), which provides the perfect opportunity to promote more sustainable food production systems in the country, resulting from food being produced closer to consumers, resulting in lower CO_2 emissions.

Our study indicated by using IRR and NPV indexes, that vertical farming can be a profitable and successful model of innovative and sustainable food production, as an investor can receive their investment back within a period of 3 to 6 years when the basil wholesale price is $\geq$ 6.36 €/kg. Thus, there is great opportunity in urban agriculture to include innovative production systems, such as IVFs. However, although IVFs are one innovative method to produce local food for megacities, there are many associated risks with such a venture. Production of fresh fruits and vegetables are low margin produce items that require relatively high initial capital investments and high lighting operational expenses should be taken into consideration when contemplating an urban agriculture business that includes growing and marketing these products.

2.2.7. Conclusions

Using an adjusted model, taking into account the lower population density than in megacities, the aim of this study was to examine the business opportunities for vertical farms in Denmark and how these, with various adjustments, can be made a viable investment. Numerous scenarios were examined, and cash flow analyses were implemented and their results used to evaluate the scenarios based on NPV, IRR, and the payback period. It was found that regardless of financing scheme, the IVF facility was much more profitable compared to the GH. In most of the GH cases examined, the investors cannot get their money back until the end of the operation in which they invest. To become a profitable GH investment, the wholesale price must be significantly higher (above 10 €/kg—a price which is objectively considered expensive in the market), and alternative funding, such as crowdfunding or a state subsidy, should be found. On the other hand, the investment opportunities for the IVF facility (based on the cash flow analyses) were considered very interesting with high IRR rates and a payback period, in most cases, between 2-6 years.

2.2.8. References

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3. How can the risks associated with artificial light operation duration be limited for indoor food production?

The second chapter defined the key characteristics of indoor vertical farms, the technical specifications and RUE, the sustainability status and the risks that are associated with IVFs. Continuously, presented a comparable research between different under-coverage agriculture methods (GHs and IVFs), that examined the profitability under different financial schemes and evaluated them based on the NPV, IRR and the payback period. This third chapter seeks to introduce new methodologies that can limit the risk that is related with the artificial light operation of indoor vertical farming installations in the Nordic countries. The following articles focus on investigating under different experimental protocols, the barriers and benefits of reduced and intermittent photoperiod for indoor plant cultivation. More specifically, the first article of this chapter focuses on reducing the light duration in indoor production and evaluates the response of plants to reduced amount of received light radiation. The second scientific paper of this chapter focuses on how intermittent light intervals can influence plant growth and development in an indoor cultivation system. The results of this experimental research that were conducted, have defined and the following studies that were conducted in this PhD research project, due to the limited literature on the topic of intermittent lighting in indoor horticulture. The following journal papers answer Research Question 2:

1. Avgoustaki, D. D. (2019). Optimisation of Photoperiod and Quality Assessment of Basil Plants Grown in a Small-Scale Indoor Cultivation System for Reduction of Energy Demand. Energies; 12(20), 3980. https://doi.org/10.3390/en12203980
2. Avgoustaki, D. D., Li J. & Xydis, G. (2020). Basil Grown under Intermittent Light Stress in a Small-Scale Indoor Environment: Introducing Energy Demand Reduction Intelligent Technologies. Food Control; 118. https://doi.org/10.1016/j.foodcont.2020.107389.

3.1. Optimisation of Photoperiod and Quality Assessment of Basil Plants Grown in a Small-Scale Indoor Cultivation System for Reduction of Energy Demand

The third journal article investigates the photoperiodic methodologies that can be applied for indoor basil production for maintaining a high-yield production but with the least possible energy demand for the system. More specifically, it contains an experimental method that was applied in an indoor small-scale growth chamber that was located at the Chem Lab of BTECH Department of Aarhus University in the campus of Herning in Denmark. The comparisons that carried out present the development growth rate of basil plants under different daily lighting periods in order to explore the tolerance levels of basil crops under reduced photoperiod. The purpose of this research is to examine how sustainability and energy efficiency of the system could be optimised while maintaining a high crop growth and development. To proceed with the performance comparisons, three different photoperiod treatments were applied to basil plants under stable daily light integral and constant nanometre (nm) peak emission wavelengths for all the different experimental sessions. Plants were daily monitored and data were collected from different physiological and morphological indices, such as chlorophyll content, different chlorophyll pigments, the photosynthetically active irradiance absorbed by the leaf and the leaf temperature. At the same time, the environmental conditions of the indoor growing area were constantly monitored to provide evidence from potential stress indications of the plants. After completing this experimental session, plants were harvested and morphologically examined and compared under post-harvest treatments such as height, leaf area and biomass production to provide sufficient evidence on plants' influence from the different and reduced photoperiod treatments. The main objective of this experiment was to investigate the possibilities of a reduced and optimised photoperiod for basil plants that will provide significant energy demand reductions and subsequently lower electricity cost for the cultivation unit.

3.1.1. Introduction

In recent years, rapid growth in urban populations has led to an increasing need for fresh food. Controlled environments located in or near the urban network allow for continuous yield production of fresh greens and fruits of high nutritious value and prevent losses in quantity and quality during transportation (Kozai et al., 2016). However, one of the major challenges that vertical farms (controlled environments with artificial lighting) face is, among others, the high-energy demand cost of the artificial lighting. The annual electricity cost of vertical farms amounts to approximately 25% of the total production cost; where 80% of this cost covers the lighting needs of the system (Johnson et al., 2019).

Many improvements and studies have been conducted in the field of lighting with the continuous optimisation of the LED technology, which is mainly used in vertical farms, as it can consume up to 70% less energy compared to traditional lighting options (Kozai, 2018). Vertical farms allow their users to simulate the most beneficial conditions for each plant species and provide an optimal environment for the highest yield and best quality of the plants. Today, LEDs are the main lighting source in vertical farms, as they consume around 40% less energy than HPS (High-Pressure Sodium) lamps and 86% less than incandescent lighting systems (Zhang et al., 2017). Due to the minimal radiant heat emitted, LEDs can be placed close to plants, reducing the cultivation space. Finally, because their function is based on the movement of electrons in a semiconductor material, they are designed to reach in the most beneficial nm for the plants. For this reason, the diodes mainly peak in the red, far-red, and blue part of the spectrum. These narrow bands of the spectrum boost the growth of the plants, as they satisfy the chlorophyll *a* (Chl *a*) and chlorophyll *b* (Chl *b*) requirements (Peng et al., 2018).

Apart from the research in the LED technology, an essential role in the energy demand of vertical farms is the duration of the plants under the artificial lighting, i.e., their photoperiod. Lighting is the factor that affects the productivity and quality of plants in vertical farms most, and it varies at different growth stages (germination, vegetation, flowering, etc.) (Touliatos & Dodd, 2016). During germination, plants are grown under long photoperiod conditions, until their roots are activated, and they start to uptake nutrients and water from the substrate (Stearns & Olson, 1958). Photoperiod and air temperature are used to control plant responsiveness and development (Keatinge et al., 1998). However, the adequacy of light for the optimal plant growth is not very clear, especially between wavelengths 400–700 nm of the solar spectrum, where the photosynthetically active radiation (PAR) occurs. Studies have shown that both light duration, the light intensity and light quality (nm selection of the lamp) particularly in green vegetables that require large amounts of light, play a critical role in the optimal distribution of instant PAR.

Light intensity, as mentioned above constitutes a major parameter in light specifications. In other words, light intensity affects the biosynthesis of the secondary metabolites (carotenoids, phenolic compounds, ascorbate, and glutathione) of plants. According to Manukyan (2013), the increase in light intensity can result with enhancement of the polyphenols' production in herbs. For this reason, vase of studies have already focus on the importance of providing sufficient light in horticulture to drive photosynthesis and modify the light intensity (quality) in order to simulate different biosynthetic pathways for maximisation of crop production under the desired compounds but also with the required plant characteristics (Zheng et al., 2019).

Finally, photoperiod is a crucial factor affecting plant growth and quality, and its optimisation seems very important. Sugumaran et al. (2013) conducted research testing both light intensity and photoperiod in lettuce plants, proving that higher light intensity combined with a short photoperiod can improve the yield of plants. Kozai Toyoki (2018) explained that after the plants' seeding and through their development, the demand in photosynthetic photon flux density (PPFD) can be reduced up to 50%.

Photosynthesis is one of the most important processes in the plant development that can control the growth rate of plants. During photosynthesis, antenna pigments in leaf chloroplasts absorb the light radiation (solar or artificial) and, via resonance transfer, plant can produce chemical energy. What actually happens is that water and carbon dioxide enter the cells of the leaves and, through the energy trapped in the chlorophyll, photosynthesis produces sugar and oxygen that exit the leaves. In other words, photosynthesis allows plants to generate oxygen from the electron transport activities of the chloroplasts and the respiration processes of mitochondria (Zheng et al., 2019).

In the photosynthesis process, chlorophyll is one of the most important antenna pigments, as it promotes the oxygen conversion of light. Chlorophyll *a* (Chl *a*) molecules can be found in all photosynthetic organisms. All the other pigments absorb the energy that cannot be captivated by Chl *a* (Chemistry for Biologists, 2019). Important pigments in the photosynthesis are also chlorophyll *b* (Chl *b*), xanthophylls, and carotenoids (*β*-Carotene). Chl *a* has the highest absorption peak at 430 nm and 660 nm, followed by Chl *b* at 450 nm and 640 nm, and carotenoids at 450–460 nm and 480–485 nm (Croft & Chen, 2018). Figure 17 illustrates the chlorophyll absorption peaks of light energy that is mainly in the red and blue wavelengths of the visible spectrum, while carotenoids mainly absorb light energy on blue and green parts of the spectrum. Chlorophyll parameters (biomass, leaf area, etc.) are very useful growth indicators for the phenological development and the physiological state of the plants (Tanaka, 2000; Kancheva 2014). This is why their behaviour and development in a crop can be used as a vegetation state indicator for plants that are under healthy cultivation conditions, as well as for plants growing under a stress treatment (Pavlović et al., 2014) due to the high importance of chlorophyll pigments (a and b) as moderators in transforming the absorbed light radiation and its activity during the process of photosynthesis and in the synthesis of organic substances in plants. Richardson A. (2002) stated that low concentrations of chlorophyll could directly reduce the photosynthetic rate of plants and, consequently, their primary production. Therefore, the assessment and development of chlorophyll and other important pigment indicators (Chl *a*/Chl *b*, Chl *tot*/car, and carotenoids) can be used for monitoring and detecting the vegetation stage of plants.

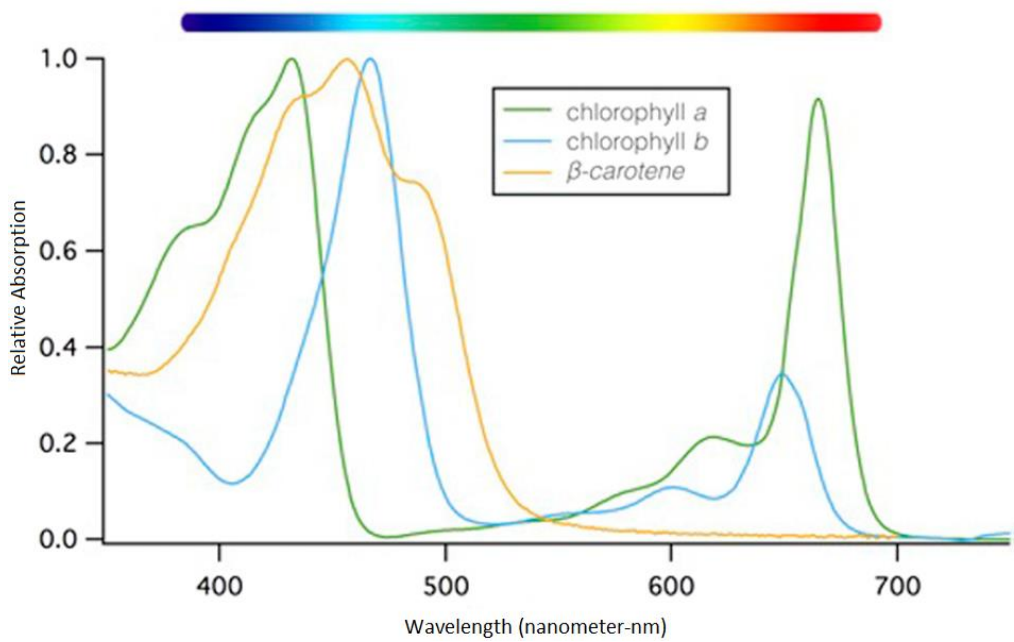


Figure 17. Absorption spectra of the main chlorophyll and carotenoid pigments of plants (Johnson, 2016)

In this research, the quality of basil plants was evaluated by measuring different physiological indices, including Chl *a*, Chl *b*, total chlorophyll (Chl *tot*), the fraction of photosynthetically active irradiance absorbed by the leaf (a), and leaf temperature; all under varying photoperiod treatments. In addition, the energy demand and the biomass production were studied to determine the sustainability and efficiency of a given estimation protocol in a small-scale indoor growth chamber.

3.1.2. Materials and Methods

3.1.2.1. Plant Material and Growing Conditions

The experiments were conducted from March to April 2019 in a controlled small-scale chamber, located at the Department of Business Development and Technology, Aarhus University in Herning, Denmark. The dimensions of the chamber were the following: Height = 1000 mm, width = 915 mm, and length = 457 mm. The air temperature, relative humidity, and CO_2 concentration were automatically controlled using a climate control sensor (TROTEC BZ30, UK). The light given in the systems came from the LED (Budmaster II GOD-2, Osram, UK) with a 90-watt energy consumption. In the LED specifications, the peak wavelengths are 400–520 nm (blue) and 610–720 nm (red and NIR); these remained stable throughout the whole experimental period.

Basil plants (Ocimum basilicum) were selected for this study, as they are one of the most frequent plant species cultivated in vertical farms, owing to their high nutritional value and cultivation density; the latter playing a key role in the yield rate of vertical farms.

The basil plants were grown by planting seedlings filled in perlite (ISOCON Perloflor Hydro 1). Two rows of plants were used, each row with four plants. The mean volumetric water content of perlite at field capacity was 53–55%. The measurements started ten days after transplanting, when the plants had about 2 pair of leaves each and were about six cm high in order to facilitate the following measurements with sufficient leaf sizes. The nutrient solution supplied to the crop via a drip system and was controlled by a commercial time irrigation controller (two irrigation events per day, at 08:00 and 20:00, for ten minutes each) with set points for electrical conductivity at 2.4 dS m^{-1} and pH at 5.6. In each plant, a constant flow dropper with a flow rate of 1 L/h was installed.

To study the effects of photoperiod on crop quality and quantity characteristics, three different photoperiod treatments were applied. The first treatment lasted for 17 days (control) as also the other two treatments lasted 17 days each treatment (stress). At the beginning of the control treatment, which covered 100% of the plants' need for lighting, the scheduled dark hours were from 10:00 to 18:00, i.e., eight hours of dark conditions (P8D16L). In the second part of the experiment, the dark hours were from 09:00 to 19:00, i.e., ten hours of dark conditions (P10D14L), and in the third part of the experiment, the dark hours were from 09:00 to 20:00, i.e., eleven hours of dark conditions (P11D13L). The average light intensity obtained at plant level when the LED was turned emitting 500 PPFD, 571 PPFD and 615 PPFD (μmol/m^2/s) for the P8D16L, P10D14L and P11D14L respectively in order to maintain a stable daily light integral DLI at 28.8 moles/m^2/day.

The total water consumption during the 31 days of the experiment was 35 L of water. At the beginning of the experiment, the water tank was filled with 15 L of water, i.e., the maximum capacity of the tank. A total of 35 L of water (20 during the experiment and 15 from the original water capacity) and 100 ml of nutrient solution (10 ml of nutrient solution for every two litres of water added, according to the protocol) were used during the experiment (excluding the relaxation phase between the two stress treatments, which lasted for two days). During the experiment, most of the water was lost due to the plants' need for water as well as evapotranspiration.

The experiment was repeated three in the same indoor small-scale chamber. It was not possible to maintain two different climate conditions (different photoperiods) for stress and control, respectively, in the chamber. For this reason, we first conducted the experiment under control conditions, and subsequently, we repeated twice the same experiment with the sequence described above, creating virtually identical environmental conditions. In the Table 16, you can see the environmental conditions throughout the whole experiment in each lighting treatment.

Table 16. The growing conditions applied to the cultivation of basil plants in the experimental small-scale lighting system.

Treatment	Length (days)	Relative Humidity (RH %)	VPD Vapor Pressure Deficit (Pa)	T_{air} (°C)	CO_2 (ppm)	Hours of Light	Energy Demand (kWh)
P8D16L	17	33 ± 5	1876 ± 207	23 ± 1	440 ± 27	18:00–10:00	76.09 ± 13.47
P10D14L	17	32 ± 5	1827 ± 133	22 ± 1	414 ± 20	19:00–09:00	64.07 ± 16.5
P11D13L	17	29 ± 4	1947 ± 73	22 ± 1	425 ± 18	20:00–09:00	58.06 ± 13.1

3.1.2.2. Data Collection

Prior to the experiment, the air temperature (T_{air} in °C), relative humidity (RH %), and CO_2 concentration of the chamber were measured and calibrated using a climate control sensor, placed 50 cm above the crop area in the middle of the chamber, to automatically log data every ten minutes (TROTEC BZ25 CO_2 Air Quality Monitor, Germany). The T_{air} and RH% values were used for the calculation of the air vapour pressure deficit values. Leaf temperature (Tleaf in °C) was measured using a thermocouple attached to the leaf surface area (Solfranc, Spain). Substrate moisture content (θ, %) and substrate temperature (Tsub in °C) were estimated using a capacitance sensor (WET-2/d Wet Sensor, Delta-T Devices Ltd., UK). Measurements took place every 30 seconds, and the average values of 10 minutes were recorded in the data logger.

The chlorophyll measurements were extracted by a chlorophyll sensor (CM-500, Chlorophyll Meter, Solfranc, Spain) that was calibrated before the experiment. The measurements were made manually every day at 08:00 in the morning (open lights). The sampling was done from five leaves of each plant from young to fully developed leaves. The portable sensor acquired data of chlorophyll based on the absorbance of plants at 660 and 940 nm (Kozai et al., 2016).

Eight basil plants of the same age and size were used for the measurements. Each plant was measured every day. The data were logged every ten minutes and the manual data once a day. According to Gonçalves L.F.C. et al. (2008), applying the method of Lichtenthaler and Welburn (1983) for detecting chlorophyll concentration with pigment extraction can be equally effective using a portable chlorophyll meter. The photosynthetically active irradiance absorbed in a leaf (a) can be described by the ratio:

$$a = \text{Chl } tot/(\text{Chl } tot + 76) \qquad [20]$$

(Evans and Poorter, 2001), with Chl *tot* (the chlorophyll content) measured in µmol m^{-2}.

3.1.2.3. Plant Biomass Measurements and Evaluation of the Electrical Energy Input Consumed for Basil Production

The fresh weight was measured separately in the root and shoot part of the plants (including stems, flowers, and leaves). For the dry weight measurements, the shoot parts of the plants were placed in an oven at 80 °C for 24 hours, during which all the water evaporated.

The input of electrical energy was measured using a power and energy logger, PEL 103 Chauvin Arnoux. The electrical energy consumed for the basil production was measured for each growing treatment, taking into account the total leaf biomass produced by the eight plants, the length of each treatment, the photoperiod (hours of light), and the energy consumed by the system per hour. The result is presented in kWh kg^{-1}.

3.1.2.4. Statistical Analysis

Data were subjected to one-way analysis of variance (ANOVA), followed by Bonferroni's multiple comparison test, and Tukey's post-hoc analysis test. Analyses were performed using SPSS for Windows (IBM Statistics for Macintosh, version 25.0).

3.1.3. Results

3.1.3.1. Development and Study of Abiotic Indicators under Different Photoperiods

In this section, the data collection results of the physiological parameters of the crop during the experiment are presented.

3.1.3.1.1. Development of Leaf Temperature

In Figure 18, the curve of leaf temperature for the three treatments is shown. The average temperature varied between 20.23 and 21.7 °C throughout the whole experiment. There was a significant effect in the change of leaf temperature at the $p < 0.05$ level for the three different photoperiod treatments ($F (2,48) = 3.787$; $p = 0.030$). Post-hoc comparisons using the Tukey HSD (Honestly Significant Difference) test indicated that the mean score for the leaf temperature in the control treatment ($M = 20.26$; $SD = 0.4$) did not differ significantly from the first stress treatment (P10D14L) ($M = 21.16$; $SD = 0.33$). Meanwhile, it was significantly higher than the second stress treatment P11D13L ($M = 20.73$; $SD = 0.88$).

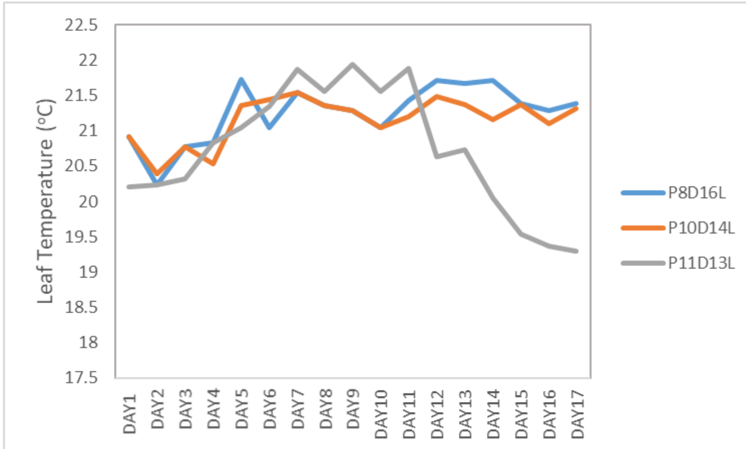


Figure 18. The daily means of leaf temperature between healthy plants (blue line) and stressed plants (orange line). Days 1–17: P8D16L (control treatment); days 1-17: P10D14L (stress treatment); days 1-17: P11D13L (stress treatment).

In Figure 19, the evolution curve of the substrate temperature (Tsub) for the three treatments is depicted. The average Tsub varied between 18.1 and 20.3 °C throughout the control experiment (P8D16L). There was no significant different between the three treatments at the $p < 0.05$ level ($F(2,48) = 2.362$; $p = 0.105$), with Tsub for the control treatment at (M= 19.3, SD= 0.71), for the P10D14L treatment at (M= 19, SD= 0.78) and for the P11D13L treatment at (M=18.7, SD= .88).

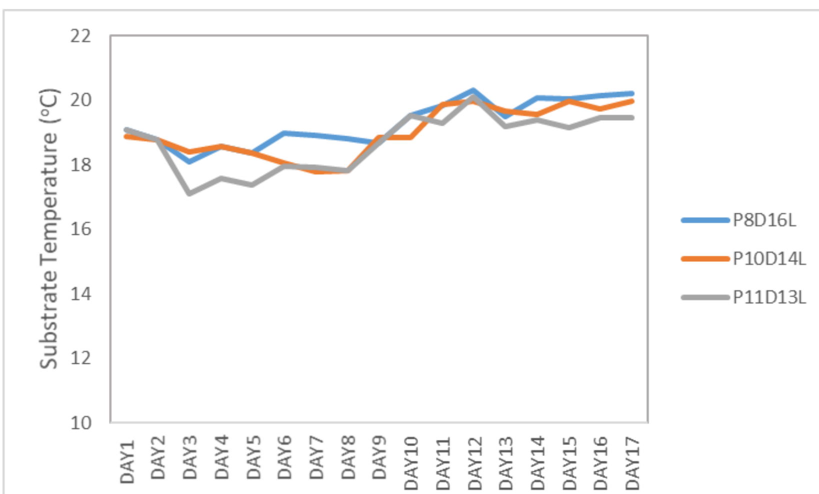


Figure 19. The average daily evolution of the substrate temperature (perlite) between healthy plants (blue line) and stressed plants (orange line). Days 1–17: P8D16L (control treatment); days 1-17: P10D14L (stress treatment); days 1-17: P11D13L (stress treatment).

3.1.3.1.2. Development of Chlorophyll Content

In Figure 20, the evolution curve of the chlorophyll content for the three treatments is shown. As can be seen from the graph, the average value of the chlorophyll content in the plants under the second stress treatment (with a 13-hour photoperiod) was drastically reduced from day 12 of the experiment (the first day of application of the reduced photoperiod for the crop). As the experiment progressed, the chlorophyll values continued to decrease until the end of the experiment, where the value was 25.44 SPAD. More specifically, the chlorophyll content of the healthy plants (P8D16L) ranged between 19.7 and 36.5 SPAD throughout the experiment, while the chlorophyll content for the stressed plants was significantly reduced when applying the second stress treatment (P11D13L). The chlorophyll content during the first stress treatment (P10D14L) was not statistically significantly reduced compared to the healthy plants with SPAD values varying between 19.6 and 38.38 SPAD.

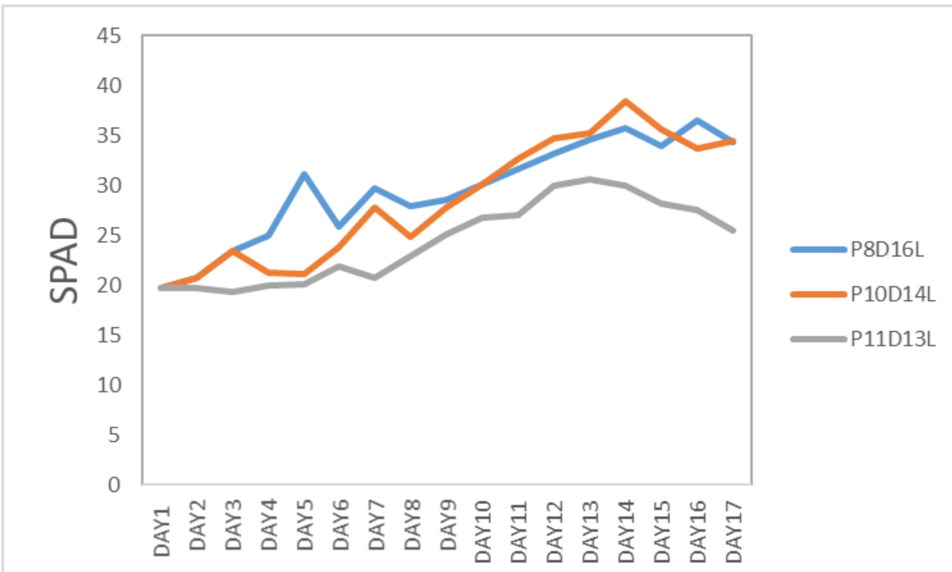


Figure 20. The average daily evolution of chlorophyll content between healthy plants (blue line) and stressed plants (orange line). Days 1–17: P8D16L (control treatment); days 1-17: P10D14L (stressed treatment); days 1–17: P11D13L (stress treatment).

3.1.3.1.3. Development of Chl *a* and Chl *b*

In this research study, a portable chlorophyll meter was applied to estimate the chlorophyll content of the basil crop. Using the research findings of Ruiz-Espinoza et al. (2008), we calculated the concentration of Chl *a,* Chl *b and* Chl *tot* from relative chlorophyll content (SPAD) values with the following equations:

$$\text{Chl } a = -0.0046+0.0008*(\text{SPAD}) \quad [21]$$

$$\text{Chl } b = -0.0014+0.0002*(\text{SPAD}) \quad [22]$$

$$\text{Chl } tot = -0.006+0.001*(\text{SPAD}) \quad [23]$$

where, SPAD is the measurement of the relative chlorophyll content retrieved from portable chlorophyll meter (CM-500).

In Figure 21, the values of the Chl *a* index can be seen. Chl *a* is one of the most important chlorophyll pigments (in combination with Chl *b*, as they differ minimally in their structure) (Stearns & Olson, 1958). A crucial property of Chl *a* is the versatility, enabling active participation in multiple functions in the photosynthetic process (Oxborough, 2004), including photon capturing, transfer and storage of photons, and energy storage at the antennas (Fiedor et al., 2008). Chl *a* absorbs radiation in the red and blue nanometers of the light spectrum. Apart from Chl *a*, plants use other pigments (Chl *b*, *c*, carotenoids, and phycobilins), which absorb radiation with intermediate wavelengths. This process makes better use of light energy.

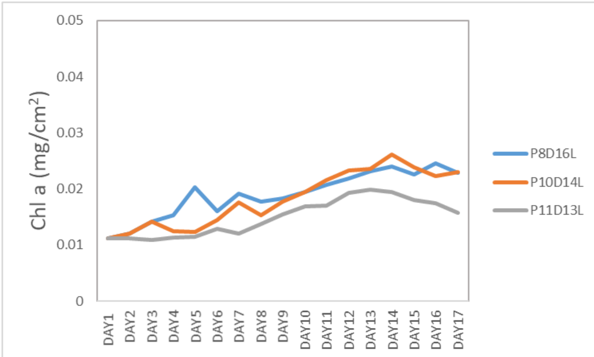
A one-way between-subjects ANOVA was conducted to compare the effects of the reduced photoperiod on Chl *a* of basil plants with the P8D16L, P10D14L, and P11D13L treatments. There was a significant effect of photoperiod on the Chl *a* (mg/cm^2) of the plants at the $p < 0.05$ level for all three treatments ($F (2,48) = 4.577$; $p = 0.015$). Post-hoc comparisons using the Tukey HSD test indicated that the mean score for P8D16L ($M = 0.019$; $SD = 0.004$) was not significantly different from P10D14L ($M =0.018$; $SD = 0.004$). However, the P11D13L treatment ($M = 0.015$; $SD = 0.003$) did differ significantly from P8D16L.

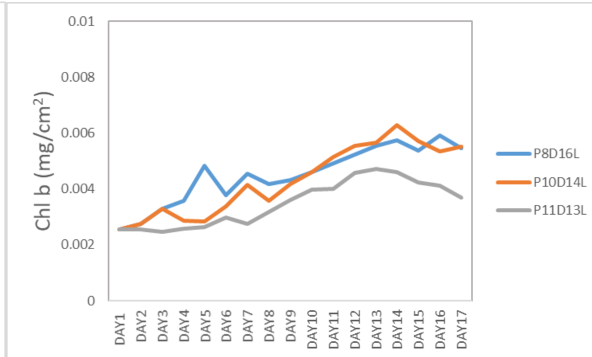
A one-way ANOVA was also conducted to estimate if Chl *b* (mg/cm^2) was affected by the different photoperiod treatments. There was a significant effect of photoperiod on Chl *b* of basil plants at the $p < 0.05$ level for the three treatments ($F (2,48) = 4.577$; $p = 0.015$). The post-hoc analysis revealed a significant difference between P8D16L ($M = 0.0045$; $SD = 0.001$) and P11D13L ($M = 0.0035$; $SD = 0$). Furthermore, P10D14L ($M = 0.0043$; $SD = 0.001$) was no statistically significant different from P8D16L.

Subsequently, a one-way ANOVA was performed for Chl *tot* (mg/cm^2) under the three treatments. There was a significant effect of photoperiod on Chl *tot* of the plants at the level $p < 0.05$ for all three treatments ($F (2,48) = 4.477$; $p = 0.015$). A post-hoc comparison test showed no significant differences between P8D16L ($M = 0.023$; $SD = 0.005$) and P10D14L ($M = 0.023$; $SD = 0.006$). However, compared to P8D16L, the P11D13L treatment ($M = 0.018$; $SD = 0.004$) showed statistical difference.

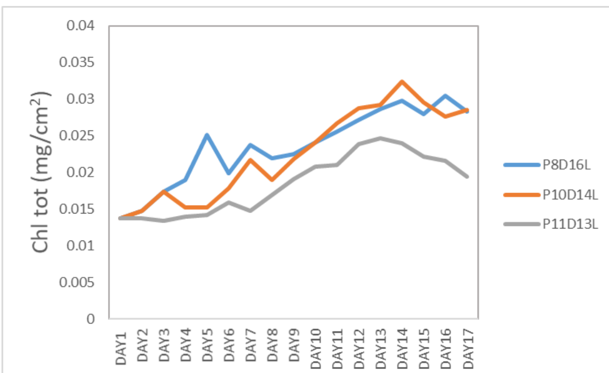
Finally, an one-way ANOVA was performed to find the fraction of photosynthetically active irradiance absorbed by the leaf between healthy plants, a, under the three photoperiods treatments. There was a significant effect of photoperiod on a of the plants at the level $p < 0.05$ for all three treatments ($F (2,48) = 4.576$; $p = 0.015$). A subsequent post-hoc analysis indicated that the mean *a* of P8D16L ($M = 0.0003$; $SD = 0.00007$) differed significantly from the mean a of P11D13L ($M = 0.0002$; $SD = 0.00005$), but not from the mean a of P10D14L ($M = 0.0003$; $SD = 0.00008$).

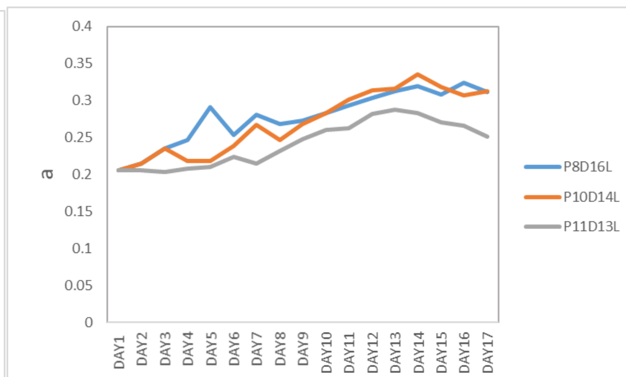
In conclusion, these results suggest that chlorophyll pigments are not affected or diminished when the photoperiod is reduced to two hours after the plants enter the germination stage. However, it should be noted that too short a photoperiod of the P11D13L treatment does not appear to promote the increase of chlorophyll pigments in basil plants and leads to a significant decrease of chlorophyll content and pigments.





(a) (b)





(c) (d)

Figure 21. The average daily evolution of the contents of (a) Chl *a*, (b) Chl *b*, (c) Chl *tot*, and (d) the fraction of photosynthetically active irradiance absorbed by the leaf (*a*) between healthy plants (blue line) and stressed plants (orange line). Days 1–17: P8D16L (control treatment); days 1-17: P10D14L (stress treatment); days 1-17: P11D13L (stress treatment).

3.1.3.2. Quality and Physiological Evaluation of Basil under Different Lighting Conditions

The length of the growing cycles was 17 days for the control treatment (P8D16L) and 17 days for each of the stress treatments with shorter photoperiods (P10D14L and P11D13L). The control treatment was longer, as the plants were in the germination stage and needed enough light intensity for their optimal development before their transplanting. The plants were subjected to shorter photoperiods at equal days after their germination period.

The yield was measured as the head biomass production for each of the plants. The leaf area index measured in the plants after the P8D16L treatment was significantly higher, with a value of 638 cm^2 compared to the two stress treatments with 379 cm^2 for P10D14L and 279 cm^2 for P11D13L, respectively.

The height of the plants measured at the end of the P11D13L treatment differed statistically from P8D16L and P10D14L treatment, with a decrease rate of 6.16%, and substantially from the P8D16L treatment, with a reduction of 21%.

The shoot fresh weight (i.e., measurements of stems, leaves, and flowers) of the P8D16L treatment with a mean value of 41 g presented a statistical difference from P10D14L and P11D13L, with mean values of 22.40 g and 19.02 g, respectively.

The leaves grown in P11D13L showed the lowest shoot dry weight (3.44 g) compared to the P8D16L treatment (4.74 g). However, there was no statistical difference compared to the values measured in the plants grown under the other experimental conditions (Figure 22d).

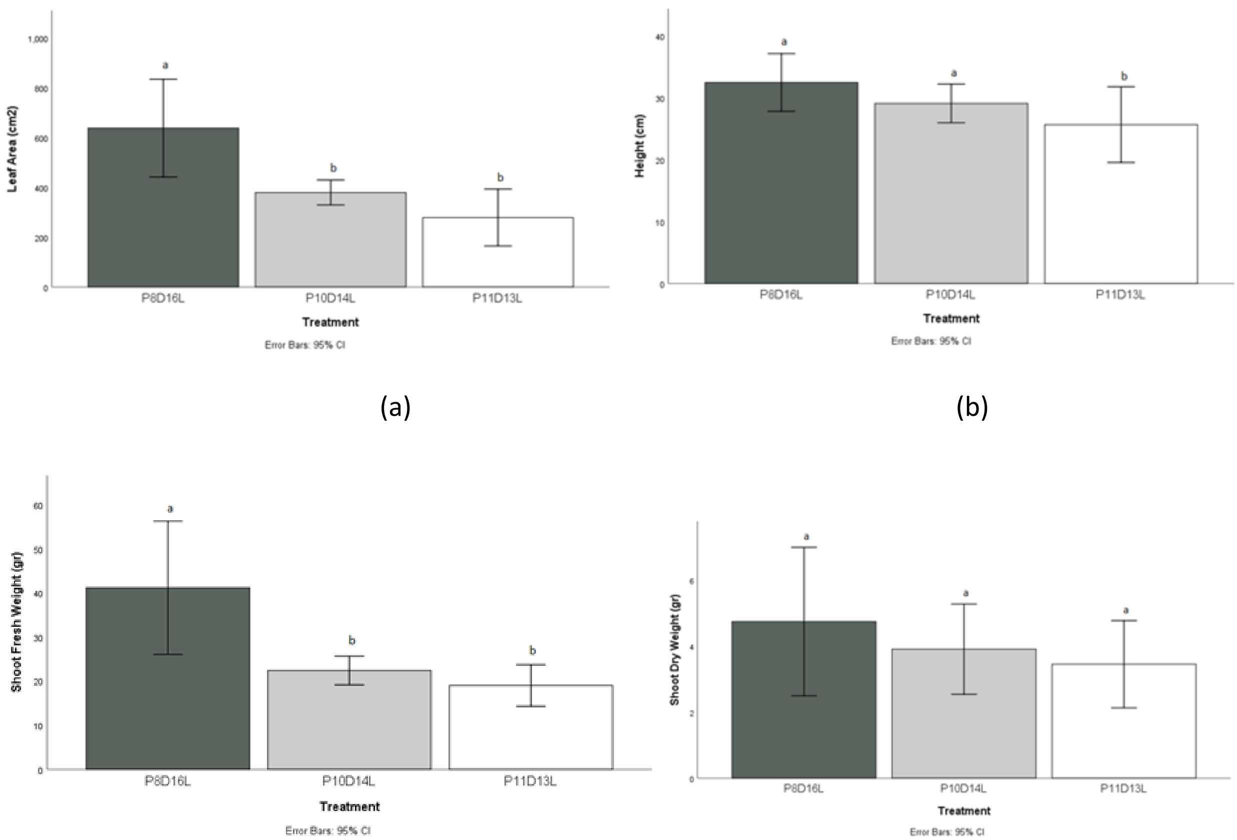


Figure 22. Effects of the different photoperiod treatments on growth and development of *Ocimum basilicum* grown in a small-scale closed-type growth chamber: (a) Leaf area (cm^2) of the plants; (b) height (cm) of the plants; (c) shoot fresh weight (gr); and (d) shoot dry weight. The values are means ± SD (n = 8). Various letters indicate significant differences among the different growing cycles ($p < 0.05$).

3.1.3.3. Plant Biomass Measurement and Estimation of the Input Energy Consumed for Basil Production

The total dry biomass of the plants was estimated by the following equation:

$$\text{Biomass} = \text{dry mass (g)} \times \text{cultivation area (m}^2\text{)} \qquad [24]$$

Figure 23 shows the electrical energy needed for the total crop production in each treatment. The conditions applied in the P8D16L and P10D14L treatments performed the highest biomass production achieved with a reduced electrical energy input compared to the P11D13L treatment. Post-hoc comparisons using the Tukey HSD test indicated that the mean score for the biomass production in the P8D16L treatment (M = 1.44; SD = 0.66) was not substantially different from the total biomass in the P10D14L treatment (M = 1.63, SD = 0.68). Furthermore, the total biomass in the P11D13L treatment (M = 1.21; SD = 0.55) did not differ significantly from the P8D16L and P10D14L treatments. However, from Figure 23, it can be observed that the highest biomass with a lower electrical energy input than the control treatment was obtained during P10D14L.

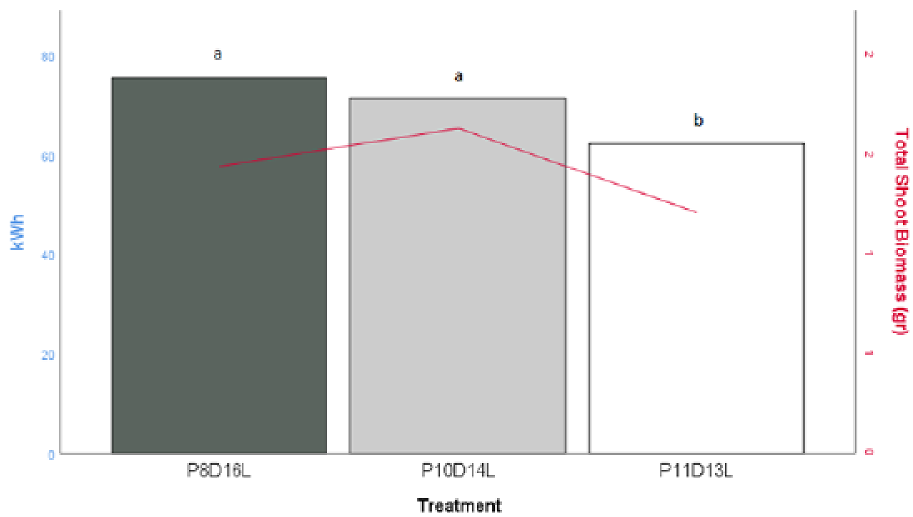


Figure 23. The left axis (histograms): The input of electrical energy consumed for basil production (kWh). The right axis (line): The total shoot dry biomass produced in each growing treatment. Various letters indicate significant differences in energy demand among the different growing cycles ($p < 0.05$).

3.1.4. Discussion

One of the most important aspects of this research was to investigate the sustainability and feasibility of an indoor cultivation system, thereby providing an even “greener” production system for fresh vegetables. The main objective was to study and optimise the energy demand in a small-scale cultivation area without affecting the yield of the crop.

The energy demand in an indoor cultivation area is mainly distributed to the lighting system (in addition to the fans and pumps of the cultivation area). Therefore, we chose to focus primarily on optimising the light emission by reducing the amount of light, i.e., the photoperiod.

3.1.4.1. Different Photoperiod Conditions Affecting Basil Quality, Physiological Parameters, and Leaf Functionality

Quality is one of the most important factors for evaluating plant growth conditions, specifically in herbs such as basil, as it can greatly affect the salable part of plants and consequently consumer's choice. Quality control can be achieved using multiple indices, devices, and protocols from a wide range, one of which can be the visual appearance (colour, shape, size) of herbal leaves. Therefore, many researchers use chlorophyll to investigate and extract results of physiological responses to the satisfactoriness and purchasing power of basil. Kopsell et al. (2005) state that chlorophyll concentration and the green colour gradation of leaves can be used as indicators of the xanthophyll carotenoid levels in basil. In these plants, xanthophyll is one of the most important carotenoids affecting the nutritional value; therefore, further research is needed to estimate xanthophyll pigments during different photoperiods in indoor cultivation areas. Johnson et al. (2019) surprisingly showed that a 24-hour photoperiod of photosynthetically active radiation has a positive effect on the flavour of basil plants cultivated under indoor environmental conditions. Since this study does not examine aroma molecules of basil plants, further research is needed in this area. In the current study, plants exposed to the second photoperiod treatment (P10D14L) showed no significant differences in the chlorophyll content of the basil leaves with a two-hour lower energy demand compared with the plants in the control treatment (P8D16L). It should be mentioned that after 10 days following the transplant, shorter photoperiods were applied to the plants (10 days from sowing to transplanting and 10 days after transplant). Furthermore, from these data, we found that the shoot biomass measured in the plants after the P10D14L treatment did not reflect a significant reduction from the shoot biomass accumulation in the plants following the P8D16L treatment. Moreover, the graphs in Figure 21 suggests that the values of Chl *a*, Chl *b*, and Chl *tot* indicate a slow and stable state of the photosynthesis efficiency when putting less energy into the system with stable smaller light periods (two hours less), since chlorophyll strongly participates in the process of photosynthesis and can be used as a useful indicator of the photosynthetic capacity (Pavlovic et al., 2014; Tanaka & Tanaka, 2000; Papageorgiou & Govindjee, 2004; Rathore & Jarsai, 2013; Kancheva et al., 2014; Maxwee & Johnson 2000; Baker & Rosenqvist, 2004). This might stimulate the activity of Rubisco, a key enzyme in the carboxylation process of the Calvin–Benson cycle. The Calvin–Benson cycle refers to the chemical reactions of photosynthesis that have the ability to convert carbon compounds and other compounds into glucose (Jablonsky et al., 2014). In other words, for most plants, the photosynthesis begins with a reaction between CO_2 and a five-carbon sugar known as RuBP (ribulose bisphosphate). This reaction is then catalysed by Rubisco, producing the G3P molecule. During the P10D14L treatment, the temperature of the cultivation area remained stable without provoking any kind of stress in the above process. In addition, it allowed leaf stomata to be open and new CO_2 to enter in order to replenish the CO_2 consumed by the cycle (Ricklefs et al., 2014). According to previous studies (Roháček and Bartak, 2008), when plants use the Rubisco enzyme (and consequently gain additional G3P) and are exposed to controlled night conditions, a short light inductance period used for chlorophyll data acquisition activates no photochemical processes scattering excitation energy to heat. In this study, Chl parameters maintained in the same level (Chl *a*: -3.6% from P8D16L to P10D14L) with a lower amount of light, implying that there was a combined effect allowing the plants to continue the photosynthesis process for a specific period of time with less energy demand. However, from P8D16L to P11D13L, there was a reduction in the Chl parameters (Chl *a*: -21.5%), indicating that there was a combined effect of the reduced light period in the development of the plants. Based on these results, we can hypothesise that plants continue to develop and increase their net primary production (biomass production resulting from photosynthesis and plant growth) when they fulfil their vegetative stage for a certain period until they realise that they receive less light energy and start reacting to the abiotic stress (Loconsole et al., 2019). The net photosynthesis was not measured in this research study; however, we can assume that the same results would be obtained with all three treatments. Further research is needed in the specific field to identify when basil plants continue to increase their chlorophyll content under a shorter photoperiod and thus less energy demand.

3.1.4.2. Effect of Different Photoperiod Conditions on Biomass Accretion and Energy Demand

Photoperiod is one of the factors that play an important role in the plants' biomass, leaf size, and area (Adams & Langton, 2005). Initially, it was expected that a longer photoperiod would result in higher biomass production for the plants. We observed a reduction of the shoot dry biomass in the P10D14L treatment; however, our analysis showed that it was not statistically significant. Nevertheless, when the photoperiod was further reduced, there was a marked decrease in the shoot dry biomass of the plants.

Moreover, it was found that a shorter day length also led to the minimised fresh weight accumulation and a lower leaf area in the shoot of the basil plants. This could be due to the photoperiod manipulation in basil production, which would reduce the concentration of nitrate and simultaneously increase the chlorophyll and carotenoid contents of the plants. As to the production of edible biomass in basil plants, Beaman et al. (2009) found that a higher carotenoid concentration, together with a reduced nitrate content, can produce a highly nutritious product with acceptable nitrate content for human consumption in basil plants that grow under 28.8 DLI. However, due to lack of measurements of nitrate in this research, this is a statement that cannot be verified by this study and future examinations are required.

Today, LED technology is the most widely used technology in large-scale vertical farms because it is considered the most energy-efficient, with a lower electricity consumption compared to all other types of lighting (Beaman et al., 2009). However, in small-scale production environments, several factors can contribute to a specific result and affect the feasibility and efficiency of the LED lighting technology. In this research study, we measured the energy input in the cultivation system that was consumed in each of the three treatments. Our goal was to identify an accurate energy saving and variation in the different growing conditions and how to reduce the production cost, specifically in a small-scale environment, including minimising energy loss and other demands (heating, ventilation, etc.) (Molin EMartin, 2018).

Based on the data collected from the experiment, the P10D14L treatment included the production of a commercially profitable product that generated the same growth rate, yield and high-quality herb leaves with lower energy cost and footprint when compared to the control environment (P8D16L). As seen in Figure 23, the biomass in P10D14L was in the same statistical range as P8D16L, but it used approximately 12.02 kWh less than the control treatment. From an economic perspective, our small-scale cultivation area is equal to an energy cost-saving trend of 5.3 €/m²/day (since the research took place in Denmark, we used the average Danish electricity price, as follows: 0.219 €/kWh for businesses (Eurostat, 2020)). Although the second stress treatment (P11D13L) provided a further decrease in the energy demand, the results for the total dry biomass of the plants were also the lowest (Figure 16). A further study is needed to determine the exact period when the basil plants are in a state of growth and where less energy can be provided without affecting the optimal development of the crop. Furthermore, a more detailed study is needed for the economic and environmental impact of a limited photoperiod in indoor farming, as well as the opportunities and results of a large-scale indoor vertical farm.

3.1.5. Conclusions

Growing basil in a small-scale indoor cultivation system, where we can control all growth parameters, presented a positive effect on the quality and quantity of the plants. A minimised photoperiod with 10 hours of darkness and 14 hours of light (as opposed to 8 hours of darkness and 16 hours of light) showed positive effects on the chlorophyll content and, thus, the physiological development of basil plants 10 days after the plants were transplanted into a hydroponic substrate and placed in the small-scale indoor chamber. The basil plants did not show significant differences in their yield when comparing the first stress treatment (P10D14L) with the control treatment. In this experiment, the main objective was to maintain a high-value product in terms of quality and quantity, yet at the lowest energy cost possible in a small-scale environment. Future research is needed in the field to examine the optimal lighting conditions (light intensity, tolerance under short-day photoperiods, and optimal nm selection in LEDs) for a larger variety of herbs and fresh vegetables and large-scale installation to increase the economic value of the product.

Since vertical farms are a novel type of cultivation that offers numerous advantages for cities to meet their demand for fresh vegetables, herbs, and fruits, many studies have been conducted to analyse and optimise the technologies and the cultivation protocols used. However, the energy demand is one of the main drawbacks limiting the feasibility of vertical farms. This is why it is important to assess the utility of vertical farms under the appropriate framework. Thus, it is crucial to continue with further studies to examine the economic and environmental potentials of vertical farms, and how they can become even more sustainable, especially in a large-scale application.

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3.2. Basil plants grown under intermittent light stress in a small-scale indoor environment: Introducing energy demand reduction intelligent technologies

The fourth journal paper of this PhD dissertation introduces the research of a new lighting methodology for artificially lighted farms. Vertical farms is a highly increasing method of cultivation that provide locally produced greeneries for consumers without agrochemicals and high automation systems. However, at the same time, the operational costs of artificial light operation can jeopardise the profitability of vertical farms. For this reason, this scientific methodology seeks to redefine the operation limits of artificial light under the scope of how they influence plants' growth and biomass production. The proposed method in this research targets to examine if indoor farms could use shifted energy demand response for lighting operation in order to exploit the opportunity of using the dynamic loads with fluctuating electricity prices that benefit Nordic countries. From the third submitted paper of this dissertation, it has been presented that basil plants can sufficiently growth in the limited light period operation of 14 hours with equally high photosynthetic capacity as the 16 hours. To provide a more fluctuating light schedule for indoor cultivation becomes very crucial to reduce as possible the light operation until the level that does not affect negatively the growth rate of plants. In order to provide valid results, this method examines and compares continuous light photoperiod with photoperiod with interrupted lighting intervals and reports and analyses the effect of intermittent lighting photoperiod on plants' development and growth rate. Under this scope, the photosynthetic rate, chlorophyll pigments, leaf area, biomass production and other physiological and morphological indices are reported to assess the quality and quantity of basil crops. The purpose of this study is to determine if intermittent lighting exposure could enhance the sustainability and efficiency of IVFs by increasing the flexibility and reducing the energy footprint of lamp operation without adversely affecting the growth rate and biomass production of the plants. The results of this experimental study indicate that the short and interrupted light cycles (10-min) were sufficient to attain the optimal photosynthetic efficiency of the cultivation for 19 days and later and until the harvest that showed signs of stress due to intermittent lighting operation. Finally, the evaluation of the energy footprint under various light treatments can have a positive contribution on the energetic, economic, business, and ecological of indoor food production.

3.2.1. Introduction

Vertical farming is a novel type of farming that provides the opportunity to cultivate plant species in an indoor, fully automated environment with a continuous monitoring of the growth and development status of the plants. Vertical farms replace solar radiation with artificial lighting, and in urban horticulture, conventional lighting is often replaced by light-emitting diodes (LEDs), which focus on specific wavelength ranges activating the spectral response of plant growth and development. LEDs convert 45% of their power supply into visible light absorbed by plants and can be used as a light source throughout the entire production process while the remaining heat requires efficient heat removal through efficient thermal management. Modern LEDs in horticulture are usually equipped with a heat dissipation system, which performs heat sinking using anodised aluminium extrusion, enabling them to achieve efficacies up to 3.2 μmol/J. Furthermore, based on Xydis et al. (2020), vertical farming is a farming business scenario that allows high profitability as well as multiple revenue streams and business models in combination with small-scale wind turbines.

According to previous research (Avgoustaki & Xydis, 2020), the electricity costs of a vertical farm accounts for the highest portion of the operating costs with around 25% of the production costs. More specifically, the lighting of a vertical farm accounts for 80% of the total electricity costs. As a result, there is an increasing demand for further optimisation on light dimensions in vertical farms to reduce operating costs. This involves light duration (photoperiod), light quality (combined wavelengths in nanometres), and light quantity (light intensity known as the photosynthetic active radiation, PAR). LEDs create electron movements in a semiconductor material, and thus they can reach the most crucial nm for plants' growth and development by activating the photosynthesis process. For this reason, a typical LED for horticulture shows a peak wavelength in the absorption spectrum at 660 nm (deep red), 450 nm (deep blue), 525 nm (green), and 735 nm (far-red) (Ashdown, 2015). LEDs perform higher correlated colour temperature (CCT) compared with HPS lamps as they perform higher levels of CCT that provide more power at the short wavelengths of the spectrum. Furthermore, LEDs can produce up to 134% more bright light compared to HPS lamps even in similar illuminance levels (Fotios & Cheal, 2011). The primary function of LEDs is to satisfy the requirements of leaf optical properties that include different chlorophyll pigments to capture the energy and initiate the photosynthesis process.

As mentioned by Touliatos, Dodd, and McAinsh (2016), photoperiodism (i.e., the duration of light that plants receive daily) can affect the productivity and quality of the canopy at different growth stages of plants (germination, vegetation, flowering, etc.). According to Kang, Sugumaran, Atulb AL, Jeong, & Hwang (2013), both optimal light intensity and photoperiod can increase the yield of plants.

The photochemical processes of plants have three different types of time constraints: 1) primary photochemistry, 2) electron shuttles, and 3) carbon metabolism (Yeh & Chung, 2009). According to Matthijs et al. (1996), longer dark periods tend to reduce the growth rate of plants. However, a decrease in light flux under intermittent light seems to reduce the growth rate of plants less than in the case of a similar flux decrease under a continuous lighting system. Intermittent light (IL) is a technique that allows us to evaluate plants' non-photochemical reactions, which are correlated with the reduction of photochemical reactions (Briggs, 1935). In other words, during intermittent light, the light is emitted intermittently in short cycle periods. The objective of using IL is to design a control energy system per growth cycle caused by saturation of the photochemical reaction. IL helps define the relationship between photochemical and non-photochemical reactions of the plants, which are related to the photoperiod.

To study whether an intermittent lighting method induces stress on plants, we examine the photosynthesis rate of basil and other physiological parameters. Photosynthesis is the process by which electromagnetic radiation (light) is converted to chemical energy, using light, water, and carbon dioxide to release carbohydrates and oxygen. The process starts with the chlorophylls (the photosynthetic pigments) that absorb light energy while air-containing oxygen and carbon dioxide enters and leaves the leaves through the stomata, i.e., the tiny pores in the leaves. The photosynthesis consists of two parts: a light reaction and a dark reaction. During the light reaction of photosynthesis, a chain redox reaction is performed of photosystem I (PSI) and photosystem II (PSII) that collects light energy and produces useful chemical energy products for the following CO_2 assimilate reaction cycle process. This process is highly dependent on the light reaction and is independent on the amount of chemical energy provided in the plant (Kanechi, 2018, chap. 3). In the photosynthesis process, chlorophyll pigments are the most important and effective absorbers of light energy. The most abundant pigment in the majority of photosynthetic organisms is chlorophyll *a* (Chl *a*) followed by chlorophyll *b* (Chl *b*), xanthophylls, and carotenoids (β-Carotene). The photosynthesis and chlorophyll parameters (as well as physiological indices such as leaf area, height, and biomass) are used as growth indicators for the phenological and physiological developmental stages of plants (Tanaka & Tanaka, 2000; Avgoustaki, 2019). For this reason, the study of the behaviour and development of a selected crop can indicate the vegetation growth of plants under healthy and stressed cultivation conditions.

In a previous study by Avgoustaki (2019), it was found that basil plants exposed to a reduced photoperiod of 14 h of continuous light did not show visible changes in their growth and development (compared to 16 h, which is considered optimal for basil). However, even if plants showed continuous development under reduced photoperiod (of 14 h), the energy grid does not provide continuous low price of electricity for the farmers to accomplish a precise shift in their production. This is the reason why we decided that it is of high importance to study plants' response under limited and intermittent lighting system. The purpose of this research is to detect the response of basil plants under continuous light with an optimal photoperiod (of 16 light hours) as opposed to plants exposed to IL and a reduced photoperiod (of 14 h). We measure the photosynthetic rate, stomata conductance as a function of CO_2, chlorophyll pigments, growth indices, and light levels to assess the impact of IL on basil from germination to harvest. Finally, the research aims to examine a lighting system that takes advantage of the fluctuating electricity market and shifts demand response to reduce the total energy costs without affecting the growth rate of the plants.

3.2.2. Material and Methods

3.2.2.1. Plant Material and Growing Conditions

The experiments were conducted in an indoor small-scale chamber located at the chemistry laboratory of the Department of Business Development and Technology, Aarhus University in Herning, Denmark. The dimensions of the chamber were the following: Height = 1000 mm, width = 915 mm, and length = 457 mm. The air temperature, relative humidity, and CO_2 concentration were automatically monitored, using a climate control sensor (TROTEC BZ30, UK). The light in the systems came from the Budmaster II GOD-2 LED with a 90-W energy consumption. In the LED specifications, the peak wavelengths are listed as 400–480 nm (blue) and 610–720 nm (red and NIR). These remained stable throughout the experimental period.

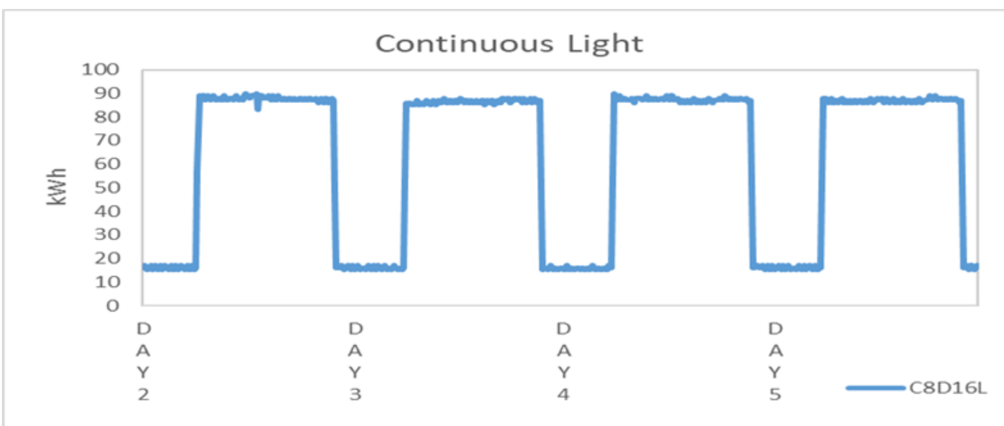
'Genovese' basil (*Ocimum basilicum*) was selected for this study, as it is one of the plant species most commonly cultivated in vertical farms due to its high nutritional value and cultivation density, which play a key role in improving yield in vertical farming. Furthermore, sweet basil belongs to the category of long-day plants, as it needs more than 12 h of light and less than 12 h of dark in order to grow. According to previous literature, the optimal photoperiod for basil is 16 h of light (Beaman et al., 2009).

Basil seedlings filled with perlite (ISOCON Perloflor Hydro 1) were planted. Two rows and five columns of plants were used, each pot with five plants. The mean volumetric water content of the perlite at field capacity was 53–55%. The measurements started three weeks after sowing, when the plants had an average height of 6.2 cm and two pairs of actual leaves. The plants were grown in an ebb-and-flow hydroponic installation, and every second day, water enriched with the nutrients was added directly at their root zone.

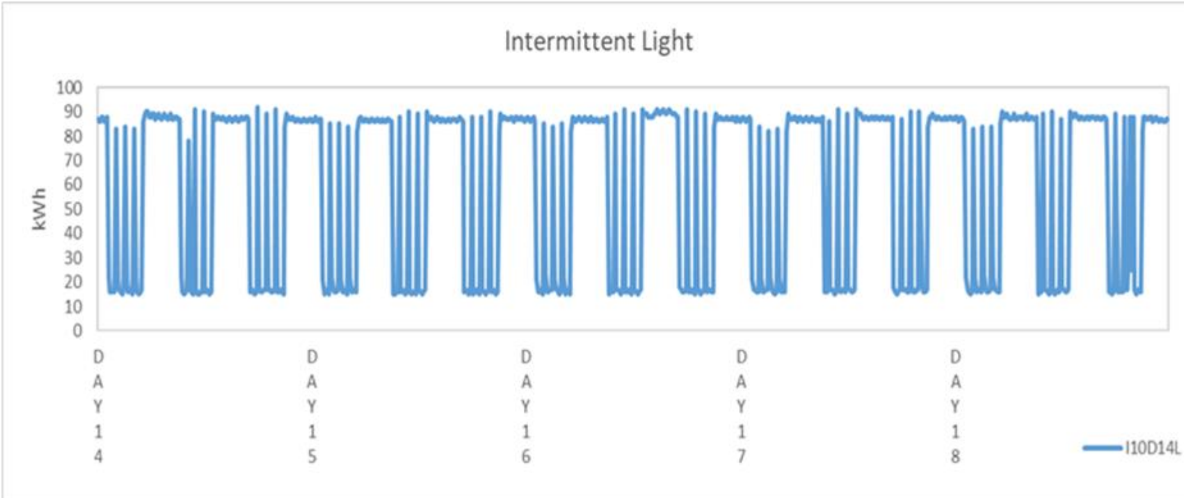
To study the effects of IL on crop quality and quantity characteristics, two experiments were performed since we only acquire one chamber that we could set with the desired conditions. Two consecutive experiments have been carried out from August to September and from November to December 2019. More specifically, throughout the whole first experiment the lighting conditions remained stable at 16 h of continuous photoperiod. This first experiment named C8D16L and referred as the control treatment that used as reference for comparison with the stress treatment. Subsequently, we repeated the same process, where we planted the same basil cultivar (Genovese basil) in the same numbers and locations. Primarily, plants sowed and grew and continuous light of 16 h photoperiod for three weeks without being able to take measurements from leaves because of the insufficient size. Continuously, when plants entered the third week and developed 2 pairs of fully developed leaves we altered the lighting system from 16 continuous photoperiod to 14 h of intermittent photoperiod, until the end of the experiment and the final harvest. The second experiment is considered as the stress treatment and is referred as I10D14L. During the I10D14L treatment, plants received light every 10 min per hour over a 4-h period followed by a 4-h period of continuous light and that was repeated in a 24-h basis (Table 17, Fig. 24). This system had a total of 14 h of light and 10 h of darkness per day (Withrow R.B. and Withrow A. P., 1944). The average amount of light obtained at the level of plants when the LED was turned on was expressed in Photosynthetic Photon Flux Density (PPFD), and adjusted at 500 and 571 μmol/m^2/s for C8D16L and I10D14L respectively to maintain a stable daily light integral at 28.8 moles/m^2/day in both treatments, and was measured daily with the spectrometer uSpectrum (UPRteck/Licor) because of the constant increase of leaves (Figure 25).

Table 17. Lighting time schedule for the two lighting treatments.

Irradiation Treatment	Light Period	Dark Period	Type of Irradiation	Total Photoperiod
C8D16L	16 hours	8 hours	Continuous	16 hours
I10D14L	4 hours		Intermittent	14 hours
	10 min	50 min		
	10 min	50 min		
	10 min	50 min		
	10 min	50 min		
	4 hours			
	10 min	50 min		
	10 min	50 min		
	10 min	50 min		
	10 min	50 min		
	4 hours			
	10 min	50 min		
	10 min	50 min		
	10 min	50 min		
	10 min	50 min		



(a)



(b)

Figure 24. Daily electricity consumption during a) continuous light treatment (C8D16L) and b) IL treatment (I10D14L).

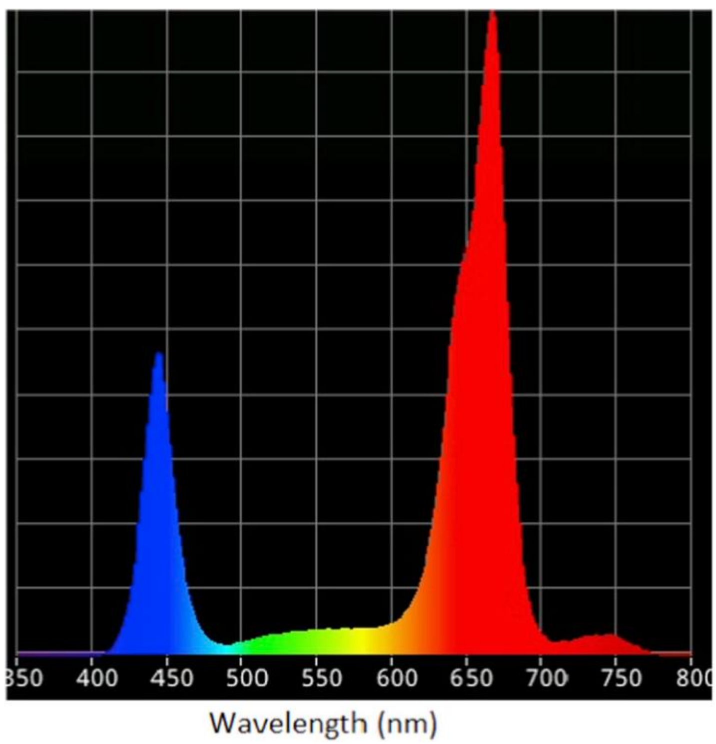


Figure 25. Relative spectral emission of the LED lamp (Budmaster II GOD-2 LED) used in the experiment and measured with the spectrometer uSpectrum.

The total water consumption during the 24 days of both experiments was 12 L. At the beginning of the stress treatment of I10D14L with the intermittent lighting application, the water tank was filled with 2 L of water, i.e., the maximum capacity of the tank. A total of 12 L of water (10 during the 24 days and 2 deriving from the original water capacity) as well as 100 ml of nutrient solution (10 ml of nutrient solution for every litre of water added) were used in the experiments (excluding the restitution phase between the two treatments, which lasted for one day). Most of the water loss during the experiment was due to the plants' need for water as well as evapotranspiration. Table 18 shows the climate conditions for each light treatment of the experiment.

Table 18. The climate conditions used for growing basil plants in the small- scale chamber.

.Treatment	Length (days)	Relative Humidity (RH %)	VPD Vapor Pressure Deficit (Pa)	T_{air} (°C)	CO_2 (ppm)	Energy Demand (kWh)
C8D16L	24	29.5 ± 5.6	2190 ± 315	24.6 ± 1.3	458 ± 10	71.57 ± 5.18
I10D14L	24	36 ± 2.3	1586 ± 88	21 ± 0.9	443 ± 13	57.63 ± 2.26

3.2.2.2. Data Collection

Before the experiment, the air temperature (T_{air} in °C), relative humidity (RH%), and CO_2 concentration of the chamber were measured and calibrated using a climate control sensor, placed 50 cm above the crop area in the middle of the chamber to automatically log data every 10 min (TROTEC BZ25 CO_2 Air Quality Monitor, Germany). The T_{air} and RH % values were used to calculate the air vapour pressure deficit values. Leaf temperature (T_{leaf} in °C) was measured using a thermocouple attached to the leaf surface area (Solfranc, Spain) [sensor error ± (0.03 + (0.005 × to)]. The measurements were performed in 30-s intervals, and the data logger recorded the average values at 10-min intervals.

The measurements of photosynthesis and chlorophyll were made manually every day in the morning at 9:00, 10:00, 11:00, 12:00, and 13:00, and in the evening at 17:00, 18:00, 19:00, 20:00, and 21:00. The sampling involved young and fully developed leaves from each plant. The portable sensor provided chlorophyll data based on the absorbance of plants at 660 and 940 nm. As seen in Table 16, the measurement from 9:00 to 17:00 coincided under the end of the 4-h of continuous light, while the rest of the measurement took place during the 10-min light cycles.

The plants were measured every day with both manual and the automated sensors. As mentioned, the data from the gas exchanger sensor and the chlorophyll content were taken manually. All the other sensors (T_{leaf}, Wet sensor and environmental conditions) were connected with data loggers and were taken automatically. To measure the temperature of the substrate we use WET-2 Sensor from Delta-T devices (UK) with the error of the sensor to be ± 10 mS*m^{-1}. The data were logged every 10 min and the manual data ten times a day according to the schedule described above. These measurements and data acquisitions were followed by the photosynthesis and chlorophyll measurements. The sensor used to collect photosynthesis data was the LCpro-SD gas exchange sensor for portable measurement of photosynthesis (ADC BioScientific Ltd., UK) (sensor error 0.1 °C). It was calibrated before both experiments. The chlorophyll measurements were extracted using a chlorophyll sensor (CM-500, Chlorophyll Meter, Solfranc, Spain), which was also calibrated before the experiments (sensor error ± 0.3 SPAD unit). The selected samples were young, fully developed leaves of Genovese basil.

3.2.2.3. Plant Biomass Measurements and Evaluation of the Electrical Energy Used for Basil Production

The fresh mass of the shoots (the stems, flowers, and leaves) was measured. For the dry mass measurements, the shoots were placed in an oven at 80 °C for 24 h during which all the water evaporated.

The input of the electrical energy was measured using the Chauvin Arnoux PEL 103 power and energy logger. The electrical energy consumed for the basil production was measured for each treatment, taking into consideration the total leaf biomass produced by the eight plants, the length of each treatment, the photoperiod (hours of light), and the energy consumed by the system per hour. The result is presented in kWh kg^{-1}.

3.2.2.4. Statistical Analysis

Data were subjected to an independent-samples *t*-test, including if they followed Levene's test for homogeneity of variances. The analyses were performed using SPSS for Windows (IBM Statistics for Macintosh, version 25.0).

3.2.2.5. Hypothesis

If we reduce the photoperiod that basil plants receive in an indoor environment, and we apply an IL treatment after the germination of the plants, the growth and development of the photosynthesis rate will not be reduced.

3.2.3. Results

For the statistical analysis of our dependent variables, we performed independent sample *t*-test under the two different independent variables of the lighting treatments (C8D16L and I10D14L). However, for sample size we used only the final 14 days in both experiments that had diversified lighting conditions. The previous 10 days of measurements, since the conditions were the same in both experiments were statistically analysed and presented no significant difference. This is the reason why they were not included in the data analysis, but they presented concisely in Table 19.

Table 19. Results of statistical analysis of the first 10 days in C8D16L and I10D14L were both followed continuous lighting of 16 h. The data presented are: Sample size (N), Mean values (Mean), Standard Deviation (SD), t (t-test), Degrees of Freedom (df), level of significance (p-value).

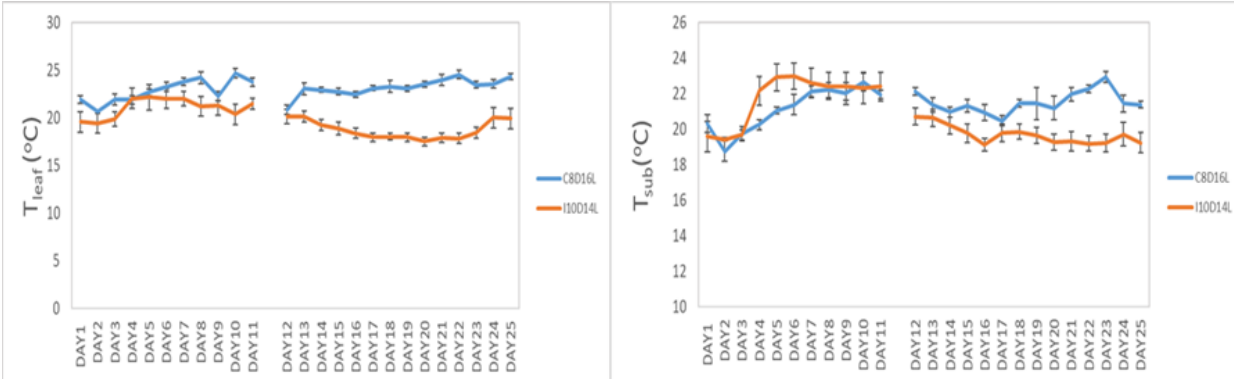
	Treatment	N	Mean	SD	t	df	p-value
Tleaf (°C)	C8D16L	10	22.75	1.2	2.028	18	.058
	I10D14L	10	21.81	0.7			
Tsub (°C)	C8D16L	10	21.05	1.2	-.987	18	.337
	I10D14L	10	21.7	1.5			
	C8D16L	10	5.7	1.1	-1.293	18	.212

As ($\mu mol*m^{-2}s^{-1}$)	I10D14L	10	6.4	1.2			
$As_{10\text{-}min}$ ($\mu mol*m^{-2}s^{-1}$)	C8D16L	10	5.8	1.1	-.693	18	.497
	I10D14L	10	6.1	1.4			
$As_{4\text{-}hour}$ ($\mu mol*m^{-2}s^{-1}$)	C8D16L	10	5.7	1.1	-1.389	18	.182
	I10D14L	10	6.5	1.3			
gs ($mmolm^{-2}s^{-1}$)	C8D16L	10	0.07	0.01	-1.210	18	.242
	I10D14L	10	0.07	,.01			
SPAD	C8D16L	10	16.9	4.6	.192	18	.850
	I10D14L	10	15.4	5			
Chl*a* ($mg*cm^{2}$)	C8D16L	10	0.0089	0.004	.718	18	.482
	I10D14L	10	00.77	0.004			
Chl*b* ($mg*cm^{2}$)	C8D16L	10	0.002	0	.718	18	.482
	I10D14L	10	0.0017	0			
Chl*tot* ($mg*cm^{2}$)	C8D16L	10	0.01	0.005	.718	18	.485
	I10D14L	10	0.009	0.005			
a	C8D16L	10	0.18	0.04	.720	18	.481
	I10D14L	10	0.17	0.04			

The data were initially tested for the homogeneity of the variance under Leven's test. The Levene's test can reject or accept the hypothesis of equal variances of the data, where F expresses the distribution of data at N-k degrees of freedom (df) at a significance level of a = 0.01. In the text is described by the following format F (df) = F-statistic, p = p–significance value. Subsequently, an independent samples *t*-test was performed for each dependent variable to determine whether there is a statistical significant difference between the mean values of the lighting treatment groups. The result of the independent samples to compare the means for the two lighting treatments (C8D16L – I10D14L) for all the dependent variables separately. In the report we included the t-statistic value (*t*-test), the degrees of freedom (df) and the value of significance of the test (p-value), using the format: t (df) = *t*-test, p = p-value.

3.2.3.1. Development and Study of Abiotic Indicators under Different Light Treatments

An independent-samples t-test was performed to compare the two light treatments (C8D16L and I10D14L) in order to determine whether there is a statistically significant difference between the means of various growth indicators for the basil plants grown in the small-scale indoor chamber (T_{leaf}, T_{sub}, SPAD, chlorophyll pigments, and As) (Fig. 26,27,28,29).



(a) (b)

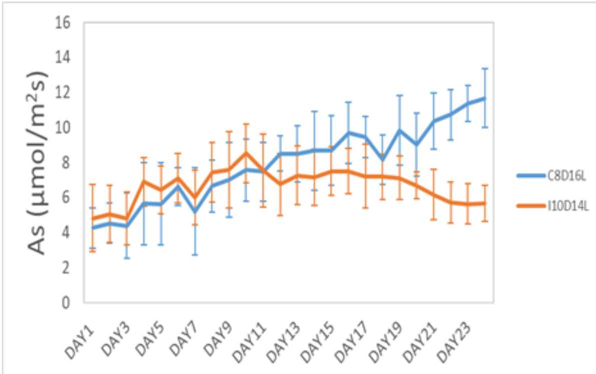
Figure 26. Average daily evolution of [a] leaf temperature (T_{leaf} in °C) and [b] substrate temperature (T_{sub} in °C) for healthy plants (blue line) and stressed plants (orange line). Days 1–10: a) C8D16L (control/continuous light); b) I10D14L (control/continuous light); days 11–24: a) C8D16L (control/continuous light); b) I10D14L (stress/intermittent light).

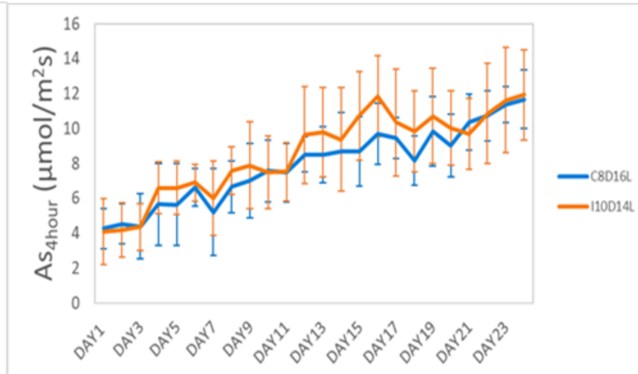
We examined multiple growth indicators of the basil plants, e.g., T_{leaf} in the control treatment (N=14) was compared with T_{leaf} = (23.2 $\pm$ 0.9) °C, and the stress treatment (N = 14) was compared with T_{leaf} = (18.75 $\pm$ 1) °C. An independent-samples *t*-test was conducted to test if the two treatments showed statistically significant different means in terms of T_{leaf}. The assumption of homogeneity of variances was tested and satisfied using Levene's F test, $F (26) = 1.371$, $p = 0.252$. The independent samples *t*-test was associated with a significant effect $t (26)= 12.682$, $p < 0.001$. Thus, the C8D16L treatment was associated with a statistically significant different mean than the I10D14L treatment. Cohen's *d* was estimated at 0.5, which is a medium effect based on Cohen's (1992) guidelines. The differences in the values of T_{leaf} and T_{sub} that can observed in the first 11 days of the two experiments in control conditions have no significance value.

There was a significant difference in the temperature of the hydroponic substrate (T_{sub}) in the C8D16L treatment T_{sub} = (21.5+-0.6) °C and the I10D14L treatment T_{sub} = (19.7 +- 0.5) °C with N = 14 for both cases. Thus, the homogeneity of variance was violated, and we proceeded without an assumption of equal variances: $F (26) = 0.165$, $p = 0.688$. An independent-samples t-test showed no statistically significant difference with $t (26) = 8.359$, $p < 0.001$. These results suggest that the light treatment had a major effect on the Tsub for basil plants.

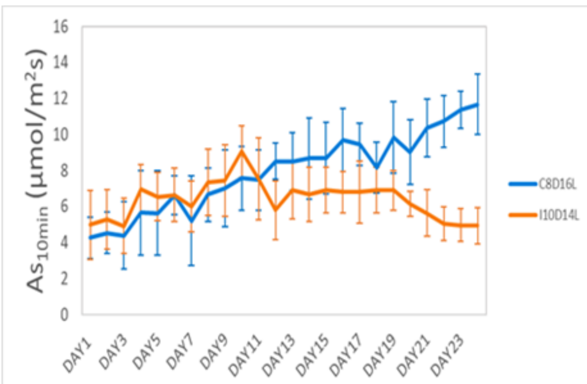
3.2.3.2. Statistical Analysis of Photosynthesis

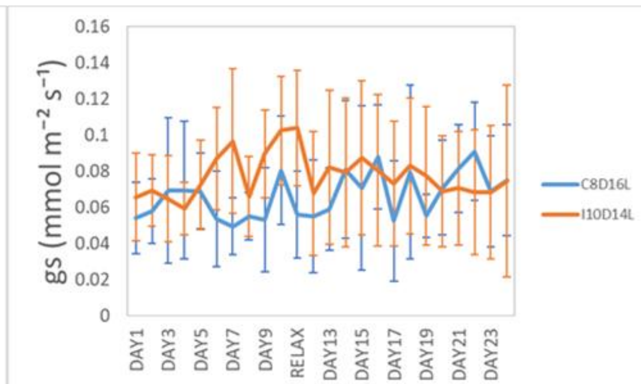
During photosynthesis, green plants capture light energy, carbon dioxide, and water and convert these into oxygen and energy-rich organic compounds. In this research, a portable gas exchange sensor (LCpro-SD) was used to estimate the photosynthesis process and its evolution during the experiment with the basil crop. Using the sensor, we monitored the photosynthesis rate (As – μmol*$m^{-2}s^{-1}$) (Fig. 27).





(a) (b)





(c) (d)

Figure 27. Average daily evolution of [a] total photosynthetic rate (As in µmol/m2s), [b] photosynthetic rate during a 4-h light period (As_{4hour} in µmol/m^2s), [c] photosynthetic rate during a 10-min light period (As_{10min} in µmol/m^2s), and [d] stomata conductance (gs in mmol/m^2s) for healthy plants (blue line) and stressed plants (orange line). Days 1–10: a) C8D16L (control/continuous light), b) I10D14L (control/continuous light); days 11–24: a) C8D16L (control/continuous light), b) I10D14L (stress/intermittent light).

The C8D16L treatment As = (9.44 $\pm$ 1.2) µmol/m^2s was compared with the I10D14L treatment As =(6.79 $\pm$ 0.7) µmol/m^2s with N=14 in both samples to test the difference in the As between the healthy and stressed plants. To examine whether As had a higher level of statistical significance with intermittent light, we performed an independent samples *t*-test. Levene's test for equality of variance was run to verify the assumption of homogeneity of variances, and equal variances were not assumed: $F(26) = 4.181$, $p = 0.051$. The independent-samples *t*-test was performed with a statistically significant effect, $t(20.694) = 6.936$, $p < 0.001$. Cohen's d was estimated at 1.5, which is a large effect based on literature. The difference between the treatments starts from day 19 of the experiment.

As mentioned previously, we performed photosynthesis measurements every day: five times in the morning hours and five times in the evening hours. The measurements made during the intermittent treatment took place during the 10-min light cycles, but also at the end of the 4-h of continuous light (Table 17). Accordingly, we tested both the evolution of As during the 10-min light cycles with limited light radiation as well as at the end of the 4-h of continuous light, which allows plants to receive, absorb, and process more light energy and convert the energy into chemical energy.

We therefore decided to perform a statistical analysis of the 10-min periods and the 4-h periods between the C8D16L treatment and in the I10D14L treatment. The C8D16L treatment $As_{10\text{-min}}$ = (9.44 $\pm$ 1.2) µmol/m^2s for the 10-min period measurements of photosynthesis ($As_{10\text{-min}}$) was compared with the corresponding measurements of the I10D14L treatment $As_{10\text{-min}}$ = (6.29 +- 0.8) µmol/m^2s with N = 14 in both samples, which found that there was statistical significant difference between the two groups: t (26) = 7.830, $p < 0.001$ by performing an independent samples *t*-test. Since the assumption of homogeneity of variances was not violated using Levene's test, we continued with the assumption of equal variances at F (26) = 1.655, $p < 0.210$. These results suggest that IL has a significant effect on the photosynthesis of plants at measurement levels of 10 min. Cohen's *d* was also calculated at 2.9 showing a strong effect.

Next, we compared the difference between the photosynthesis during the 4-h period of light (A4-hour) in both the continuous treatment – C8D16L with $As_{4\text{-hour}}$ = (9.44 $\pm$ 1.2) µmol/m^2s and the intermittent treatment – I10D14L with $As_{4\text{-hour}}$ = (10.28 +- 1.1) µmol/m^2s with N = 14 in both samples. Based on the Levene's test of homogeneity of variance, the results are F (26) = 0.266, p = 0.611, showing that our variances are equal. An independent-samples t-test was performed under the two treatments. There was no significant effect of IL on $A_{4\text{-hour}}$ at the level $p < 0.05$ for the two treatments at t (26) = −1.864, p = 0.074. The negative mean differences indicate higher mean of the I10D14L treatment than the C8D16L treatment. Our results show that plants under IL continued to develop steadily as the plants under continuous light. More specifically, 4-h of IL was sufficient for plants to develop their photosynthetic capabilities and absorb enough light energy to grow. Conversely, when the plants only received 10 min of light, they did not receive the energy needed to perform photosynthesis. Even when As was reduced because of the intermittent light, the plants in the I10D14L treatment showed no significant difference in the photosynthetic rate during the 4-h interval in comparison with the photosynthetic rate of the C8D16L treatment (Fig. 18b).

The analysis of the stomata conductance (gs) between the C8D16L treatment is gs = (0.071 $\pm$ 0) mmol$m^{-2}s^{-1}$ and the I10D14L treatment with gs = (0.077 $\pm$ 0) with N=14 in both samples, showed a no statistically significant difference at t (26) = −1.394, p = 0.175 (two tailed). As can be observed from the climatic conditions in the growth chamber, there is a negligible increase in the CO_2 and vapor pressure deficits (VPD) of our experiment that could have caused the increase in stomatal conductance between the two treatments. Furthermore, the increase in stomatal conductance following the 10-min cycles is also worth mentioning.

3.2.3.3. Statistical Analysis of Chlorophyll

For data collection, the portable chlorophyll sensor (CM-500, Chlorophyll Meter, Solfranc, Spain) was used to measure the relative chlorophyll content (SPAD) of the basil plants. As mentioned above, the data acquisition during the experiment was conducted in specific time periods as presented in Table 17.

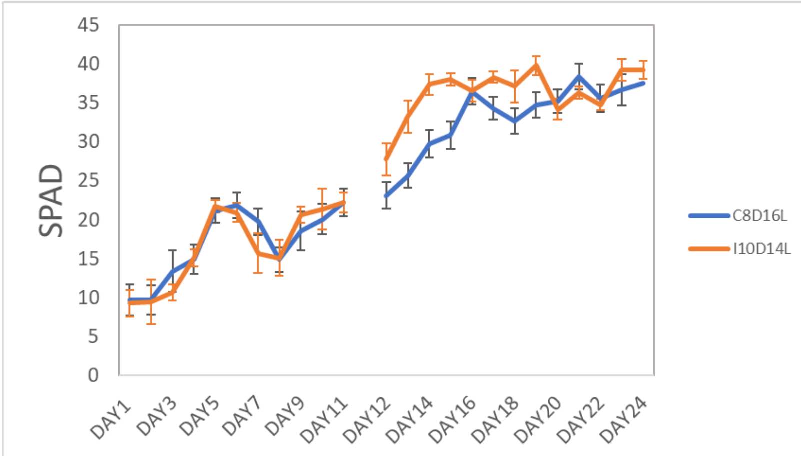


Figure 28. Average daily evolution of chlorophyll content (SPAD) for healthy plants (blue line) and stressed plants (orange line). Days 1-10: a) C8D16L (control/continuous light); b) I10D14L (control/continuous light). Days 11-24: a) C8D16L (control/continuous light); b) I10D14L (stress/intermittent light).

In Figure 28, the evolution curve of chlorophyll content (SPAD) under the two light treatments is presented. As can be observed, the curve shows an aligned development of chlorophyll production for the plants subjected to the stress treatment with 14 h of photoperiod and IL (I10D14L) and the plants following the control treatment (C8D16L). Measurements obtained from the C8D16L treatment is SPAD = (33.16 $\pm$ 4.6) and the I10D14L treatment is SPAD = (36.33 $\pm$ 3.2) with N = 13 in both samples, showed no statistically significant difference between the two treatments, $t(26) = -2.016$, $p = 0.055$. As the experiment progressed, the chlorophyll values continued to increase until the end of the experiment, reaching 39.82 SPAD. More specifically, the chlorophyll content of the healthy plants (C8D16L) varied between 27.7 and 39.82 during the stress days of the experiment (days 10–24). (The last day- No25 of the second experiment the CM-500 Chlorophyll Sensor presented malfunctions, so we could not take the last day's data of I10D14L to compare them with C10D14L).

Using the research findings of Ruiz-Espinoza et al. (2008) and Evans & Poorter (2001), we calculated the concentration of Chl *a*, Chl *b*, Chl *tot*, and *a* (the fraction of PAR absorbed by the leaf of the plants) with the following equation:

$$\text{Chl a} = -0.0046+0.0008*(\text{SPAD}) \quad [21]$$

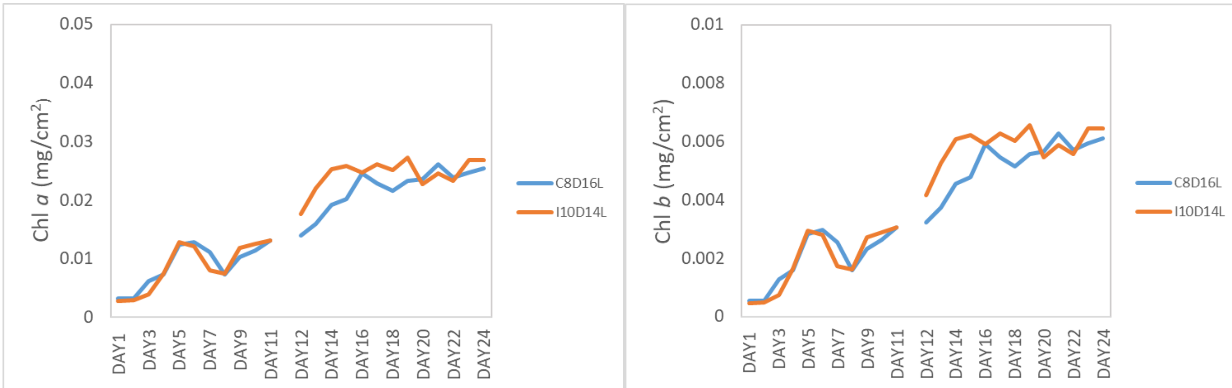
$$\text{Chl b} = -0.0014+0.0002*(\text{SPAD}) \quad [22]$$

$$\text{Chl } tot = -0.006+0.001*(\text{SPAD}) \quad [23]$$

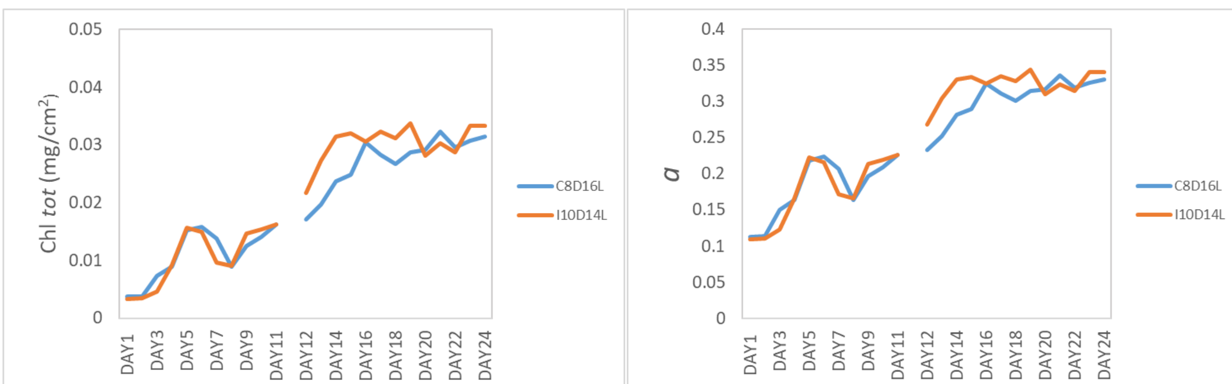
$$a = \text{Chl } tot/(\text{Chl } tot + 76) \quad [20]$$

where, SPAD is the measurement of the relative chlorophyll content retrieved from portable chlorophyll meter (CM- 500).

We compared the daily mean values of the two treatments. An independent samples *t*-test was performed to compare the effects of the IL on the plants' chlorophyll pigments in the two treatments.



(a) (b)



(c) (d)

Figure 29. Average daily evolution of [a] Chl *a* (mg/cm^2), [b] Chl *b* (mg/cm^2), [c] Chl *tot* (mg/cm^2), and [d] the fraction of PAR absorbed by the leaf (*α*) for healthy plants (blue line) and stressed plants (orange line). Days 1–10: a) C8D16L (control/continuous light); b) I10D14L (control/continuous light). Days 11–24: a) C8D16L (control/continuous light); b) I10D14L (stress/intermittent light) ($p<0.01$).

Chl *a* is the most important chlorophyll pigments (in combination with Chl *b*, as they differ minimally in their structure) [Stearns & Olson, 1958]. A crucial property of Chl *a* is the versatility, enabling active participation in several functions of the photosynthetic process, including photon capturing, transfer and storage of photons, and energy storage at the antennas (Oxborough, 2004). Chl *a* absorbs radiation in the red and blue nanometres of the light spectrum (Fiedor, Kania, Myśliwa-Kurdziel, Orzel, & Stochel, 2008). Apart from Chl *a*, plants use other pigments (Chl *b*, c, carotenoids, and phycobilins), which absorb radiation with intermediate wavelengths. This process makes better use of solar energy (Avgoustaki, 2019) (Fig. 29).

In order to examine the differences in the Chl *a* (mg/cm^2) between the plants in the control and stress groups, an independent-samples *t*-test was conducted for each one of the dependent variables. To start with Chl *a*, Levene's test for homogeneity of variances was satisfied with F (24) = 1.838, p = 0.188. The results of the *t*-test indicated that there was no significant difference in Chl *a* between the two treatments, t (24) = −2.016, p = 0.055. These results suggest that the plants in the C8D16L treatment with Chl *a* = (0.022 $\pm$ 0.004) had a similar Chl *a* content compared to the plants in the I10D14L treatment with Chl *a* = (0.025 $\pm$ 0.003) with N = 13 in both samples.

Subsequently, the Chl *b* (mg/cm^2) for the two treatments was analysed and compared. The independent samples *t*-test indicated that the C8D16L treatment with Chl *b* = (0.005 $\pm$ 0.001) showed smaller mean values in comparison with the I10D14L treatment with Chl *b* = (0.006 $\pm$ 0.0007) with N = 13 in both samples, t (24) = −2.016, p = 0.055 (two-tailed) with no significant statistical difference.

The Chl *tot* (mg/cm^2) measurements of the C8D16L treatment with Chl *tot* = (0.027 $\pm$ 0.005) and the I10D14L treatment with Chl *tot* = (0.03 $\pm$ 0.003) with N = 13 in both samples, did not show a statistically significant effect of the IL at t (24) = −2.016, p = 0.055.

An independent samples *t*-test was performed to find *a* (the fraction of PAR absorbed by the leaf) of the healthy plants and the stressed plants exposed to intermittent light. The results from the independent samples *t*-test indicated that the C8D16L treatment with a = (0.3 $\pm$ 0.03) showed similar mean values compared to the I10D14L treatment with a = (0.32 $\pm$ 0.02) with N = 13 in both samples, with no significant different results t (24) = −1.972, p = 0.060 (two-tailed).

3.2.3.4. Quality and Physiological Evaluation of Basil Grown under Different Lighting Conditions

The length of the continuous light was ten days in both treatments. After a restitution day, we modified the light treatment in the I10D14L group with IL for the next 13 days. The C8D16L group continued to grow under continuous light, allowing us to examine the difference in the performance of the two treatments. The control treatment with the continuous 16 h of light was shorter when we started the first measurements after the germination period had elapsed (i.e., after the third week), and the plants had a sufficient leaf size area for measurement (Table 20). After ten days, the plants had received enough light for their optimal growth, and we were able to start the stress treatment and examine the response of the plants to the limited photoperiod and IL (Table 18b).

The yield as the head biomass production for each of the plants was measured. To measure the leaf area of plants we used the sensor Li-3100 Area Meter (cm^2) from Li-CoR INC, Lincoln, Nebraska borrowed by the Food Department of Aarhus University (AU Foulum). The leaf area (LA-cm^2) measured after the C8D16L treatment was not significantly different with a value of 85.6 cm^2 compared to the stress treatment with 87.5 cm^2.

Table 20. Results of statistical analysis of the mean values of quantity assessment first 10 days in C8D16L and I10D14L were both followed continuous lighting of 16 hours. The columns present Sample size (N), Mean values (Mean), Standard Deviation (SD), t (t-test), Degrees of Freedom (df), level of significance (p-value).

	Treatment	N	Mean	SD	t	df	p-value
Number of Leaves	C8D16L	8	19.3	1.7	-0.138	14	0.892
	I10D14L	8	19.5	1.8			
LA (cm^2)	C8D16L	8	85.6	27	-0.146	14	0.886
	I10D14L	8	87.5	24			
Height (cm)	C8D16L	8	12.3	2.6	-0.431	14	0.673
	I10D14L	8	12.8	1.9			
Fresh Mass (g)	C8D16L	8	3.3	1	-0.428	14	0.675
	I10D14L	8	3.5	1.2			
Dry Mass (g)	C8D16L	8	0.34	0.2	-0.199	14	0.845
	I10D14L	8	0.36	0.2			
Fresh Biomass (g)	C8D16L	8	1.38	0.4	-0.428	14	0.675
	I10D14L	8	1.48	0.5			
Dry Biomass (g)	C8D16L	8	0.14	0.06	-0.199	14	0.845
	I10D14L	8	0.15	0.07			

Table 21. Results of statistical analysis of the mean values of quantity assessment of the 14 stress days between C8D16L and I10D14L.The columns present Sample size (N), Mean values (Mean), Standard Deviation (SD), t (t-test), Degrees of Freedom (df), level of significance (p-value).

	Treatment	N	Mean	SD	t	df	p-value
Number of Leaves	C8D16L	8	40.4	11	-1.513	14	.152
	I10D14L	8	48.9	11			
LA (cm^2)	C8D16L	8	286	66	0.122	14	.912
	I10D14L	8	282	57			
Height (cm)	C8D16L	8	17.6	2.4	-0.383	14	0.708
	I10D14L	8	18	2.1			
Fresh Mass (g)	C8D16L	8	12.5	2	0.412	14	0.686
	I10D14L	8	12	2.8			
Dry Mass (g)	C8D16L	8	1.17	0.2	-1.696	14	0.112
	I10D14L	8	1.38	0.2			
Fresh Biomass ($g*m^{-2}$)	C8D16L	8	5.24	0.8	0.413	14	0.686
	I10D14L	8	5.03	1.1			
Dry Biomass ($g*m^{-2}$)	C8D16L	8	0.49	0.1	-1.696	14	0.112
	I10D14L	8	0.57	0.1			

From Table 21, it can be seen that some of the measurements of plant quality and physiology did not show a statistically significant difference between the two treatments.

3.2.3.5. Plant Biomass Measurement and Estimation of the Input Energy Consumed for Basil Production

The total biomass of the plants was estimated by the equations:

Dry biomass = dry mass (g) / cultivation area (m^2) [24]

Fresh biomass = fresh mass (g) / cultivation area (m^2) [25]

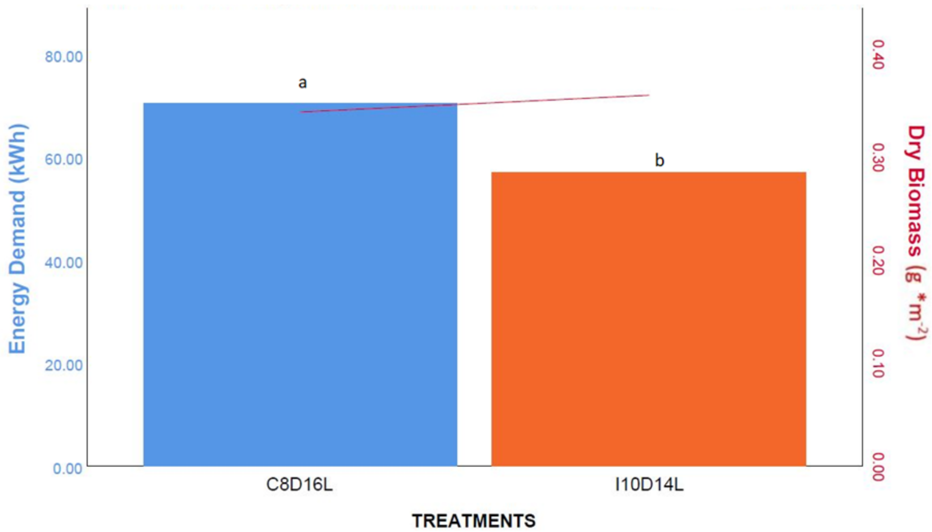


Figure 30. The left axis (histograms): The average input of electrical energy consumed to produce basil plants (kWh). The right axis (line): The average shoot dry biomass produced in each lighting treatment during the 14 stress days (g*m−2). The letters ('a' and 'b') indicate significant differences in energy consumption between the two treatments ($p < 0.05$).

Figure 30 shows the electrical energy necessary for the total crop production in each treatment. The conditions applied in the I10D14L treatment produced the highest biomass production with a reduced electrical energy input compared to the C8D16L treatment. As presented in Table 21, the independent-samples t-test indicated that there was no statistical significant difference in the mean dry biomass ($g*m^{-2}$) for the two treatments. Finally, we could observe a statistically significant difference in the energy demand of both treatments, caused by the reduced photoperiod.

3.2.4. Discussion

One of the aims of this research was to investigate the sustainability and applicability of indoor cultivation systems to create a more affordable and ecological production for plants, mainly to address the urban demand for fresh food. In an indoor urban farm, the majority of the energy is consumed for lighting the premises, making it the most costly process of running an indoor farm. Therefore, by reducing the amount of light/photoperiod (Avgoustaki, 2019) without reducing the growth rate of the plants, the purpose was to decrease the operational costs of indoor urban farming.

The main purpose of this study was to optimise the light conditions for growing basil indoors by alternating the light from a continuous to an intermittent flow and identifying the plants' response to the light treatments. More specifically, our goal was to examine the difference in photosynthesis between the two treatments as well as if and for how long we could shift the demand response to more cost-effective energy without affecting the yield and the quality of the crop.

Abiotic factors like light, CO_2, water, and nutrients as well as physiological factors such as stomatal conductance and transpiration can strongly influence the photosynthetic activity of plants and their optimal growth. In this study, we followed the growth, pigment concentrations, gas exchanges, and photochemical efficiency in basil plants to detect their response to intermittent light.

3.2.4.1. The Effect of Different Light Treatments on Basil Quality, Leaf Functions and Physiological Parameters

Throughout all the phases of the experiment, the leaf temperature (T_{leaf}) was sufficiently lower than the air temperature in the chamber. According to Gimnez and Thompson (2005), this difference indicates a healthy water status of the canopy sourcing from the cooling effect caused by the evaporation of the plants. Furthermore, leaf temperature is closely related to incidental radiation and vice versa (Jones, 1985). Based on Figure 28, the difference between the two treatments can be explained by the reduced thermal radiation reaching the leaf surface under the intermittent light.

In addition, the substrate temperature (T_{sub}) or the root zone temperature, plays an important role in the water and nutrients uptake of the plants. This is because T_{sub} can alter the responses of the plant shoots by affecting the temperature of a shoot apical meristem (McMaster and Wilhelm, 2003) and continuously regulate the hormonal balance in water and nutrient uptake (Bhattacharya, 2019).

Stomatal conductance (g_s) allows the stomata to absorb CO_2 and can be used for evaluating the plant water status. In other words, the role of stomata is to control the leaf transpiration and maintain the leaf water status by opening and closing the stomata (Moriana et al., 2002). According to Kirschbaum and Pearcy (1987), stomatal conductance is an important factor in the photosynthetic induction response of a leaf. In systems with no limitation and controlled CO_2, the photosynthetic induction has a duration of a few minutes, whereas plants with unstable, lower concentrations of CO_2 require at least half an hour to complete the induction process, which is closely correlated with stomatal conductance. Stomatal conductance is highly affected by VPD and tends to decrease when there is an increase in CO_2 in the cultivation area (Field C. B., 1995). However, the graph of stomatal conductance (Fig. 29 [d]) shows that the transpiration rate of the leaves was stable and with a significant increase in the water level and absorbed CO_2 of the basil leaves (Gimnez & Thompson, 2005). Furthermore, the significant increase under the IL indicates that the plants can successfully absorb CO_2 and traverse it via the epidermal cell layer, at the photosynthetically active leaf mesophyll cells.

Light is probably the most crucial factor that can affect the growth and development of green species as well as the production and the biomass levels. A plant's response to light can provoke physiological alterations that can affect the CO_2 assimilation and optimisation of gas exchanges in the plant. Furthermore, light plays an important role in the quantitative and qualitative process of plants (Gonçalves et al., 2008). For this reason, it is important to examine the enhancement of photosynthesis under continuous light compared to photosynthesis under intermittent (fluctuating) light. Grobbelaar et al. (1996) stated that longer and continuous dark periods do not necessarily lead to higher photosynthetic rates and efficiency. According to Iluz et al. (2012), plants absorb all the necessary light during the light period (gross photosynthesis) and use it continuously in the dark period. More specifically, an increase in light intensity can reduce growth and photoinhibition (significant loss of photosynthetic production) due to the production of damaging reactive oxygen intermediates. Fig. 27 [b] and [c] show the differences in photosynthetic rate measurements of the plants under intermittent light. As can be observed from the graphs, there was a significant difference in the measurement of As for the 10-min light period compared with the measurement of the 4-h light period, which did not show significant differences compared with the continuous light. This can be explained by the fact that cells are not able to generate enough energy through the photosynthesis process in just 10 min to meet their metabolic requirements. However, during the 4-h period, the cells managed to process enough energy via photosynthesis, which shows that plants can increase As without affecting the yield production. Further research is needed to uncover the dark periods.

Photoacclimation is the process by which plants modulate the function and the structure of the photosynthetic device at growth irradiance. According to Adams et al. (1999), during short-term photoacclimation (seconds to minutes), a heat dissipation of the excess excitation energy through carotenoids is observed, which can influence the distribution of absorbed light energy between PSI and PSII. Further research is needed to analyse the carotenoid level under IL in detail.

Another important point that can explain our results is the RuBisCO model, which is a useful tool for clarifying the IL that can increase the photosynthetic efficiency. More specifically, from the experiment, we can deduce that the number of artificial photosynthesis generated in the photon reception process determine the discrete RuBP particles circulating in the Calvin cycle as well as their speeds in the cycle.

The measurements of various chlorophyll pigments from chloroplasts and their analyses were used as stress indicators of high irradiance in the plants (Ruiz-Espinoza et al. (2008). Based on previous literature (Tzina et al., 1987), the amount of the chlorophyll accumulation in the early growth stages of the plants depends on the total radiation received by the crop and is independent of the intervals during the dark period of the photoperiodic cycle. Furthermore, as previously mentioned in this study, the rate of photosynthesis for IL depends on the interpolation between the dark intervals. When exposed to shorter dark intervals, plants contain larger photosystems units, i.e., large protein complexes embedded in the thylakoid membrane for absorbing and converting solar energy. Fig. 29 depicts that the chlorophyll content followed an increasing rate throughout the experiment, indicating that the plants had a stable and increasing rate if they absorbed the given photoperiod. In the short dark periods of intermittent light, thylakoids with few and large-in-size photosystems were found, while the thylakoids found in the longer dark periods were more and smaller in size to maintain the same accumulation rate of chlorophyll.

3.2.4.2. Effect of Different Lighting System on Biomass Accretion and Energy Demand

Photoperiod and light distribution are vital in plant biomass production, leaf size, and leaf area (Adams & Langton, 2005). Initially, the treatment with the continuous light and the longer photoperiod was expected to result in higher biomass production of basil plants. However, in Fig. 31, we can observe an increase in the shoot dry biomass with the I10D14L treatment, without any statistical difference compared to the C8D16L treatment. At the same time, the energy demand in kWh was significantly lower [$t(23.624) = 25.961$, $p = < 0.001$] under the intermittent treatment. The dry shoot biomass in the I10D14L treatment averagely consumed less energy (13.94 kWh) than the C8D16L treatment. From an economic perspective, the electricity price in Denmark (where the experiment took place) is around 0.219 €/kWh in Denmark (Eurostat, 2020) giving an energy cost saving of 6 €/m^2/day with a 90-Watt LED. Further research on larger vertical farms with more LED installations and greater energy loss is needed.

Moreover, it was found that a shorter photoperiod and IL slightly reduced the fresh mass and the leaf area of the plants but without any statistical significance. This may be due to the lower radiation that the basil plants received during the I10D14L treatment, reducing the nitrate concentration and at the same time increasing the amount of chlorophyll and carotenoids contained in the plants (Avgoustaki, 2019). Beaman et al, (2009) observed that a fresh biomass production with a higher carotenoid concentration and lower the nitrate content results in high-nutrient products.

In this research study, we focused on measuring the energy input in a small-scale cultivation area consumed for different treatments. Our goal was to identify energy savings depending on light conditions as well as to reduce the energy production costs in indoor cultivation systems. Based on the data collection from this experiment, the yield of the treatment with IL was the same as that of a commercial product, but with a lower energy costs compared to the continuous light treatment.

3.2.5. Conclusions

Cultivation of basil in a small-scale growth chamber under intermittent lighting showed a positive effect on the growth, development, quality, and quantity of the plants compared with the control conditions of continuous lighting. The plants grown under IL with a reduced photoperiod had a positive effect on the final biomass production. In addition, the daily measurements used to monitor the rate of photosynthesis of the plants showed no negative results until day 19 of the experiment. The photosynthetic rate and the chlorophyll content of the plants continued to grow exponentially during the days of the experiment when the plants were exposed to shorter light intervals (4 h). Furthermore, the chlorophyll content and the chlorophyll pigments maintained a steadily increasing rate throughout the plants' entire growth process. The purpose of this experiment was to test the response of basil plants under IL as well as to examine their growth rate and quality using an energy-efficient production system for indoor farming. The results of the experiment suggest an electricity system in vertical farms based on energy prices across countries. The research shows that vertical farms can design their lighting system, adjusting the consumption based on low or high electricity prices. A potential taste assessment of plants under the different lighting systems would be an interesting addition to the process. Future research is needed to investigate the response of plants under various durations of IL and with various LED spectrum combinations.

Vertical farms are a great opportunity to design more sustainable systems using innovative technologies to meet the urban energy demand. However, since these systems still present new opportunities for additional energy optimisation, it is crucial to develop smarter, more efficient applications and techniques, enabling vertical farms to produce high-quality products while minimising costs.

3.2.6. References

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4. What is the impact of intermittent photoperiodic light application in the energy footprint and the growth of plants in an IVF in the Nordic context?

The third research question is answered by introducing the following two articles:

1. Avgoustaki, D. D., Bartzanas, T. & Xydis, G. Minimising the energy footprint of indoor food production while maintaining a high growth rate: Introducing disruptive cultivation protocols. Under submission with Journal of Cleaner Production.
2. Avgoustaki, D. D. & Xydis, G. Reduction of Energy Costs in Indoor Farms for Artificial Lighting by Shifted Energy Demand Response. Under review with Biosystems Engineering.

The papers that are presented in this chapter look into the implementation of intermittent lighting in Nordic Counties and more specifically in the case of Denmark that is characterised by dynamic electricity prices due to the participation in the Nordpool Energy Exchange System. The first paper examines the influence load-shifted IL operation to basil plants, whereas the second presents the energy savings that result from the light optimisation model development. Continuously, this research examines the importance of the potential cost savings from lighting optimisation and how they can increase the revenues of IVFs and also how they can influence the IRR, the NPV and the payback period of vertical farming investment projects.

4.1. Minimising the energy footprint of indoor food production while maintaining a high growth rate: Introducing disruptive cultivation protocols.

The fifth paper of this dissertation presents the examination of a light methodology that uses dynamic light provision linked to the electricity market price fluctuations in order to provide an optimised lighting schedule for indoor crop cultivation. More specific, in this paper compares and examines the performance of basil crops grown in indoor control environmental areas under three treatments of light: continuous photoperiod, normalised intermittent photoperiod and shifted demand response intermittent photoperiod. The cost of electricity can be very high due to the many hours of artificial light operation, which can be an inhibiting factor for the enhancement of vertical farming projects around the world as it reduces their profit margin. This paper researches a light methodology in which the time intervals of intermittent lighting are provided to plants based on the actual electricity prices of the Danish energy market. For this reason, leaf physiological traits from the three different photoperiod treatments are assessed and used to estimate the toleration rate of basil plants under the different light schedules. The purpose was to evaluate and design a flexible IL exposure with reduced photoperiod in order to further decrease the light energy demand for crops that grow in indoor environments while maintaining a high growth rate and biomass production of the plants. The presented results of this experimental research show a positive correlation of the plants' responses to abiotic stress when exposed to short ten-minute periods of IL (with different repetition and sequence rates in the two intermittent treatments), without having significant effects on the physiological responses of the crop. The physiological, biochemical, and morphological status of the plants were assessed in terms of photosynthetic rate, chlorophyll pigments, stomatal conductance, and transpiration rate of the plants. The protocol with IL exposure induced a significant increase in biomass production as well as significant decrease in electricity consumption compared to the continuous photoperiod, resulting in a more economical, sustainable, business, and ecological impact on the energy footprint of indoor food production.

4.1.1. Introduction

Vertical farming is a revolutionary and more sustainable farming technique that allows plant growth in indoor, fully isolated, and automated environments under continuous monitoring conditions. Here crops grow under carefully selected conditions that support optimal growth and a year-round production (Despommier, 2010). The indoor environment and the application of soilless cultivation techniques lower water requirements by up to 95%, maximise land use efficiency, and increase crop yields (76-116%) (Barbosa et al., 2015; Snir et al., 2015).

Light is one of the most crucial environmental factors that highly affects plant growth and development. In addition to having a major impact on the quantity and quality of crop growth and development, the selection and operation of light sources can significantly determine the capital and operational cost of an indoor farm. Based on previous research (Avgoustaki & Xydis 2020b), lighting can account for 80% of the total electricity cost of an indoor vertical farm. Light is electromagnetic energy that includes wavelengths from 100 (ultraviolet) to 2,500+ (infrared). Visible light (380-780 nm) is essential to plants, as it roughly corresponds to photosynthetically active radiation (PAR, 400-700 nm). In solar radiation, 43% consists of visible light that can be used by plants for growth; 43% is infrared light that produces heat (4% is ultraviolet). Light, unlike other factors such as temperature, humidity, and CO_2 concentration, varies under three fundamental and different dimensions: quality (wavelength combination of the light source), quantity (radiation intensity, i.e., the number of photons that reach the growing area), and duration (photoperiod, i.e., the daily hours of light).

Photoperiodism, i.e., the duration of light hours per day that plants receive, has a marked effect on growth rate, productivity, and quality of the canopy at the different growth stages of the plants (Touliatos et al., 2016). Many researchers (Kang et al., 2013; Kozai et al., 2018) have previously stated that the optimal selection of light intensity and photoperiod has a major impact on crop yield. Briggs and Onley (2001) referred to the high correlation between a plant's ability to maximise photosynthetic productivity and its capability to sense, evaluate, and respond to the composition of light. It has also been pointed out how the appearance and development of various growth phenomena in a plant's life cycle, such as entering the inertia phase, highly depends on a plant's ability to adapt to changes in day length. The term 'inertia' was analysed by Von Holle et al. (2003). It describes the persistence of plant organisms to resist to insufficient environmental factors long after the effect of their operational cause.

Photosynthesis is the photochemical process of plants by which they absorb light energy, and by absorbing the atmospheric carbon dioxide, they release oxygen and sugars (carbohydrates). Photosynthesis is the vital process that enables plants to grow and develop, and for this reason, optimising the various elements of the process can help us understand, analyse, and develop suitable models for plant growth. The photochemical processes of plants play an important role in triggering the chemical reaction initiated by light absorbed as energy. A previous study conducted by Matthijs et al., 1996 found that longer dark periods of light tend to reduce the growth rate of plants. The same study also noted that the light flux under continuous and IL is one of the most important factors influencing plant growth. IL is a technique in which light is emitted in short cycle periods instead of continuous light intervals. In other words, IL allows us to examine and evaluate the non-photochemical reactions of plants associated with reduced photochemical reactions (Avgoustaki et al., 2020a). With the correctly framed intermittent use, a control energy system per growth cycle can be designed that can help saturate the photochemical process.

To examine whether an intermittent lighting system can reduce or increase the photochemical reactions of plants, we examine the photosynthetic rate and other physiological parameters used as growth indicators of basil plants. Photosynthesis is defined by two sequences of reactions: a light and a dark reaction. More specifically, during the light reaction of photosynthesis, a chain redox reaction of photosystem I (PSI) and photosystem II (PSII) enables light energy collection and production of useful chemical energy, the latter of which is used for the CO_2 assimilation reaction cycle. According to Kanechi, (2018, chapter 3), this photochemical reaction is highly dependent on the light reaction as well as the amount of chemical energy absorbed by plants. Chlorophylls (photosynthetic pigments) are the most important and effective light energy absorbers that initiate the process of photosynthesis, while the atmospheric air contains the necessary carbon dioxide and the oxygen (respiration and transpiration, respectively) that enter the leaves through the small pores on the leaves, i.e., stomatal. In the majority of all the photosynthetic organisms, the highest percentage consists of chlorophyll *a* (Chl *a*), followed by chlorophyll *b* (Chl *b*), and carotenoids (β-carotene), all of which are located in the plant leaves. The use of photosynthesis and chlorophyll (as well as leaf temperature, transpiration, and stomatal conductance) is commonly monitored and examined as growth indicators for the physiological and phenological developmental stages of plants (Cavender-Bares & Bazzaz, 2004). For this reason, in agricultural research, the study of plant growth and development rate as well as plant behaviour can provide useful information for growing plants under controlled and stressed cultivation conditions.

Previous studies (Avgoustaki 2019; Avgoustaki et al., 2020a) have shown that basil plants grown in indoor environments can highly perform and yield when exposed to a reduced photoperiod of 14 hours with intermittent light. To be more specific, the results showed no significant differences in growth rate and development between the plants grown under a continuous treatment with 16 hours of light and the plants grown under an intermittent 14-hour light treatment with four hours of continuous light followed by four hours of darkness with ten minutes of light per hour. However, even with a positive correlation between the light treatments and the development of the plants, there is a need for utilities to provide hours of low electricity prices during daytime hours, which would help the growers organise the operation of their lighting equipment in standard time intervals. This is why we decided to study the response of plants under an intermittent lighting system in which light was emitted when both energy demand and electricity prices were low (fluctuating electricity prices, which are applied in Denmark, Iceland, Germany, among others). In doing so, we have measured the chlorophyll pigments, the photosynthetic and transpiration rate, stomatal conductance, growth and environmental indices, and the light levels of the basil plants from germination to harvest. Finally, this research aims to propose a lighting system that can be applied in countries with fluctuating electricity prices, establishing demand response facilities, which shift to off-peak hours, thus reducing the total operational energy cost of a vertical farm without affecting plant growth rate.

4.1.2. Material and Methods

4.1.2.1. Plant Material and Growth Conditions

The experiments were conducted in three identical indoor chambers (Chamber A, Chamber B, and Chamber C) with controlled conditions of temperature and relative humidity. The chambers were located in the laboratory of agricultural constructions “Kyritsis” at the Department of Natural Resources Management and Agricultural Engineering, Agricultural University of Athens, Greece. The external dimensions of the climate chambers were the following: height = 200 cm, width = 82 cm, and length = 72 cm, while the internal dimensions of the chambers were the following: height = 140 cm, width = 60 cm, and length = 60 cm. The growing area in each chamber was 30 cm * 20 cm. The air temperature (T_{air}) and the relative humidity (RH%) were controlled and set at 25°C and 55%, respectively. The climate growth conditions in the chambers, including T_{air}, RH%, and CO_2 concentration, were automatically monitored using a climate control sensor (TROTEC BZ30, UK); one in each chamber throughout the experimental period. The light given in the systems came from the LED (AstroPlant LED panel, Holland) with a 43-watt energy consumption. In the LED specifications, the composition and peak wavelengths were the following: 8 SPC of red peaking at 650 nm, 4 SPC of blue peaking at 450 nm, and 4 SPC of near infrared (NIR) peaking at 730 nm (Figure 31). One LED lamp was installed in each chamber, remaining under stable intensity throughout the whole experiment (Figure 33b).

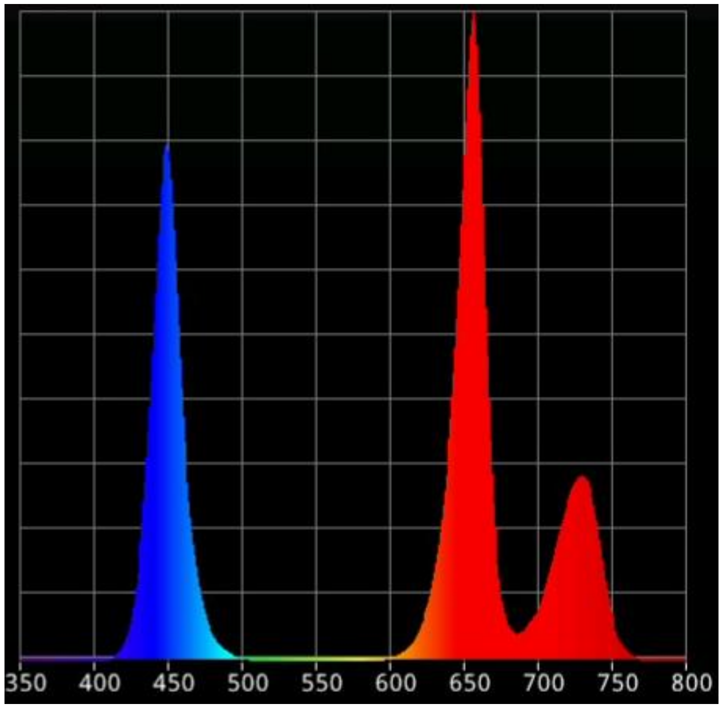


Figure 31. Relative spectral emission of the LED lamp (AstroPlant LED panel, Holland) used in the experiment and measured with the spectrometer uSpectrum.

Long-leaf basil plants (*Ocimum basilicum*) were selected for this study, as they are one of the most frequently selected plant species cultivated in vertical farming due to their high nutritional value, high cultivation density, high yield rate, and its high purchase value. More specifically, the selected basil variety was platyphyllum.

In each chamber, seedling plants (two weeks from sowing) filled with perlite (ISOCON PerloflorHydro 1) were grown. Two rows of plants were sown, each row with four pots and four plants in each pot. In total, each chamber held 32 basil plants. The mean volumetric water content of perlite at field capacity was 53-55%. The measurements started one week (seven days) after transplanting, when the plants were approximately 6 cm tall with two pairs of leaves each. The plants were grown in an ebb-and-flow hydroponic installation, and every other day, water enriched with nutrients was added directly into the root zone of the plants. The nutrient solution supplied to the plants comprised the following components: 12-6-4 (N-P-K). The solution was diluted in water with 9 mL of nutrient solution into 1 L of H_2O.

Basil belongs to the category of long-day plants, i.e., to grow optimally, they need more than 12 hours of light and less than 12 hours of darkness. Previous literature (Beaman et al., 2009) has noted that the optimal photoperiod for basil is 16 hours of light. However, in vertical farms, which only use artificial light sources, this increases the operational costs, leading to a higher risk and, often, unprofitable cases. In a study conducted by Avgoustaki et al. (2020a), the effects of IL on basil crop both in quality and quantity level were presented. The study, which evaluated the characteristics of basil plants under 16 hours of continuous light and 14 hours of intermittent light, respectively, showed significant differences of the photosynthetic rate after 19 days of IL application, while the rest of the physiological indices (chlorophyll, stomatal conductance) showed no significant differences. The IL pattern used in the previous research was normalised under ideal conditions with alternating light-dark periods; more specifically, three cycles per day consisting of four hours of continuous light followed by four hours of IL with ten-minute light cycles per hour (I14L10D). The purpose of the present research was to reduce the energy footprint of indoor cultivation with LEDs by shifting the energy demand response and instead using a dynamic light provision linked to the fluctuating electricity prices in the Nord Pool market. Based on this, we proceeded to analyse the daily fluctuations in electricity prices in Denmark and concluded that the most expensive hours of electricity usage are between 7 a.m. and 10 p.m., including a drop in electricity prices between approximately 1 p.m. and 5 p.m. (Energinet, 2016; Karabiber and Xydis, 2019). With this in mind, we designed an additional IL treatment that mimicked the actual fluctuations in electricity prices (I14L10Dshifted). Figure 32 below illustrates the light treatment used in each chamber.

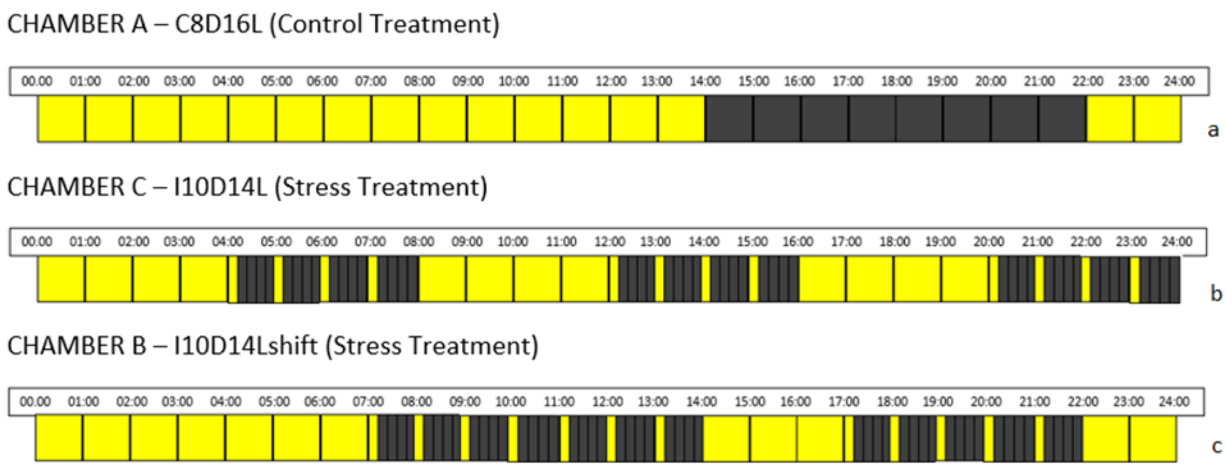


Figure 32. Graphical representation of the light schedules in each camber. [a] Control treatment (C8D16L) with 16 hours of continuous light and eight hours of continuous darkness. [b] Stress treatment (I10D14L) with four hours of continuous light followed by four hours of darkness with ten minutes of light per hour of darkness. [c] Stress treatment (I10D14Lshift) with fluctuating electricity prices: Nine hours of continuous light (10 p.m.-7 a.m.), seven hours of darkness with ten minutes of light per hour of darkness (7 a.m.-2 p.m.), three hours of continuous light (2 p.m.-5 p.m.), and five hours of darkness with ten minutes of light per hour of darkness.

To study the effects of IL on crop quality and quantity, an experiment with three different treatments (one treatment in each climate chamber) was performed. The experiment was conducted from June to July 2020. As seen in Figure 32, the light conditions in Chamber A with 16 hours of continuous light remained stable throughout the whole experiment. This C8D16L treatment was a control treatment that was used to compare the other two treatments. In Chamber C, the basil plants were grown under 14 hours of IL until the end of the experiment and the final harvest of the plants. The treatment in Chamber C was a stress treatment and is referred to as I10D14L. More specifically, and as visualised in Figure 1, the plants in the I10D14L treatment were grown under an equally distributed IL schedule, receiving radiation every ten minutes per hour over a four-hour period of darkness and followed by four hours of continuous light.

The plants in this treatment received a total of ten hours of darkness and 14 hours of light each day (Withrow R. B. and Withrow A. P., 1944). The third treatment, I10D14Lshift (abbreviated 'I10D14Ls'), was also a stress treatment. In this treatment, which took place in Chamber B, the plants followed an IL treatment that mimicked the actual fluctuations in electricity prices. For this reason, the plants received light for ten minutes per hour of darkness, when the electricity prices were high and four hours of light when the electricity prices were low (Figure 32).

The plants in all three chambers were planted at the seedling stage within two weeks after sowing and received 16 hours of continuous photoperiod for these two weeks. When the experiment started, the light schedules was transformed to the above treatments (Figure 32). The experiment lasted for 37 days in all three chambers, after which the plants were harvested and measured for quality characteristics (Figure 33a).

(a) (b)

Figure 33. (a) Small-scale growth chamber for indoor production of basil crop under controlled and monitored environmental conditions and (b) LED lamp overview

When the LED was turned on, the amount of light reaching the plant canopy expressed in Photosynthetic Photon Flux Density (PPFD) was maintained at 200 μmol/m^2/s for the C8D16L and at 228 μmol/m^2/s for the I10D14L and I10D14Ls in order to maintain a stable daily light integral at DLI 11.5 moles/m^2/day. It was measured daily with the spectrometer uSpectrum (UPRteck/LI-COR) due to the constant development of leaves.

The total water consumption during the 37 days varied among the different treatments. In the C8D16L treatment, the water consumption was 9 L and 18 g of nutrient solution. In the I10D14L treatment, the water consumption was 6.82 L and 13.64 g of nutrient solution, while in the I10D14Ls treatment, the water consumption was 6.67 L with 13.34 g of nutrient solution (Table 22). Most of the water was absorbed during the experiment due to the plants' need for water to grow, but also due to evapotranspiration.

Table 22. Climate conditions in the three climate chambers (Chamber A: C8D16L; Chamber B: I10D14Ls; Chamber C: I10D14L).

Treatment	Length (days)	Relative Humidity (RH%)	Vapour Pressure Deficit (VPD) (Pa)	T_{air} (°C)	CO_2 (ppm)	Energy demand (kWh)
C8D16L	37	64.6 ± 4.3	1118.9 ± 145.3	25 ± 0.4	589 ± 39.4	545 ± 20.7
I10D14L	37	58.5 ± 4.4	1187 ± 157.1	24.5 ± 0.7	614 ± 43.8	458.4 ± 41.7
I10D14Ls	37	61.6 ± 3.9	1200 ± 141.9	24.8 ± 0.4	614 ± 66.1	457.3 ± 46.6

4.1.2.2. Data Collection

In order to calibrate the air temperature (T_{air} in °C), the relative humidity (RH%), and the CO_2 concentration in the three chambers, a climate sensor (TROTEC BZ25 CO_2 air quality monitor, Germany) was placed in each chamber 50 cm above the crop area in the middle of the chamber, which automatically logged data every ten minutes. We used the logged average values of T_{air} and RH% to calculate the air vapour pressure deficit (VPD) values as shown in Table 22. To measure the leaf temperature of the basil plants (T_{leaf} in °C), we used thermocouples (chromel-constantan, type E) in each chamber attached to the surface area of young, fully developed leaves. The measurements were performed at ten-minute intervals, and the data logger recorded the average values of the intervals. To measure the temperature of the hydroponic substrate and the electric conductivity (EC), we used the WET-2 Sensor from Delta-T devices (UK) with the sensor error ± 10 $mS{*}m^{-1}$. The data logger connected to the above sensors and the three chambers simultaneously was the Campbell PC200W software – AM16/32 (Campbell Scientific, Inc., USA).

Measurements of photosynthesis and chlorophyll were made manually every day from 9 a.m. to 9 p.m. every two hours. The samples used as the most representative index of plant growth were young and fully developed leaves from each plant in all three chambers. To measure the chlorophyll content of the plants, a portable chlorophyll sensor (CCM – 200plus, OPTI-Sciences, Inc., USA) was used to provide chlorophyll data based on the absorbance of the plants at the 653 nm and 931 nm (accuracy ± 0.1 CCI unit). The sensor used to collect photosynthesis data, stomatal conductance data, and transpiration data was the LCpro-SD gas exchange sensor for portable photosynthesis measurements (ADC Bioscientific Ltd., UK) (sensor error 0.1°C). The sensor was calibrated before the experiment. Using a portable sensor (Crop Circle, Holland Scientific, USA), manual measurements were also made for data collection of the normalised difference vegetation index (NDVI) of the canopy in the three chambers.

4.1.2.3. Plant Biomass Measurements and Evaluation of the Electrical Energy Used for Basil Production

The weights of fresh matter and dry matter of the shoots and roots were determined after counting the number of leaves and measuring the surface area with the Li-3100 Area Meter (Li-COR Inc., USA), which we borrowed from the Laboratory of Vegetable Production at the Agricultural University of Athens (AUA). To collect the dry matter data of the roots and shoots, the different parts of the plants were placed in a dry oven at 80°C evaporating water until constant weight. We used four plants from each chamber as samples for the post-harvest measurements.

The leaf area (LA) in cm^2 was measured using a sensor, and finally, in order to measure the input of the electrical energy in each chamber, we used the PEL103 power-energy logger (Chauvin Arnoux, UK). The electrical energy consumed for the basil production was measured for each treatment taking into consideration the total leaf biomass produced by eight plants in each chamber, the photoperiod (hours of light) for each treatment as well as the energy consumed in each chamber. The results are presented in $kWh\ kg^{-1}$.

4.1.2.4. Statistical Analysis

Data were subjected to a one-way analysis of variance (ANOVA) followed by Bonferroni's multiple comparison test, and Tukey's post-hoc analysis test. The analyses were performed using SPSS for Windows (IBM Statistics for Macintosh, version 25.0).

4.1.2.5. Hypothesis 1.

There is no significant difference in the growth rate of basil plants grown under different light treatments of continuous and intermittent photoperiods.

4.1.2.6. Hypothesis 2

There is no significant difference in the growth rate of basil plants grown under a normal distributed IL schedule and basil plants grown under IL with a load-shifted energy demand response (LSEDR).

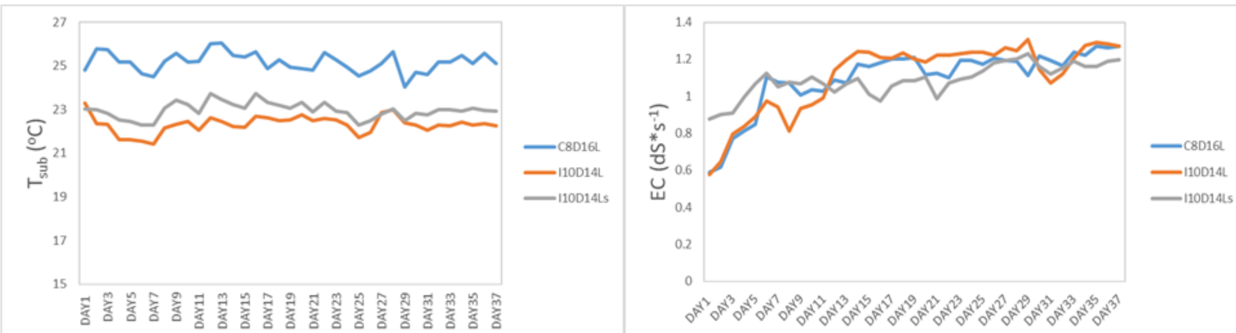
4.1.3. Results

This section presents the data collection results for various physiological parameters of the basil crops during the experiment. For the statistical analysis, we performed a one-way ANOVA on each of the three independent variables (C8D16L, I10D14L, and I10D14Ls). The sample size of our statistical analysis was the 37 days of the experiment. The data were tested for homogeneity of variances using Levene's test. The one-way ANOVA tests were followed by post-hoc tests in order to identify the current statistical significant differences between the groups (only for those variables that showed statistical significant difference in the ANOVA table). The one-way ANOVA table can accept or reject the null hypothesis of the three independent variables under each dependent variable. In the text, it is described by the following format F (df1, df2) = F-test, p-value = sig, where F expresses the distribution of data at N (sample size) with (degrees of freedom) df1 = k-1, df2 = N-k at a significant level of 0.05. Additionally, I10D14Ls (M = 23, SD = 0.4) was also significantly different from C8D16L.

4.1.3.1. Water Status of Basil Crops under Different Photoperiod Treatments

The substrate temperature (T_{sub} in °C) of the basil grown under each of the three light treatments (C8D16L, I10D14L, and I10D14Ls) was compared to identify statistical significant differences between the means of the groups. The one-way ANOVA analysis showed that C8D16L presents a statistically significant difference of the control treatment compared to the two stress treatments I10D14L and I10D14Ls at the $p < 0.05$ level with $F (2, 108) = 512.9$; $p = 0.00$. The post-hoc analysis revealed a significant difference between C8D16L (M = 25.2, SD = 0.4) and the two stress treatments I10D14L (M = 22.3, SD = 0.4) and I10D14Ls (M=23, SD= 0.4).

A one-way ANOVA performed to compare the electric conductivity (EC in $dS*s^{-1}$) of the substrate environment in the three chambers showed no statistically significant results between C8D16L (M = 1.1, SD = 0.16), I10D14L (M = 1.11, SD = 0.19), and I10D14Ls (M = 1.09, SD = 0.09) at the $p < 0.05$ level with $F (2, 108) = 0.180$, $p = 0.836$. Figure 34 shows the daily evolution curve of T_{sub} and EC with the three light treatments.



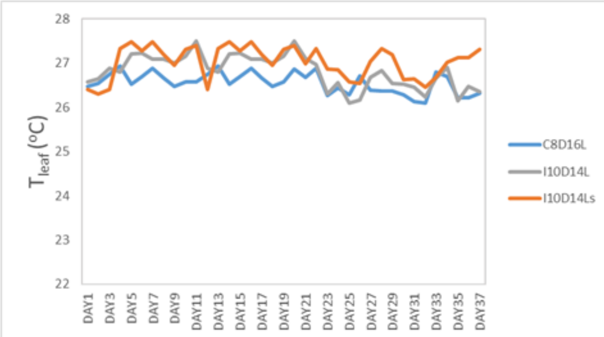
(a) (b)

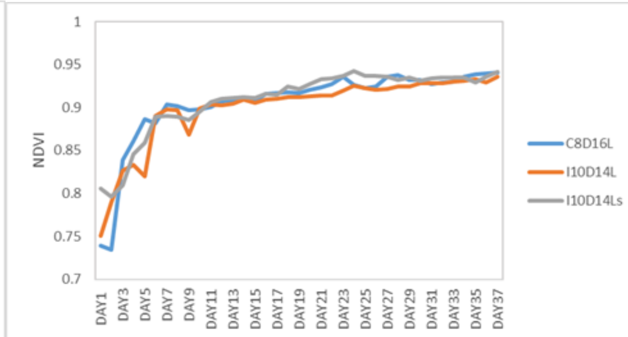
Figure 34. Average daily evolution of [a] substrate temperature (Tsub in °C) and [b] electric conductivity (EC in $dS*s^{-1}$) for healthy plants, i.e., C8D16L (the blue line), and stressed plants, i.e., I10D14L (the orange line) and I10D14Ls (the grey line). Days 1-37: a) C8D16L (control/continuous light), b) I10D14L (stress/normal intermittent light), and c) I10D14Ls (stress/shifting intermittent light).

4.1.3.2. Development and Study of Physiological Parameters under Different Photoperiod Treatments

A one-way ANOVA was performed to compare the three light treatments to determine if there was a statistically significant difference between the daily means of the multiple growth indicators for basil crops grown in an indoor controlled environment.

One of the indices examined was the leaf temperature (Tl_{eaf} in °C). The average leaf temperature varied from 24.1°C to 25.5°C for the C8D16L treatment, from 24°C to 25.6°C for the I10D14L treatment, and from 24°C to 25.3°C for the I10D14Ls treatment. There was no significant effect in the change of leaf temperature at the $p < 0.05$ level for the three photoperiod treatments, $F (2, 108) = 512.9$, $p = .060$. Post-hoc comparisons using Tukey's honestly significant difference (HSD) test indicated that the mean value of the leaf temperature with the C8D16L treatment (M = 24.63, SD = 0.37) did not differ much from the I10D14L treatment (M = 24.44, SD = .39) or the I10D14Ls treatment (M = 24.47, SD = .36). In Figure 35, the curves of leaf temperature for the three treatments are shown.





(a) (b)

Figure 35. Average daily evolution of [a] leaf temperature (Tleaf in °C) and [b] NDVI for healthy plants, i.e., C8D16L (the blue line), and stressed plants, i.e., I10D14L (the orange line) and I10D14Ls (the grey line). Days 1-37: a) C8D16L (control/continuous light), b) I10D14L (stress/normal intermittent light), and c) I10D14Ls (stress/shifting intermittent light).

NDVI is an important indicator for quantifying the amount of green vegetation in an area. To be more specific, NDVI measures the difference between the near-infrared light (which the vegetation strongly reflects) and red light (which the vegetation strongly absorbs). It is one of the most common and accurate indicators for estimating plant biomass and water content in crops, and it is well correlated with the intercepted photosynthetically active radiation (PAR) (Cabrera-Bosquet, 2010).

$$NDVI = (R800 - R680) / (R800 + R680) \qquad [26]$$

where, R800 and R680 are the reflectance values at 800 nm and 680 nm, respectively.

From Figure 35b, we observe that there is a continuous and parallel increase in the NDVI in all three light treatments. More specifically, the one-way ANOVA showed no statistical significant differences between C8D16L (M = 0.906, SD = 0.05, N =37), I10D14L (M = 0.9, SD = 0.04, N = 37), and I10D14Ls (M = 0.909, SD = 0.04, N = 37) with $F(2, 108) = 0.419$, $p = 0.659$.

4.1.3.2.1. Statistical Analysis of Photosynthesis

In this study, we used the LCpro-SD gas exchange sensor to evaluate crop photosynthesis under the three light treatments. With this sensor, we could monitor and retrieve data on the photosynthesis rate (As in $\mu mol{*}m^{-2}s^{-1}$) for all the scheduled time intervals.

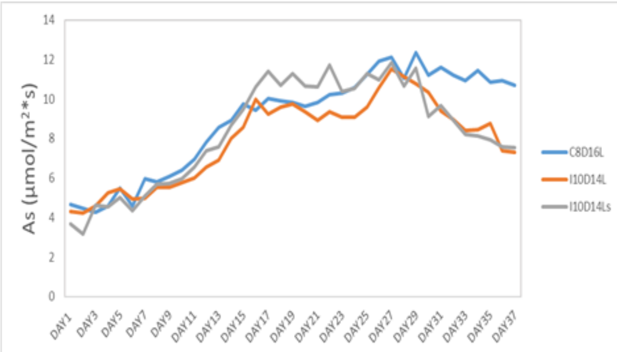
To identify statistical differences in terms of As ($\mu mol{*}m^{-2}s^{-1}$) between the three treatments, the C8D16L treatment (M = 8.96, SD = 2.57) was compared with the I10D14L treatment (M = 7.93, SD = 2.13) and the I10D14Ls treatment (M = 8.34, SD = 2.61) with N = 37 in all three treatments. Subsequently, we used a one-way ANOVA to examine and compare the differences in terms of the photosynthetic rate among the three groups. The ANOVA tests showed that the means between the groups performed no statistically significant differences under continuous or IL with $F(2, 108) = 1.656$, $p = .196$.

As mentioned in the methodology section, we measured the photosynthesis every day and seven times a day from 9 a.m. to 9 p.m. The measurements made during the intermittent treatment took place during the ten-minute light intervals with limited radiation. In both stress treatments (I10D14L and I10D14Ls), we also measured the photosynthesis rate at the end of each continuous light treatment, where the plants had sufficient time to receive, absorb, and process more light radiation and convert the electrical energy into chemical energy. Therefore, we decided to perform a statistical analysis on the photosynthetic rate during the ten-minute and continuous treatments (every three to six hours depending on the treatment).

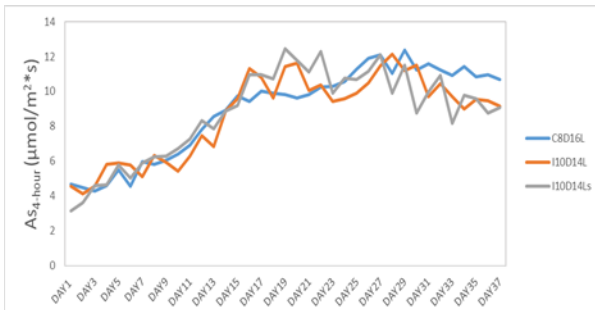
The C8D16L treatment $As_{10\text{-}min}$ with (M = 8.96, SD = 2.57) for the ten-minute measurements of the photosynthesis rate ($As_{10\text{-}min}$ in µmol*$m^{-2}s^{-1}$) was compared with the corresponding measurements of the I10D14L treatment (M = 7.47, SD = 2.07) and the I10D14Ls treatment (M = 7.94, SD = 2.68) with N = 37 in all the three samples. A one-way ANOVA was conducted for each of the three groups, showing a statistically significant difference at $F(2, 108) = 3.546$, $p = 0.32$. These results suggest that intermittent light, when applied for ten minutes, has a significant effect on the photosynthesis of the plants.

Subsequently, we compared the mean values of the three treatments during the continuous light periods as well. More specifically, the I10D14L treatment with the three continuous light periods lasted four hours each, while for the I10D14Ls treatment, the first continuous light period lasted nine hours and the second 3 hours. For practical reasons, we refer to this as a '4-hour' light period for both treatments: $_{As4\text{-}hour}$ in µmol*$m^{-2}s^{-1}$. A one-way ANOVA used to compare the four-hour time intervals in the C8D16L treatment (M = 8.96, SD = 2.57, N = 37), the I10D14L treatment (M = 8.66, SD = 2.4, N = 37), and the I10D14Ls treatment (M = 8.78, SD = 8.78, N = 37) showed no statistically significant difference among the groups with $F(2, 108) = 0.132$, $p = 0.876$.

The above results indicate that the plants under IL continued to grow in a steady pace like the plants under continuous light. To be more specific, the four hours of IL were sufficient for the plants to develop their photosynthetic capabilities and absorb enough light energy to grow. On the other hand, when the plants only received ten minutes of light, they failed to achieve an optimum level of photosynthesis. However, as can be observed from As, when comparing the means of the three groups, the total photosynthetic rate of the groups increased continuously without any statistical difference between the three groups during the experiment (Figure 36). As seen in Figure 36, the photosynthetic rate of the I10D14L and I10D14Ls treatments started to decrease on Day 29 of the IL until the end of the experiment (day 37).



(a) (b)



(c)

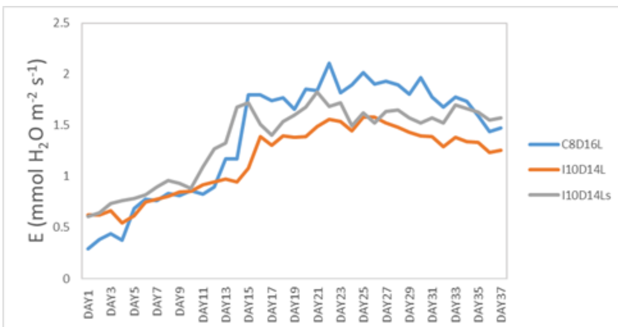
Figure 36. Average daily evolution of [a] the photosynthetic rate As (in µmol*$m^{-2}s^{-1}$), [b] the photosynthetic rate during the ten-minute light period As_{10min} (in µmol*$m^{-2}s^{-1}$), and [c] the photosynthetic rate during the four-hour light period $As_{4\text{-}hour}$ (in µmol*$m^{-2}s^{-1}$) for healthy plants, i.e., C8D16L (the blue line) and stressed plants, i.e., I10D14L (the orange line) and I10D14Ls (the grey line). Days 1-37: a) C8D16L (control/continuous light), b) I10D14L (stress/normal intermittent light), and c) I10D14Ls (stress/shifting intermittent light).

4.1.3.2.2. Statistical Analysis of Transpiration Rate

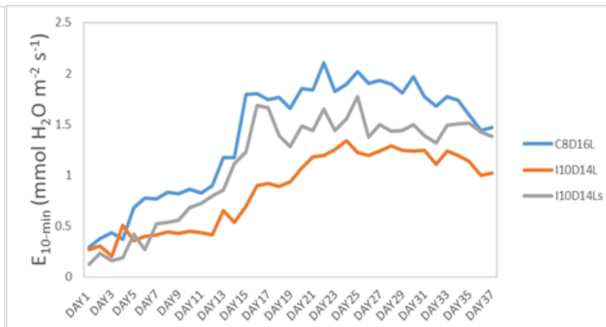
The transpiration rate (E in mmol H_2O m^{-2} s^{-1}) of the basil leaves under the three light schedules was also examined. We performed a one-way ANOVA to compare the daily means between the C8D16L treatment (M = 1.39, SD = 0.56, N = 37), the I10D14L treatment (M = 1.16, SD = 0.33, N = 37), and the I10D14Ls treatment (M = 1.36, SD = 0.37), which showed no statistical significant differences: $F(2, 108) = 3.018$, $p = 0.53$.

Similarly, we conducted a statistical analysis of the three light variables with the ten-minute intermittent radiation and the four-hour continuous light treatments. The transpiration rate in the ten minutes of radiation showed statistically significant results at $F(2, 108) = 3.546$, $p = 0.032$ between the C8D14L treatment (M = 1.39, SD = 0.56, N =37), the I10D14L treatment (M = 0.85, SD = 0.38, N = 37), and the I10D14Ls treatment (M = 1.11, SD = 0.41, N = 37). Post-hoc analysis showed significant differences between C8D16L and the two stress treatments (I10D14L and I10D14Ls); however, the two stress treatments did not present any significant difference between them (Figure 37).

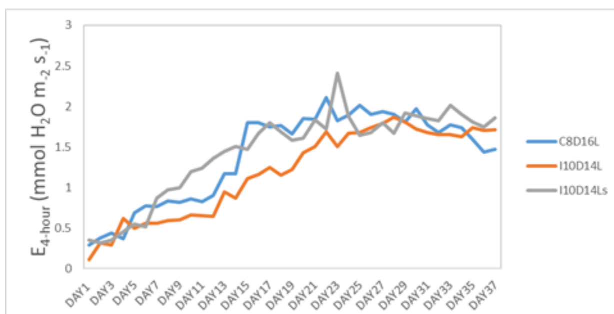
Subsequently, the one-way ANOVA comparing the four-hour intervals of light between the three groups C8D16L (M = 1.39, SD = 0.56, N = 37), I10D14L (M = 1.19, SD = 0.54, N = 37), and I10D14Ls (M = 1.44, SD = 0.54, N = 37) showed no statistical significant differences: $F(2, 108) = 2.234$, $p = 0.112$. As can be observed from the presented data, E had a similar pattern as As, where ten minutes of light was not sufficient for the plants to transpire. However, the following continuous light treatments provided the crops with enough light to compensate the transpiration rate in the control group.



(a)



(b)



(c)

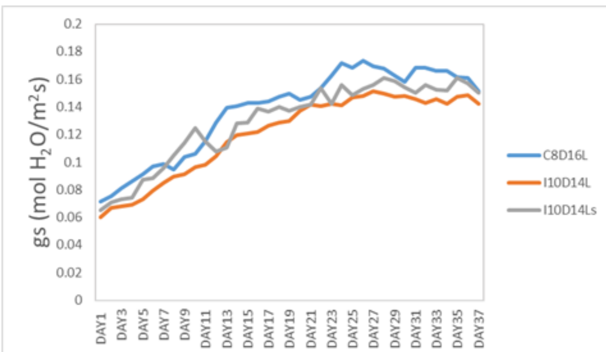
Figure 37. Average daily evolution of [a] transpiration rate E (in mmol $H_2O*m^{-2}s^{-1}$), [b] transpiration rate during the ten-minute light period $E_{10\text{-min}}$ (in mmol $H_2O*m^{-2}s^{-1}$), and [c] transpiration rate during the four-hour light period $E_{4\text{-hour}}$ (in mmol $H_2O*m^{-2}s^{-1}$) for healthy plants, i.e., C8D16L (the blue line) and stressed plants, i.e., I10D14L (the orange line) and I10D14Ls (the grey line). Days 1-37: a) C8D16L (control/continuous light), b) I10D14L (stress/normal intermittent light), and c) I10D14Ls (stress/shifting intermittent light).

4.1.3.2.3. Statistical Analysis of Stomatal Conductance

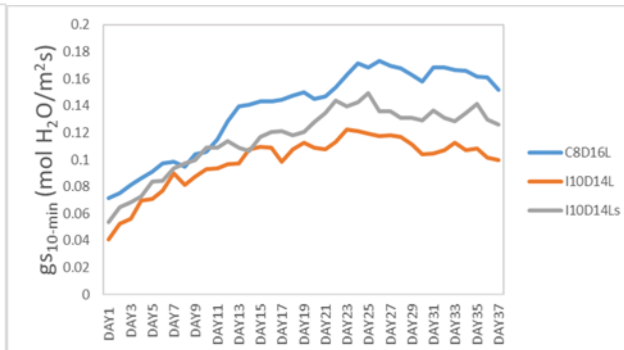
An analysis of stomatal conductance (gs in mmol/m^2s) was conducted between the C8D16L treatment with (M= 0.15, SD = 0.032, N = 37), the I10D14L treatment with (M = 0.12, SD = 0.02, N = 37), and the I10D14Ls treatment with (M = 0.13, SD = 0.03, N = 37). A one-way ANOVA test showed no statistical significant differences between the three treatment groups: $F(2, 108) = 2.924$, $p = 0.058$.

We then performed a further analysis of the two time intervals with IL (ten minutes) and continuous light (four hours) to test whether the stomatal conductance was affected by the limited radiation. A one-way ANOVA comparing the continuous treatments with the four-hour light intervals ($gs_{4\text{-hour}}$ in mmol/m^2s) between the three groups C8D16L (M = 0.15, SD = 0.032, N = 37), I10D14L (M = 0.136, SD = 0.034, SD = 37), and I10D14Ls (M = 0.15, SD = 0.036, N = 37) showed no statistical differences: F (2, 108) = 2.884, p = 0.06 (Figure 38).

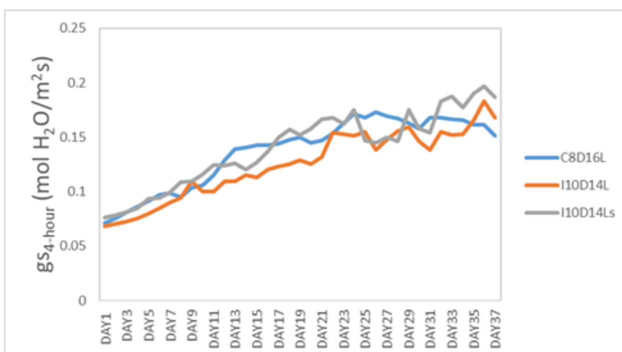
The IL treatments with only ten minutes of light radiation ($gs_{10\text{-min}}$ in mmol/m^{2}s) were tested using the one-way ANOVA, where C8D16L (M = 0.15, SD = 0.032, N = 37), I10D14L (M = 0.099, SD = 0.02, N = 37), and I10D14Ls (M = 0.12, SD = 0.024, N = 37) showed statistically significant differences at F (2, 108) = 20.811, p = 0.00. A post-hoc analysis revealed significant differences between C8D16L and the two stress treatments I10D14L and I10D14Ls, indicating that the limited light radiation of ten minutes was not sufficient to open the stomata during the photosynthetic process.



(a)



(b)



(c)

Figure 38. Average daily evolution of [a] stomatal conductance gs (in mmol $H_2O*m^{-2}s^{-1}$), [b] stomatal conductance during the ten-minute light period $gs_{10\text{-min}}$ (in mmol $H_2O*m^{-2}s^{-1}$), and [c] stomatal conductance during the four-hour light period $gs_{4\text{-hour}}$ (in mmol $H_2O*m^{-2}s^{-1}$) for healthy plants, i.e., C8D16L (the blue line) and stressed plants, i.e., I10D14L (the orange line) and I10D14Ls (the grey line). Days 1-37: a) C8D16L (control/continuous light), b) I10D14L (stress/normal intermittent light), and c) I10D14Ls (stress/shifting intermittent light).

4.1.3.2.4. Statistical Analysis of Chlorophyll

For data collection, the portable CCM-200 plus sensor was used to measure the chlorophyll content index (CCI) of the basil plants. As mentioned above, the data acquisition was tested over the specific period presented in Figure 39. The figure presents the evolution curve of the CCI under the three light treatments.

The curve shows an aligned development of chlorophyll production for the plants exposed to the stress treatment with a 14-hour photoperiod and IL (I10D14L), the plants grown under a load-shifted IL treatment (I10D14Ls), as well as the plants following the control treatment (C8D16L). The CCI measurement for the C8D16L treatment was (M = 24.87, SD = 3.69, N = 37), (M = 23, SD = 3.7, N = 37) for the I10D14L treatment, and (M = 23.72, SD = 4.18, N = 37) for the I10D14L treatment. The three samples showed no statistically significant differences between the three treatments: $F(2, 108) = 2.221$, $p = 0.113$. As the experiment progressed, the values of chlorophyll content continued to increase until day 27, after which the values for all three treatments remained stable until the end of the experiment, i.e., 28.7 for the C8D16L treatment, 28.1 for the I10D14L treatment, and 28.03 for the I10D14Ls treatment.

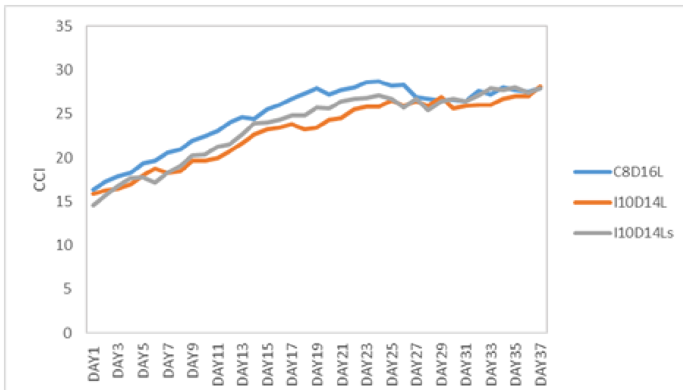


Figure 39. Average daily evolution of chlorophyll content for healthy plants, i.e., C8D16L (the blue line) and stressed plants, i.e., I10D14L (the orange line) and I10D14Ls (the grey line). Days 1-37: a) C8D16L (control/continuous light), b) I10D14L (stress/normal intermittent light), and c) I10D14Ls (stress/shifting intermittent light).

4.1.3.4. Quality and Physiological Evaluation of Basil Grown under Different Light Treatments

The duration of the experiment was 37 days for the three treatments (C8D16L, I10D14L, and I10D14Ls). The yield was measured in terms of the shoot and the root biomass in each of the three chambers. The leaf area (LA) measured at the end of the experiment obtained with the destructive method showed no significant differences after the statistical analysis with the one-way ANOVA. From Table 20 below, it can be seen that the mean values of the I10D14L treatment (417.5 cm^2) and the I10D14Ls treatment (422.9 cm^2) are higher than the mean values of the C8D16L treatment (410.4 cm^2).

Table 23 shows that the measurements of plant quality and physiology did not show statistically significant differences. For most indices, however, a small increase in height as well as mass and surface area was observed among the crops that received the IL treatment (I10D14L and I10D14Ls) compared to the mean values of the control treatment (C8D16L).

Table 23. Results of statistical analysis comparing the quantitative mean values of the three treatments C8D14L (control), I10D14L (stress), and I10D14Ls (stress). The columns represent the sample size (N), mean values (Mean), standard deviation (SD), degrees of freedom between the groups and (df1) and within the groups (df2), F-test (F), and level of significance (p-value). Significant at the $p < 0.05$ level.

	Treatment	N	Mean	SD	df1	df2	F	p-value
$Height_{shoot}$ (cm)	C8D16L	12	18	1.4	2	9	.191	.829
	I10D14L	12	18.25	1.3				
	I10D14Ls	12	18.5	0.6				
$Height_{root}$ (cm)	C8D16L	12	6	0	2	9	.457	.647
	I10D14L	12	6.75	1.7				
	I10D14Ls	12	6.25	1				
Number of leaves	C8D16L	12	13.7	1.9	2	9	.076	.929
	I10D14L	12	14	1.6				
	I10D14Ls	12	13.5	1.9				
LA (cm^2)	C8D16L	12	410.4	74.6	2	9	.034	.966
	I10D14L	12	417.5	51.5				
	I10D14Ls	12	422.9	74.8				
Fresh $mass_{root}$ (g)	C8D16L	12	9.8	2.7	2	9	.020	.980
	I10D14L	12	9.9	3.2				
	I10D14Ls	12	10.2	2.5				
Fresh $mass_{shoot}$ (g)	C8D16L	12	31.3	7	2	9	.127	.882
	I10D14L	12	33.2	5.2				
	I10D14Ls	12	33.1	5.4				
Dry $mass_{root}$ (g)	C8D16L	12	1.14	.48	2	9	1.141	.362
	I10D14L	12	1.87	.91				
	I10D14Ls	12	1.38	.62				
Dry $mass_{shoot}$ (g)	C8D16L	12	1.91	.36	2	9	5.747	.025
	I10D14L	12	2.76	.41				
	I10D14Ls	12	2.8	.47				

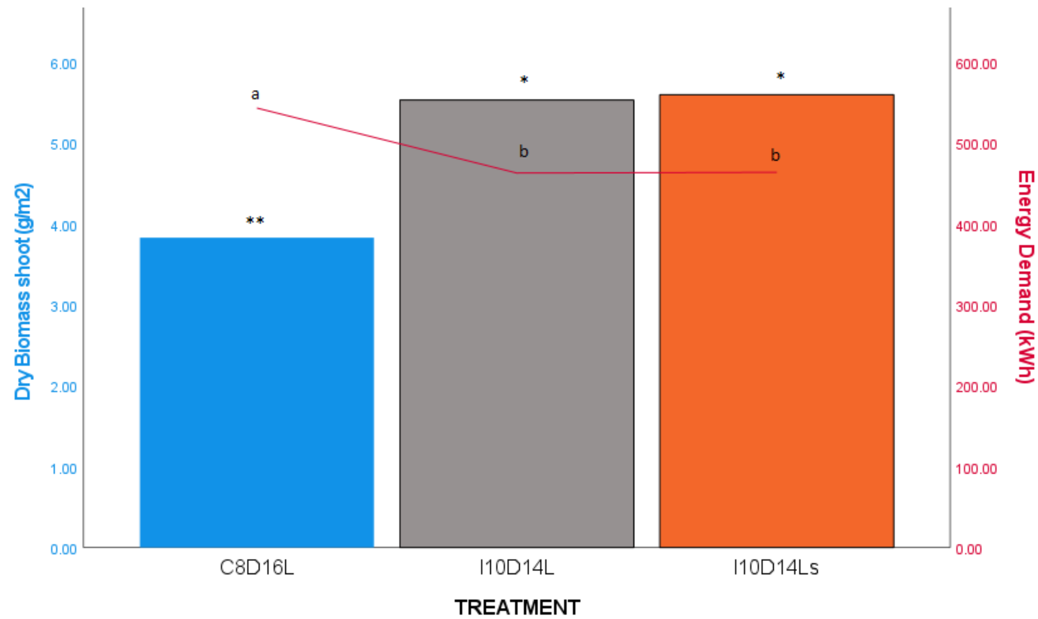
The total biomass of the plants in each treatment was estimated by the following equation:

$$Biomass_{shoot} = Dry\ mass_{shoot}\ (g)\ /\ growing\ area\ (m^2) \quad [24]$$

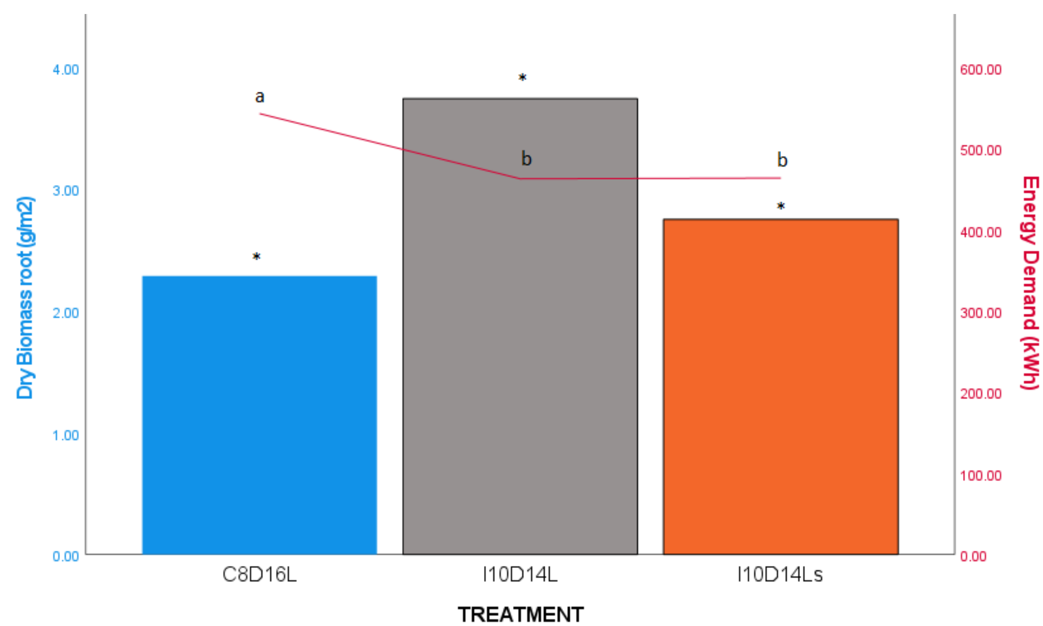
$$Biomass_{root} = Dry\ mass_{root}\ (g)\ /\ growing\ area\ (m^2) \quad [27]$$

where, the growing area was 0.5 m^2 within each of the harvested plots. The biomass was measured in g/m^2.

Figure 40 shows the electrical energy necessary for the total crop production in each treatment. The different light conditions applied in each chamber resulted in a statistically significant decrease in electricity consumption in both stress treatments; in fact, the two intermittent treatments led to a reduction in electricity consumption of approximately 16%. A one-way ANOVA showed a statistically significant reduced $Biomass_{shoot}$ production ($g*m^{-2}$) with F (2, 9) = 5.747, p = 0.025 for the C8D16L treatment (M = 3.8, DS= 0.7, N=12) compared to the I10D14L and I10D14Ls treatments with (M = 5.5, SD = 0.8, N = 12) and (M = 5.6, SD = 0.9, N = 12), respectively (Figure 40a). We also found a significant increase in the Dry $Biomass_{shoot}$ of the two IL treatments of approximately 45% compared to the continuous light treatment. In addition, a significantly lower electricity consumption in the cultivation system was also registered, and finally, the results of the one-way ANOVA for the Dry Biomass$_{root}$ measurements showed no significant differences between the three treatments (Figure 40b).



(a)



(b)

Figure 40. [a] The left axis (histograms): The average shoot dry biomass (g*m^{-2}). The right axis (line): The average electrical energy consumption to produce basil (kWh) grown under the three light treatments (g*m^{-2}). [b] The left axis (histograms): The average shoot dry biomass (g*m^{-2}). The right axis (line): The average electrical energy

consumption to produce basil (kWh) grown under the three light treatments ($g*m^{-2}$). The letters 'a' and 'b' indicate significant differences in energy consumption between the three treatments ($p < 0.05$). The '*' and 'a' indicate significant differences in dry biomass production between the three treatments ($p < 0.05$).

4.1.4. Discussion

The purpose of this study was to investigate and optimise the sustainability and efficiency of an indoor cultivation system by designing a more cost-effective, flexible and ecological plant production, mainly to satisfy the urban demand for fresh food. Especially in indoor vertical farms relying on artificial lighting, optimising the operation of a lighting system has a significant impact on the running costs. Therefore, reducing the amount of light delivered to the crops (photoperiod) and designing a more flexible system that balances the supply and demand in the electricity market without negative effects on yields and crop quality can greatly affect the profitability and yield production of indoor farms. To test this hypothesis, we examined the differences between the three light treatments under various growth indices such as photosynthesis rate, transpiration rate, and stomatal opening. An important part of the study was also to find the best timing to switch to/off a LSEDR technique without affecting the crop yield and quantity of the basil.

Teskey et al. (1995) note the importance of primarily environmental factors such as light, water, and CO_2, which have a major impact on photosynthesis, as they can easily alter the rate of chemical processes that take place. Apart from the direct regulators of photosynthesis, a group of substances composes the physiologically active compounds and structures that form the basis of the dark and light reactions responsible for photosynthesis. These substances define the photosynthetic framework that determines the physical structure of the plant, the arrangement of the organs that promote photosynthesis as well as the nutrients involved in the photosynthetic pathway. To determine the response of the plants to intermittent light, we followed the growth pigment concentrations, gas exchanges, and the photochemical efficiency of the basil plants.

4.1.4.1. The Effect of Different Light Treatments on Basil Quality, Leaf Function and Physiological Parameters

Throughout the experiment, the leaf temperature (T_{leaf}) of the plants under the continuous light treatment was not significantly lower than the two IL treatments, the main cause probably being evaporation that cools the leaves while light (radiation from the light source) heats them up. The foliage, which is exposed to higher radiation levels, rarely performs temperatures that are equal to the air temperature (Idso et al., 1981; Gimnez and Thompson, 2005). Our results showed a positive difference between the leaf and air temperature, indicating that the growing conditions were sufficiently cool for plants growth. Additionally, the non-significant decrease in leaf temperature under the control conditions could be attributed to the increased thermal radiation reaching the leaf area surface under the continuous light.

The substrate temperature (T_{sub}), is one of the most important factors affecting the nutrient uptake from the water into plants. According to McMaster and Wilhelm (2003), T_{sub} can control the responses of plant shoots by changing the temperature of a shoot apical meristem, which allows controlling and regulate the hormonal balance in the water and nutrient uptake (Bhattacharya, 2019). The values of electrical conductivity (EC) presented no statistical significant differences, indicating that there were no disturbances in the nutrient concentration of the irrigation water, which enhanced water and nutrient uptake in all three light treatments.

Light is one of the most crucial factors that directly influences plant growth and biomass production. The amount of light harvested by plants is highly determined by the relationship between the optical characteristics and the physiological-biochemical capacity of the leaves (Smith and Hickley, 1995). Light is transmitted or scattered forward through the epicuticular layers and interacts with the cuticle of the leaves and the epidermal/hypodermal layers. The way plants respond to light can provoke physiological alterations that affect the CO_2 assimilation and optimisation of gas exchanges inside the plants. As already stated by Savvas (2016), the photoperiodic reaction is very important in the cultivation of leafy greens intended for the production of edible fresh products such as basil. For such vegetables, the goal is to delay the growth of flowers in order to increase the amount of edible shoots. In other words, flowering is undesirable in crops such as basil, since it causes hardening of the leaves, i.e., they become inedible and fail to grow properly. Therefore, when growing such vegetables, the light period should not coincide with the flowering needs of the plants.

Since light has such a major impact on various qualitative and quantitative processes in plants (Gonçalves et al., 2008), we proceeded to study the photosynthetic status of plants under continuous and IL periods. In a previous publication by Avgoustaki et al. (2020a), the significance of dark periods was examined and explained, including how their duration and frequency can affect the response and processing of the plants in the following light period. Regardless the length of the intervening dark period in the 24-hour cycles, the same amount of photochemical product was obtained with only a few minutes of light in the initial period of high irradiation to which the plants were exposed. According to Grobbelaar et al. (1996), longer and continuous dark periods do not necessarily lead to higher photosynthetic rates. This has been studied by various researchers (Tzinas, 1987; Iluz, 2011; Withrow and Withrow, 1944), who have found that the balance between light and dark cycles is significant in improving the photosynthetic activity of plants. Many studies focus on defining the optimal irradiation that plants receive daily and the dark and light intervals to which they are exposed. Iluz et al. (2012) stated that plants absorb all the necessary irradiation during a light period (gross photosynthesis) and use it continuously during the following dark period. Our results showed that the photosynthetic rate of the plants receiving fluctuating light performed higher, independently of the limited irradiation. The only statistically significant difference was observed in the As of the ten-minute light interval after Day 29 of our experiment. This could be explained by the fact that the cells did not have sufficient energy to perform photosynthesis with a ten-minute light interval; thus meeting their metabolic requirements. However, as can be seen in Figure 36a, the total daily photosynthetic rate of the plants was not significantly affected by the using of intermittent light. At the same time, during the four-hour light period, the cells actually managed to process enough energy through photosynthesis, i.e., the photosynthetic rate (As), without affecting the yield production.

As mentioned previously, stomatal conductance (gs) is a measure of the degree of the opening and closing of stomata on a leaf's surface. It can be used to indicate the water status of the canopy and has a significant role in regulating the gas exchanges between the exterior environment (atmospheric CO_2

concentration) of the plant and the interior of the leaf (Zhu et al., 2018). In other words, the role of stomata is to control the leaf transpiration and maintain the water status by closing and opening the stomata pores (Moriana et al., 2002). Water stress causes stomata closure, where the amount of the CO_2 available in the chloroplast is reduced, which ultimately reduces the photosynthetic capacity (Smith and Hinckley, 1995). This is the reason why stomata is considered one of the most important regulators of the leaves' photosynthetic induction response (Kirschbaum and Pearcy, 1987). In a growing environment with a controlled CO_2 level, a photosynthetic induction response takes a few minutes while it takes at least 30 minutes when the CO_2 status is unstable. This is because stomatal conductance is largely correlated with the induction process and therefore highly affected by the VPD values, which tend to decrease when the CO_2 level in the growing area increases (Gimmez and Tompson, 2005). As a result, the stomatal conductance showed significant differences between continuous and IL during the ten-minute light intervals but not in terms of the average daily means. Our data indicate that the plants could successfully absorb CO_2 and traverse it via the epidermal layer at the photosynthetically active leaf mesophyll cells, contributing to the steady, continuous growth of the plants. Finally, according to (Kinoshita et al., 2001) small portions of blue light can increase stomatal opening in order allow more CO_2 to enter the leaves. At the same time, the photosynthetic rate is saturated at high levels of intercellular CO_2 concentrations.

Previous research (Tzina et al., 1987) has shown that the amount of chlorophyll accumulation in the early growth stage of plants depends on the total daily amount of light radiation that plants receive and does not depend on the dark periods of the daily photoperiodic cycle. As mentioned, the photosynthetic rate during the intermittent photoperiod is highly depended on the interruption and sequence of the dark intervals. Figure 39 shows that the chlorophyll content index maintained an increasing rate during the experiment in all the three light treatments, demonstrating a positive, stable, and increasing rate at the different radiation treatments. This phenomenon can be explained by the behaviour of plants that are exposed to shorter dark periods of light to develop larger photosystem units, such as large protein complexes implanted in the thylakoid membrane of plants to absorb and convert the given light radiation. In order for plants to maintain the same accumulation rate of chlorophyll, thylakoids found in short dark periods develop few but large photosystems, as opposed to thylakoids found in long dark periods that develop small photosystems. Additionally, changing the photoperiod did not seem to affect the circadian clock of plants which acts to regulate the chlorophyll pigments binding protein responsible for forming parts of the photosynthetic machinery of plants. Finally, as Agati (2011) reports, non-destructive measurements of chlorophyll by optical portable sensors can be used as assessors and indicators of flavonoids in plants.

Transpiration is the loss of water vapour from plants and consists of a physical process that is highly dependent on the external physical and physiological factors of plant growth. Transpiration refers to the water losses from the foliage of the canopy and is involved in the carbon assimilation process. The movement of any type of gas from and to the leaves is controlled by the gradient of water vapour pressure between the tissue of the plant and the surrounding atmosphere (Madani B. et al., 2019). Light radiation provides the necessary energy light source to perform the transpiration process. Previous studies have addressed the link between stomatal function and control of photosynthesis and transpiration processes of plants. Stomata allow plants to minimise water loss while obtaining CO_2 for photosynthesis (Jones, 1997). In Figures 37 and 38, similar patterns and tendencies in transpiration rate and stomatal conductance can be observed. Our results showed that on a daily average, the photoperiodic treatments produced similar transpiration rates and stomatal conductance values. The high level of atmospheric CO_2 concentration in all three treatments led to an increase in the photosynthetic rate (As) of the plants despite the reductions in stomatal conductance and transpiration rate during the intermittent photoperiod. The reduction in average transpiration and the slightly higher leaf temperature under IL could increase the evaporative demand of the plants (Jarvis A. J. et al., 1999).

Finally, another explanation of our results could be the appearance of plant photoreceptors. Plants that develop large leaf areas (light receiving area) are able to maintain a high photosynthetic rate and growth rate. By allowing farmers to control the morphology of plants, not only they can ensure the appearance commands in high purchase value crops, but also they can influence the enhancement of plants' growth rate. Apart from photosynthesis, photoreceptors are the compounds of plants that via stimulation of multiple light-receptors can influence the morphology and physiology of plants by the light environment they are exposed. In more details, the Spectral Photon Flux Density (SPFD) of light affects plants though numerous reactions. Photoreceptors such as phototropin, cryptochrome and phytochrome are the receptors that affect plant morphology.

Phototropin is a blue light receptor that affects plant morphology by getting involved in the photoperiodism process where stems tend to extend towards the light, and at the same time, they are involved in the stomata opening as phototropin redundantly control the exchange of water and carbon dioxide (Sharma et al., 2014). Activation of phototropin is suggested to have an impact on enhanced photosynthetic activity due to its correlation with the increasing capability of plants to maximise the utility of PAR without influencing chloroplasts' position for capturing the photosynthetically active radiation (Takemiya et al., 2005). Phototropin, is highly related to leaf angling and flattering in order allow plants absorb larger amount of light radiation and promotes plant growth. It should be noted that phototropins have the ability adapt on different light responses and enhance plants' photosynthesis, chloroplast movement and stomatal opening (Chen et al., 2004).

Cryptochrome consists another blue receptor that participates in several processes of plants including photomorphogenesis and influences the circadian clock (Gliberto et al., 2005). Cryptochrome activity is linked with a lot of significant agronomical traits such as repression on leaf elongation, leaf sequence, seed germination, plant height, flowering and regulation of transcription (Kang & Ni, 2006; Mawphlang & Kharshiing, 2017; Facella et al., 2017). Sharma (2014), stated that the high performance of chryptochrome provide plants an adaptive advantage in stress environmental conditions. Pedmale (2016) reported that chryptochrome have the ability to promote plant development under shaded environment as they can alter the shade responses of plants by suggesting a new molecular target. In this direction, activation and manipulation of this photoreceptor can highly affect the molecular pathways that are correlated with biotic/abiotic stress (like intermittent lighting treatments) and photosynthesis but also secondary metabolic biosynthesis (flavonoid and phenolic) (Lopez et al., 2013).

Finally, phytochrome is a receptor that is strongly affected by red and far-red wavelengths of the spectrum but at the same time, it performs weakly connection with blue and green bands of the light spectrum. The action of phytochromes allows plants to quantify the shade in their surrounding environment by detecting variations in the red/far-red ratios and activate a sequence of developmental responses that are considered to provide plants a competitive advantage over their surrounding neighbours (Mawphlang & Kharshiing, 2017). Phytochromes can highly influence and enhance plant elongation and at the same time causes a reaction called shade avoidance syndrome, in which plants shaded leaves of plants elongate to escape the shading environment they are and get access to further parts of the light spectrum (Shibuya et al., 2016). Additionally, such responses of phytochromes include apart from elongation growth, enhance of apirical dominance, coupled with decreased leaf development and decrease in branching (Franklin, 2008). At the same time, photoreceptors' developmental plasticity in limited light provision, allow plants to increase the survival percentage under diminished light treatment (Weinig et al., 2006). Under this scope, indoor crops could result with enhanced productivity especially in indoor vertical farms with high planting densities.

Photoreceptors are photo-regulation systems that control the expression of specific genes in plants and influence the development, growth and secondary metabolic processes (Furuya, 1989). According to Dong et al. (2015), light sources that provide different intermittent lighting modes can activate different photoreceptors of plants in order to control pigment synthesis. Generally, photoreceptors follow two different switching categories. In the first one, the alteration of the photoreceptors is reversible and can be regulated anytime, but on the second category of switch, once they activated then the process is irreversible (Dong et al., 2015). Since chlorophyll production in our study remained stable on transferring cells in the dark for several minutes, light radiation should not work reversible but irreversibly. Under this scope, an intermittent light could preserve high chlorophyll production levels until another mechanism is activated or the light-activated state will be decreased. In our system, phytochrome is suggested to be activated by light-induced production (Kurata et al., 1998; Kurata, 2000). Once the phytochrome is activated by light radiation, it may keep the activation state for several seconds of intermittent dark periods. Similarly with phyotochrome, cryptochrome can keep their activation state for several minutes during short intermittent dark periods, adjusting to short light/dark intervals in order to capture the available light and meet the photosynthetic demand of plants (Dong et al., 2015; Steinger et al., 2003).

4.1.4.2. Effect of Different Light Treatments on Biomass Accretion and Energy Demand

As previously mentioned, NDVI is a great indicator for assessing the green biomass and nitrogen content of the plant canopy to support crop management (Cabrera-Bosquet et al., 2010). NDVI constitutes a fast, non-destructive meter for estimating the green biomass, leaf area index (LAI), chlorophyll content as well as the grain yield at canopy level. Leaf area showed no significant differences between the continuous and the load-shifted intermittent photoperiod. As mentioned by Goswami et al. (2015), there is a strong exponential relationship between NDVI and biomass. Adams and Langton (2005) have also highlighted that photoperiod and light distribution have a major impact on plant biomass production, leaf size, and leaf area. Table 23 presents the decrease in leaf area (LA) under the normalised IL treatments. As explained by Cockshull (1966), this has an effect on plants despite the intermittent light, while the photoperiod treatments continue to affect the final leaf size in the final stages of leaf elongation and expansion when the rate of the cell division decreases. We can assume from our results that the plants under IL correlated positively with endogenous gibberellins, i.e., a group of hormones responsible for the stem elongation, germination, and flowering. It seems that the slight decrease in the daily averages of chlorophyll pigment for all the three light treatments from day 26 was merely an incidental side effect of the increased expansion of the leaves at this time in their growth stage. As observed by Adams and Langton (2005), no significant reduction in chlorophyll concentration per unit LA is caused by increase in chlorophyll content during leaf expansion growth of plants.

A continuous and longer photoperiod was expected to result in a higher biomass production. In Figure 41a, it can be seen that the shift from the continuous to an intermittent photoperiod did affect the plant growth of the basil plants, resulting in the same increased amount of biomass production for the two intermittent treatments. In parallel, the energy demand in kWh was significantly reduced [F (2, 108) = 2143.25, p = < .001] under the intermittent and shorter daily light treatment. The energy demand in the I10D14L and I10D14Ls treatments was 86 kWh and 89 kWh, respectively less electricity-consuming than the C8D16L treatment. Using the price of electricity in Denmark, which is around 0.219 €/kWh for businesses, the I10D14Ls treatment with a LSEDR that mimicked the daily electricity prices in the peak period resulted in an energy cost saving of 18 €/day with a 43-watt LED.

The purpose of this research was to determine the energy savings that could be made from growing basil under IL in an indoor cultivation system. To test our hypotheses, we performed phenological measurements on the plants' reactions both in terms of photosynthesis and carbon export linked to the electrical energy input for cultivation under continuous and IL conditions. Post-harvest data collection of this experiment, including biomass production and leaf area, showed a positive correlation. A further research study is needed to make a taste evaluation and determine the correlation and variation of secondary metabolites (flavonoids, phenolics, etc.), carotenoids concentration, and essential oils in basil plant cells.

4.1.5. Conclusions

Basil cultivation in an indoor controlled environment under IL showed a positive effect on the growth, development, and quantity of the plants compared to continuous light, which is widely used in IVFs. More specifically, basil plants grown under IL with a reduced daily photoperiod presented a significantly enhanced final biomass production. Additionally, the daily monitoring of the photosynthetic rate, chlorophyll content, transpiration rate, and stomatal conductance of the basil plants followed the same average development rate between the intermittent and the continuous treatment. The photosynthetic rate of the plants continued to increase during the experiment, where the plants were exposed to ten-minute light intervals followed by 50 minutes of darkness both in the normal intermittent treatment (I10D14L), but also in the treatment that mimicked time-of-day pricing of electricity (I10D14Ls). Furthermore, the chlorophyll content and the chlorophyll pigments maintained a steadily increasing rate under the intermittent and continuous light treatments. In this experiment, the irradiance (i.e., the flux density) was constant in both the continuous and the two intermittent treatments at 200 and 228 PPFD respectively in order to maintain a stable DLI 11.5 moles/m^2/day. Therefore, the intermittent photoperiod was confounded by the decrease in the total PAR integral that the plants received daily.

In this experiment, the main objective was to maintain a high-value product in terms of quantity and quality and at the same time at the lowest possible energy cost. Based on our results, we could conclude that from an energy consumption and biomass production perspective, IL treatments during dark hours were more efficient than providing the same light during daylight hours. The results of this experiment suggest a flexible electricity consumption system that is highly based on the energy prices across countries in parallel with monitoring the crop growth rate. Finally, vertical farms can profitably implement lighting systems, where the energy consumption is adjusted on fluctuations in electricity market prices.

Future research is needed in this field to examine the optimal light conditions in terms of light intensity and the selection of LEDs for more species that are best suited for indoor vertical cultivation. The experiment should also be repeated and adjusted in a larger-scale installation with more complicated cultivation system to assess and prove the economic value of the energy savings and the crop production from load-shifted light operation. A potential taste assessment as well as a post-harvest quality assessment (essential oils and secondary metabolites, such as flavonoids and phenolics) would be an interesting addition to and evaluation of the process. Future investigation is also necessary for the examination of photoreceptor compounds and their expression reaction under daily IL intervals.

Vertical farming is indeed one of the most innovative and continuously evolving cultivation techniques offering numerous advantages for cities to meet the demand of urban citizens for fresh, nutritious herbs and vegetables. Thus, it is important to conduct several studies to analyse and optimise the technology and the cultivation protocols. Although it is absolutely necessary for the best and fastest crop production, the energy consumption for artificial lighting is one of the main drawbacks of vertical farming, limiting the feasibility of the farms. Therefore, in order to assess and optimise the utility costs of vertical farms, further research should examine economic and environmental potentials, making indoor farming even more sustainable, especially in a mass deployment.

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4.2. Reduction of Energy Costs in Indoor Farms for Artificial Lighting by Shifted Energy Demand Response

The sixth article of this dissertation looks into the electricity costs and benefits from the proposed energy optimisation model for IVFs deployment including a farm-to-grid operation of artificial lighting. To fully explore the benefits and costs of load-shifted lighting schedule, the Danish electricity market has been used in this case study, where consumers receive every day the hourly settlement by the Transmission System Operator (TSO), Energinet. This research targets to investigate the cost savings that result from the LSEDR and reduced photoperiod method that is analytically described in the previous paper (fifth) of this PhD thesis. The purpose of this paper is to apply and present an algorithm that by comparing hourly the electricity market prices and combining with reduced and flexible lighting operation, can propose an electricity price-focused lighting system for indoor food production. The methodology of energy optimisation based on the hourly fluctuations of the power grid presents an advanced communication connection between the power grid and the energy demand for a vertical farming unit. This paper proceeds with a comparison between a vertical farm case study that uses LSEDR and a similar farm facility that does not use a flexible energy consumption but operate lamps during the night hours. Under this scope, the study examines the differentiations of operation costs, calculates the monthly cost savings by load-shifted lighting implementation. At the end of this paper, different cash flow scenarios of flexible-loaded farms are examined under their investment payback period, the IRR and NPV indices. Results show that even if capital expenses are not improved with the proposed methodology, the operational expenses of artificial light inside vertical farms contain one the major bottlenecks and can highly influence the profitability of indoor farms. Finally, the last part of this research output targets to present and discuss the opportunities that arise from mass deployment installation of vertical farming units within urban areas that can locally produce fresh vegetables, fruits and greeneries and how they could benefit on further CO_2 savings, city decarbonisation as also rationalisation within the cities based on an Energy-Food Nexus.

4.2.1. Introduction

Indoor vertical farming is a novel type of under-coverage farming technique with a fully isolated environment and replacement of solar radiation with artificial lighting. Since all the installations are totally controlled and automated, they offer the opportunity to farmers to apply innovative and pioneering techniques including both software and hardware tools that can enhance the production of the farms and increase the yield production per growing area via a more sustainable usage of resources such as water, nutrients and CO_2 (Al-Kodmany, 2018). One of the major bottlenecks of IVFs is the high electricity cost, sourcing mainly from the increased operational demand of artificial lighting (Avgoustaki & Xydis, 2020a). Over the last years, with the technological progress of lighting materials, the main source of radiation in IVF is coming from LED lights (Lighting Emitting Diodes) that convert electrical energy into light that plants absorb in order to activate and drive their photosynthetic processes (Sukhova et al., 2018). LEDs offer specific band peaks of the spectrum that plants can use for growth and development. LEDs present high performance and efficacy of converting energy into usable light for the plants' growth, which is critical for the optimal growth of plants in an indoor environment and achieves 45% higher photon efficacies in comparison with HPS (Hyper Sodium Lamps). Finally, LEDs have high photon efficacy, meaning high efficiency in converting electrical energy into photons that promote activation of the photosynthetic ability of plants (Serôdio et al., 2018). Lighting in IVFs has a crucial part and many groups focus on optimising the different dimensions of lighting (light intensity, spectrum combination, uniformity of light distribution, energy efficiency and fixture lifespan) in horticulture in order to reduce the energy cost but at the same time to provide the optimal growing conditions for plants. Since LEDs are the only lighting source that can support plants' growth in an enclosed environment, they operate multiple hours to support the photoperiodism of the plants according to cultivars' demand and their growth stage.

Photoperiod as one of the most important light dimensions that primarily affects the flowering of plants but after the latest research, it was proven that actually influences the development of morphological and physiological characteristics (leaf expansion, flowering etc.) and the biomass production (Adams & Langton, 2005). Light duration affects at a high level the quality and quantity of plants but also the energy demand of the system that has to meet the plants' daily photosynthesis demand. Based on previous research (Avgoustaki & Xydis, 2020a) lighting costs are approx. 80% of the electricity demand for IVFs, while electricity reaches up to 40% of the total operating expenses (Avgoustaki & Xydis, 2020c). It is clear that optimisation in lighting properties will reduce the energy demand for indoor farming while at the same time, it will increase their profitability and investment opportunities.

The purpose of this paper is to present an algorithm that compares the prices of the electricity market on an hourly basis and combines with limited hours and flexible photoperiod, in order to provide energy into the growing area when the electricity prices are cheap (based on DR or based on power curtailment decisions) and finally propose an electricity price-based lower cost lighting system for indoor farming. The target of this research is to deliver a shifted electricity demand approach of the indoor food production that can maintain the high product value of greeneries both in quantity (yield biomass) and quality (chlorophyll, photosynthesis, secondary metabolites). Under this scope, this research paper examines and proposes a resilient and viable Energy-Food nexus that can influence the sustainability and lower the risks of food systems in the urban environment.

4.2.2. Material and Methods

An indoor small-scale chamber experiment with hydroponic production was conducted from October to December 2019 at the BTECH Department of Aarhus University, Herning, Denmark. The growth, yield, quality of basil plants (*Ocimum basilicum L.*) as cultivar, were evaluated under continuous and intermittent lighting. These results are reported in the fifth submitted paper of this dissertation show that basil plants presented no significant differences between the different treatments in the chlorophyll pigments, the photosynthetic rate of plants (between the continuous and the reduced load-shifted lighting intervals). In this direction, monitored basil crops that receive daily 14 hours of short light cycles with 10 minutes of light per dark hour, showed adaptation results on this lighting method by maintaining a high growth and development rate during the whole crop cycle. At the same time, a significant reduction of energy demand in the small-scale installation using a 97 Watt LED lamp (deriving from the limited photoperiod, from 16 continuous hours of light to 14 hours of intermittent light), is observed with the use of a specialised energy analyser. Based on these evidence it was deemed necessary the translation of these results in a larger scale vertical farm case with 675 m^2 growing area with multiple tiers of growing crops in the area of Aarhus of Denmark. Based on the second research article of this dissertation (Avgoustaki & Xydis, 2020b) that intensively describes the case study scenario, the electricity consumption per compound per month inside an IVF is presented in table 24:

Table 24. Total monthly electricity consumption in the IVF facility with basil.

Month	Electricity (kWh)			
	Ventilation	LEDs lighting	A/C Cooling	Total electricity
Jan	4	59,076	0	59,081
Feb	4	53,359	0	53,363
March	4	59,076	0	59,081
April	4	57,171	0	57,175
May	4	59,076	0	59,081
June	4	57,171	2,041	59,261
July	29	59,076	1,950	61,055
Aug	29	59,076	3,273	62,378
Sep	28	57,171	0	57,199
Oct	4	59,076	0	59,081
Nov	4	57,171	0	57,175
Dec	4	59,076	0	59,081
Total	125	695,576	7,265	702,966

4.2.2.1. Nordic Energy Market

Denmark is a world-leading country in renewable energy and more specifically in wind energy. According to Danish Energy Agency (2019), Denmark is one of the most energy self-sufficient countries in the world in terms of gross energy consumption deriving from renewable energy sources and waste. According to Reuters (2020), in 2019 almost 50% of the total energy consumption sourced from wind turbines sustaining a greener energy system. One of the most essential characteristics that makes Denmark a very interesting case study, is the hourly settlement provided to consumers by the Transmission System Operator (TSO) of Denmark, Energinet. Consumers and market have access to hourly available data sourcing from smart meters giving analytical information of the hourly settlement and the price signals from the wholesale market. Based on this fact, it is easier to define the real cost of energy, detect the possible increases and organise the IVF's production to fit the most energy-efficient hours. Danish vision in data sharing and management is based on ensuring and providing to consumers and the production market an efficient and competitive electricity retail market that can support the innovation of new products and services towards a more sustainable future (Energinet, 2020).

4.2.2.2. Nordpool Market

The well-developed Nordpool market is a power exchange system (synergies among the Nordic and the Baltic markets between hydro, wind, thermal and very recently solar power) offering time-based trading (intraday, day ahead etc.) aiming to limit high fluctuations of energy prices and assure balance between the demand and supply (Danish Energy Agency, 2015). Nordpool spot market is an hourly spot market price that is available one day ahead in Denmark among other Nordic countries, where power contracts are traded for the next day's delivery (Hu et al., 2010). Every hour, purchasing and selling curves are created and the crossing point defines the spot market price and the volumes that will be traded the following day in an hourly analysis. The electricity spot price is fluctuating (Figure 41[a]) and according to Hu et al. (2010) and Roungkvist et al. (2020), the hourly spot market price is available one day ahead in Denmark (36-hours price forecast), giving the producer the opportunity to organise efficiently the production to fit the lowest-cost energy hours.

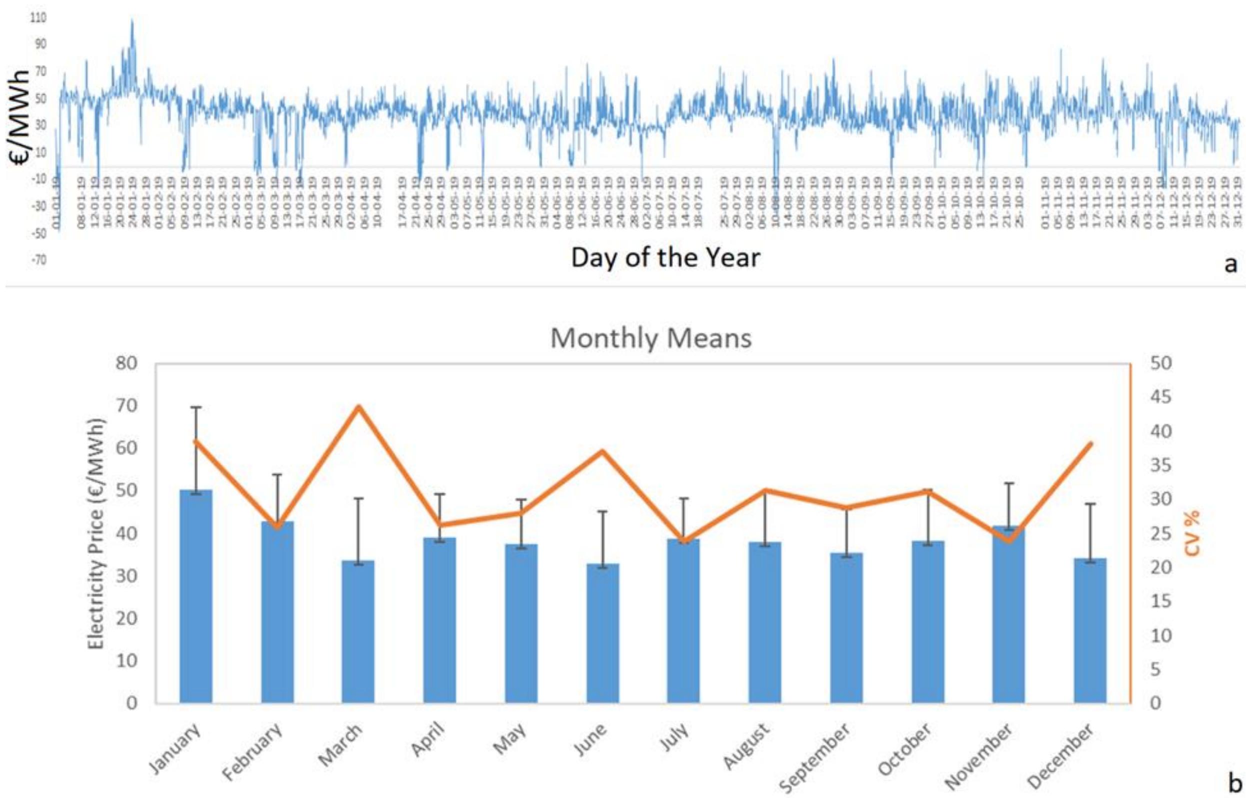


Figure 41. The spot price of east Denmark during the year 2019 [a], monthly mean, coefficient of variation and standard deviation [b].

As a general rule, at the end of December, there is a noticeable negative jump in the energy prices (negative prices are often observed throughout the year). Due to the dates, it can be assumed that this can be related to Christmas holidays. The same pattern is observed on March and can be assumed that is linked to Easter holidays. However, in general, the prices are maintained at similar levels apart from January and February that we notice a significant increase. This can be possibly explained by the decrease of the outdoor temperature and thereafter, the increasing heating demand. The lowest average electricity prices are observed in June (Fig 41 [b]) and the highest in January. The standard deviation has the highest values in March, December and June possibly due to various holidays. The lowest standard deviation is noticed in July.

Figure 42, presents the daily average price values and the standard deviation for each weekday. As it is noticed, there is a significant decrease in the electricity prices during the weekend, possibly due to the reduction of the industrial demand, marking a specific pattern that is followed each week.

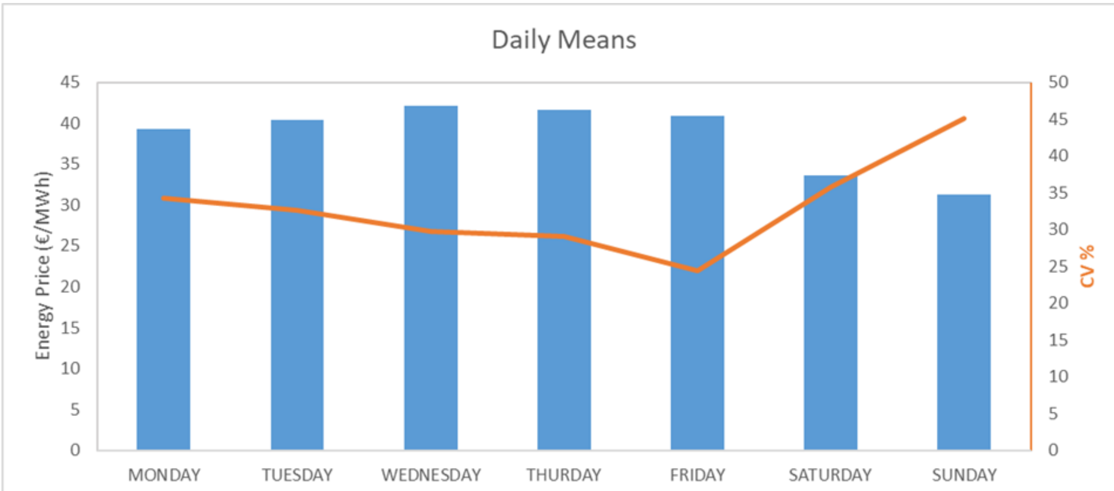


Figure 42. The ahead spot electricity price of east Denmark, coefficient of variation and standard deviation.

To design the algorithm we used the electricity data being provided by the Danish TSO (ENTSO-E, 2020) with an hourly electricity data resolution throughout a full year (from 1-1-2019 until 31-12-2019). Energinet (the Danish TSO) is responsible for securing a balance between production and demand. The main purpose is to create a tool for system operators that helps balance the energy generation to the load at all times during real-time operations (Michalitsakos et al., 2017; Roungkvist et al., 2020).

According to Karabiber & Xydis (2019), a daily pattern that is appeared during weekdays' peaks from 9.00 until 18.00, while during weekends the maxima hours are from 11.00 until 20.00. Furthermore, the peak electricity prices during the weekends are significantly lower in comparison to the corresponding peak hours during the weekdays (Borenstein et al., 2002; Panagiotidis et al., 2019).

Under this scope, and due to the increasing number of wind turbines installed in Europe, bottlenecks are created in energy exchange between countries due to congestions and co-generation, resulting numerous times to curtailments and wasted energy production. Since curtailments and wasted energy production are going to keep occurring while the share of wind energy sector constantly increases, it is of vital importance to examine and develop novel nexus projects. Energy-Food nexus is a model that integrates various markets under one business system that could lead to alternatives of energy solutions' implementation within the cities for food production of the citizens.

4.2.3. Model Design

4.2.3.1. Model Assumptions

In our optimisation algorithm, we use the east Danish power system (DK1), which is the one that provides energy in the whole area of Jutland (including Aarhus and Herning our installation sites). In previous research articles of this dissertation (research paper 4 and 5), the growth rate of basil plants grown in an indoor small-scale environment under intermittent lighting instead of a continuous was tested. The results indicated that intermittent and load-shifted lighting recipe did not significantly limit the development rate, the growth, and the harvest-ready size of the plants. In specific, the experimental analysis showed that plants grown under continuous lighting with 16 hours of daily light (control treatment- C8D16L) in comparison with plants grown under intermittent lighting and limited photoperiod of 14 hours (stress treatment- I10D14Ls) showed no significant differences of physiological and morphological development. The intermittent lighting system was developed with 12 hours of continuous light and 10 minutes of light cycles for every hour of dark (2 hours in total). The whole daily amount of photoperiod that was given to the crops was 14 hours of light with a higher degree of freedom and flexibility in terms of the opportunity for hour-selection and application.

The objective of the present study was to develop an algorithm that will provide an energy saving-protocol for automated artificially-lighted indoor farms. The software tool that was used to develop the code, was MATLAB (2018), version 9.4.0.813654 (R2018a). One of the basic assumptions that we used in order to perform the model development, repeat the commands, and enhance model validity was that the format of the inserted excel file into the Matlab commands should have the form presented in Table 25:

Table 25. Excel format date, time, and price in euro (€) per hour, per day, per month.

DATE	TIME	PRICE (€)
01-01-19	00:00 – 01:00	28.32
01-01-19	00:00 – 01:00	10.07
01-01-19	00:00 – 01:00	-4.08
01-01-19	00:00 – 01:00	-9.91

After the analysis of data collection, deriving from the photosynthetic curve, we did proceed to the assumption that if photosynthetic rate (As) during hourly interval shows no statistically significant difference under intermittent lighting operation compare with the As of plants growing under 16 of continuous light, then the plants can continue growing under load-shifted photoperiod. The moment that the development curve will reach to the curve point with zero tangent, followed by a decrease of the As curve of plants, that is what was named the “inertia point” in plants’ photosynthesis (or else minimum lighting point). Therefore, the thinking behind is that plants have a minimum lighting point in their photoperiodic demand for optimal biomass production and nutritional quality. The meaning of the inertia point was to develop a lighting system for plants with load-shifted photoperiod that subsequently will decrease the energy demand cost of artificially-lighted farms while vertical farms can act as an alternative stream to support the grid by offering high flexibility. To accomplish that, further research is necessary in order to define the detailed plant tolerance limits and the photoperiodic intervals that allow plants to achieve optimum development rate under the minimum electricity costs (lighting demand).

4.2.3.2. Optimal Energy Usage

With the results of the fifth experiment of this PhD research and the lighting protocol that was followed (defining the time intervals), an algorithm was developed that compares the hourly energy price of the electricity market of Denmark and subsequently can shift the light energy demand response to cost-efficient hours throughout the day. The flow chart in Figure 43 was designed and followed to calculate the minimum energy demand of the IVF case in the current study. By assuming the energy price (EP) in EUR (Table 26), the flowchart calculates the sum time of lighting operation and ends up to the daily suggested energy demand.

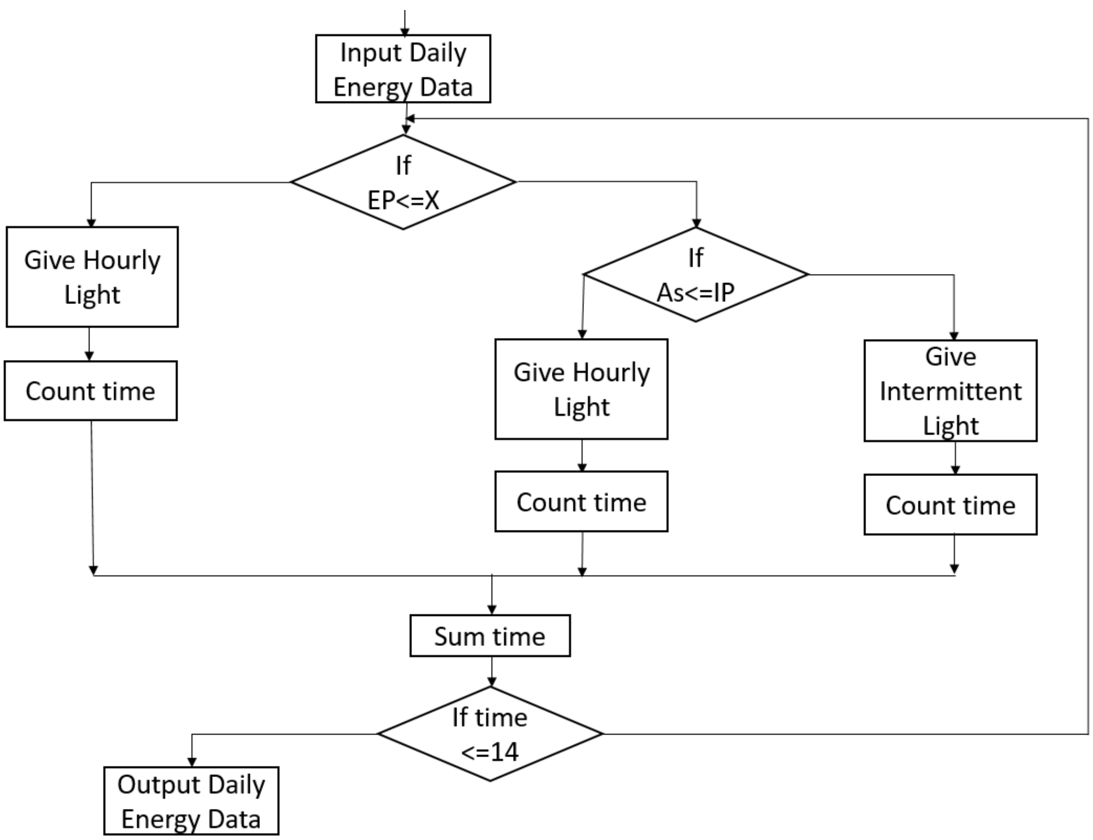


Figure 43. Flow chart of the limited energy demand method.

Table 26. Abbreviation list of the coding orders used in above flowchart (included in Fig. 44)

Abbreviation	Description	Measurement Symbol
EP	Energy Price	Euro (€)

IP	Inertia Point of Plants	
As	Photosynthetic Rate	µmol/m^{2}s

4.2.4. Results

After the design and the implementation of the above optimisation model, the annual energy demand of an IVF in a 24-hour basis lighting schedule is presented. As it can be seen (Figure 44[b]), it is clear that there is a significant decrease in the energy usage during the expensive electricity hours of the day. If we compare Figure 44[a] to Figure 41[a] there is a difference between the energy pricing given by the TSO and the actual energy demand applied in an IVF to maintain the same lighting levels that plants need for their optimal growth.

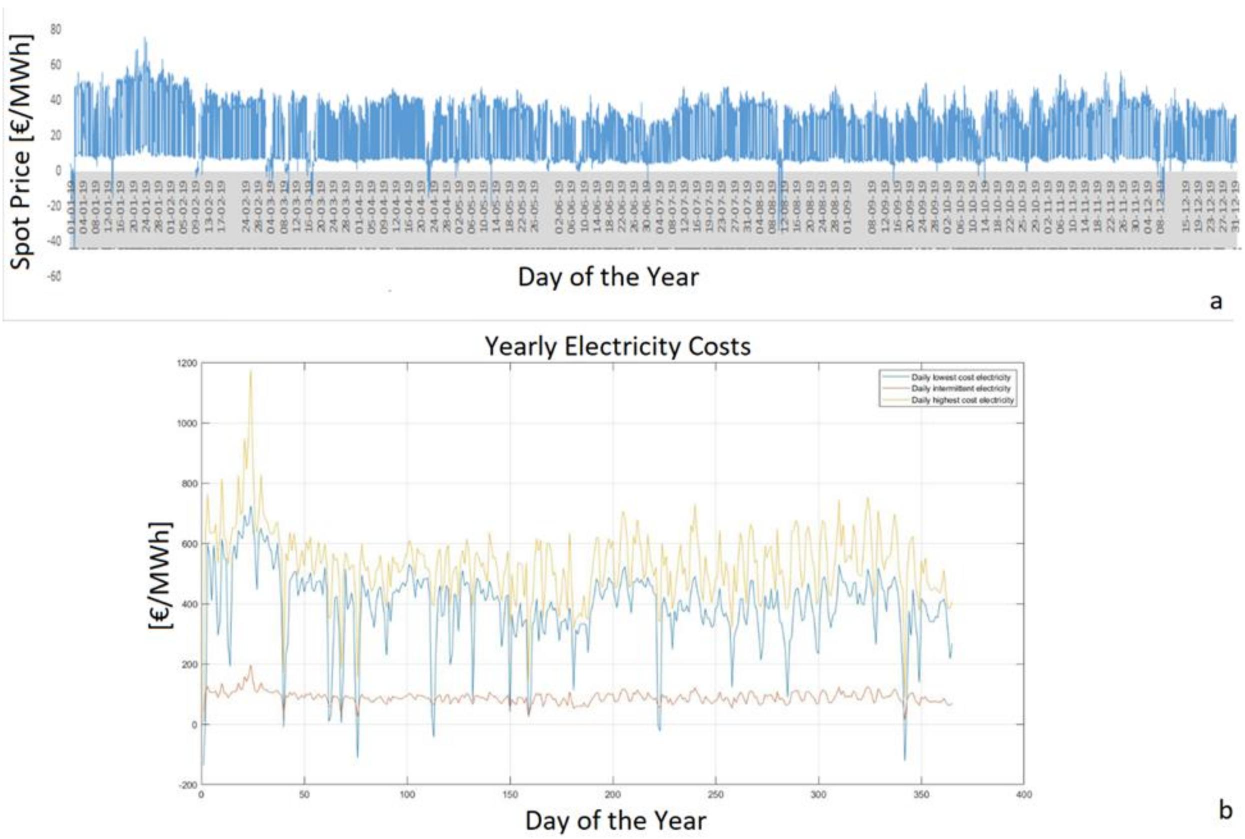
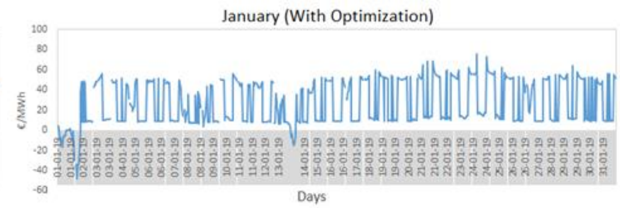


Figure 44. Energy reduction sourcing from shifted energy demand response at an annual range [a], and the different electricity pricing ranges that are followed according to the lighting treatment [b].

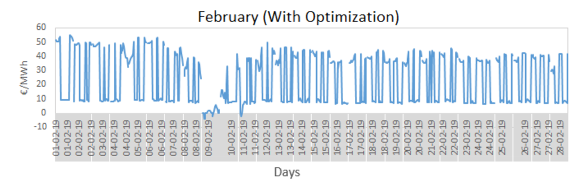
What we observe is that the algorithm identifies the 12 cheapest hours of the day and automatically provides a solution for the 24-hour light operation; while for the 12 most expensive daily electricity prices, it provides only 10 minutes of light operation per hour. According to data analysis we extract from the model implementation, we detect a smarter energy consumption system that takes advantage of the electricity variations of the marginal system. From Figures 45a-45x, it can be seen (in a more detailed way) the monthly energy reduction and the efficient energy use of lighting operation for fresh food production in the urban network with the implementation of the decision-making algorithm.

(a)



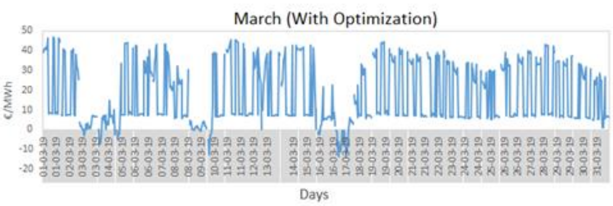
(b)

(c)



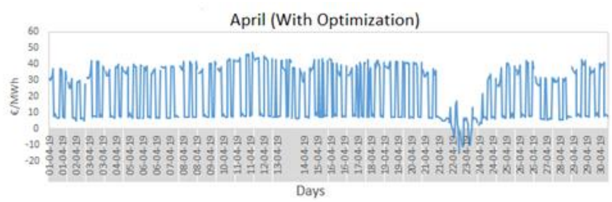
(d)

(e)



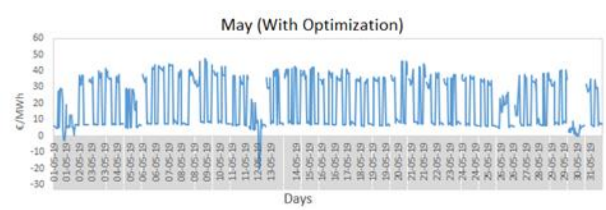
(f)

(g)



(h)

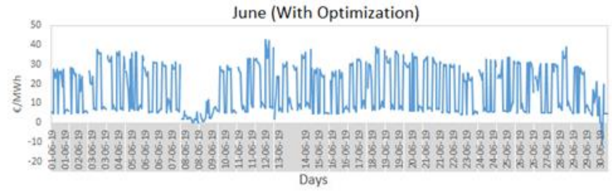
(i)



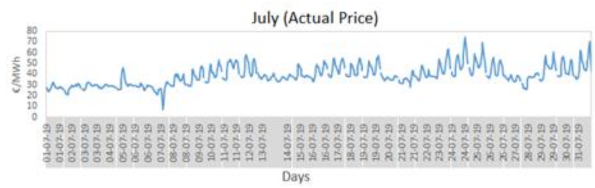
(j)


June (Actual Price)
€/MWh
Days

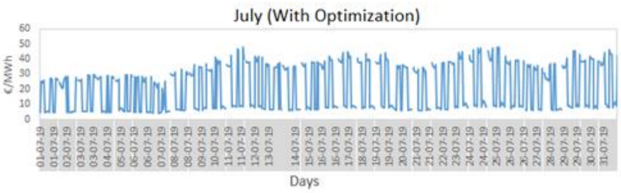
(k)


June (With Optimization)
€/MWh
Days

(l)


July (Actual Price)
€/MWh
Days

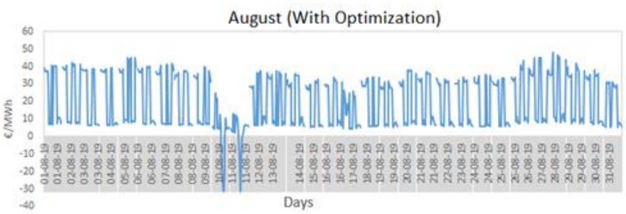
(m)


July (With Optimization)
€/MWh
Days

(n)


August (Actual Price)
€/MWh
Days

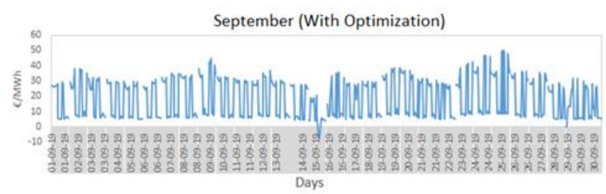
(o)


August (With Optimization)
€/MWh
Days

(p)


September (Actual Price)
€/MWh
Days

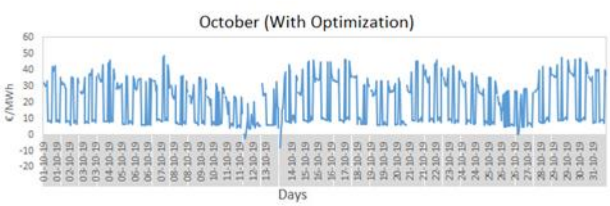
(q)


September (With Optimization)
€/MWh
Days

(r)

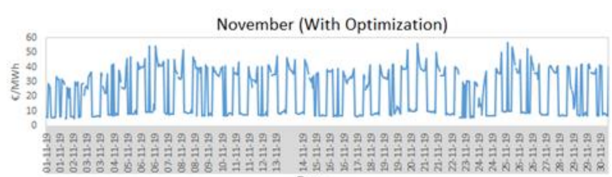

October (Actual Price)
€/MWh
Days

(s)

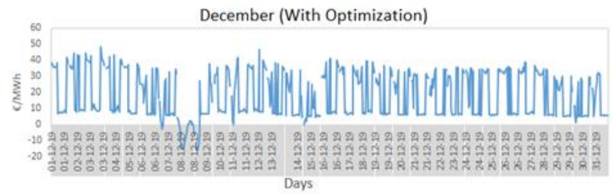

October (With Optimization)
€/MWh
Days

(t)


November (Actual Price)
€/MWh
Days


November (With Optimization)
€/MWh
Days

(u) (v)



(w) (x)

Figure 45. Energy demand cost per month for the year 2019 for east Denmark for the actual price is given by the TSO [left column] and after the shifted energy demand response [right column].

4.2.4.1. Energy Savings and Effects on Operational Costs of an IVF

Shifted energy demand response to more efficient hours for the production is of vital importance for IVFs that demand a lot of electricity to meet the high photoperiodic demand of long-day plants such as the vegetables that farmers select to grow indoor. The significance of artificial lighting was previously mentioned by multiple researchers in the field (Lu et al, 2019; Pennisi et al., 2019) as it can trigger the growth rate, the quality level and the biomass production of plants that grow in a controlled and isolated environment. The selection of the most suitable lighting conditions plays one of the most essential roles in the production and the cultivation process. Photoperiodism (as also light intensity and light quality) can highly affect plants' performance. The majority of the companies operate LEDs for 16 continuous hours daily when it comes to indoor basil production, while usually LEDs switch on during the nighttime that energy prices tend to be lower (in comparison to the daytime). Based on a previous research (Avgoustaki & Xydis, 2020b), a rather detailed scenario-based cash flow model for an IVF of 675 m^2 growing area that uses artificial lighting as the only source of light radiation for the plants is presented. The results of the operational expenses of the IVF case are presented in Table 27, and they are compared to the operational expenses that result from the energy optimisation algorithm of this research project. The purpose is to examine and quantify the importance of the energy model in terms of sustainability, energy efficiency as also the profitability that offers to indoor urban farms that use artificial light for food production.

Table 27. Energy savings from IL operation in the IVF per month.

Month	Operating Expenses (OPEX) Continuous (€)	OPEX Intermittent (€)	Reduction Percentage	Final Cost Savings (€)
January	23.610	19.444	-18%	4.166
February	18.666	15.455	-17%	3.211
March	16.287	12.598	-23%	3.688
April	19.092	14.945	-22%	4.147

May	18.914	14.642	-23%	4.272
June	16.120	11.875	-26%	4.244
July	19.363	15.553	-20%	3.810
August	19.284	14.665	-24%	4.618
September	17.188	13.036	-24%	4.152
October	18.089	14.316	-21%	3.772
November	18.654	15.736	-16%	2.188
December	15.588	12.852	-18%	2.736
Total	**220.861**	**175.117**		**45.738**

4.2.5. Policy Implications

Operating IVFs without a concrete and profitable plan makes no sense. There are several reasons that justify moving from the field to indoor production and cost and efficiency are two of those. It was proven for basil, that by shifting electricity demand according to electricity pricing, it can result in significant cost reductions throughout a year (approximately 22%) for IVFs under a flexible load system. This result came out independently of the outdoor climate or the area where the vertical farming unit is installed.

A mass deployment of IVFs can promote vegetables and fruits production within cities creating agro-related jobs within the urban environment. That could eventually lead to different land occupation and usage compared to now. Yet, this cannot be said also for the traditional farming of wheat, barley etc. which they will continue need to be produced in large outdoor fields until it is proven that it could become viable, both technologically and financially, to be produced indoors with advanced technology and special design.

What can be said though, is that for basil and products similar to basil, such as mint, spearmint, cherry tomatoes, lettuce etc., that they can be produced in cities contributing to significant minimization of food transportation that burdens environment with huge CO_2 emissions. There will not be a need for transporting these products into cities since they will be produced inside the demand centres.

Last, but equally important, is the fact that via a large-scale deployment of such systems the TSO will have the opportunity to absorb high amounts of intermittent resources due to the offered pricing policy. In modern systems, various demand response programs will be offered. When there will be an abundance on wind-based produced electricity, the TSO will offer low prices and therefore, IVFs can use and provide the required light or store the energy for later usage. When the prices will be increased due to insufficient renewable energy sources, then the IVFs operators can offer the required darkness to the plants – saving from consuming expensive electricity. Additionally, countries that are highly dependent on renewable energy such as Denmark enforce a market model that the marginal prices will present high fluctuations due to existence of multiple flexible units (Bistline, 2017; Höschle et al., 2017).

4.2.6. Cash Flow Analysis: Scenarios Proposed

This subchapter presents the influence of flexible-load intermittent lighting in the revenues, the IRR, the NPV and the return period of investment under multiple proposed financial schemes of vertical farming. Different scenarios were formed and tested based on LSEDR. The Operating Expenses (OPEX) of the two examination cases, under intermittent lighting operation and under continuous light application are presented in Table 27. Due to lack of governmental subsidy from Danish authorities, an approved loan was assumed to cover 50% of the total initial investment (the other 50% is equity funding) taking only into consideration the IVF basic scenario. The loan was fully amortised over 10 years, following periodic payments into a sinking fund, depending on the market rules. The calculations for the operating cash flow (OCF) will repeat the same equations (10-19) presented in subchapter 2.2.4.

The scenarios presented in Table 28 (part 1 & 2), reflect the productivity and profitability of an IVF case that apply load-shifted IL schedule. The “Equity/loan/(subsidy) (price)” for scenario 1 states “50-50”, which means that 50% of the funding comes from equity financing and 50% from a bank loan (0% funding from other sources) at a basil price of 7.37 €/kg. In the default examined case, the “50-50” (equity-loan) approach has been used. The 20-year cumulative gross profit and OPEX were calculated at 6,418,264€ and 3,291,238€ respectively, with sweet basil’s purchase price at 7.37 €/kg. The IVF project cost was estimated at 321,763 €, and for the investment, an interest rate of 6.50% was estimated. The NPV was calculated to be 1,186,529 € and the IRR to 47.91 %, with the payback period down to three years. In scenario 8, “20-50-30”, indicates that 20% of the funding comes equity financing, 50% from a bank loan, and 30% from other sources (e.g., crowdfunding) at a basil price of 7.37 €/kg, while scenario 5, “50-50-6.37” indicates 50% of the funding comes from equity financing, 50% from bank loan and the basil’s price is 6.37 €/kg.

The cash flow analysis shows that the 20-year cumulative gross profit significantly increases while we increase the wholesale price of sweet basil but also that the 20-year cumulative OPEX and the total costs of the project remain stable. It is noticed that for the scenarios of “50-50”, “40-50-10” and “50-40-10” (that all include a wholesale price of 7.37€ in the calculations), there are small differentiations in the IRR and NPV index with an equal payback period at three years. The comparison with the data from Table 14 of this dissertation between the OPEX under continuous light and OPEX under flexible IL (Avgoustaki & Xydis (2020b), shows a significant reduction of one-year payback period, compare with the payback period of four years if the IVF does not operate with reduced load-shifted photoperiod system.

It should be noted that when we examine the profitability and viability of the IVF case even with a wholesale price of 5.37€/kg and 6.37€/kg, the business is viable with a payback period of eight and four years respectively (but not with a lower price). Furthermore, the comparison between the two different lighting methods of IVFs suggests that for example under the continuous lighting, the pricing scheme of “50-50-5.37” the payback period of investment reaches the 21 years, while under flexible-load lighting, the scenario “50-50” presents 4 years of payback period and for the “50-50-6.37” scenario, there is a 6-

year payback period of investment. In comparison to the extracted values that result in this paper from the cash flows scenarios with energy optimisation application, we notice that payback periods presented in Table 28, show a significant reduction of the investment payback period compared with the results from same scenarios without the proposed energy optimisation. TO be more specific, flexible-load lighting model leads to significant reduction of payback of the investment results with 13 years ("50-50-5.37") to two years ("50-50-6.37") and one year ("50-50") for the different case scenarios. Additionally, we examined also extreme business plans that apply the LSEDR model, constitute from 70% equity, 30% of the total budget from bank loan and the same 5.37€ wholesale price of basil, resulting in the project's IRR 10.94% which is significantly increased from the resulting 0.04% IRR of the same scenario without the energy optimisation model application.

For Scenario 6 (with an equity of 25%, bank loan of 75% and interest rate of 6.25%), results are significantly improved compared to the values of IRR before the proposed lighting optimisation (IRR 63.3% and 3-year payback period), as now they result in IRR of 90.74% and two years of payback period. Finally, in the described scenarios that include a supplementary funding ("20-50-30"), the cash flow analysis indicates that the business plan is very profitable with an NPV value around 1.5€ million, IRR almost 100% and two years payback period! Figure 46 presents the results of NPV and IRR of the updated funding scenarios of IVF with reduced and load-shifted photoperiod.

Table 28. Vertical farming scenarios and cash flow analysis (part 1).

VERTICAL FARMING	SCE_1	SCE_2	SCE_3	SCE_4	SCE_5
Equity-Loan-(Subsidy)-(price)	***50-50***	***40-50-10***	***50-50-5.37***	***50-50-8.37***	***50-50-6.37***
20-years cumulative Gross Profit [€]	6,418,264	6,418,265	4,676,537	7,289,128	5,547,401
20-years cumulative OPEX [€]	3,319,624	3,319,624	3,319,623	3,319,623	3,319,623
sweet basil [Price/kg]	7.37	7.37	5.37	8.37	3.37
Project Cost [€]	321,763	321,763	321,763	321,763	321,763
Subsidy/Alternative Funding	0%	10%	0%	0%	0%
Loan	50%	50%	50%	50%	50%
Equity	50%	40%	50%	50%	50%
Interest Rate	6.50%	5.80%	6.50%	6.50%	6.50%
NPV [€]	1,186,529	1,259,356	456,955	1,550,781	822,277
Project IRR (%)	47,91%	62,12	13,85%	65.8%	30.56%
Period Payback (Yrs)	3	3	8	3	4

Table 28. Vertical farming scenarios and cash flow analysis (part 2).

VERTICAL FARMING	SCE_6	SCE_7	SCE_8	SCE_9
Equity-Loan-(Subsidy)-(price)	***25-75***	***50-40-10***	***20-50-30***	***70-30-5.37***
20-years cumulative Gross Profit [€]	6,418,264	6,418,264	6,418,264	4,676,537
20-years cumulative OPEX [€]	3,319,623	3,319,623	3,319, 623	3,319,623
sweet basil [Price/kg]	7,37	7,37	7.37	5.37
Project Cost [€]	321,763	321,763	321,763	321,763
Subsidy/Alternative Funding	0%	10%	30%	0%
Loan	75%	40%	50%	30%

Equity	25%	50%	20%	70%
Interest Rate	6.25%	5.90%	4.40%	6.70%
NPV [€]	1,138,607	1,278,274	1,427,699	507,733
Project IRR (%)	90.74%	50.83%	99.8%	10.94%
Period Payback (Yrs)	2	3	2	9

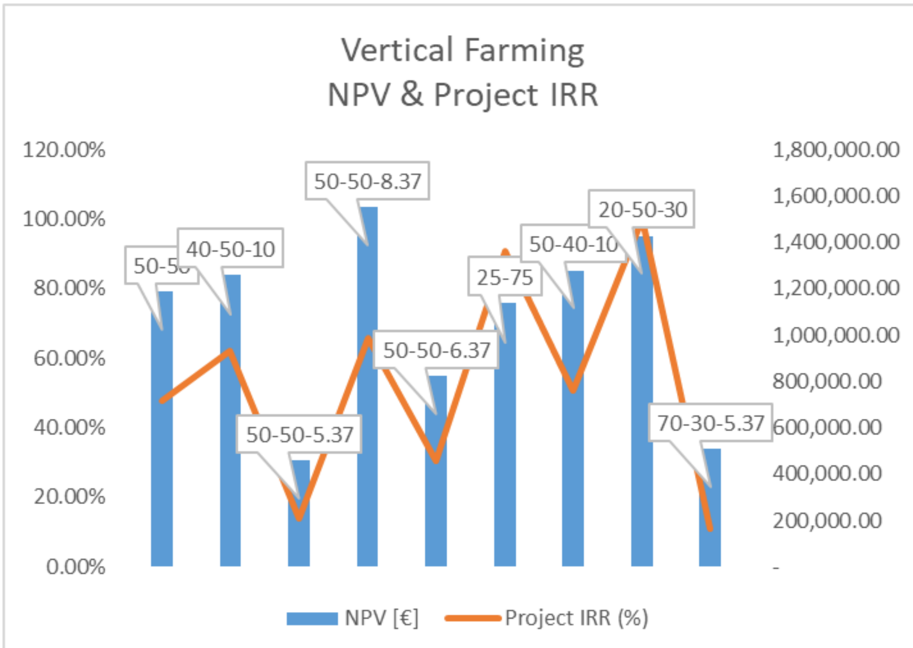


Figure 46. Comparative results of different scenarios of an IVF.

4.2.7. Conclusions

Using a partial balance model of the electricity market, we could extract some further insights concerning the financial benefits of different electricity pricing schemes for indoor farming. Our case for data acquisition was Denmark, since we were able to collect and analyse the interaction between demand response among multiple levels of electricity prices (entsoe, 2020) and food production in indoor farming as also due to the high renewable energy participation in the grid offered by multiple units that lead to significant marginal price fluctuations. The results indicate that load-shifted IL strategy in indoor farming can promote and ensure an efficient response and high motivational rate for indoor farmers to shift the demand load. Our results suggest that it would be recommendable to implement and apply fluctuating lighting schemes in indoor farms, to develop a more sustainable and viable demand response scheme.

Apart from optimising the properties of lamps and the light dimensions, it is of vital importance to develop techniques that can optimally use the energy demand of a fluctuating grid such as Denmark's without affecting negatively crops' quantity and quality. Based on the presented protocol for load- shifted energy demand response, it was found that the electricity reduction savings were between 16-26% (for all months), which in practice significantly decreases the annual cost from lighting. It is clear that time-fluctuating electricity prices can lead not only to the reduction of the procurement costs, but also to meeting the capacity reserve requirements for the optimal production. The incorporated demand application from indoor farms will allow more flexibility adjustments avoiding the unnecessary production generation, production costs, and ultimately promote a smarter urban environment introducing a new multivalued business model that could enhance the industry and couple IVFs with the grid needs' under a holistic energy-food nexus approach.

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5. A roadmap of design and operation principles to limit the challenges of vertical farms in Denmark

The final chapter of this dissertation reflects and concludes on the main findings from the six articles that are presented in this PhD dissertation regarding answering the three research questions. The purpose of this chapter is to provide sufficient argumentation towards the main research enquiry: **"What are the techno-economic benefits, risks and potential of indoor vertical farms under a Food-Energy Nexus in the Nordic context?"** Apart from the six research papers that have been presented in the previous chapters, this PhD thesis includes some additional perspectives of supplementary work that was conducted during the three-year PhD project and provide supportive knowledge in this topic. This chapter addresses the outlook and future research that would benefit the expansion of vertical farming in the Nordic countries and mainly in Denmark and proposes a more holistic and viable Energy-Food nexus solution.

5.1. The specifications and economics of indoor vertical farms

The second chapter of this dissertation introduced two published papers in respond to the first research question: *"What are the benefits and challenges of indoor vertical farms?"* The first article explores the concept of vertical farming and compares the efficiency level of the resource inputs and outputs in IVFs and relates them with those from the two major agricultural systems for food production, open-field farming and greenhouses. Under this scope, the article examines the methods and the generic pattern approaches of different agricultural techniques in terms of sustainability, efficiency and food safety, which are summarised below:

- The operation of IVFs is totally independent of soil and solar radiation, and as such may be built in every location and size.
- The growing environment in IVFs is not affected by severe and unpredictable outdoor weather conditions like rain, hail and wind; contributing in particular to reduced vulnerability and variability of crops' quality and quantity.
- Soil fertility status neither affects the productivity capacity of crops growing in IVFs nor hinders food supply.
- In comparison with open-field agriculture, vertical farms present over 100 times higher productivity per year per unit land area by implementing multiple layers, optimal environmental control and achieving minimal crop losses from pests and insects contamination. At the same time, vertical farms occupy the minimum land area is for producing fresh and nutritious food directed to urban consumers.
- IVFs achieve year-round production with maximisation of the harvested yield compared with the longer crop cycles and limited production from outdoor farming and greenhouses.
- In IVFs, crops are free from pesticides, herbicides and fertiliser use.

- The limited bacterial activity of vertical farming crops compared with traditional farming products contributes to longer product shelf-life.
- Vertical farms present high level of flexibility in relation to their installation in indoor spaces and the close-distance to urban consumers, leading to significantly lower fuel consumption for transportation purposes but also reduced carbon emissions' footprint of the products due to the elimination of food miles.
- IVFs present high RUE with minimum emission of pollutants.
- IVFs have no agricultural run-off by applying close loop that allow recycle, reuse and recirculation of both water and nutrients to the crops.
- IVFs use 80-95% less water compare with traditional farming (farm facilities that apply drip irrigation are excluded). The high level of airtightness in IVFs can provide 30-50 times higher WUE compared with that in greenhouses, due to the high level of water-saving that can achieved by collecting and reusing condensed evaporated water for irrigation purposes (Kozai, 2016).
- IVFs provide higher control of food safety and security, because they follow specific design principles and intensive care unit design, construction and operation that exclude most of the known crop treats (insects and microbial pathogens).
- IVFs promote ecosystem restoration as for most of the crops that grow indoor, the relevant maximised acreage that would be occupied by outdoor farming techniques, can now be converted into hardwood forests, minimising the ecological footprint of agriculture.

Since this literature review does not provide any economical information about the construction and operation of a new vertical farm, deemed essential to quantify the balance between the different compounds of IVFs. Thus, the second research paper examines the investment volume requirements for vertical farming concerning both the resources flows but also the CAPEX and OPEX and finally, the profitability rate under various financial schemes.

The second journal article presented in this PhD dissertation, introduces the economic data resulting from the development and comparison between an IVF case and a GH case. Under this scope, the findings from the techno-economic analysis of the two case studies followed by different cash flow scenarios are presented below:

- Light, apart from the influence on plants' development and growth, has a significant effect on both the initial and the running production costs of an IVF due to the multiple hourly operation and the installation of numerous light sources. LED lamps perform significantly higher efficiency and efficacy compared with other light sources (HPS, fluorescent lamps) and other numerous advantages (robustness, long-lived, lightweight etc.), nevertheless; at present almost 20 kWh of electrical energy is consumed to support the production of 1 kg of fresh basil (Kozai, 2016). Further improvement of the economic value per kilo of produced plants or per kWh of electric energy is required.
- Denmark is a country that can benefit from the high renewable energy production mainly sourcing from wind energy (both from onshore and offshore wind turbines) that numbers almost 50% of

the total energy usage. At the same time, Denmark participates in Nordpool that delivers power tradings across multiple European countries while by providing the day-ahead and intraday trading prices, manages to offer high flexibility and improved energy efficiency (by 7.6%), enhanced intrusion of renewable energy (by 35%) and reduced emissions (by 34%) (Lin et al., 2017).

- The comparison between a GH and an IVF facility showed significant differences in the initial capital investment amounts, as the IVF require approximately double amount of money to cover the initial investment mainly because of high demand for artificial lighting hardware installation (LEDs), lighting connections and electrical energy distribution. Our model analysis suggests that LED capital expenditures consist 65% of the total CAPEX of the IVF's initial investment, which is 33% greater compared with the LED CAPEX of a greenhouse facility that uses only supplementary lighting to maximise their yield production per unit of land area.
- In contrast with CAPEX, it is observed that the production cost of an IVF is almost the same with the production cost of a greenhouse for that size of farm units. We could conclude that IVFs consume significantly lower amount of water and nutrients. Furthermore, a significantly lower heating demand compared with greenhouses is observed due to the LEDs operation that convert into heat energy the remaining electrical energy (from what plants fix as chemical energy) in the growing area. In well-thermally insulated indoor farms even in very low outdoor temperatures, heating costs are really low while cooling is mainly connected with the LED operation (Beacham et al., 2019).
- The IRR and NPV of the IVF facility indicate that this farming model could offer a sustainable and profitable farming strategy in Denmark for channeling in the market fresh, nutritious and locally produced vegetables for the urban consumers. The cash flow analysis shows that investors could receive back the amount of their investment in between a period of 2 to 6 years when the wholesale price of basil is from 6.36 €/kg to 7.36 €/kg. It should be noted that the average wholesale price of organic basil varies in between the same limits. Additionally, retailers such as big supermarket chains and grocery stores apply a plafond price for farmers that cannot be exceeded in order these companies to maintain their profitability, making fresh greeneries' production a low profit margin production market that at the same time comes with high demand for initial and operational expenditures.

5.1.1. Other Perspectives on Research Question 1

Other studies were carried out throughout this PhD project that bring clarity to Research Question 1. Avgoustaki & Xydis (2020) is a systematic bibliographic review of 100 publications in international journals, conferences, reports and book chapters that analyse the design requirements, the technologies, the specifications and the challenges that vertical farms have to confront and solve for further spreading of this novel type of farming around the globe. The purpose of this paper was to explore the topic of IVFs and analyse it, by dividing it into sub-sections that facilitate the exploration and examination of such a complex and demanding subject. This study seeks to interpretatively broad the understanding of IVFs, reveal patterns and methodologies in peer-reviewed publications, reveal the necessities for further improvement and define clear research questions and hypotheses for future experimentation. Under this scope, this paper presents a systematic literature review of different urban farming model applications focusing in three major elements:

a) The technical requirements, equipment and growing systems that enable indoor agriculture under the most efficient and sustainable way,

b) The energy requirements of production systems, energy distribution and solutions for energy's efficiency optimisation and

c) The technological innovations that focus on improving crop management in indoor and controlled-environment agriculture.

The last decade, is observed an increasing demand and application of multiple urban farming cases in all over the world while at the same time, the scientific community shows a growing interest for the study and optimisation of environmental conditions, development of new technological solutions, digitalisation and RUE in indoor horticulture. This research explores the challenges and the bottlenecks of IVFs based on systematic selection of peer-reviewed literature and the main findings are presented below:

- Increased production costs of IVFs highly affects the profitability and investment payback period of new high-equipped and automated IVF facilities. Electricity and labour are the most costly elements of the total production in an indoor urban farm (Figure 47).
- The multiple hourly operation of LED lamps in IVFs (between 14-24 hours/daily, depending on the crop species and the growth stage) provokes high electricity demand that focus on maximising the production and quality (colour, taste and texture) of plants and at the same time reducing crop cycles. The LED operating cost of IVFs vary between 30-40% of the total production cost (Figure 48), when only 1-2% of the electrical energy is finally fixed as chemical energy by salable parts of plants. For this reason, it becomes obvious that additional optimisation is required to reduce further the electrical energy cost and the electricity consumption per kilo of salable plants. Further improvements on the three dimensions of light (intensity, spectrum selection and photoperiod), the technical characteristics in the farm facilities such as well-designed reflectors, the environmental control (temperature, humidity, CO_2 concentration and nutrient solution) and cultivar selection can maximise the salable part of plants and increase the revenue streams of the farms.
- One of the major challenges highly addressed from various researchers is the optimisation of energy demand but also the type of energy usage. Electricity generation from renewable energy and biofuels is one of the major priorities in the energy policy strategies in both national and global level. The combination of green energy with novel technologies, techniques and materials can lead to significant reductions in the energy footprint of IVFs, given the fact that until now 1 kg dry weight of lettuce requires an input of 247kWh in an IVF (Graamans et al. 2018). Renewable energy such as wind, solar and geothermal are environmentally friendly, require low maintenance, do not incur fuel expenses and constitute a cost-effective and efficient form of energy for the operation of indoor production areas.

- Labour cost values around 30-35% of the total operational cost of IVFs due to the necessity for numerous handling and delicate operations that are conducted manually but also due to the necessity for experienced and specialised employees. According to Kozai (2016), it is estimated that for a 15-layer IVF with floor area 10,000 m^2, 300 full-time employees to cover the handling operations of the farm facility are required. In modern IVFs that reach a production capacity of approximately 10,000 heads of leafy greeneries, there is an increasing demand for automations and robotics that can handle some manual operations such as transplanting, harvesting and logistics. At the same time, investments in hardware and software solutions apart from handling operations, are involved in data collection processes such as advanced and mobile robots that provide remote sensing, image analysis, cloud computing, 3-D modelling and big data analysis operations. Under this scope, indoor farmers have access to a plethora of data that can improve plant growth, resource consumption, transplanting, harvesting but also logistics, shipping and sales.
- High land-price is one of the most controversial risks that are associated with the profitability of indoor farms. More specific, land price is in general higher in urban areas; nevertheless, indoor urban farms have high installation flexibility as they can be built in underground spaces, abandoned buildings, and they are not affected by shaded, infertile and idle land areas. IVFs present high land use efficiency, as they occupy almost 1% compare with open-field agriculture and 10% compare with the land that greenhouses require for the same production volume.
- Finally, another barrier that vertical farms face is the limited selection of cultivar species that are suitable for indoor growing. Currently, the majority of IVFs focus on growing leafy vegetables, fruits, herbs, roots and microgreens, although the cultivar selection is expected to increase with the reduction of production costs and further technological development. The cultivar selection is highly influenced by the planting density, the size of crops (height of both root and shoot with unfolded leaves) and purchase price value. Further optimisation is necessary in order to upgrade the list of crops that could be commercially grow in IVFs, not only for fresh salad consumption but also as raw materials.

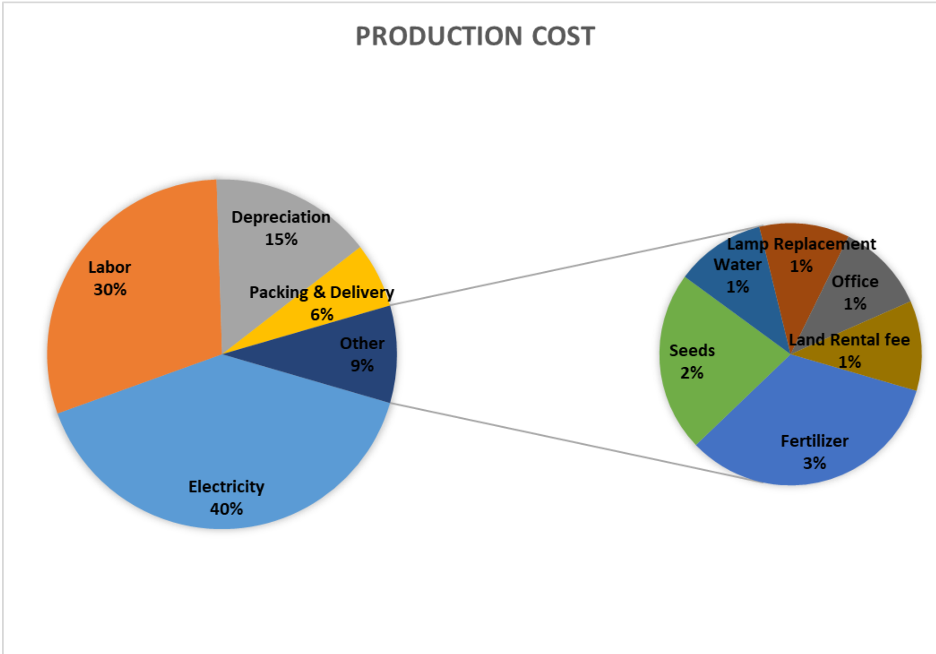

Figure 47. Production costs by components in an IVF (Note: IVF production capacity of 550 kg fresh weight of lettuce per day)

Data collection, data mining as well as development and promotion of innovative software solutions provide advanced decision-making and production management to farmers that can accomplish further improvements on the energy efficiency of their facility and create new opportunities for data-driven autonomous farms. For further energy demand reduction in indoor growing areas, the use of artificial light sources under the optimal light quality, intensity and duration is of vital importance. Additionally, further energy savings can occur by well-designed lighting reflectors, which can maximise the ratio of light energy that plants receive to the light energy that is actually emitted by lamps and promote light uniformity in all leaves' surfaces. Optimisation on the transplanting schedules and/or automated spacing could further increase the density of plants in the culture panels, providing yield maximisation under the same volume of electricity consumption. Finally, several types of controllers and robotic solutions are continuously developing to provide further improvements on the cultivation systems and the environmental control of the farms. Such novel controllers consist of pioneering computer modelling for monitoring and controlling the motion of plants by image recognition, sensors and signalling.

Additional research for this PhD dissertation and vertical farming exploration has also been provided by the published research paper conducted by Xydis et al. (2020) that examines if and how wind energy microgeneration by small-scale wind turbines could sufficiently cover the energy demand of small-scale indoor urban farms. The purpose of this paper is to research the ability of the grid system to provide an alternative revenue stream for the wind energy companies and in parallel support with fresh fruits and vegetables the local community. For this analysis, three of the most frequently cultivated crops in under-coverage agriculture (tomato, lettuce and basil) are examined and compared based of their profitability under multiple financial scenarios. This research study explores the possible alternatives for small-wind and hydroponic/horticulture investors to improve their business case and at the same time sustain a critical investment ecosystem. The increasing demand in European governmental authorities for addressing smarter solutions, creates the necessity for cheaper and more efficient energy systems with initiative paradigms and balanced investment incentives. Towards the target of green transition, this research examines the idea of a multiple revenue stream business model that can make income from the already existing Feed-in-Tariff (FiT) supporting mechanism for the small-scale wind turbine market while at the same time, promotes the transition from open-field agriculture to controlled-environment agriculture. In this content, this research examines if mass deployment of IVFs could be a viable option for the development of a small-wind turbine project, where 20% of the generated wind energy could cover local vertical farming units while the 80% could be offered to FiT to support the mechanism operation under a profitable price. The cash flow analysis under specific FiT schemes showed positive results with successful business projections ensuring profitability to stakeholders. Basil and lettuce showed higher profitability compared to tomato crops as the IRR index for tomato crops varied between 2.5 to 11.3% among the different scenarios. On the contrary, basil and lettuce grown under the described smart energy grid resulted with IRR index, which could even exceed 100%. The payback period of investment for these two crops vary between 6 to 2 years for the scenarios of 5% to 20% wind-turbine energy generation respectively (the remaining percentage of each case is offered for the FiT mechanism under difference pricing schemes). Under the extreme case scenario that the small-scale wind turbine FiT reached a selling price of 80 €/MWh, the IRR of lettuce and basil maintain their overall profitability, while the IRR for tomato showed negative results for the majority of the examined scenarios. It should be noted that the project is viable for the case of basil and lettuce with 20% wind energy generation and 80% of energy that is offered to the FiT even when the prices that are offered to the small-scale wind turbine are equal with the market's marginal price. This research publication explores the concept of smart energy grid that supports local fresh food production under a smart city/region of a multiple revenue business approach facilitating such an implementation for both the public and the private sector. This paper examines the possible transformative alternative for investors of small-wind turbines and indoor farming systems that want to increase their business case. In that way, a critical investment ecosystem can be maintained, contributing on smoothening the imbalance of investment initiatives by addressing a smarter and cheaper energy system, while providing locally grown herbs and vegetables for the citizens.

As such, in answering Research Question 1, these studies further explored the concept of vertical farming while researched the benefits, the barriers and the opportunities and helped the researcher to develop the strategy and the protocol designs for the following experiments that focus on researching and optimising the energy demand for indoor food production.

5.2. The risks associated with artificial light operation

The third chapter of this PhD thesis introduces two journal articles answer Research Question 2: *"How can the risks associated with the artificial light operation in indoor food production be limited?"* For this purpose, the third article of this dissertation presents the experimentation method and results of basil plants grown under different photoperiodic treatments. Basil plants were the selected cultivar, and they grew indoor under monitored environmental conditions of approximately 22°C air temperature, 35% relative humidity and 425 CO_2 concentration. Three different experimental sessions were performed with the following lighting diversifications, the control treatment (P8D16L) where plants grew under 16 hours of continuous photoperiod, the second treatment (stress treatment 1 – P10D14L) where plants grew under 14 hours of daily continuous photoperiod and the third treatment (stress treatment 2 - P11D13L) where plants grew under 13 hours of daily continuous photoperiod. Daily measurements of various plant growth parameters and post-harvest measurements were subjected under statistical analysis to examine and evaluate plants' responses under reduced photoperiodic schedules. The main findings of this research are listed below.

- Photoperiod needs further optimisation due the significant role on plant biomass production, leaf elongation, size, leaf sequence but also can highly influence seed germination processes, plant height, flowering and regulation of transcription. Improvement on photoperiod can lead to significant energy demand reduction for an indoor cultivation area but also influence plants to develop specific physiological and morphological characteristics.
- The 3 hours of reduced photoperiod (P11D13L) showed significant negative impact on basil plants' quality and quantity and statistical analysis of daily measurements showed significant reduction of the chlorophyll content and the dry biomass production, compared with the control treatment – P8D16L. Based on these results, could conclude that 13 hours of photoperiod can negatively influence the growth and development rate of basil plants. Therefore, we had to reject the 13 hours of daily photoperiod as a possible solution that could provide the desired reduction of electricity demand in indoor growing areas; and thus, we excluded this treatment from our future experimental research.
- The 2 hours reduced photoperiod (P10D14L) showed a positive impact on basil plants' quality and quantity. In more details, plants with 14 hours of daily light duration showed a significant increasing rate on their chlorophyll pigments during the whole experiment. Chlorophyll is considered an indicator for the photosynthetic efficiency as also a significant measure of the physiological responses and the satisfactoriness and purchase power of basil (Tanaka, 2000; Gonçalves et al., 2008) due to chlorophyll's ability to regulate the photosynthetic antenna of plants. Continuous growth and daily evaluation of chlorophyll content and various pigments indicates that plants developed satisfactory protein complexes of chlorophyll under the reduced photoperiod of 2 hours that allow them to absorb enough light radiation and follow an increasing rate for indoor basil production.
- The equal development of Chl *a* under 14 hours of photoperiod in comparison with the 16-hours implies could be a combined effect of Calvin cycle, photoreceptors and environmental conditions that promoted stomatal opening and CO_2 absorption, indicating that basil plants continued the photosynthetic process and development with less energy consumption under specific period of time. Further molecular biological research is required to reveal the metabolic responses of basil plants that regulate photosynthesis, respiration and transpiration.

- No significant differences in shoot biomass of plants grown under 14 hours of photoperiod compared with the control treatment (P8D16L), indicates absence of difficulty on receiving and processing sufficient amount of light radiation and dry matter synthesis (Khan et al., 2016). Furthermore, LA measurements showed that shorter light radiation, reduced leaf size and increased the number of leaves' pairs with smaller leaves per plant. Plants under reduced photoperiod developed plants with smaller leaf area that indicates a faster rate of water loss and carbon assimilation and could give them the adaptive advantage to develop smaller light cycles with high intensity (Wang et al., 2019).
- The resulted energy savings between the 16 hours and the 14 hours of photoperiod raise up to 15.5% for an indoor small-scale growth chamber with the use of a 90-watt LED lamp that was the only source of light energy. Further exploration of reduced photoperiod in large-scale vertical farms is essential to calculate the exact inertia point of basil crops under reduced photoperiod and project the potential energy savings.

The reduction of energy demand for indoor cultivation is one of the main goals of this PhD research and continuously the design and development of a lighting methodology that can use the electricity price fluctuations of modern energy systems in order to achieve high EUE. Energinet, the Danish energy transmission system that provides hourly electricity prices for consumers, allow users to perform very flexible consumption decisions. Under this scope, it becomes clear that even if indoor crops showed a positive reaction under the two-hour reduced photoperiod, still the structure of lighting operation is very concrete, robust and long-lasting, leading to really limited resilience for selection or rejection between the hourly electricity prices. Such an approach was sought to be introduced in the fourth journal paper of this dissertation, where the 14-hours of daily photoperiod were divided into short hourly intermittent lighting cycles and responses of plants were monitored, and their results were evaluated via statistical analysis. The purpose of this paper was to examine the hypothesis that indoor plants could grow under a flexible, load-shifted lighting demand response with the optimal plant quality and quantity. For this reason, physiological responses of basil plants under reduced and intermittent photoperiod were monitored in a daily basis and compared with that of plants under 16 hours of continuous photoperiod. The main findings of fourth research paper are listed below:

- Substrate temperature is highly affected by light intensity (Stone et al., 1999), nevertheless in our results we observe that air temperature and substrate temperature are approximately at the same level during the intermittent lighting mode causing no abnormalities in plant growth. Furthermore, substrate temperature influences photosynthesis involving both stomatal and nonstomatal regulation due to differentiations of water level absorption as also the rate of CO_2 uptake from plants (Gruda N., 2005). Additionally, substrate temperature influences the gas exchange processes between the atmosphere and the growing substrate and according to the received radiation can influence the plant growth and nutrient availability of crops (Probert, 2000). The slightly lower temperatures due to limited heating radiation from reduced photoperiod in this study, could benefit plants with higher water supply efficiency, advanced root growth, respiration decomposition, and nitrogen mineralisation (Waring & Running, 2007). In our experiment, substrate temperature showed no significant differences between the intermittent treatment (I10D14L) and the control-continuous light treatment (C8D16L), hence we could assume that basil plants successfully absorbed water and nutrients via the root zone since substrate temperature reflects the heat storage capacity of the substrate and depends on the ratio of the absorbed energy to the lost energy from the substrate (Onwuka, 2016). Additionally, the positive reaction of basil plants under I10D14L treatment indicates that root temperature could sufficiently alter and modify the response of the shoot part of plants by regulating the temperature of a shoot apical meristem and promoting the hormone balance in water and nutrient uptake of plants.

- Leaf temperature (T_{leaf}) was significantly lower during the IL schedule due to the limited amount of light radiation that reached daily the canopy. The difference of T_{leaf} of basil plants between the two light treatments indicates a healthy water status under reduced and IL conditions, due to the cooling effect that is promoted by plants' evaporation and the reduced heating due to limited radiation in the growing area.
- Photosynthesis as one of the major processes that controls plant growth and development, is the procedure that plants follow in order to carbohydrate and produce sugars-fuels from light radiation, atmospheric carbon dioxide and water. Measurements on the photosynthetic rate of basil plants grown under reduced-IL showed significant reduction under the 10-minute time interval of radiation after 17 days of experiment that by extension influenced and the overall daily photosynthetic rate. Nevertheless, extracted results from the 4-hour light interval showed that basil plants absorbed and processed sufficient amount of light radiation to perform photosynthesis while at the same time presented high mass production.
- Photoacclimation could be a possible explanation of our results, as is the process that plants perform to modulate the function and the structure of the photosynthetic device under the light irradiance they receive. Based on previous studies, photoacclimation during short light periods (between second to minutes) could cause heat dissipation of the excited energy and therefore, can affect the distribution of the absorbed light energy (Adams et al., 1999).
- RuBisCO model, is another useful tool that could explain and clarify the high photosynthetic efficiency of basil plants under intermittent light. The discrete RuBP particles that circulate in the Calvin cycle as also their cycle speeds, can promote plants' photosynthesis by enhancing the photon reception process. Further biological analysis is required to reveal the physiological and metabolic responses of plants in connection with IL.
- Stomatal conductance (g_s) constitutes the parts of plant leaves that allow CO_2 absorbance and are useful indicators of the water and growth status of plants, due to their ability to open and close stomata pores that regulate leaf transpiration, leaves' water status and the inductive photosynthetic response of leaves. The environmental conditions and the IL in this experiment did not disturb stomata from successfully absorbing the atmospheric CO_2 for their photosynthetic purposes managing to maintain a steady growth rate under intermittent light.
- The amount chlorophyll accumulation is highly dependent on the total amount of light energy that crops receive in a daily basis and highly independent of the daily dark period intervals (Tzina

et al., 1987). Chlorophyll as one of the most significant growth and stress indicators was examined in this experimental research, showing no significant differences between 16-hours of continuous and 14-hours of IL radiation.

- Plants that grow under short dark periods of IL seem that in order to maintain an increasing accumulation rate, develop thylakoids with few and large-in-size photosystems compare with plants that are exposed to longer dark cycles that present more and smaller-in-size photosystems.
- The photosynthetic rate under IL depends on the interpolation between dark intervals as well as shorter dark intervals contribute development of larger photosynthetic unit in plant. Thus, we could conclude that plants accomplish the photosynthetic requirements for absorbing and converting the available and interrupted light energy.
- The inertia point of stress tolerance of basil crop under 14 hours of reduced and intermittent lighting operation is defined to 17 days from the seedlings' transplant, when the light source emits at 571 PPFD (μmol/m^2/s) and DLI 28.8 moles/m^2/day.
- Basil plants that grow under reduced intermittent photoperiod produced slightly, yet insignificantly increased shoot dry biomass compared to the continuous photoperiod. At the same time, the energy demand of the stress treatment was almost 12.5 kWh lower compared with the control treatment providing energy savings of approximately 20%, and simultaneously developed a more flexible lighting schedule that could support a LSEDR for indoor basil production.

Energy demand is one of the major challenges that vertical farms face in order to maintain a high profitability rate. For this reason, this article introduces the examination of a new system of lighting schedule that allow farmers to use the already existing technology of their farms without the necessity for further initial investment, and by providing short light and dark cycles to plants, mange to reduce their energy footprint. Under this direction, indoor urban farmers could perform and organise their cultivation program based on the electricity price fluctuations and simultaneously, by continuously monitoring the growth and development rate of crops, and the environmental conditions of cultivation area, manage to detect stress signals of possible physiological or metabolic alterations of plants. Ultimately, Chapter 3 of this dissertation examines the influence of an IL methodology with short light cycles that provide IVFs higher flexibility, efficiency and sustainability of their lighting operation while preserving a high development and growth rate of basil crops.

5.3. The impact of intermittent photoperiodical light application in the energy footprint and the growth of plants in indoor environment in the Nordic context

The fourth chapter of this dissertation introduces two research articles to answer the Research Question 3: *"What is the impact of intermittent photoperiodic light application on the energy footprint and the growth of plants in IVFs in the Nordic context?"* Based on our results from the previous chapter, there was a necessity to repeat the experimental protocols under a different indoor cultivation installation for results' validation and development of a more representative intermittent lighting schedule that reflects the actual daily electricity price fluctuations of Denmark. In doing so, the fifth article presents the final experimental application that took place in the Agricultural University of Athens (external stay), where the tolerance of basil plants under normal-distributed IL (I10D14L) and load-shifted IL operation (I10D14Ls) was examined and the results were compared with a control treatment of 16 hours of continuous light (C8D16L). The experiment took place simultaneously in three identical growth chambers with controlled-environment conditions, where each one hosted one of the described lighting treatments. Plants were daily monitored under their most valuable physiological and morphological indices to provide evidence on the growth status of plants. The main findings from this research are listed below:

- Leaf temperature, substrate temperature and electrical conductivity of basil crops grow under reduced and IL photoperiod showed a stable rate during the whole experiment indicating sufficient and continuous growth of plants. Basil plants presented no water and nutrient uptake stress due to the high performance of the root zones in all the three different lighting treatments.
- Plant growth is highly dependent on photosynthesis, making of crucial importance the enhancement of plant net photosynthetic rate and maintenance in high levels during the whole crop cycle. The photosynthetic rate is highly connected to the leaf area and the different light-harvesting complexes that absorbs light energy, but also to the amount of light that plants actually receive in a daily basis. The performed experiments for the elaboration of this dissertation, indicate that the light energy that plants received during the IL treatments were sufficiently enough in order plants to continue increasing their photosynthetic rate and keep a stable and positively increasing growth rate.
- In Day 29 of this experiment, basil plants start showing stress signs due to limited and IL, but the differences were statistically significant only during the 10 minutes light intervals indicating that plants tolerance in IL started getting affected. Nevertheless, during the whole experimental period the daily average photosynthetic rate of plants showed no significant evidence of stress under the load-shifted lighting demand response. Based on these results, we could conclude that plant cells managed to process enough light energy for photosynthesis purposes during the 4-hour light operation and support the growth of plants.
- Similar results have been extracted from stomatal conductance (gs) and transpiration rate (E) between the three different treatments showing that basil plants that grow under load-shifted lighting operation can successfully absorb CO_2 from their leaves for fulfilling their photosynthetic demand and at the same time minimise water losses from stomatal pores. Reduced transpiration status per growing area indicates higher WUE and better water use from the leaves of plants (Lake & Woodward, 2008). Based on the results, we could conclude that load-shifted light operation does not reduce the mass production of basil crops in an indoor environment by the continuous creation of new organic matter and the uninterrupted development and growth of the various examined physiological parameters. Under optimal nanometre band selection and intensity of the lighting source, load-shifted intermittent lighting could really contribute to significant reduction of the energy footprint while maintaining an increasing crop growth rate.

- The results of plants' growth and development under intermittent and reduced photoperiod, imply a significant contribution of photoreceptors on the biological clock of plants. Photoreceptors' activation can express various changes and adaptation strategy of plants to abiotic stress conditions. Inputs of the endogenous clock of plants are of vital importance for the physiological responses and the development rate of plants. Photoreceptors can significantly contribute to the optimal regulation of the endogenous clock in respond to light manipulation and can highly affect important agronomical characteristic of crops and subsequently influence final plant productivity. Photoreceptors and/or engineering of their signalling mechanisms could significantly modulate the response of pants to light inputs duration. Alterations on the expression level of photoreceptors under IL could possibly produce agronomical desirable characteristics in plants quality and quantity. Further research is required to investigate the molecular reaction of photoreceptors under IL intervals and how these proteins are involved in conformational transitions under the formation of this signalling status.
- Plant reaction to light provokes physiological alterations that influence CO_2 assimilation and optimise gas exchanges processes in the interior of plants. In leafy vegetables such as basil that its value increases with the amount quality and quantity of their leaves (salable part), the delay of flowering increases the amount of edible shoot part. Additionally, flowering causes hardening of the leaves reducing their purchase value. By reducing the photoperiod of basil plants we could postpone flowering and maximise the harvested yield of fresh mass in edible crops such as basil.
- NDVI, a great indicator for green biomass assessment and nitrogen content of plant, provides further assistance in crop management. In our results, we observe a continuous increase of NDVI under load-shifted lighting operation with the same pace and the same capacity as in the control lighting treatment. Thus, we could conclude that basil plants can sufficiently develop and grow their leaves in terms of size, elongation and expansion without being negatively influenced with reduced and intermittent photoperiod of 10 minutes light intervals.
- Destructive post-harvest and quantity measurements between the three photoperiodic treatments showed a significant increase of approx. 7% on fresh shoot and 45% of dry shoot biomass production between the I10D14Ls and C8D16L treatments. Load-shifted IL with 10 minutes of light intervals seems to correlate positively with endogenous gibberellins leading to stem and leaf elongation of basil plants. Referring to basil crops, the shoot part of the plant has the significant purchase value and further maximisation of the production volume could offer farmers additional revenue.
- The inertia point in stress tolerance of basil crop under 14 hours of reduced lighting operation is defined to 29 days when the light source emits at 228 PPFD ($\mu mol/m^2/s$) and DLI 11.5 moles/m^2/day, resulting in 12 days more flexibility compare with the 571 PPFD and DLI 28.8 moles/m^2/day, applied in the previous experiment. Since the total photosynthetic rate of plants and multiple physiological indices never showed significant differences between the continuous and intermittent lighting operation, we could conclude the basil crops that are harvested in 40 days from seedling transplants could use reduced and load-shifted intermittent lighting after transplant and until the end of their growth cycle.

- Energy consumption analysis on each chamber showed that load-shifted and reduced lighting demand response consumed approximately 90kWh less compared with the control light treatment resulting in significant energy cost savings due to the reduction of energy consumption at approximately 25% between C8D16L and I10D14Ls treatments. Necessary condition for load-shifted intermittent lighting is the continuous and optimal management of the crops and the environmental and physiological conditions. In that way, crops are protected from undesired stress while preserving optimal environment and resources flow for maximisation of production's quality and quantity. Based on these results, we could conclude that LSEDR with IL intervals increased the productivity per unit of land area. Further research is necessary for large-scale vertical farms with higher energy demand but also energy losses.
- As we observe from data collection but also from previous literature, the cost reduction in lighting operation is essential for optimising the crop productivity per kWh of electrical energy. Around 30-40% of the electrical energy that LEDs consume is converted to photosynthetic photons (1mol = $6.022 * 10^{23}$ photons) and approximately 60% of the photosynthetic photons plants can actually receive from their leaves (Kozai, 2018). Afterwards, only a small portion of the photosynthetic photon that plants receive is only converted to chemical energy and carbohydrates. Under this scope, it becomes clear that is of high importance the improvement of the productivity of electrical energy for lighting but also the productivity of the photosynthetic photons (kg/mol). To achieve this optimisation, further improvement is necessary on the conversion factors of electrical light energy and light chemical energy.

The final research article of this dissertation presents the development of an algorithm that uses the electricity market price fluctuations of the Danish energy market and by comparing the values of the hourly data sets of electricity prices, manages to propose an intermittent lighting protocol for the operation of LEDs in artificially-lighted farms. Initially, this algorithm examines the hourly electricity price and decides if is expensive or cheap according to the daily forecast of electricity prices provided by Nordpool. Continuously, the algorithm examines the growth rate of plants and the environmental conditions sourcing from data collection from various horticultural sensors in the cultivation area. Furthermore, the algorithm counts each and every hourly lamp operation to reach the total daily photoperiod of 14 hours (under 228 PPFD maintaining a stable DLI 11.5 moles/m^2/day) for basil production. Under this scope, the inertia point of stress tolerance of plants under partial lighting is of major importance. The constant monitoring of growth indices from plant development and growth enables the detection of potential crop stress from reduced and intermittent photoperiod, and immediately restores the lighting operation to control conditions by providing full-hour of lighting. The purpose of this research is to provide an electricity price-focused lighting system for indoor food production that is based on scientific data collection and analysis from plant physiology and morphology in order to reduce the lighting operating expenses and provide IVFs higher profit margin by increasing system's flexibility. To validate the importance of the resulted energy savings and the yield enhancements deriving from the optimisation model, an OPEX analysis with the updated and optimised resource flow inputs of a vertical farm case study with 675 m^2 growing area and multiple tiers of growing space follows. Basil plants as the selected crop cultivar of experimentation during this entire PhD dissertation were selected as the model plant for the energy optimisation algorithm. Based on the evidence from previous published experimentation research, basil presents high tolerance on reduced intermittent daily light intervals as for 40 days no significant differences observed on the overall daily values among multiple growth and development indices. Under this scope, the energy optimisation algorithm takes advantage of the electricity price fluctuations for the entire grow cycle of basil crops. In case of a different cultivar selection or stress indicators from crop monitoring that would influence the inertia point and the algorithm directly provides the necessary lighting input in the cultivation area. The main findings of this research are presented below:

- The proposed energy model provides monthly average savings approximately 25% of the energy demand due to 2-hour reduction of light operation in the examined vertical farm case. Furthermore, lighting operation contains almost 90% of the energy footprint of the specific vertical farm case (Chapter 2.2.3.4. Table 8); thus it consists one of the most significant factors that challenges farms' profitability and efficiency. The OPEX comparison between the IVF unit that uses 16-hours of continuous photoperiod and IVF that apply 14-hours of load-shifted IL showed significant energy cost savings of around 21% per month for the case farm.
- Different cash flow scenarios were examined showing between one to three years significant reduction of the investment payback period for most of the cases after the implementation of a LSEDR lighting operation. Worth to mention that scenarios "50-50-5.37" and "70-30-5.37" presented a payback period of 21 years in both cases before the energy optimisation model, while after the application of the LSEDR algorithm, the payback period was significantly reduced to 8 and 9 years respectively with an IRR increase from 0.38% to 13.85% and from 0.04% to 10.94% respectively. Furthermore, for most of the examined scenarios the investment's payback period comes at 3 to 4 years, which is around 1 to 2 years less compared to the cash flow scenarios before the energy optimisation model.
- IL could provide a competitive advantage in IVFs by allowing farmers to precisely use the minimum amount of light radiation to the crops in respect to their growth and development. Based on our results we could conclude that shifted energy demand response of artificial light in horticulture could limit the profitability risk that is highly correlated with artificial light operation and at the same time enhance the efficiency, sustainability and profit margin of IVFs by introducing a flexible and resilient lighting system for indoor food production.
- Lastly, Denmark's participation in Energinet and the access on multiple different pricing energy schemes but also due to the high renewable energy participation in the grid, offers significant marginal price fluctuations for indoor food production. At the same time, the severe and harsh winter environmental conditions and the extremely limited solar radiation (during the winter months) makes Denmark a great case for further installations of IVFs to support the local fresh greeneries' production while being able to fully support the renewable energy grid. The integration of shifted energy demand response can result in development of optimised and flexible lighting strategies for IVFs. Finally, creates a more adaptable multidisciplinary system that under mass deployment could evolve to an Energy-Food nexus with multivalued business model generation that could enhance the industry and link IVFs to the grid's necessities.

5.3.1. Other perspectives on Research Question 3

In looking other perspectives to answer Research Question 3, this dissertation further investigates the impact of vertical farming mass deployment as a proposed solution towards the severe consequences of rapid urbanisation rate of our times. Xydis et al., (under submission with Sustainable Energy Technologies and Assessments) examine the concept of Energy-Food Nexus as a multidisciplinary proposal that by combining the interaction of energy and food demand in high-urbanised cities, aims to provide sufficient evidence on how vertical farms could support the electricity grid while producing fresh greeneries for the industry. Under this scope, various scenarios are examined in a techno-economical study, in order to reveal the profitability and viability of possible collaboration cases between wind energy and vertical farms. The goal of this research is to examine the concept and implementation of vertical farms in the urban areas as an alternative revenue stream for renewable energy application projects and at the same time researches the potential of supporting and offering high flexibility to the energy grid by connecting electricity markets with controlled local food production systems.

In short, high urbanisation and urban densification are the main challenges that threaten the regional sustainability but also play a major role in the global energy and matter flow and balance (Haaland & van de Bosch, 2015). It becomes essential the design and development of resource-efficient centres that can limit the degradation of biodiversity and destruction of environment (Phillis et al., 2017). The predicted high expansion of urban density by further built-up environment that can cover the increasing urban population (more than 70% of global population will be located in urban areas), creates a growing demand for defining, developing and promoting sustainable habitats. The purpose of such projects is to contribute significantly on reducing the CO_2 emissions and optimising the EUE in the urban and near-urban environment (Martos et al., 2016; Phillis et al., 2017). This research examines how the application of urban vertical farms could influence and advance the resilience and sustainability of near-urban and touristic settlements by integrating load flexibility farm units such as electric vehicles (EV) and heat pumps act in modern grids.

Due to the significant increase of wind turbine installations the last years in Europe, the cogeneration and congestion of energy has managed to limit the bottlenecks between the countries. At the same time, this occurs curtailments and wasted energy, putting renewable energy investments under pressure (Xia et al., 2020). More specific, in the case of Denmark, there are cases where wind parks were shut approximately 30% of the expected operating time, making investors and stakeholders to urgently look for feasible optimisation solutions. In reality, in 2016, the average electricity wholesale price that was generated by wind turbines valued only 0.025 €/kWh, which is almost 10% less than the average electricity price in the Danish wholesale market, ended to no profit for investors (Danish Wind Industry Association, 2017). This problem could be partially solved via a wide electricity distribution that meets the energy demand of an Energy-Food nexus. There are various proposals of integrated solutions in the market that combine different markets under one business scheme (such as tesla batteries, prosumers and heat pumps) in order to provide energy balance and business schemes that can be viable alternatives for urban areas, however they are at a primary perception yet.

Similarly, in multiple countries such as Greece, due to absence of available flexible units that limit the options for ancillary services to the major energy player of the country and due to the private players in the market that try to overcharge for their spinning reserves (thermal units), the marginal price of electricity is highly increased and consequently electricity bills of the end-up user (Public Power Corporation -- PPC). Alternatively, in order the Greek Independent Power Transmission Operator (IPTO) select the cheapest unit as priority (algorithm design), is addressed to the hydroelectric plants of the country that provide the reserved hydroelectric energy to meet the daily demand. Therefore, when private producers offer high energy prices, the draw to meet the demand is automatically addressed to hydropower. Thus prices are retained, but in the meantime the national hydropower reservoirs are constantly getting empty, continuing this vicious cycle. Under this approach, both the PPC and the IPTO decide to reject vast amounts of renewable energy from other units and contributing on maintaining a non-viable national grid policy. Part of this problem could be solved with the implementation of electric vehicles (EVs), heat pumps, storage units but also flexible farm units' investments that could perform a flexible and on-demand energy usage.

The whole inspiration of this research is based on the fact that vertical farms could become a support system for storing and distributing the energy with rejected/curtailed power in order to produce leafy vegetables, herbs and fruits for the local consumers. Vertical farms due to the advanced equipment and the multiple daily lamps' operation have a constant energy demand. The implementation of a load- shifted lighting demand respond performs more resilient and by taking advantage of the curtailed and excessive energy that would be rejected, can finally support various vertical farming units. In this context, such a collaborative project could lead to important reduction of CO_2 emissions by decreasing the food transportation demand and resulting in decarbonisation of cities from the transportation sector and also support and improvement of the local production systems. The implementation of indoor urban farms under a mass deployment could work towards integrating greater amounts of wind energy generation while participating in the energy market as an authorised electric supplier.

The followed methodology of this research paper that is graphically described in Figure 48, is based on yearly data collection followed by microanalysis for a wider urban area. In this direction, it is very important the site selection of research and the accurate sizing of the system through an explanatory energy analysis that could precisely propose a holistic and viable Energy-Food nexus.

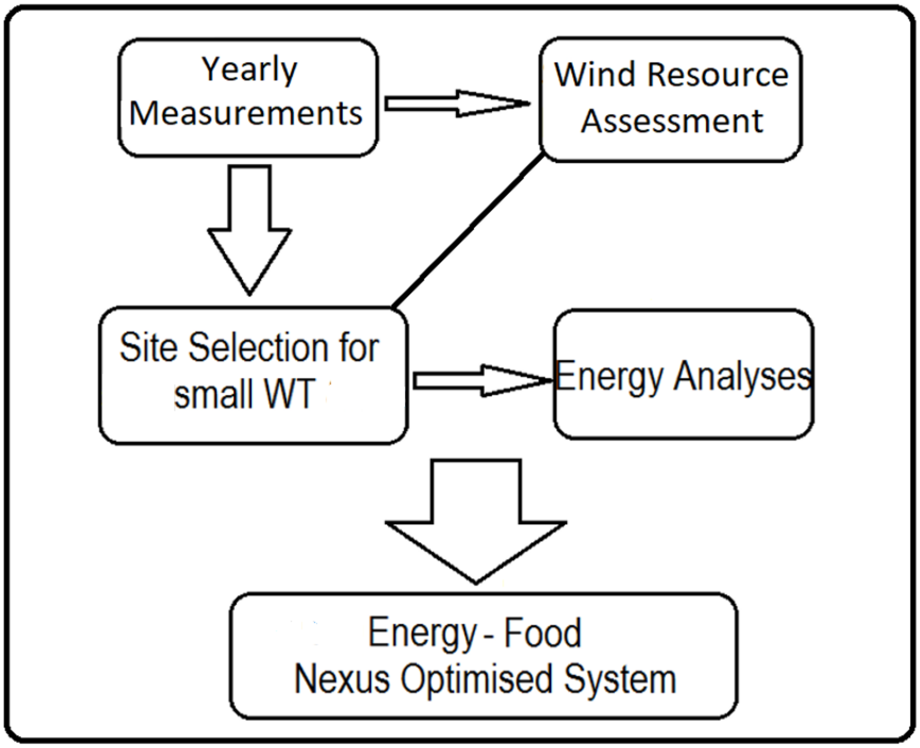

Figure 48. Flowchart of the applied methodology for the design of a collaborative decision making project between sustainable energy technologies and mass deployment of vertical farms.

This research introduces a viable investment option inside the city network that further improves food supply safety in a constantly expanding urban environment. The examined hypothesis is that vertical farms could be wind energy-assisted and operated under specific opportunities that rise from demand response or according to the curtailed power. For a mass deployment scheme of urban indoor vertical farms, abandoned areas, terraces and unused flats could be ideal selection options for vertical farming applications. The goal is the examination and proposal of a hybrid system that by focusing on renewable energy, interconnects dynamic pricing energy markets and urban food production. In modern power systems, the grids can efficiently attain maximised integration of renewable energy sources by promoting demand response participation. This research examines when power is needed (in urban and suburban areas), if vertical farming units could reduce their power supply requirements and develop a resilient energy consumption system , allowing the unit not use the expensive and less clean thermal power plants for the system's operation. Under this scope, farm units could avoid using the peak demand by postponing the power supply needs via the demand response option. By managing to control the electricity needs of vertical farming systems and simultaneously optimising the lighting operation of the units and the plants' growth, IVFs could provide great opportunities and potentials on succeeding a unique integrated Energy-Food nexus.

In the examination, it was assumed for most of the scenarios that 5% of the to-be-curtailed power was delivered to the local IVF unit under two different electricity prices (0.03 and 0.07 €/kWh) and the rest 95% was offered to the electricity market ("95/5") under two different prices (45 and 65 €/MWh).

Additionally were examined “95/0” scenarios where no power was offered to the IVFs and therefore, the energy was wasted giving no additional earnings. Finally, were examined “90/10” scenarios, meaning that 90% of the energy was offered to the electricity market and 10% was distributed to the IVF unit. Additionally, further scenarios were developed based on the wind farm capacity were six different categories were included (12, 10, 8, 6, 4 and 2 MW).

The economic analysis of this multivalued business model revealed that in the best-case scenarios the payback period reached 4 years for the investors to take back their investment while simultaneously covered the requirements of several IVFs for local food productions. Other case scenarios showed that by maximum increase of capacity, they could cover the requirements of IVFs and take the investment back in a period of 8 years (Table 29). Financial results show that the surplus energy that would be rejected or offer to negative prices (based on the Transmission System Operator (TSO)), could be directed to local vertical farming units for production and distribution, achieving to develop a multiple revenue stream approach that under mass deployment could save millions of tons of CO_2 in the urban networks. Table 29 indicatively presents 8 out of the 34 examined scenarios.

Table 29. Presentation of some of the examined case scenarios (further scenarios included in the research publication). Note: Gij indicates the difference in ij (ratio of NPV to GWh annually produced) between 0.07 €/kWh and 0.03 €/kWh. (part 1).

SCENARIOS	95/0; 12MW;0kWh;65MWh	95/5; 12MW;0.07kWh;65MWh	95/5; 12MW;0.07;45MWh	95/5; 10MW;0.07kWh;45MWh	95/5; 10MW;0.07kWh;65MWh
Capacity [MW]	12	12	12	10	10
GWh annually produced	36.24	36.24	36.24	30.80	30.80
Net Operating Hours	3,178.75	3,178.75	3,178.75	3,242.50	3,242.50
Project Cost [M€]	12	12	12	10	10
NPV [M€]	16.11	17.53	9.61	8.29	15.00
Project IRR	13.08%	14.83%	4.82%	5.25%	15.41%
Period Payback (yrs)	8	8	15	14	7
retail sales [€/yr]	0	133.508	133,508	113,488	113,488
tot sales [€/yr]	2,355,454	2,488,961	1,764,206	1,499,656	2,115,731
spot market sales [€/yr]	2,355,454	2,355,454	1,630,699	1,638,169	2,002,115
NPV [M€]/[GWh annually produced]	44.47%	48.37%	26.52%	26.90%	48.68%
Dij		2.23%	2.39%	2.39%	2.23%

Table 30. Presentation of some of the examined case scenarios (further scenarios included in the research publication). Note: Gij indicates the difference in ij (ratio of NPV to GWh annually produced) between 0.07 €/kWh and 0.03 €/kWh. (part 2).

SCENARIOS	95/5; 8MW;0.07kWh;65MWh	95/5; 6MW;0.07kWh;45MWh	95/5; 4MW;0.07;45MWh	95/5; 2MW;0.07kWh;45MWh	90/10; 2MW;0.07kWh;65MWh
Capacity [MW]	8	6	4	2	2
GWh annually produced	25.20	19.47	13.37	6.68	6.33
Net Operating Hours	3,316.13	3,415.33	3,517.50	3,518.00	3,518.00
Project Cost [M€]	8	6	4	2	2
NPV [M€]	12.35	5.42	3.78	1.88	3.36
Project IRR	16.08%	6.43%	7.09%	6.98%	18.10%
Period Payback (yrs)	7	13	13	13	6
retail sales [€/yr]	92,852	71,722	49,245	24,626	49,252
tot sales [€/yr]	1,731,017	947,755	650,738	325,415	460,858
spot market sales [€/yr]	1,638,166	876,033	601,493	300,789	411,606
NPV [M€]/[GWh annually produced]	49.02%	27.85%	28.32%	28,.11%	53.12%
Dij	2.23%	2.38%	2.23%	2.37%	4.70%

To conclude, this dissertation focuses on proposing a flexible-load lighting methodology for IVFs by mainly studying on the influence of IL cycles on the development and growth rate of plants, by establishing a crosstalk between plant physiology and intermittent lighting energy demand. A large-scale deployment could be translated to millions of tons of CO_2 savings in the urban environment around the world while provide fresh, nutritious and locally grown herbs and vegetables. The approach of an interdisciplinary and multivalued business model could lead to the creation of a new valid product within the urban network that is based on an Energy-Food nexus and with the vital contribution of city councils, city planners, vertical farming units, grid operators, independent energy producers and energy consultants, we could move towards holistic solutions. Ultimately, this dissertation brings additional value to the management of vertical farming projects in the Northern European markets; and thus, the impact of this dissertation can make smoother and easier the expansion of vertical farming units in these markets.

5.4. References

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6. Appendix

6.1. Other contributions

The following is a list of scientific contributions not included in the dissertation that was made during the PhD-period. A division of published and submitted contributions is used for clarification purposes along with a division of the type of contribution and a note of Danish Bibliometric Research Indicator for contributions that are listed.

Published Journal Articles – Danish Bibliometric Research Indicator 2

1. Avgoustaki, D. D., Li, Jinyui & Xydis, G. (2020). Basil plants grown under intermittent light stress in a small-scale indoor environment: Introducing energy demand reduction intelligent technologies. Food Control, Vol. 118, https://doi.org/10.1016/j.foodcont.2020.107389.

2. Xydis, G., Liaros, S. & Avgoustaki, D. D. (2020). Small scale Plant Factories with Artificial Lighting and wind energy microgeneration: A multiple revenue stream approach. Journal of Cleaner Production, Vol. 255, 120227. https://doi.org/10.1016/j.jclepro.2020.120227.

3. Avgoustaki, D. D. (2019). Optimisation of Photoperiod and Quality Assessment of Basil Plants Grown in a Small-Scale Indoor Cultivation System for Reduction of Energy Demand. Energies, 12 (20), 3980https://doi.org/10.3390/en12203980

Published Journal Articles – Danish Bibliometric Research Indicator 1

1. Avgoustaki, D. D. & Xydis, G. (2020). Indoor Vertical Farming in the Urban Nexus Context: Business Growth and Resource Savings. Sustainability. 12 (5), 1–18. https://doi.org/10.3390/su12051965.

2. Avgoustaki, D. D. & Xydis, G. (2020). Plant factories in the water-food-energy Nexus era: a systematic bibliographical review. Food Security. https://doi.org/10.1007/s12571-019-01003-z.

Published Book Chapter

1. Avgoustaki, D. D. & Xydis G. (2020). How energy innovation in indoor vertical farming can improve food security, sustainability, and food safety? Elsevier. Chapter One. 5, pp. 1-51. https://doi.org/10.1016/bs.af2s.2020.08.002.

Submitted Journal Articles – Danish Bibliometric Research Indicator 1

1. Avgoustaki, D. D., Bartzanas, T. & Xydis, G. (2021). Minimising the energy footprint of indoor food production while maintaining a high growth rate: Introducing disruptive cultivation protocols. Under submission with Journal of Cleaner Production.

2. Avgoustaki, D. D. & Xydis, G. (2021). Energy cost reduction by shifting electricity demand in indoor vertical farms with artificial lighting. Under review with Biosystems Engineering.

3. Xydis, G., Strasszer, D., Avgoustaki, D. D. & Nanaki, E. (2021). Mass Deployment of Plant Factories as a Source of Load Flexibility in the Grid under an Energy-Food Nexus. A Technoeconomics-based Comparison. Under review with Sustainable Energy Technologies and Assessments.

Conference Keynote Speaker

Indoor Urban Farming, the Beginning of a Sustainable Era in Food Production. How We can Reduce the Energy Demand Cost. (2019). Vertical Farming Conference, Venlo, Netherlands. https://www.verticalfarmingconference.com/speaker/indoor-urban-farming-sustainable-food-production-dafni-avgoustaki-aarhus-university/

Published Conference Posters

Optimisation of Energy Consumption Cost in Vertical Farms under Different Photoperiods. Avgoustaki, Dafni D. 2019. Poster session presented at VertiFarm, Wageningen University & Research (WUR), Wageningen, Netherlands.

6.2. Co-author Statements

The purpose of this section is to document the required co-author statements for the articles used in this dissertation. The statements are presented in the same sequence as introduced in the dissertation: article 1-6 (note article 3 is a monograph and therefore is not included in this appendix).

AARHUS BSS SCHOOL OF BUSINESS AND SOCIAL SCIENCES AARHUS UNIVERSITY

Declaration of co-authorship*

Full name of the PhD student: Dafni Despoina Avgoustaki

This declaration concerns the following article/manuscript:

Title:	How energy Innovation in Indoor Vertical Farming can Improve Food Security, Sustainability and Food Safety.
Authors:	Dafni Despoina Avgoustaki; George Xydis

The article/manuscript is: Published

If published, state full reference:
Avgoustaki D. D. & Xydis G. (2020). How energy Innovation in Indoor Vertical Farming can Improve Food Security, Sustainability and Food Safety. Elsevier. Chapter One. 5, pp. 1-51. https://doi.org/10.1016/bs.af2s.2020.08.002.

Has the article/manuscript previously been used in other PhD or doctoral dissertations?
No

The PhD student has contributed to the elements of this article/manuscript as follows:

A. Has essentially done all the work
B. Major contribution
C. Equal contribution
D. Minor contribution
E. Not relevant

Element	Extent (A-E)
1. Formulation/identification of the scientific problem	B
2. Planning of the experiments/methodology design and development	A
3. Involvement in the experimental work/clinical studies/data collection	A
4. Interpretation of the results	B
5. Writing of the first draft of the manuscript	A
6. Finalization of the manuscript and submission	D

Signatures of the co-authors

Date	Name	Signature
13.01.2021	George Xydis	

In case of further co-authors please attach appendix

Date: 16.01.2021

Signature of the PhD student

*As per policy the co-author statement will be published with the dissertation.

AARHUS BSS SCHOOL OF BUSINESS AND SOCIAL SCIENCES
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Declaration of co-authorship*

Full name of the PhD student: Dafni Despoina Avgoustaki

This declaration concerns the following article/manuscript:

Title:	Indoor Vertical Farming in the Urban Nexus Context: Business Growth and Resources Savings. Sustainability
Authors:	Dafni Despoina Avgoustaki and George Xydis

The article/manuscript is: Published

If published, state full reference:
Avgoustaki D. D. & Xydis G. (2020). Indoor Vertical Farming in the Urban Nexus Context: Business Growth and Resources Savings. Sustainability; 12, 1-18. https://doi.org/10.3390/su12051965.

Has the article/manuscript previously been used in other PhD or doctoral dissertations?

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- C. Equal contribution
- D. Minor contribution
- E. Not relevant

Element	Extent (A-E)
1. Formulation/identification of the scientific problem	C
2. Planning of the experiments/methodology design and development	B
3. Involvement in the experimental work/clinical studies/data collection	C
4. Interpretation of the results	C
5. Writing of the first draft of the manuscript	B
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Declaration of co-authorship*

Full name of the PhD student: Dafni Despoina Avgoustaki

This declaration concerns the following article/manuscript:

Title:	Basil Grown under Intermittent Light Stress in a Small-Scale Indoor Environment: Introducing Energy Demand Reduction Intelligent Technologies.
Authors:	Dafni Despoina Avgoustaki; Jinyue Li and George Xydis

The article/manuscript is: Published

If published, state full reference:

Avgoustaki D. D., Li J. & Xydis G. (2020). Basil Grown under Intermittent Light Stress in a Small-Scale Indoor Environment: Introducing Energy Demand Reduction Intelligent Technologies. Food Control; 118. https://doi.org/10.1016/j.foodcont.2020.107389.

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4. Interpretation of the results	A
5. Writing of the first draft of the manuscript	A
6. Finalization of the manuscript and submission	D

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AARHUS BSS SCHOOL OF BUSINESS AND SOCIAL SCIENCES
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Declaration of co-authorship*

Full name of the PhD student: Dafni Despoina Avgoustaki

This declaration concerns the following article/manuscript:

Title:	Minimizing the energy footprint of indoor food production while maintaining a high growth rate: Introducing disruptive cultivation protocols.
Authors:	Dafni Despoina Avgoustaki; Thomas Bartzanas and George Xydis

The article/manuscript is: Submitted

If accepted or submitted, state journal:
Innovative Food Science & Emerging Technologies

Has the article/manuscript previously been used in other PhD or doctoral dissertations?
No

The PhD student has contributed to the elements of this article/manuscript as follows:

- A. Has essentially done all the work
- B. Major contribution
- C. Equal contribution
- D. Minor contribution
- E. Not relevant

Element	Extent (A-E)
1. Formulation/identification of the scientific problem	B
2. Planning of the experiments/methodology design and development	A
3. Involvement in the experimental work/clinical studies/data collection	A
4. Interpretation of the results	A
5. Writing of the first draft of the manuscript	A
6. Finalization of the manuscript and submission	D

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AARHUS BSS SCHOOL OF BUSINESS AND SOCIAL SCIENCES
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Declaration of co-authorship*

Full name of the PhD student: Dafni Despoina Avgoustaki

This declaration concerns the following article/manuscript:

Title:	Reduction of Energy Costs in Indoor Farms for Artificial Lighting by Shifted Energy Demand Response.
Authors:	Dafni Despoina Avgoustaki and George Xydis

The article/manuscript is: Submitted

If accepted or submitted, state journal: Food Security

Has the article/manuscript previously been used in other PhD or doctoral dissertations?

No

The PhD student has contributed to the elements of this article/manuscript as follows:

A. Has essentially done all the work
B. Major contribution
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1. Formulation/identification of the scientific problem	C
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