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## CONTRIBUTION OF VERTICAL FARMS TO -INCREASE THE OVERALL ENERGY EFFICIENCY OF CITIES

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Lectured by **y‘plus**

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# Preface

I first came into contact with the Hubbert's curve and the Peak-Oil-theory in 2006. From then on, I proceeded to deepen my knowledge on this topic, initially by reading the publication of ASPO[1], the Peak-Oil-Protocol[2] and several books written by Colin Campbell, founder of ASPO and author of the protocol. I had the privilege of meeting him twice in Ireland. The awareness of the finite resource of hydrocarbon energy and the significance of the consumption of this source of energy, which has led to the total dependency of an entire culture, developed through modernism. This situation in turn prompted my decision to postulate "The Last Skyscraper of the 21st century" as a diploma at the Academy of Fine Arts in Vienna, with the skyscraper monumentally ignoring every reflection of scale and meaning, keeping 80% of its volume free from every use and re-establishing nature within the void.
It need not be said that finding arguments in support of this huge vertical green structure proved to be an intellectual hike to nowhere. Continuing discussions with Prof. Wolfgang Tschapeller on this topic, however, and his persistence in wishing me to find a plausible argument to keep the concept afloat, led me as an incidental, side-effect to the website of Prof. Dickson Despommier of Columbia University, where he published his first experimental works developed with his students all around the issue of Vertical Farming.

This idea exerted an immediate attraction on me. The sculptural dystopian monumentality of the developed skyscraper project turned overnight into an interest in what the actual potential of a vertical greenhouse could be and what it might offer both in an architectonic and an urban context. Furthermore, intensive research was called for to examine the extent to which Vertical Farming might actually make sense in practical terms. Both the city and the site for the diploma project were found immediately - London, Canary Wharf, on the banks of the River Thames. A DEFRA-study[3] came to the conclusion that over 80% of all food consumed in London is imported from abroad and the food footprint for this one city was equal to that for the whole of Sweden. Based on the statistics published on Prof. Dickson Despommier's website, a building was developed which would have the capability of feeding 1% of London's population by 2050. I am very grateful for the support and for the discussions I had with Prof. Dickson Despommier during the diploma work and during
a meeting in Sweden.
The interest in Vertical Farms[4] and their challenges and potentials has been kept alive in the meantime. However, the necessity grew for deepening the approach to the question

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[1] Association for the Studies of Peak Oil and gas. http://www.aspo2012.at/

[2] CAMPBELL, C. J. 1996. The Oil Depletion Protocol. Available: http://richardheinberg.com/odp/theprotocol.

[3] WATKISS, P., SMITH, A., TWEEDLE, G., MCKINNON, A., BROWNE, M., HUNT, A., TRELEVEN, C., NASH, C. & CROSS, S. 2005. The Validity of Food Miles as an Indicator of Sustainable Development: Final report produced for DEFRA. AEA Technology.

[4] DESPOMMIER, D. 2010. The Vertical Farm, New York, St. Martin's Press.

and critically seeking a raison d‘être for this structural typology, which on a superficial analysis might turn out to consume a vast amount of energy by substituting artificial light for most of the sunlight needed for plant growth and also for providing ideal climate conditions.

This controversy came to a head in the question of to what extent Vertical Farming could actually increase the overall energy efficiency of cities, or in other words: if the energy consumption of this typology could balance out all side effects of our actual world food system in terms of energy consumption.

I was conscious of the need here for in-depth knowledge inputs from many fields of expertise, ranging from detailed understanding of plant physiology to quantum physics, together with the need to acquire advanced knowledge in simulation processes in order to establish the value approximations for energy consumption assessments.

To cut a long story short, this ambitious scheme provided more than enough work for five years of work and to fill a book with additional contributions for this fascinating and highly controversial discussion.

## Acknowledgements

I would like to thank Prof. Brian Cody and Prof. Nirmal Kishnani for their support and contributions throughout the last few years.

Thanks to “mi moglie” Maria Huber, probably the only art historian (involuntarily) able to explain what PPFD is. Thank you for your support, your contribution on every imaginable level, and for your patience, as well as for your encouragement during the summer “we didn’t have”.

Markus Godez, Kathi Schegula, it must be said that you not only made this period possible in the first place, but very much easier, too. Your extraordinary hospitality must not only be gratefully acknowledged, but praised in its every detail as such a valuable contribution to my activity at the institute.

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Lastly, I thank my voluntary lecturers, Maria Huber, Georg Holländer and Lucas Kulnig.

# Synopsis

Vertical Farming has been an issue of controversial discussion since the publication of the manifesto by Dickson Despommier[5] . This doctoral thesis with the search for a raison d‘être for Vertical Farming by sketching the current situation of world agriculture in terms of energy consumption, land use, potential and the consequences in increasing productivity on the actual agricultural land in use and also the potential increase of natural land conversion into agricultural land, exploiting the total biocapacity of the world.

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[5] DESPOMMIER, D. 2010. The Vertical Farm, New York, St. Martin‘s Press.

Typologies and the cultivation- and production methods currently in use on existing Vertical Farms are compared, before proceeding to the development and analysis of the lighting- and heating demand for three specific Vertical Farm building types.

World total primary energy supply (TPES) in 2014 was around 550 Exajoule (EJ)[6]. A third of this is consumed by the food sector.[7] For every calorie we need to cover our daily energy requirement, we consume nearly six calories of total primary energy. One percent of the global landmass is defined as built-up land, where with the exception of a small percentage of indigenous populations, more than 7 billion people live. The area required to supply the world population with food is ten times higher. A food production network has been required for emerging and developed countries over the past few, which is completely dependent on hydrocarbon energy on a global scale.

The world population will continue to grow over the next decades, reaching a plateau in 2075 at 9.22 billion people before it starts to decline.[8] This work intends to contribute to the discussion on urban and Vertical Farming, aiming to find indicators for answering the question of to what extent Vertical Farming could actually increase the overall energy efficiency of cities.

# Abstract

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Keywords: Vertical Farming, world agriculture, world population growth, land use, biocapacity, world energy consumption, fossil fuels, food production, *Lycopersicon Esculentum* (Mill.)

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[6] http://www.iea.org/publications/freepublications/publication/KeyWorld2013.pdf, retrieved 05.04.2014

[7] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 2011.Energy-Smart Food for People and Climate, Issue Paper, Rome:FAO, p.10

[8] http://www.un.org/esa/population/publications/longrange2/WorldPop2300final.pdf, p.1, retrieved 10.09.2015

*While currently still being constructed as prototypes and for research purposes, Vertical Farming facilities are nevertheless providing food for thought for architects everywhere. The purpose of this work is to answer the question as to what extent Vertical Farming can contribute to disburdening the current alarming situation in conventional soil based agriculture in terms of land use, and to sketch in the potentials of whether Vertical Farms have the capacity to increase the overall energy efficiency of cities.*

*As world population is expected to peak in 2075 with an estimated 9.22 billion people*[9] *and changes in diet*[10] *are most likely to be expected, especially in emerging countries, additional food production is needed to cover the total nutritional energy requirements of both humans and livestock. Potential exists on various levels here, e.g. by increasing productivity, or expanding the area for soil based agriculture. Biocapacity of the earth is adequate*[11] *for feeding future generations.*

*Does this mean that the raison d'être for Vertical Farming is shrinking and it is thus a lost cause? By no means. When the potentials are turned into practice, dramatic side effects are entailed on the energy and climatic levels. This work defines the potential of land use reduction and frames the impetus to what extent Vertical Farming actually can contribute to making cities more energy efficient.*

## *FOOD AND ENERGY*

World total primary energy supply (TPES) was around 550 Exajoule (EJ) in 2014.[12] A third of this energy is required by the food sector.[13] For every calorie we need to cover our daily nutritional energy requirement, we consume nearly six calories of primary energy. One percent of the global landmass is defined as built-up land, where, except for a small percentage of indigenous populations, more than 7 billion people live. The area required for cropland to supply the world population with food is ten times higher. A food production network which is

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[9] http://www.un.org/esa/population/publications/longrange2/WorldPop2300final.pdf, p.1, retrieved 10.09.2015

[10] KASTNER, T., IBARROLA RIVAS, M. J., KOCH, W. & NONHEBEL, S. 2012. Global changes in diets and the consequences for land requirements for food. Available: http://www.pnas.org/content/early/2012/04/10/1117054109.full.pdf+html.

[11] FISCHER, G., VELTHUIZEN, H. V. & NACHTERGAELE, F. O. 2000. Global Agro-Ecological Zones Assessment: Methodology and Results. International Institute for Applied Systems Analysis, FAO. Executive Summary

[12] http://www.iea.org/publications/freepublications/publication/KeyWorld2013.pdf, retrieved 05.04.2014

[13] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 2011.Energy-Smart Food for People and Climate, Issue Paper, Rome:FAO

completely dependent on hydrocarbon energy on a global scale has been required for emerging and developed countries over the past few decades.

This work is structured primarily in three parts: Chapter 2 and Chapter 3 investigate whether there is a raison d'être for Vertical Farming, or to put it in other words, if the necessity exists for developing additional production and cultivation methods within cities. Statistical analysis of different research results by the Food and Agriculture Organization, IIASA[14] and PNAS[15] are compared quantitatively for the purpose of sketching the consequences of changing current actions in the traditional world agriculture and attempting to define the limits for the biocapacity of the earth capable of use for food production.

Existing Vertical Farms were examined qualitatively in terms of food cultivation methods and compared by means of ratio assumption as to their potential to reduce the footprint of agricultural land, related to annual crop yield.

Part two correlates to Chapter 4 where parameters needed to substitute primary growth factors are defined, primarily concentrating on light and temperature demand for *Lycopersicon Esculentum* (Mill.). Based on these factors, lighting- and heating Schedules will be developed that serve the simulation model.

The third part, Chapter 5, includes three parametrically generated Vertical Farms which are compared on the basis of their energy consumption and capacity for reducing agricultural land use.

## *LAND USE, BIOCAPACITY AND ENERGY CONSUMPTION*

Covering the total energy requirement of a sedentary man requires 11.3 MJ, or 8.82 MJ for a sedentary female.[16] Since human beings are heterotrophs, energy must first be captured from sunlight by plants either for direct human consumption or indirectly through use as feed for livestock. Considering cultural, and thus dietary differences, the size of the food footprint is different in every region of the world. We can claim that the higher the vegetal ratio in everyday diet, the lower the footprint tends to be.

In addition, Kastner et al.[17] identified three main drivers which influence the food footprint: population numbers, diet and the level of technological development. The main findings of this study are that the biggest driver in cropland expansion is not population growth, but socioeconomic development. What has been observed is that by increasing GDP population growth slows down, but the effects on dietary change still make increases essential in the area of

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[14] International Institute for Applied Systems Analysis, Vienna

[15] Proceedings of the National Academy of Sciences of the United States of America

[16] http://ajcn.nutrition.org/content/51/2/241.abstract, retrieved 12.06.2014

[17] KASTNER, T., IBARROLA RIVAS, M. J., KOCH, W. & NONHEBEL, S. 2012. Global changes in diets and the consequences for land requirements for food. Available: http://www.pnas.org/content/early/2012/04/10/1117054109.full.pdf+html.

food production. This means that by area and on a global scale, the average cropland needed for feeding a single person (food supply) is 1,732 m2/a.[18]

The agricultural land of 15,529,767 km2 (10% of the earth‘s land mass) produced more than 9.5 bn metric tons of primary products in 2011.[19] By assuming a per capita food supply of 900 kg/a which corresponds to FBS[20] of a European high GDP country and dividing it by the total primary production every person could be supplied with 1,399.80 kg of food annually. Enough food for all? Not so. Roughly 795,000,000 people are undernourished or suffer from hunger.[21] From the total primary production of animal feed (for a world livestock of 57,064,502,778 animals)[22], seeds, wastes, other (non-food/feed) uses and food manufacture has to be subtracted - with remaining 688,03 kg per person/a. In terms of calories only 55% of the global crops produced are consumed directly by humans. By theoretically eliminating every calorie which is lost from the food sector (both feed and biofuel production), an additional four billion people could be fed, enough to feed the expected world population by 2075.[23] Additional potential also exists in changing diet, although it is very unlikely that policies in this area will be supported by social acceptance. The trends clearly go in a quite different direction.

Research findings on the global agro-ecological zones (GAEZ) and the biocapacity of the world estimate that agricultural land could be more than doubled to exploit all land that is very suitable, or at least suitable for agricultural production.[24] Natural land, of which over 40% is currently covered by forests, would thus need to be converted into arable land. This is a scenario that is not desirable for two reasons: the vast CO2 release from slash-and-burn-practices and the loss of natural habitats.

Productivity could be intensified on the land we already cultivate. By learning from history in this and by looking back at the 20th century we see that to increase yield by 600% between 1900 to 2000 energy subsidies had to increase 8,500%.[25] The energy dependency of conventional soil based agriculture would most likely continue to increase further along the same projection track by continuing to follow this policy.

Some 32% of global energy demand is currently used by the food sector, whereas 24% is consumed until the farm gate. 14% is used for transportation and distribution and twice this value

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[18] KASTNER, T., IBARROLA RIVAS, M. J., KOCH, W. & NONHEBEL, S. 2012. Global changes in diets and the consequences for land requirements for food. Available: http://www.pnas.org/content/early/2012/04/10/1117054109.full.pdf+html. p.2

[19] http://faostat3.fao.org/download/Q/*/E

[20] Food Balance Sheets, http://faostat.fao.org/site/354/default.aspx, retrieved 14.09.2015

[21] http://www.fao.org/docrep/018/i3434e/i3434e.pdf, p.4 retrieved 13.08.2015

[22] faostat3.fao.org/ live animals, 2011, retrieved 28.08.2015

[23] CASSIDY S. EMILY, WEST C. PAUL, GERBER S JAMES and JOLEY A JONATHAN, 2013. Redefining agricultural yields: from tonnes to people nourished per hectare. Environmental Research Letters, IOP PUblishing, p.1, p.4

[24] FISCHER, G., VELTHUIZEN, H. V. & NACHTERGAELE, F. O. 2000. Global Agro-Ecological Zones Assessment: Methodology and Results. International Institute for Applied Systems Analysis, FAO

[25] SMIL, V. 2008. Energy in Nature and Society, Cambridge, Mass., MIT Press., p.304

for food processing.[26] The difference of the total 176 EJ TPES is consumed by retail, for preparation and cooking. Agriculture is dependent on hydrocarbon energy, from production of macronutrients to the global transportation network, which is almost entirely petroleum driven. Food prices are thus strongly related to oil prices. Their fluctuations, primarily in the developing countries, have a negative impact and endanger global food security and threaten inequality of distribution.

If Vertical Farming has the capacity to disburden the current situation of the world agricultural system, primarily through reduction in land use and energy consumption, this structural typology could well be worth considerable further investigation. Before setting up a Vertical Farm simulation model, an investigation of the indicators for vertical greenhouses that are already built and operational is recommended.

## *THE VERTICAL FARM REFERENCE MODELS*

Four verticalized cultivation methods are compared for estimating the actual potential in land reduction for agricultural production. Four prototypical Vertical Farms are selected with different production methods and the same cultivation methods (hydroponics).

A unit established 120 m2 at „Paignton Zoo“ Devon, UK, in 2009, has horizontally rotating elements and produces leafy vegetables for the zoo animals. The building footprint is 144.45 m2, the cultivation area 388.32m2. Comparing the annual yield with soil based agriculture only 9.09% of the required soil based area is used. The soil based equivalent would be some 1,580 m2.

The horizontal conveyor system enables equal light exposure to the stacked vegetables.

A Vertical Farm with a climatically induced short period for plant growth and a combination of horizontally static layers and vertically rotating elements for fresh vegetable and herbs production has recently been established in Jackson, Wyoming, USA. An annual yield is expected within the greenhouse volume of the building (roughly 2,000 m3), which corresponds to more than 1.5 ha. The building „Vertical Harvest“ footprint is 488.44 m2, a reduction of the food footprint compared to conventional agriculture of nearly 97%.

SkyGreens in Singapore implemented vertically rotating elements. On the principle of a classical greenhouse, combined with this technique the building height can be expanded, the rotation enables equal light distribution to the plants throughout the day. The salad production on a building footprint of 196.16 m2 achieves an annual yield where 2,369.15m2 would be needed, a reduction of nearly 92%.

Lastly, the most promising Vertical Farm both in terms of production method used and the ambition of developing a new typology, is Plantagon‘s Vertical Farm for Linköping in Sweden, which had its ground breaking ceremony by the year 2012, and referring to information provided during the „Urban Agriculture Summit“ in Linköping two years ago, should in all probability be built within the next years.

The production is done on a 3D-conveyor belt where seedlings are planted at the top of the spiral and move down to the ground floor level throughout the crop rotation when ready to harvest. From an architectural perspective it should be mentioned that an office building is situated on the

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[26] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 2011.Energy-Smart Food for People and Climate, Issue Paper, Rome:FAO

north side of the productive greenhouse, enabling synergy potentials in terms of energy flows, oxygen- and CO2-cycles.
Pak choi is produced in a vertical greenhouse volume of 15,003 m2 on a building footprint roughly of 1,000 m2. The annual yield of this Vertical Farm reaches an estimated quantity for which over 8 ha would be needed if it were to be produced conventionally. A yield on an area corresponding to only 1.18% of that require for soil based agriculture.

The right choice of crop type combined with the appropriate production method can drastically reduce land use for food production. But the question still to answer is at what energy cost? All these listed reference models were mostly transparent on the top level, with some reduction taking place „Vertical Harvest“. What potential do Vertical Farms currently have for crop production in a stacked greenhouse? And to increase the challenge, what if we produce crops with a high light demand? To answer these question a clearer picture needs to be drawn on what growth factors must be established within a building to establish ideal conditions.

## *SUBSTITUTION OF NATURAL GROWTH FACTORS*

Greenhouses have been established, largely in temperate zones, since the 17th century. They are used for growing more sensitive plants and also to produce crops. Crops in greenhouses were planted mainly to enlarge the crop rotation scope and to make fresh food available over a longer period of time.

Greenhouses are now established everywhere around the world and now cover an area of some 4,000 km2 worldwide[27], although this area is very likely a significant underestimation by the FAO of the real greenhouse area now in use. High-tech-greenhouses not only boost the crop rotation, but also offer a means to benefit from the greenhouse effect, since the photoperiod throughout the day has now been extended around the world and the conversion of light into sugar is the key for food production.

Plants need a specific part of the electromagnetic spectrum for photosynthesis. From 400-700 nm light affects photosynthesis. The ratio of the total spectrum is thus termed PAR, or photosynthetic active radiation. This photosynthetically active radiation is the waveband 400 to 700 nm, this being the wavelength limitations that are of primary importance for plant photosynthesis. The PPFD, photosynthetic photon flux density is the number of photons in the PAR waveband that are incidental on a surface in a given time period (μmol/m-2/s-1). The quantum sensor will measure this value.“[28] To set up the simulation parameters, requirements for greenhouse tomatoes, Lycoper sicon esculentum (Mill.), was chosen. This cultivar has a high requirement in terms of light and a relatively high requirement in terms of temperature.

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[27] FAO Good agriclutural practices for greenhouse vegetable crops.pdf, p.9

[28] GIACOMELLI, G. 1998. Components of Radiation Defined: Definition of Units, Measuring Radiation Transmission, Sensors. CCEA, Center for Controlled Environment Agriculture, rutgers university, Cook College.

## *THE VERTICAL FARM - SIMULATION MODEL*

The location for the simulation model is Vienna, Austria with 4,401 daylight hours, 43% of them are sunshine hours. The annual total solar horizontal radiation is 1,119.32 kWh/m2 which corresponds to 559.66 kWh/m2 PAR. 263.62 kWh/m2/a PAR is the lighting demand for L. esculentum through the sigmoidal growing curve.

Three different building types are parametrically generated and compared. The volume, is oriented to the volume of the Vertical Farm planned in Linköping, Sweden.
The volume of each VF is oriented to 15,000 m3. The dimensions: VF7 (36m x 7.2m x 61m), VF14 (36m x 14.4m x 33m) and VF32 (36m x 32m x 12m). All farms get simulated with three different building envelopes: Single glazing (U-value= 5.88 W/m2/K, VT=0.85, SHGC=0.8), Double-ETFE (U-value= 2.90W/m2/K, VT=0.85, SHGC=0.65) and double-glazing (U-value= 1.70 W/m2/K, VT=0.91, SHGC=0.7). L. esculentum will obtain daylight through the facade, the difference to the DLI needed will be supplied by LED -lighting (Lumigrow 325PRO).

On top of the building, if DLI exceeds the needed value, LED will be turned off the whole day. At all other level, without excess light, LEDs will be turned on to cover 57,600 seconds or 16 hours of photoperiod. Ventilation and infiltration is not considered. Key findings are that Vertical Farms, developed with intermediate levels as stacked greenhouses, connected to a conventional energy grid and producing crops with high lighting- and heating demand in temperate climate zones can‘t compete with nowaday‘s practise of soil based agriculture.
Low lighting demand show VF32 with its compactness which led to the biggest rooftop surface, where a third of the cultivars gain daylight throughout the whole dayhours. Maximizing all facades to all cardinal directions (nearly) equally, also positively influences the relatively low lighting demand. The fact that 1,144 m2 (0C= 572 m2 and 1C = 572m2), which is 33.10% of the cultivation area, are offset by 5m from the facade and therefor has the maximum lighting demand, still makes results comparable to VF7.
Compactness, activation of the top level for cultivation and optimizing the building orientation towards the sunpath seems to be the recommended way for following studies to optimize the building shape for Vertical Farming.

The difference of the results to VF7 only are around 2.4% (SG) to 1.5% (DG). VF7 with its minimized building depth might also be worth to be investigated more deeply for future Vertical Farm building typology studies. The building depth of 7.2m and south orientation has the lowest light requirement of all three Vertical Farm building types analyzed. Although, through its highest A/V ratio of 0.36 heating demand is the highest, this picture doesn‘t add up in the moment when the values, shown on this pages, get changed from end energy use to total primary energy supply (TPES), visualized on the next pages.

## *TOTAL PRIMARY ENERGY DEMAND AND LAND USE OF VERTICAL FARMS*

In terms of building types we see a strong difference in energy consumption. Whereas lighting demand is strongly dependent from the building type, heating demand is more influenced by the building envelope. Theoretical crops with lower lighting and heating demand in ratio, though, have a stronger impact in reducing TPES[29] than an optimized building envelope or the building type.

The simulation results of the different building types show that a careful followed design strategy for Vertical Farms can reduce the energy consumption up to 800%.

In numerical terms encapsulating the simulation results, a Vertical Farm with some 15,000m3 within a temperate zone, must envisage a TPES of 376.56 kWh/m2/a, with three quarters of this related to lighting demand (353.65 kWh/m2/a), 22.91 kWh/m2/a for heating for crops with high light requirement and relatively high temperature needs. This leads to CO2-emissions of 311.17 t/a or 0.51 kg CO2/kg *L. esculentum*.

By considering these values we see that vertical production is more energy intense than the actual practise in world agriculture. Around 1.50 GWh/a (400 kWh/m2/a TPES) per square meter are needed for annual production of *L. esculentum*. The actual world average of energy supply for the food sector per square meter agricultural land is 11.73 MJ/m2/a or 3.25 kWh/m2/a. Subtracting the energy for retail, preparation and cooking, this number is reduced to 7.80 MJ/m2 or 2.16 kWh/m2/a.[30]

The effect on reducing land use for agricultural production based on the upmentioned simulation models and considering the assumptions of other Vertical Farms[3] draws a clear picture: Land use can be reduced up to 50 times comparing the cultivation area of the production entity to the alternatively needed area for traditional soil based agriculture. More precisely, depending on the building types VF32 uses 1/10th of SBA-area, VF14 1/25th and VF7 uses a ratio of 1/53 compared to SBA.[1] Compared to traditional greenhouse practises, VF 32's ratio is 1/6.5, for VF14 1/16 and VF7 1/33.

The advantage of land set free by optimized cultivation practises and stacking principle, though, with high-energy requiring crops, can be canceled out by adding to calculation the area needed to cover the energy demand with renewable energy.

The thesis, though, also reveals potentials which could make Vertical Farming competitive with nowaday's agriculture practise: Beyond adapting an intelligent energy concept though the following decisions (meant as future fields of research) can reduce the energy demand for Vertical Farms:

- Optimization of the building shape[31]

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[29] We assume the ratio that 24% of TPES of the food sector is related to the energy consumption until the farmgate. See Chapter 2.

[30] We assume the ratio that 24% of TPES of the food sector is related to the energy consumption until the farmgate. See Chapter 2.

[31] CODY, B. 2012. „Form follows Energy - Beziehungen zwischen Form und Energie in der Architektur und Urban Design, DBZ Deutsche BauZeitschrift, Bauverlag BV GmbH, Gütersloh. p.211 ff.

- Sunlight analysis, daylight availability and solar heat gain within the Vertical Farm zones are the decision making factors which crop type will be cultivated throughout the year or shorter crop rotations will be defined to adopt products to the specific seasonal conditions.[32]
- Requirement of light vary strongly from crop to crop. (*L. esculentum* has been chosen within this dissertation because it has the highest light requirement of all our food items.)[1] Results clearly picture expectable TPES on the top of the scale.

# Introduction

Vertical Farming is defined as a highly industrialized year round cultivation method for food production, adaptable for multiple crop types, where the verticalized building typology, its programme and functions primarily focus on optimium plant growth. The building is seen as a structural element of the urban ecosystem. In addition to food production, the Vertical Farm must incorporate elements of the food sector which, at present, are spatially detached from each other on a global scale, something which has a severe impact on energy consumption and the environment.Form Follows Energy[33] for Vertical Farms in three ways: to grant optimum growing conditions for crops, optimized to follow the position of the sun all year round and guaranteeing energy flows, meaning phenomenologically, on the ground level of the city, or preferably, also vertically for public use. Primarily the development of the building itself must follow two main

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[32] By adapting Harald von Witzke‘s postulate that each region (in our case ‚zone‘ „produces the food most appropirate to that region at a relatively low, affordable cost, and these products are subsequently made available to the market (...). WITZKE, H. V. 2011. Bananas from Bavaria?, Augsburg, Ölbaum-Verlag., p.9

[33] CODY, B. 2012. „Form follows Energy - Beziehungen zwischen Form und Energie in der Architektur und Urban Design, DBZ Deutsche BauZeitschrift, Bauverlag BV GmbH, Gütersloh, p.48 ff.

goals: Increasing the overall energy efficiency of a city and also attempting to bring about a considerable reduction in land use, as a result of the favorable comparison between vertically achieved yield and traditional agricultural practices.

Vertical Farming is a subject of controversial discussion. Throughout my last exhibitions, lectures and public presentations, the boundless fascination this theme unleashes among some audiences is as notable as the emphatic refusal it provokes from others. The typology of the Vertical Farm has deepened considerably since my diploma at the Academy of Fine Arts in Vienna, supported by Prof. Markus Schäfer. This progress is primarily due to the potential of the Vertical Farm to re-establish local social and economic interdependencies within the city on the one hand, while on the other, even if it does not seem to be the full solution at first sight, it at least presents a partial opportunity to relieve the burden on the current situation of conventional world agriculture practices and the dependency of the urban population on it.

> Energy consumption, soil erosion, the conversion of natural land for farming use, especially using slash-and-burn methods in rain forests to make additional arable land available, i.e. the Neolithic Revolution, probably the biggest revolution of humankind in which hunters and gatherers became farmers, is now turning into a dystopia.

World total primary energy supply (TPES) in 2014 was around 550 Exajoule (EJ).[34] A third of it is used by the food sector.[35] On a global scale, for every calorie we need to cover our daily energy requirement, we consume nearly six calories of total primary energy. One percent of the global landmass is defined as built-up land, where with the exception of a small percentage of indigenous populations, more than 7 billion people live. The area required to supply world population with food is ten times higher. Countries with emerging economies and above all the developed countries require and have established a food production network over the past few decades, which has reached a global scale and is completely dependent on hydrocarbon energy.

The world population will continue to grow within the next decades, reaching a plateau in 2075 of 9.22 billion people before it starts to decline.[36] This work aims to contribute to the discussion on whether Vertical Farming entails the potential to increase the overall energy efficiency of cities.

The architectural interest in how this typology could be interwoven into the city fabric first needed to be reset before fundamental questions could be answered, at least in part. There is no doubt, even without simulating the energy demand of a verticalized food production entity that this must be higher than it is on the field. In addition, the building is not planned as a principle for humans who have completely different requirements regarding the indoor climate. Light is perceived

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[34] http://www.iea.org/publications/freepublications/publication/KeyWorld2013.pdf, retrieved 05.04.2014

[35] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 2011.Energy-Smart Food for People and Climate, Issue Paper, Rome:FAO, p.10

[36] http://www.un.org/esa/population/publications/longrange2/WorldPop2300final.pdf, p.1, retrieved 10.09.2015

differently, humidity and temperature must be in a different relationship. What does a crop plant actually need to turn light into sugar to be a relevant deliverer of calories and nutrients for human consumption? These questions led to the decision to start an excursion through plant physiology and quantum physics for the development of parametric Vertical Farm models and to develop an aligned simulation tool especially for this calculation.

Throughout this research work, however, a number of limitations must be made, for reasons of time and complexity. The parametric Vertical Farm primarily attempts to find answers to the influence of different orientations or, more precisely, to find guidelines for future typological developments, especially in the context of the zoning of the building and the building depth. Water evaporation from the plants was not considered, although this clearly has an impact on heating demand. Plant growth, especially growth in height has a strong impact on the lighting demand. Although techniques are being developed by the author of this thesis to simulate the auto-shading of the plants themselves, this emerging research did not find a place in this work by the time the dissertation was completed.

## STATE OF DESIGN

There are already plenty of design proposals for Vertical Farming with most of them unfortunately stopping at the design level. Over the past few years, since my diploma in 2008, some prototypes and research entities of Vertical Farms have now been built or are about to be built ranging from Suwon in South Korea to Paignton Zoo in Devon, or the exciting “Vertical Harvest” project in Wyoming, USA, and above all the strong architectural statement that has been made in Linköping, Sweden, where Plantagon had its ground breaking ceremony in 2012.

## STATE OF RESEARCH

In most cases, academic research papers, dissertations or master theses dealing with Vertical Farming are an attempt to frame the state of (research)design, touching as raw assumptions the widely discussed topics on (Vertical) farming, namely water, land use and energy consumption. Vertical Farming is complex and current speed of growth of companies, industries, plant physiologists, horticulturists, urbanists and architects dealing with this topic makes it necessary to accept that the practice of stacking the cultivation area is still in a state of infancy.

On a qualitative level, Gordon Graff‘s thesis has to be mentioned here.[37] His work highlights the necessity of reading the Vertical Farm-building as an integrative part of the city‘s metabolism. A work which delivers quantitative values was written by Chirantan Banerjee.[38] The market analysis of a Vertical Farm elaborates predictions in energy and investment costs.

Basic research data for crop production in controlled environments delivers, above all, the National Aeronautics and Space Administration.[39] Abundance of activity in research on high-tech

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[37] GRAFF, G. 2011. Skyfarming. Master of Architecture, University of Waterloo, Ontario, Canada.

[38] BANERNJEE, C. 2012. Market Analysis for Terrestrial Application of Advanced Bio-Regenerative Modules: Prospects for Vertical Farming. Masterarbeit, Rheinische Friederichs-Wilhems-Universität, Hohe Landwirtschaftliche Fakultät.

[39] https://www.nasa.gov/image-feature/space-farming-yields-a-crop-of-benefits-for-earth, retrieved 31.10.2015

greenhouses is noticeable especially in the Netherlands[40] and Germany[41] as well as in the US[42]. Recommendations for literature can be retrieved from the bibliography of this work. The quickly growing interest on agriculture within controlled environments within the last years makes it understandable that the list on this page must be considered as incomplete.

The doctoral thesis at hand is enlarging the research on energy consumption of Vertical Farming. By concentrating on tomatoes, *Lycopersicon Esculentum* (Mill.), it was possible to consider specific plant needs, to highlight parameters influencing photosynthesis in more detail and to integrate them into a parametric simulation model. The simulation method, especially developed for the thesis, unlike simulation software widely used for building simulations, evaluates year round solar radiation in WPAR within a Vertical Farm by using specific climate data. The simulation model was built up in a way so that parameters such as plant needs, climate data and building geometry can easily be substituted and therefore help to optimize future studies on an architectural level and will facilitate predictions relating to energy consumption of specific crops cultivated in Vertical Farms in specific climate zones.[43]

The integration of agriculture into discussions about architecture and urbanism is actually experiencing a revival. Concepts on (horizontal) urban farming from Ebenezer Howard to Frank Lloyd Wright and Le Corbusier are well known and documented. Vertical Farming as a substitution of traditional soil based agriculture or a supplement in food production is increasingly becoming an integral part of research works, theses, design projects and competitions dealing with urbanism in general[44] [45] [46], smart cities[47], „productive cities“[48] [49] or „Hyperbuilding cities“[50].

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[40] http://www.wageningenur.nl/en/Expertise-Services/Research-Institutes/Wageningen-UR-Greenhouse-Horticulture.htm, retrieved 31.10.2015

[41] http://www.zineg.net/ZINEG_E/, retrieved 31.10.2015

[42] http://ag.arizona.edu/ceac/, retrieved 31.10.2015

[43] CODY, B. 2012. „Form follows Energy - Beziehungen zwischen Form und Energie in der Architektur und Urban Design, DBZ Deutsche BauZeitschrift, Bauverlag BV GmbH, Gütersloh, p.48 ff.

[44] VIE:BRA - Vienna-Bratislava-City, urban strategies: http://www.dieangewandte.at/jart/prj3/angewandte/main.jart?rel=en&reserve-mode=active&content-id=1234966513566&Akt-Id=4493, retrieved 31.10.2015

[45] http://www.braincitylab.org/, die angewandte, Coop Himmelb(l)au, retrieved 31.10.2015

[46] http://milliardenstadt.at. University of Technology, Vienna. Project initiator: Lukas Zeilbauer

[47] LIM CJ, ED LIU. 2010. Smartcities + Eco-warriors. Oxfordshire (first published), New York. Routledge.

[48] NELSON, N. 2009. Planning the productive city. Available: http://www.nelsonelson.com/DSA-Nelson-renewable-city-report.pdf. Delft Technical University, Wageningen University and Research, NL

[49] http://www.futurarc.com/index.cfm/competitions/2013-fap/. Addressing „adaptation of existing building typologies for agriculture (...) urban networks for production [and] distributions (...)

[50] CODY, B. 2014. Form Follows Energy - Die Zukunft der Energie-Performance, energy2121, Bilder zur Energiezukunft, Klima- und Energiefonds, Vienna, omninum, p. 121 ff.

Vertical Farms as buildings or elaborated design proposals can be retrieved from the world map on page 124.

# Landuse, Biocapacity and Energy Consumption

## Compiling a status quo model of traditional agriculture

Ever since agriculture became more and more structurally coupled with industry, especially the oil- and armament‘s industries[51] [52], agricultural production has not only completely changed in

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[51] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 2011.Energy-Smart Food for People and Climate, Issue Paper, Rome:FAO

practice and scale, but also in its energy consumption patterns. From the Neolithic Revolution to the Green Revolution the only energy source for food production was direct solar radiation and human labor which was then supplemented increasingly by the use of electricity and, above all, by fossil fuels.

Agricultural production is becoming ever more energy intensive, if not altogether dependent on -cheap and abundant oil and gas.[53] It is becoming a widespread concern that the reliance of the global food system on fossil fuel increases drastically.“[54] In fact there is an intrinsic factor of energy consumption in conventional food production that lies behind the structural coupling of the oil- and the food industries. Regarding future food supply, it is necessary to understand if Vertical Farming can make cities more energy independent, especially from hydrocarbon energy. At the present time one third of world energy consumption is accounted for the "nutrition" system (food sector), 25 % of this within the farm gate.

Beyond the production entity of the Vertical Farm although a significant reduction of hydrocarbon energy and CO2-emissions with urban Vertical Farming can be assumed. Substitution of natural sunlight with electrical power and heating demand for year round crop production however, might well increase energy demand in urban agglomerations. The question is if the reduction of energy consumption beyond the Vertical Farm gate (Vertical Farm-gate) can balance out the surplus in energy consumption for indoor crop production.

Before this question can be investigated with appropriate depth, a brief digression on the issue of energy consumption in the global food sector is appropriate at this point. The objective of this chapter is to investigate the current situation of world agriculture in terms of land use efficiency and to what extent it can be increased, while additionally presenting an all-round view of the limits to the current biocapacity of the earth for meeting future food demand. Investigations of landuse, energy consumption and biocapacity have the purpose of establishing the degree of pertinence Vertical Farming has gained in the face of this situation.

## Land requirement for daily coverage of essential nutritional -value for the human body

The human body, like that of every living being needs energy to sustain its biological functions and life. There are multiple calculation models to define the specific energy need per person. In addition to several prediction equations one of the most notable of these for calculating the Basal

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[52] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 2011.Energy-Smart Food for People and Climate, Issue Paper, Rome:FAO. p.6

[53] ibid. p.6

[54] "It is this increased reliance of global food systems on fossil fuels that is now becoming cause for concern." Energy-Smart" Food for People and Climate Issue paper, FAO, 2011, http://www.bigpictureagriculture.com/2011/12/fao-report-warns-about-fossil-fuel.html (19.05.2014)

Metabolic Rate (BMR)[55] is the Harris-Benedict equation, created in 1919. This equation was revised in 1984 using new insights in biology. This was widely regarded and used as the best prediction equation until 1990, when Mifflin et al. introduced the Mifflin St. Jeor- Equation[56]. A simplification based on this equation will be used in this work to define the basal metabolic rate of the human body - which is „relatively constant among population groups of a given age and gender. (...)“[57]

male: 1 kg of body mass consumes 24 kcal/day
female: 1 kg of body mass consumes 24 * 0.9 kcal/day

BMR, broken down on organs and muscles of the human body, are divided as follows:

| | |
|---|---|
| liver | 26 % |
| muscles | 26 % |
| brain | 18 % |
| heart | 9 % |
| kidney | 7 % |
| other organs | 14 %[58] |

In addition to BMR, the Physical Activity Level (PAL) is of importance to calculate the total energy requirement. The Food and Agriculture Organization defines three ranges of values:

| | |
|---|---|
| sedentary or light activity lifestyle | 1.40 - 1.69 |
| active or moderately active lifestyle | 1.70 - 1.99 |
| vigorous or vigorously active lifestyle | 2.00 - 2.40[59] |

This PAL-value is the factor multiplied by, BMR to obtain the needed daily energy requirement for the human body.[60]

With these figures we can now make an assumption about the daily energy requirement of an adult person, irrespective nationality or culture:

adult male, 75 kg, sedentary: 75*24*1.5 = 2,700 kcal/day
adult female, 65 kg, sedentary: 65*24*0.9*1.5 = 2,106 kcal/day

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[55] Basal metabolic rate (bmr), index of the general level of activity of an individual’s body metabolism, determined by measuring its oxygen intake in the basal state—i.e. during absolute rest, but not sleep, 14 to 18 hours after eating. The higher the amount of oxygen consumed in a certain time interval, the more active is the oxidative process of the body and the higher is the rate of body metabolism. (...) http://www.britannica.com/topic/basal-metabolic-rate, retrieved 25.08.2015

[56] http://ajcn.nutrition.org/content/51/2/241.abstract, retrieved 12.06.2014

[57] http://www.fao.org/docrep/007/y5686e/y5686e07.htm, retrieved 25.08.2015

[58] http://www.fao.org/3/contents/3079f916-ceb8-591d-90da-02738d5b0739/M2845E00.HTM, retrieved 25.08.2015

[59] „PAL values higher than 2.40 are difficult to maintain over a long period of time.“, ibid.

[60] It is explanatory, that there are additional variables throughout a human lifetime which cannot be considered here, such as pregnancy-periods, lactating women, the length of adolescence, etc. Additional information about the principles followed by the 1985 FAO/WHO/UNU expert consultations can be found on http://www.fao.org/docrep/007/y5686e/y5686e07.htm, retrieved 19.08.2015

The total energy requirement of a sedentary male can therefore be assumed as

| | |
|---|---|
| 2,700 | kcal or |
| 11.30 | MJ or |
| 3.14 | kWh or |
| 0.30 | OE[61]. |

The total energy requirement of a sedentary female therefor can be assumed as

| | |
|---|---|
| 2,160 | kcal or |
| 8.82 | MJ or |
| 2.45 | kWh or |
| 0.24 | OE. |

This total energy requirement[62] (Tab.1) for the human body must be get provided through a continuously operating food supply system, at the beginning of which agriculture is to be found, with the exception of some very few aboriginal populations the provision is thus based on the cultivation care of fertile land.

By the end of the Paleolithic period, human societies made a sweeping change in their habits. „(...) [A]fter hundreds of thousands of years of biological and cultural evolution, human societies were able to make increasingly varied, sophisticated, and specialized tools, thanks to which they developed differentiated modes of predation (hunting, fishing, gathering), adapted to the most diverse environments.“[63]

Back then, with the emergence of a radical change in food provision, a single person would have needed between 40 and 150 ha to cover the total energy requirement of an estimated 3,960 kcal (75*24*2.2) per day, by hunting, fishing and gathering, depending on the fertility and topography of the land. That means a family of five would have required approx. 200 ha. „This estimate is based on an ideal ecosystem, one containing those wild plants and animals that are most suitable for human consumption.“[64]

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[61] http://www.aie.org.au/AIE/Energy_Info/Energy_Value.aspx, retrieved 09.09.2015: 1 l oil = 42 MJ, 1 kg of oil equals 37 MJ

[62] Data retrieved for the extrapolation of Tab. 1: https://www.cia.gov/library/publications/the-world-factbook/fields/2018.html, retrieved 01.06.2015
http://www.fao.org/docrep/meeting/009/ae906e/ae906e35.htm, retrieved 01.06.2015
http://www.eia.gov/forecasts/steo/report/global_oil.cfm, retrieved 01.06.2015
http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=5&pid=53&aid=1&cid=ww,&syid=2010&eyid=2014&unit=TBPD, retrieved 01.06.2015
„The reference man and woman“, FAO, http://www.fao.org/docrep/meeting/009/ae906e/ae906e35.htm, retrieved 31.10.2015

[63] MAZOYER, M. & ROUDART, L. 2006. A History of World Agriculture, London, Earthscan. p. 71

[64] PIMENTEL, D. et al. 2008. Food, Energy and Society, third edition, CRC Press Boca Raton. p. 45-46.

We are entered the final period of prehistory, around 10,000 years ago. Several societies, among the most advanced ones of the time, enabled one of the most radical and influential changes in human history - the Neolithic Revolution.

„At the beginning of this change, the very first practices of cultivation and animal raising, which we will call protocultivation and proto-animal raising, were applied to populations of plants and animals which had not yet lost their wild characteristics. But, as a result of such practices, these populations acquired new characteristics, typical of domestic species, which are the origin of most of the species that are still cultivated or bred today.“[65]

Within this change of habits, the creation of new social organizations were possible, or necessary. To plant grains in an already prepared fertile ground, or to capture and raise wild animals is not the challenge that was faced here. The difficulties at this stage of evolution were the following:

„To arrange a social organization and rules that make it possible for units (or groups) of producer-consumers to subtract from immediate consumption an important part of the annual harvest in order to save it as seed stocks“(...)[66]

„To exempt from slaughter enough reproductive and young animals to make it possible for the herd to reproduce itself“ (...)[67]

„To protect the fields planted by one group from the previously recognized right of other groups to ‚gather‘ in those areas and to protect the animals being raised from the right of those groups to ‚hunt‘ them.“[68]

„Lastly, what is difficult is to ensure the distribution of the fruits of agricultural work among the producer-consumer of each group, not only every day, but above all (...) when the eldest die and when the group becomes too large and must be subdivided into several smaller groups.“[69]

Still it took four thousand years until the first state-governmental structures in Egypt arose, but by settling down permanently for the first time in human history it was possible to build the first fortified villages and towns. The surplus of density of people around agriculture land directly led „to the rise of cities and civilization because it allowed people to develop and concentrate on manufacturing, trading and other specializations (...) like advances in technology, art and other innovations.“ [70]

The natural landscape became divided in two cultured landscapes - land for agriculture and land for cities, spatially united - as the nucleus for further civilizations.

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[65] MAZOYER, M. & ROUDART, L. 2006. A History of World Agriculture, London, Earthscan. p. 71,

[66] MAZOYER, M. & ROUDART, L. 2006. A History of World Agriculture, London, Earthscan. p.71

[67] ibid. p.71

[68] ibid. p.71-72

[69] ibid. p.72

[70] MC.KINNEY, M. et al. 2012 „Environmental Science: Systems and Solutions“, Burlington, Logan Yonavjak Jones & Bartlett Publishers. p. 36

Approximately 50 million people lived on earth by the beginning of the Neolithic Revolution.[71] This revolution now started a steady and continuous growth of the world population. Several factors have been attributed to this:

„Settlement on farms may have allowed women to bear and raise more children; freed from the nomadic lifestyle, women no longer had to carry young offspring for great distances (...)“

Labor capacities of children can more easily used in agriculture than in gathering and hunting

„Agriculture and domestication may have made softer foods available, which allowed mothers to wean their children earlier.“ More children a mother therefor could bear.

Higher densities of people were possible, as a consequence of agriculture and domestication. „(...)[W]ith farming, one family or group of persons could raise more food than they personally needed.“

The upcoming developments of tools, achieved knowledge in plant culture, seed production and husbandry and especially the capacity in storing sun energy through feed and food storage for periods when nothing can be harvested because weather or seasonal conditions radically reduced the area needed to supply human beings with their daily energy requirements to guarantee a personal healthy life for the individual and on a communal level - maintaining social cohesion.

Before we come up with a concluding ratio in land use between hunters/gatherers and sedentary people, an important concept for food supply needs to be explained, the food balance sheets, as defined by the Food and Agriculture Organization.

## Food Balance Sheets

Food balance sheets create a picture of the pattern of food supply of a specific country in a defined period. This information sketches the daily consumption of food items of a country both in terms of the amount (g/day) and the nutritional value (kcal). In addition FBS provide information about the quantity of imports and exports, items used for feed (livestock), used for seeds and for food losses or food waste. Apart from several weaknesses, e.g. they do not provide any information on differences in food supply within a country or seasonal differences, the FBS are (...) the only source of standardized data that permit international comparison over time.[72] FBS „do provide an approximate picture of the overall food situation in a country and can be useful for (...) nutritional studies. In addition FBS provide data to estimate future changes in food supply or, more correctly, food consumption, especially in countries with emerging markets.“[73]
As we have seen before in our two assumed examples, an average person needs around 2,500 kcal/day. By contrast with the data provided by FBS, this is data for food consumption, specifically the amount of energy a human being needs per day to sustain biological functions and life. Before

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[71] ibid. p. 35

[72] FOOD AND AGRICULTURE ORGANISATION OF THE UNITED NATIONS 2001. Food balance sheets. A handbook. Rome: FAO. p.4

[73] ibid.

food can be consumed, it must first be provided - this is defined as food supply. The values for this are always are higher than those for consumption, since supplied food will not be consumed completely because of food losses, food waste and various other differences. What area does single human being need to cover his daily nutritional value requirement? In January 2012 Steffen Noleppa and Harald von Witzke[74] published a detailed account of the situation in Germany with the aim of providing recommendations for the German Society for Nutrition (Deutsche Gesellschaft für Ernährung, DGE). Single food items of daily consumption were analyzed by their land requirements and related food losses and food wastes. For more detailed information I recommend the above mentioned study. For this work it is of interest to approximate the effective use of land to cover the food supply. The following diagram shows the area a German needs for food production, 2,300 m2. The total agricultural land per person is 2,900 m2. This area also includes land considered for agriculture products, which are not intended for direct consumption but are used for other purposes such as those agricultural products used for industry and agricultural products for clothings such as cotton or for rubber production and also plants cultivated for biofuel production. A factor that is also visible is the enormous difference between the different food items, compared with the actual amount of food consumed and the land area required to produce it, e.g. potato provision for a year needs only 15 m2, whereas grain requires 115 m2 and pork production 498 m2.[75] In brief of the 2,900 m2 needed per person for agriculture products annually 1,099 m2 are for animal products, including meat, milk and dairy products and eggs.[76]

Coming back to the initial steps of the Neolithic Revolution we can say that the land needed for people to cover the total energy requirement for the human body has shrunk within the past 11,000 years from 40 ha (highly fertile land) per person to 1,3 ha. In terms of the ecological food footprint[77] (Fig. 2), this is a reduction of more than 30 times, taking into account that the ecological food footprint of hunters and gatherers was close to 0.

These data now are focused on the one single country Germany, which is highly technologized, with one of the highest GDPs in the world and, as in most other countries, with its own unique and specific culturally characterized diet. How can we obtain an image of world food data in order to establish firm statistics for the effective land use of the global population and simultaneously to venture a picture of future land use?

Tab. 2 on page 46 shows the difference between the consumption of food items of different countries (USA, Italy, Germany, Austria and China). We know that the area we need for food supply is dependent on the items consumed. The more the diet of culture is oriented to food of vegetable origins, the less area is required per person. The question here is whether this is the only parameter for defining the area needed.

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[74] NOLEPPA, S. & WITZKE, H. V. 2012. Tonnen für die Tonne. Berlin: WWF

[75] ibid. p. 42.

[76] ibid. p.42-43

[77] VALE, R. & VALE, B. 2009. Time To Eat The Dog?, London, Thames & Hudson. p.36

In an effort to investigate this question more deeply, Kastner et al.[78] was looking for the main drivers in changes in land use and future requirements of croplands by comparing FBS of different subcontinents. Major findings are that the size of the population, the average food consumption pattern and the output per unit land define the cropland needed. In other words, it is population change, diet (FBS) and agriculture technology in use. „The amount of cropland needed depends on population numbers, average food consumption patterns, and output per unit of land.“[79] (...) „Population, diets, and production techniques change over time and show large spatial variation. With socioeconomic development, population growth rates decrease and diets change: typically, consumption of animal protein, vegetable oils, fruits and vegetables increases, while starchy staples become less important. The change from these staples toward richer diets implies that cropland demand for average diets will in general increase. By contrast, the introduction of new technologies leads to improvements in agricultural area productivity through time.“[80] [81]

In order to form a clear picture of the actual food consumption and the required land to cover daily food requirements Kastner et al. used FAO FBS and grouped them on subcontinental levels. For the task of evaluating which are the main drivers related to land use for agricultural production, FAO data from 1961 to 2007 was analyzed. Major findings, relevant for this work are that on a global level, the „average land area needed to feed a person in 2005 was two thirds of the corresponding value in 1963, decreasing from approximately 2,650 to just over 1,732 m2/person/y. (...) Across the regions, per capita cropland requirements for food in 2005 were lowest in much of Asia, with approximately 1,300 m2/person/y in Southeast Asia (...). The highest values, with more than 3,000 m2/person/y, were found in Oceania and Southern Europe, two dry regions with a large annual variability. Western Africa and Northern Europe, two regions at very different ends of the global spectrum in terms of per capita food supply, show the same per capita values in 2005, at approximately 2,350 m2/person/a.“[82]

While the cropland needed per capita has decreased since 1963 the effective area increased from 8,400,000 km2 to 11,000,000 km2, an increase of 32%, while world population increased from 3,201,000,000 to 6,540,000,000 in the decades from 1963 to 2005 (=103%). „This was mostly driven by growing land demand for animal products, which accounted for almost 50% of the total increase.“[83]

Before we take a look at the total agriculture land in use, the main highlights of this study must be pointed out:

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[78] KASTNER, T., IBARROLA RIVAS, M. J., KOCH, W. & NONHEBEL, S. 2012. Global changes in diets and the consequences for land requirements for food. Available: http://www.pnas.org/content/early/2012/04/10/1117054109.full.pdf+html.

[79] ibid. p.1

[80] ibid. p.1

[81] VALE, R. & VALE, B. 2009. Time To Eat The Dog?, London, Thames & Hudson.

[82] KASTNER, T., IBARROLA RIVAS, M. J., KOCH, W. & NONHEBEL, S. 2012. Global changes in diets and the consequences for land requirements for food. Available: http://www.pnas.org/content/early/2012/04/10/1117054109.full.pdf+html. p.2

[83] ibid. p.2

The biggest drivers in cropland expansion is not population growth, but socioeconomic development (Tab. 3 on page 48). What has been observed is that by increasing GDP population growth slows down, but the effects on dietary changes still have the result of an increase in the area needed for food production. „It suggests that pressures on land resources linked to the provision of food are likely to remain high in the coming decades, as these dietary changes affect a large share of global population.“[84] In addition, an increase in land use efficiency, something that mostly occured in the industrialized countries within the last fifty years, and led to a decrease in land use per person on a global scale, can only be possible with an increase in external inputs, mostly hydrocarbon energy used for fertilizers, pesticides etc. but also for machinery and irrigation infrastructure with all the environmental impacts entailed which are to expect.
We now have a clearer picture in what area is needed to provide people with food, what main drivers are responsible for the change of cropland requirements and the uneven distribution in total land use of different subcontinents.

The study of Kastner et al. focused on 11 mostly cultivated food categories produced on croplands. „(...) [M]ore than 90% of all food calories and approximately 80% of all food protein and fats available in the world were derived from croplands.“[85] But the output of the agricultural land per person is not all used for direct human consumption (diagram on the next page). Before coming back to yield or calories as output of cropland directly available for human consumption, we will investigate to what extent this area currently can be extended by answering the question of how much is in use at the present time and what is the expectable biocapacity of the world.

## World land masses and the ratio of land used for agricultural production

On a global scale the average cropland needed for a single person (food supply), as we have seen in the previous subchapter is 1,732 m2/a. Land for agriculture use, is divided in arable land[86] (=cropland), land for permanent crops[87] and pastures[88].

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[84] KASTNER, T., IBARROLA RIVAS, M. J., KOCH, W. & NONHEBEL, S. 2012. Global changes in diets and the consequences for land requirements for food. Available: http://www.pnas.org/content/early/2012/04/10/1117054109.full.pdf+html. p.4

[85] KASTNER, T., IBARROLA RIVAS, M. J., KOCH, W. & NONHEBEL, S. 2012. Global changes in diets and the consequences for land requirements for food. Available: http://www.pnas.org/content/early/2012/04/10/1117054109.full.pdf+html. p.2 and http://faostat.fao.org/, retrieved 13.05.2013

[86] Arable land is the land under temporary agricultural crops (multiple-cropped areas are counted only once), temporary meadows for mowing or pasture, land under market and kitchen gardens and land temporarily fallow (less than five years). The abandoned land resulting from shifting cultivation is not included in this category. Data for “Arable land” are not meant to indicate the amount of land that is potentially cultivable. faostat.fao.org/site/375/default.aspx; retrieved 26.08.2015

[87] Crops are divided into temporary and permanent crops. Permanent crops are sown or planted once, and then occupy the land for some years and need not be replanted after each annual harvest, such as cocoa, coffee and rubber. This category includes flowering shrubs, fruit trees, nut trees and vines, but excludes trees grown for wood or timber. ibid.

The world‘s surface area is some 510,072,000 km2. 29,10% of this is distributed over the continents, the remaining 70,90 % is the surface of the oceans.[89] The landmass is distributed as follows: forests cover more than a quarter of the continent‘s surface, pastures around 23 %. The inland water (rivers and lakes) some 3 %. Antarctica and agricultural land have equal dimensions, both being around 15,000,000 km2 each.

On a first glance on the agricultural land in use (both for permanent crops and cropland) and dividing it by the world population of 2007 (6,646,374) when the study of Kastner et al. was published, we can suggest that there is enough agricultural land available. 2,336.57 m2 would be available for a single person, a surplus of around 600 m2 compared to the world media of 1,732 m2. This is a potential expansion in world average to meet future demand for the growing world population, or rather reducing hunger and the percentage of undernourished people.

Now as we know the availability of land per person and the caloric values needed demant a look at the total produce from agriculture. The following comparative data retrieved by the database of the Food and Agriculture Organization are all from the year 2011. This is information on the above statistics (and following on from this) on available agricultural land, FBS, world population numbers and agriculture primary production for food, food manufacture and animal feeds.
The following table shows the FBS of the world. It differentiates between the total production of food, food manufacture, feed and seed-production and also gives information on estimated quantities of food waste and also changes in food stock, and imported and exported food. The methodology and definitions can be obtained from the Nomenclatura.

Agricultural land of 15,529,767 km2 produced more than 9.5 bn metric tons of primary products in 2011. By assuming a per capita food supply of 900 kg/a (2.4 kg/d) which corresponds to a European high GDP country[90] and dividing it by the total primary production worldwide (9,585,647,000 metric tonnes)[91] every person could be supplied with 1,399.80 kg/a. A number which could lead to the conclusion that there is enough food on earth but unevenly distributed if we consider how some 795,000,000 people are undernourished or suffer from hunger[92 93].

Now subtracting feed, seeds, wastes, other (nonfood/feed) uses and food manufacture, and dividing the result of 4,712,094 by the world population in 2011 the statistic to emerge appears quite different: 688,03 kg/y (1.88 kg/d) are directly related to food supply. Adding food manufacture (which is a consumable part of food production, more specifically explained in the Chapter Nomenclatura) the per capita food supply rises to 997 kg/year. We can assume as a rule of

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[88] Mainly meant as grasslands. ibid.

[89] https://www.cia.gov/library/publications/the-world-factbook/geos/xx.html, retrieved 12.03.2012

[90] Austria: 1,027.50; Germany: 979.90; Italy: 1,051.90; FBS faostat.org, retrieved 28.08.2015

[91] http://faostat3.fao.org/download/Q/*/E

[92] http://www.fao.org/docrep/018/i3434e/i3434e.pdf, p.4 retrieved 13.08.2015

[93] Undernourishment means that a person is not able to acquire enough food to meet the daily minimum dietary energy requirements, over a period of one year. FAO defines hunger as being synonymous with chronic undernourishment..

thumbthat world‘s productivity per km2 (cropland and permanent crops) is 617 kg of which only 50 % is used for direct food production or 70 % when also considering food manufacture.

One squaremeter of the world‘s agricultural land supplied the amount of 617 g/a of primary production with a caloric value of 2,870 kcal/d (1,047,550 kcal/a) or 12.01 MJ/d (4.38 GJ/a).

A total primary production of 9,585,647,000 metric tons must feed 6,847,859,000 people and some hundreds of million pets, about which precise statistics are difficult to obtain.[94]

Faced with these numbers at this stage we can clearly maintain that an increase in agriculture land will almost certainly be a necessity in future. In this context it must first be pointed out that 795 million people are still undernourished or suffer from hunger in 2015.[95] Secondly, a caloric value of 2,870 kcal/day might be enough for most sedentary populations with a high consumption of animal products, but for populations with a higher percentage of labor in agriculture (less technologized) a much higher total energy requirement is necessary. More than 2.6 billion people work in the primary sector[96], more than 70 % of them still till the soil by hand or with animal power. Taking into consideration those countries in a process or rapid growth such as China and India and other emerging economies, it must be borne in mind that their socioeconomic development is directly related to a change in diet with a move to a consumption of more animal products. Returning briefly to the contemporary situation in 2015: in the time since FAO published the data given above, the world population increased from 6,847,859,000 to more than 7,320,000,000 - in other words half a billion additional people are now on the plantet.
According to the UN-World Population Report we will have to expect a world population of some 8,920,000,000 people in 2050. Furthermore growth will continue and peak in 2075 by some 32 billion before a slight decline is expected to begin.

An additional need for land area for food and feed production now seems to be an unavoidable necessity. The interesting question at this stage now would firstly be to what extent agriculture land needs to increase, in other words, how much land surface - nature - must be converted in to cropland?

And, more importantly what is the total biocapacity of the earth that is - suitable for agricultural production? Does the earth‘s landmass have the potential to feed more than 9 billion people?

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[94] http://pets.thenest.com/number-dogs-cats-households-worldwide-8973.html, retrieved 03.09.2105

[95] http://www.fao.org/news/story/en/item/288229/icode/, retrieved 28.08.2015

[96] http://www.worldwatch.org/asia-and-africa-home-95-percent-global-agricultural-population-0, retrieved 26.08.2015

## Biocapacity of the Earth

Some 120,000,000 km2 we are defined as biologically productive land and water surfaces in 2011.[97] This corresponds to 1.75 ha (or global hectare [gha]) per person. It is the land and water (sea and inland water) „that supports significant photosynthetic activity and the accumulation of biomass used by humans. Non-productive areas as well as marginal areas with patchy vegetation are not included. Biomass that is not of use to humans is also not included.“[98] Also included is the area with the capacity to capture CO2.

„Land is an indispensable resource for the most essential human activities: it provides the basis for agriculture and forest production, water catchment, recreation, and settlement.“[99] For assessing agricultural resources and potentials for the growing world population over the last thirty years FAO together with the International Institute for Applied System Analysis (IIASA) developed the Agro-Ecological Zones (AEZ) methodology which „provides a standardized framework for the characterization of climate, soil and terrain conditions relevant to agricultural production.“[100] Five major thematic areas are covered within GAEZ:

„Land and water resources, including soil resources, terrain resources, land cover, protected areas and selected socio economic and demographic data;

Agro-climatic resources, including a variety of climatic indicators;

Suitability and potential yields for up to 280 crops/land utilization types under alternative input and management levels for historical, current and future climate conditions;

Downscaled actual yields and production of main crop commodities, and

Yield and production gaps, in terms of ratios and differences between actual yield and production and potentials for main crops.“[101]

Of major interest for us are findings regarding the actual potential of suitable land for agricultural production. Major findings of this study are as follows:

Resources (both land and biological) are „sufficient to meet the needs of food and fiber of future generations, and more in particular for a world population of 8.9 thousand million, as projected for the year 2050 by the UN medium variant.“[102]

A closer look at the dataset, however, also leads to „(...)profound concerns. Several regions exist, where the rain-fed cultivation potential has already been exhausted (...)“[103]

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[97] http://www.footprintnetwork.org/en/index.php/GFN/page/glossary/#biologicallyproductivelandandwater, retrieved 28.08.2015

[98] ibid. Glossary.

[99] FISCHER, G., VELTHUIZEN, H. V. & NACHTERGAELE, F. O. 2000. Global Agro-Ecological Zones Assessment: Methodology and Results. International Institute for Applied Systems Analysis, FAO., Executive Summary, p.x

[100] ibid. p.x -

[101] http://www.fao.org/nr/gaez/en/#, retrieved 28.08.2015

[102] FISCHER, G., VELTHUIZEN, H. V. & NACHTERGAELE, F. O. 2000. Global Agro-Ecological Zones Assessment: Methodology and Results. International Institute for Applied Systems Analysis, FAO. Executive Summary, p.xi

[103] ibid. p.xi

Global warming „may alter the condition and distribution of land suitable for cropping. (...)

Socioeconomic development may infringe on the current agricultural resource base for want of a concomitant rapidly expanding industrial and service sector. (...)

Land degradation, if continuing unchecked, may exacerbate regional land scarcities. Concerns for the environment may prevent some resources from being developed for agriculture.[104]

Roughly two thirds of the total land mass (Antarctica included) „suffer rather severe constraints for rain-fed crop cultivation“[105], an area of 105,000,000 km2.

At this point after subtracting the area suffering from severe constraints for rain-fed agriculture practices from the total land mass of the earth, we can assume 44,428,500 km2 will be left. This suggests that the potential exists for more than doubling the actual total agricultural area. Estimating the possible extent of land with the potential to grow rain-fed crops is depending on „a variety of assumptions: the range of crop types considered, the definition of what level of output qualifies as acceptable, the social acceptance of land-cover conversion (in particular forests), and the assumption on what land constraints may be alleviated with modern inputs and investment.“[106] This explains GAEZ‘s estimation ranges from 13,000,000 km2 of land „very suitable and suitable for major cereal crops, under high inputs and mechanization, outside current forest areas“[107] to some 33.000.000 km2 which is defined as land „very suitable, suitable or moderately suitable for at least one of the AEZ crop types, within or outside current forest areas.“[108]

In absolute numbers we can state in summary that from the 149,428,500 km2 of land mass area:
32,698,612 km2 is very suitable or suitable

116,610,121,566 km is land area with constraints for agricultural production of which

75,446,748.65 km2 has bad soil conditions

31,601,342.94 km2 is too dry

15,392,536.04 km2 is too cold and

13,759,994.34 is too steep.

Tab. 6 gives an overview of the actual results of GEAZ-study. The potential land is subdivided into six classes: VS is prime land (very suitable) „with attainable yields of over 80 % of maximum constraint-free yields. Good land [S] represents suitable and moderately suitable [MS] land with attainable yield levels of 40 to 80 percent of maximum constraint-free yields (...)“[109] Marginally suitable land (mS) has an attainable yield of 20-40 %, very marginally suitable (vmS) from 5-20 % and lastly NS, not suitable land less than 5 %. In this study major crops which were considered were cereals, roots and tubers, sugar crops, pulses and oil-bearing crops.

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[104] ibid. p.xi

[105] ibid. p xi

[106] FISCHER, G., VELTHUIZEN, H. V. & NACHTERGAELE, F. O. 2000. Global Agro-Ecological Zones Assessment: Methodology and Results. International Institute for Applied Systems Analysis, FAO. Executive Summary, p. xii

[107] ibid. p.xii

[108] FISCHER, G., VELTHUIZEN, H. V. & NACHTERGAELE, F. O. 2000. Global Agro-Ecological Zones Assessment: Methodology and Results. International Institute for Applied Systems Analysis, FAO. Executive Summary, p.xii

[109] ALEXANDRATOS, N. & BRUINSMA, J. 2012. World Agriculture Towards 2030/2050. The 2012 Revision. [Rome]: Agricultural Development Economics Division, FAO. p. 102

As a conclusion to this brief perspective of the biocapacity of the earth we could claim on the one hand that there would be enough land usable for agricultural production, considering our above defined world average land use for food production of a single person of 1,732 m2: Counting the potential of land very suitable, suitable and marginally suitable the world could feed more than 25 billion people, 28 billion with a diet corresponding to Asia, 19 billion with a North American diet, 17 billion with a European diet and 12 billion with a diet typical to Oceania.

On the other hand one must be conscious about the fact that some 30,000,000 km2 of natural land has to be converted into agricultural land. Our built up land is currently around one percent of total landmass, but we need 10 % of the total landmass to supply ourselves with food. 25 % of the total land is covered with forests. Nearly a third of it in South- and Central America, or in other words: 75 % of the existing forests are located in developing countries.[110]
World Agriculture is already responsible for 17 - 32 % of total greenhouse gas emissions.[111] Around 47 % of this is related to land conversion to cropland. Considering a media of 300 t/ha of CO2 a rainforest can store which would be released by slash-and-burn methods one can readily imagine that other solutions to increase the total amount of available food for the growing and prospering world population should be considered.

When the area for agricultural production is not to be increased then two options are available to meet future demands: One of these would be to radically change the agricultural system by exclusively delivering every single calorie of crops for human consumption and the second option would be to increase yield per hectare.

## *CROPLANDS EXCLUSIVELY DELIVER CALORIES FOR HUMAN CONSUMPTION?*

Higher incomes (Tab.8)[112] are directly connected in the societies where these occur to changes in diets[113], with a move away from more vegetal to more animal products.[114] This consequently increases the footprint related to agricultural production per person. The following table gives an insight about changes of FBS globally from 1961 to 2007 compared to the Gross Domestic Product. China is presented as an exemplary case as a country which greatly changed its FBS - a traditionally vegetal kitchen increased its consumption of animal products fourfold - a change which is most likely to continue and typical for developing countries.

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[110] FAO Global Forest Resources Assessment 2010, retrieved 28.08.2015

[111] MILLSTONE, E. & LANG, T. 2008. The Atlas of Food, London, Earthscan. p.62

[112] GDP-statistics from http://data.worldbank.org/indicator/NY.GDP.MKTP.CD, retrieved 18.08.2015

[113] KASTNER, T., IBARROLA RIVAS, M. J., KOCH, W. & NONHEBEL, S. 2012. Global changes in diets and the consequences for land requirements for food. Available: http://www.pnas.org/content/early/2012/04/10/1117054109.full.pdf+html.

[114] What also can be observed is that countries with higher GDPs consume less starchy roots or pulses and increase its consumption of sugar and sugar crops and cereals.

Kastner‘s et al. findings show that the main drivers „call to dramatically boost global crop production.“[115] What would be the potential in radically changing crop production to exclusively direct every calorie to human consumption? What would be the potential?

„Currently, 36% of the calories produced by the world‘s crops are being used for animal feed, and only 12 % of those feed calories ultimately contribute to the human diet (as meat and other animal products). Additionally, calories edible for humans are used for biofuel production“[116] additionally reducing the available calories for human consumption.

In terms of mass, two thirds are thus produced for direct human consumption. Feed crops „represent 24% of global crop production“[117] on 75 % of all agricultural land, including pastures, which correspond to 36,837,235 km2 of the total of 49,116,313 km2.

Crops for industrial uses „including biofuels, make up 9 % of crops by mass, 9% by calorie content (...)“[118]

From the calorie perspective only 55 % of the global crops produced are consumed directly by humans. 36 % of these go to animal feed, „of which 89 % is lost, with the result that only 4 % of crop-produced calories are available to humans in the form of animal products. Another 9% of crop-produced calories are used for industrial uses and biofuels and so completely lost from the food system.“[119]

When counting both human-edible crop calories and feed-produced animal calories 59 % of the total production is delivered to the world‘s food system and 41 % of the total calories „available from global crop production are lost to the food system.“[120]

By radically reshaping the production of the food system we could estimate that by not enlarging the agricultural land and by using the actual rate of technologization the calories available for direct human consumption would increase by some 70 %, or in terms of population, it „could potentially feed an additional ~4 billion people.“[121]

Addressing challenges for a future food security and considering the actual number of undernourished people „making human consumption a top priority over animal feed and biofuels (...)“[122] emerges as priority. The pressure on the agricultural production is high and will increase. Theoretically there is enough land to feed the population of our world, enough to release 745 million people from undernourishment and hunger and to additionally feed the next 3 billion people. If we again call to mind the numbers of UN-World Population Report statistics and the number of 9.22 billion people at which world population is expected to peak in 2075 before it begins to decline, taking the 2003 statistics (latest reference year of CASSIDY et al.) with a world

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[115] CASSIDY S. EMILY, WEST C. PAUL, GERBER S JAMES and JOLEY A JONATHAN, 2013. Redefining agricultural yields: from tonnes to people nourished per hectare. Environmental Research Letters, IOP PUblishing, p.1

[116] ibid. p.1

[117] ibid. p.3

[118] ibid. p.3

[119] ibid. p.4

[120] ibid. p.4

[121] ibid. p.4

[122] CASSIDY S. EMILY, WEST C. PAUL, GERBER S JAMES and JOLEY A JONATHAN, 2013. Redefining agricultural yields: from tonnes to people nourished per hectare. Environmental Research Letters, IOP PUblishing,. p.6

population of 6,310,000,000 people - we can say that the actual extent of agricultural land can stop world hunger and feed the whole human population until the number will peaks and then it moves to decline.

However, by studying different reports from FAO, e.g. the „World Livestock 2001"-report shows the regrettable inference is a trend going in the opposite direction. The demand for meat and dairy products will increase by more than two thirds, meat consumption will increase by roughly 60 %, biofuel production „has increased sharply in recent years, which has directed more calories away form feed and human food. (...)"[123] Thus land conversion from nature to agricultural land is most likely to continue.

Of particular concern „is the environmental impact of developing new agricultural land. In 1980s and 1990, tropical forests were the source of over 80% of new agricultural land."[124]

The discussion that emerges with the conclusion of the study „Redefining agricultural yields: from tonnes to people nourished per hectare" (exclusively producing food for direct human consumption) is to what extent this might be achievable, whether based on political decisions, which must find social acceptance. It is hard to imagine that the interests of industry and biofuel producers could be stemmed or ignored. Nevertheless the findings of this study explicitly show the dramatic inefficiency of our food system from the perspective of land use but, primarily from that of solar energy conversion to cover the total energy requirement of humans.

Although the potential exists to meet global food demand, the trends go are taking a different way for various reasons.[125] So we could put our question on food security in different terms, for example as: could world food demand be met by increasing yield per hectare?

## *INCREASING CROP PRODUCTION ON THE CURRENTLY USED AGRICULTURAL AREA TO MEET WORLD FOOD DEMAND*

Considering FBS of rich industrialized countries it might be contradictory that the per capita land area needed for food supply is often much lower than that in developing or emerging countries (with the exception of countries with traditional vegetal diets like India or China). But also, for instance, comparing FBS between the USA and Italy one might say that the USA with high meat and other animal product consumption and a high consumption of alcoholic beverages (processed primary product) must have a much higher land use per person. But, in this case it is not so. This is a good example of a comparison between two different countries with a similar GDP but a completely different level of technologization. Whereas the USA is the paragon of the implementation of the Green Revolution principle, Italy's agriculture mostly is industrialized in the north and only marginally in the south. This, together with other reasons, leads to the huge

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[123] CASSIDY S. EMILY, WEST C. PAUL, GERBER S JAMES and JOLEY A JONATHAN, 2013. Redefining agricultural yields: from tonnes to people nourished per hectare. Environmental Research Letters, IOP PUblishing,.. p.6

[124] ibid. p.6

[125] ibid. p.6

difference in land use per individual food supply of 2,364 m2 (USA) to 3,084 m2 (Southern Europe).[126]

What the developed countries have achieved following World War Two, is to drastically improve yield. Combined with the inventions of the previous century (internal combustion engine, railway and the expansion of the road system) the Green Revolution reshaped the whole agricultural production within a few decades. „(...) [I]nternational centers of agricultural research, financed by large American private foundations (Ford, Rockefeller), selected high-yield varieties of rice, wheat, maize and soya requiring high inputs in fertilizers and treatment products and developed appropriate cultivation methods on experimental stations.“[127] The research results, the new cultivated varieties (or optimized varieties) increased yield in many countries. „This large-scale expansion of some elements of the second agricultural revolution (plant and animal selection, mineral and synthetic fertilizers, treatment products, pure culture of genetically homogeneous populations, partial mechanization, strict control of water) to three main grains widely grown in the developing countries was called the „Green Revolution“. The benefits, however, hat their focus in the most fertile regions, with higher returns to compensate „the necessary costly inputs.“[128]

This brief digression explaining the beginnings of the Green Revolution was necessary to sensitize the reader to an inherent consequence of this: that most likely every intensification of active farming, every intention of increasing productivity, increasing yield per hectare is connected to an increase in energy inputs for (whatever is missing or necessary) building up infrastructure, watering systems (canals or sprinkling systems), greenhouse constructions, mechanization (tractors, trolleys, etc.) or the production of hydrocarbon-based macronutrients, pesticides, herbicides, etc.

> „In general, the sustainability of the food production system is being questioned. Doubts are cast on the possibility to continue doing more of the same, that is, using high levels of external inputs in production, increasing the share of livestock in total output, expanding cultivated land and irrigation, and transporting products over long distances.“[129]

The following subchapter aims to examine the actual energy dependency of world agriculture. In addition a short presentation is made concerning which intersection of the food supply chain consumes most of the energy.

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[126] KASTNER, T., IBARROLA RIVAS, M. J., KOCH, W. & NONHEBEL, S. 2012. Global changes in diets and the consequences for land requirements for food. Available: http://www.pnas.org/content/early/2012/04/10/1117054109.full.pdf+html. Table

[127] MAZOYER, M. & ROUDART, L. 2006. A History of World Agriculture, London, Earthscan. p. 450

[128] ibid.

[129] ALEXANDRATOS, N. & BRUINSMA, J. 2012. World Agriculture Towards 2030/2050. The 2012 Revision. [Rome]: Agricultural Development Economics Division, FAO. p.8

## Energy Consumption

### Looking back a century

Approximately 119 EJ a year of all energy used in the world is consumed by the food system, a quarter of this within the farm gate. The green revolution radically changed the production method of the primary sector. Energy inputs per ha soil based agriculture exploded in the last decades.
The world cultivation area nearly doubled from 1900 to 2000, world population increased from 1.500.000.000 to over 6 billion, while the agricultural land only had to be expanded between 80 to 100%. Energy subsidies and technologization increased the yield output up to 600% to feed the exploding human population. In other words, by relating to the question of increasing productivity to the existing land used for crop production, the Green Revolution clearly brought about a great improvement and led to a productivity increase which is sixfold compared to that at the beginning of the 20th century. The price for achieving this was the enormous intensification of energy subsidies by 8,500 %.

Breaking that global scenario down to wheat cultivation in the U.S., „[i]n 1945 average subsidies of nearly 6 GJ/ha helped to produce about 2.2 t/ha of grain (...). By 2003 subsidies of about 18 GJ/ha aided in harvesting 9 t/ha (..). The energy subsidy rate had tripled, but the efficiency of converting solar radiation into harvested grain had more than quadrupled.“[130]
This increase in crop yield led to the situation that in 1945 one single hectare of agricultural land was able to provide enough grain for 1.5 people, covering 10 MJ/cap/d. Today it is possible to produce grain for up to six people on the same area, by means of an even higher energy supply - 15,7 MJ/cap/day - before losses.[131]
If higher energy subsidies result in higher productivity, then the conversion efficiency of a cropping system is clearly increasing.[132]

These examples show the obvious success of modern agriculture in the context of increasing productivity, yield and also, the in energy output per hectare.
On one hand in the context of energy efficiency, it must be said that „[t]he overall magnitude of agricultural energy subsidies is insignificant compared to the input of solar energy.“[133] On the other hand, on a global scale, we have now created an agricultural system which is directly dependent upon hydrocarbon energy, not only to maintain yields at the levels of today, but there might also be a considerable need to increase the use of fossil fuels in the field of traditional soil based agriculture.

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[130] SMIL, V. 2008. Energy in Nature and Society, Cambridge, Mass. MIT Press. p.304

[131] SMIL, V. 2008. Energy in Nature and Society, Cambridge, Mass. MIT Press. p.301

[132] ibid. p.303 and 304

[133] ibid. p.300

Where exactly, looking throughout the food supply chain, is the most energy input needed? How much is used directly on the farm and how much is needed to process food, to transport and cook it? And, lastly, by considering Vertical Farming as an alternative, what parts of the food sector might have the potential to minimize energy subsidies? The following subchapters aim to establish the status quo for traditional soil based agriculture.

## Energy and the Food Supply Chain

The findings of the Food and Agriculture Organization (FAO) study " 'Energy-Smart' Food for People and Climate"[134] confirm the large share of global energy supply required and the strong reliance on fossil fuels „to meet production targets and contribute to greenhouse gas emissions. The study concluded that agrifood systems will have to become „energy smart" to meet future food and energy challenges, and recommended establishing a major long-term multipartner program on energy-smart food systems (...)."[135] One of the main aims and objectives of this study is to „evaluate how the fossil fuel dependency of the transport and processing components of the food sector can be reduced together with energy costs and GHG emissions."[136]

The key findings of this study are the following:

The agrifood chain consumes 32 percent of the world's available energy - with more than 70 percent consumed beyond the farmgate.

The agrifood chain produces about 20 percent of the world's greenhouse gas emissions.

More than one-third of the food we produce is lost or wasted, and with it about 38 percent of the energy consumed in the agrifood chain.

*The total world primary energy consumption in 2011 was 549,02 EJ [137] 32 % of world end-energy-consumption is related to the food sector, 24% of it until the farmgate.*

The food system is heavily dependent on fossil resources. A study from 2014 claim to a drastic reduce its dependencies, especially by industrialized countries, such as the UK. „Both direct

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[134] In all quotations used in this dissertation „food sector", „food systems" and „food chain" are used interchangeably. These terms refer to stages from the production on-farm, through manufacturing to consumption.

[135] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 2011.Energy-Smart Food for People and Climate, Issue Paper, Rome:FAO

[136] ibid, p.7 and 8

[137] http://www.iea.org/publications/freepublications/, retrieved 05.04.2014

energy use for crop management and indirect energy use for fertilizers, pesticides and machinery production have contributed to the major increases in food production (...).“[138]

The achieved results relate as a principle to „increasingly volatile fossil fuel prices. (...)

Fossil fuel prices, particularly those of oil-derived products, will increase significantly over the coming decades and will become more volatile.

Prices, on a unit energy basis, between oil, gas and coal, are likely to diverge with the possibility of a break in the traditional linkage between gas and oil prices emerging Unless substantive agreements emerge from the UNFCCC‘s[139] intergovernmental negotiations that limit access to coal, its large and widely distributed reserves will mean that it is the least vulnerable of the fossil fuels to price increases; a switch to coal away from oil and natural gas is probably where that is possible e.g. for processing and nitrogen fertilizer production.

The world‘s major crops are dependent on different shares of their energy inputs from oil, gas and coal. Thus, relative changes in fossil fuel prices will affect each crop type differentially.“[140]

Major areas of concern are identified in

Fuel use for tillage, transport from farmgate to storage to proecessing and end use will be directly affected by increasing oil prices.

Nitrogen fertilizer prices are immediately affected by increasing natural gas prices.

„Coal is still used for nitrogen fertilizer production, particularly in China, and is likely to be least affected by worries about reserve depletion. From a GHG perspective, a switch away from oil and gas to coal, rather than to renewable, would be detrimental.

Increased costs for direct and indirect energy inputs for agriculture may lead to lower yields for the world‘s major agriculture commodity crops. In turn, this is likely to bring an expansion of land areas unter these crops, leading to increased GHG emissions, as a result of LUC, and increased prices owing to less efficient production.

Significant land expansion will also have detrimental effects on biodiversity and possibly on water resources.“[141]

An issue that should be questioned is how the situation may develop by 2050. The use of fossil fuel in agriculture will in all probability not decrease over the coming decades. Future prospects on world population growth, changes in per capita-income, especially in developing countries and changes in diets suggest the assumptions that dependencies between the primary sector and fossil fuel will increase, not least because an intensification in farming practices to increase yield

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[138] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 2011.Energy-Smart Food for People and Climate, Issue Paper, Rome:FAO, p.1

[139] The United Nations Framework Convention on Climate Change is an environmental treaty on an international level, a climate policy venue with a broad legitimacy due its universal membership, negotiated at the Earth Summit, Rio de Janeiro (3.-14.6.1992), the UNCED (United Nations Conference on Environment and Development) intentionally to stabilize greenhouse gass concentrations in the atmosphere at a level to prevent „anthropogenic interference with the climate system“.

[140] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 2011.Energy-Smart Food for People and Climate, Issue Paper, Rome:FAO, p.1

[141] WOODS, J., WILLIAMS, A., HUGHES, JOHN K., BLACK, M., MURPHY, R. 2010, Energy and the Food System, Philosophical Transactions of the Royal Society. 2991-3005. Available: http://rstb.royalsocietypublishing.org/content/roypth/365/1554/2991.full.pdf, retrieved 14.10.2015

per hectare might only be achievable by increasing the use of macronutrients, supplemental watering systems and additional production and use of machinery.

## *ENERGY CONSUMPTION FROM FARMGATE TO FARM GATE*

„Once conventional oil and gas flows reach a peak as is predicted, the food sector's continued reliance on these non-renewable resources for production, processing and transportation activities will lead to greater business risks, especially from unpredictable price spikes.“[142]

Fossil fuel is needed through the entire food supply chain. But where is most of the overall energy consumed within the food sector? Directly on the farm, or up to the farm gate (without the inclusion of energy consumption for products or media used and needed for cultivation), and human and animal power excluded, the world energy demand on farm is estimated with 6 EJ per year. Around 50% of that energy is consumed by OECD-countries. Fig. 10 shows the ratios of energy consumption within the food sector and the related CO2-emissions.[143]
Indirect energy demand for food production is 50% higher, namely 9 EJ per year. This value includes energy demands for boats, tractors and other farm machinery - operations and fertilizer manufacturing.[144]

## *ENERGY DEMAND FOR PRIMARY PRODUCTION*

The biggest variations in energy demand for primary food production are at the level of the farm and the crop itself. „The energy demand for the production of similar food products under different production systems can be used to compare fossil fuel dependency. For example, the direct energy inputs of an extensive, unsubsidized, grazing enterprise in Australia (2-3 GJ/ha) can be compared with intensive, subsidized, dairy farming systems in the Netherlands (70-80 GJ/ha).[145]
In terms of energy consumption in 2005 tractors and other agriculture machinery consumed around 5 EJ of diesel for land development, transport and field operations. „A further 1.5 EJ per year was used for the manufacture and maintenance of tractors and farm implements.“[146] Exact numbers of two-wheel design agricultural machinery, primarily used by small-scale farms is difficult to gather and therefore not covered by the 5 EJ. Additional machinery such as balers, combined harvester-threshers, manure spreaders, fertilizer distributors, milking machines, ploughs, root and tuber harvesting machines, threshing machines, seeders, planters and

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[142] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 2011.Energy-Smart Food for People and Climate, Issue Paper, Rome:FAO, p.9

[143] ibid. p.III

[144] ibid. p.13

[145] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 2011.Energy-Smart Food for People and Climate, Issue Paper, Rome:FAO, p.13

[146] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 2011.Energy-Smart Food for People and Climate, Issue Paper, Rome:FAO

transplanters are not included in this calculation. FAO is currently updating and extending the lists of machinery used for primary production. Current data are only available for parts of the above mentioned items, but only in import and export data and not for those units in working use.[147]

## *FISHERIES AND AQUACULTURE*

World fish production per year is approximately 130,000,000 t. In 2012 136,000,000 t were produced for direct human consumption (86 %) and roughly 22,000,000 t were destined for non-food uses such as fishmeal or fish oil, ornamental purposes, for culture, bait pharmaceutical uses, etc.[148] Some 2 EJ are consumed directly by the global primary production. This figure is mainly associated with fish aeration, water pumping and diesel propulsion for vessels and boats. 400 PJ or 0,4 EJ per year „of indirect energy is embedded in aquaculture feedstuff.“ [149]

## *IRRIGATION*

As we have seen in the former subchapter, of the potential 44,950,000 km2 only a third (14,120,000 km2) is a net balance of land with rain-fed potential. If pressure on agricultural land in existence at present increases furtherand land conversion for agriculture is needed, irrigation demand will most likely also increase. The current consequences of world climate change already affect vast landfills with water shortages, as can be observed in various parts of the world. Around 17% of all agricultural land in use is irrigated. These 2,760,000 km2 and the additional water consumption for agricultural production together consume 70% of all freshwater withdrawals. By comparison Industry and domestic use consume 22% and 8% respectively.[150]

As a result of increasing the agricultural area during the past century demand for irrigation also increased, made possible by developing more efficient technologies for watering and by using hydrocarbon energy to operate the watering plants. „Traditional agriculture provided the needed water by simple open-ditch irrigation fed by gravity flows or by a variety of human- or animal-powered devices (...). Modernizing agricultures retain the inefficient ridge-and-furrow arrangements and supply them with simple mechanical pumps. (...) The global dependence on irrigation has trebled since the end of World War II, when about 75 million ha of cropland were watered. A generation later the total was 140 million ha, and by 2000 the figure topped 275 million ha, with three-fifths in Asia and nearly one-fifth in China alone.“[151]

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[147] http://faostat3.fao.org/download/I/RM/E, retrieved 12.10.2014

[148] FAO. The state of World Fisheries and Aquaculture 2014, Rome. p. 42

[149] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 2011.Energy-Smart Food for People and Climate, Issue Paper, Rome:FAO, p.9

[150] http://www.ifad.org/english/water/key.htm, retrieved 06.09.2015

[151] SMIL, V. 2008. Energy in Nature and Society, Cambridge, Mass., MIT Press. p. 294

Some 0,225 EJ per year are needed to power the pumps for irrigation. The mechanical pumping of water on approximately 10 percent of the world arable land area (around 300 Mha) consumes around 0.225 EJ/a to power the pumps. In addition, another 0.05 EJ/a of indirect energy is required to manufacture, deliver equipment for irrigation.[152] Irrigated lands produce higher yields than rainfed systems and allow for yield increases of up to threefold. These lands areas for example, provide 40 % of the global cereal supply.[153]

## *MACRONUTIRENTS*

The synthesis of nitrogenous fertilizers, also known as macronutrients such as nitrogen, phosphate and potassium account for approximately 7 EJ/year (accounting approximately 5 % of the world gas consumption per year).[154] „Chemical fertilizers represent the largest indirect energy subsidy in nonirrigated farming. No other innovation has contributed so much to increased yields as the three macronutrients (...) [155]- phosphate, nitrogen and potassium.

The production of phosphates requires more than 50% of the total embodied energy consumption for macronutrient production (or 4-5 GJ/t), 2,8 EJ, production of nitrogen 1,85 EJ (or 55 GJ/t) and Potassium 0,25 EJ (or 5 to 20 GJ/t). Every year 198,5 million tonnes of macronutrients are produced. The biggest share is phosphates with 140 Mt, followed by nitrogen with 33,5 Mt and potassium with 25 Mt.

By dividing the area of arable land referred to above (15,529,767 km2) with the annual total use of nitrogenous fertilizers (198,5 million tonnes) on one single hectare on average roughly 130 kg of macronutrients is used. This, of course, is unevenly distributed worldwide - with no use at all in Sub-Saharan Africa and up to 500 kg/ha/a in China.[156]

## *PEST CONTROL*

The explosion in macronutrient production was „accompanied by increasing use of herbicides to control weeds, and insecticides and fungicides to raise the yields of new high-yielding varieties. (...) Like most of the changes in modern agriculture we find its application origins after World War I and World War II.“[157] Starting around 1945 the first weed and insect controls were used on agricultural fields, today more than 50,000 different types of products used as pesticides have been registered „to fit thousands of specific applications, but the bulk goes to only handful of corps. Pesticide applications are highly effective and economically rewarding. Although the

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[152] ibid. p. 294

[153] http://www.fao.org/docrep/004/y3557e/y3557e08.htm, retrieved 28.08.2015

[154] ibid. p.9

[155] SMIL, V. 2008. Energy in Nature and Society, Cambridge, Mass., MIT Press. p.294

[156] ibid, p. 295

[157] ibid. p.295

compounds are derived by energy-intensive processes from petrochemical feedstocks, their low application rates translate to only minor subsidies in absolute terms.“[158]
With around 500 PJ, or 0.5 EJ per year production of herbicides and pesticides contributes to the energy consumption of the world agriculture system. These data relate to the year 2000. „Synthesis of common active ingredients atypically requires 100 - 200 MJ/kg, and total energy costs, including formulating, packaging, and marketing, are mostly 200 - 300 MJ/kg (...).“[159]
Making allowance for a conservative average of 150 MJ/kg as the sum of energy subsidies for synthesis including the embodied energy for formulating, packaging and marketing today‘s energy consumption we can assume that the global energy consumption for pest control has increased by around 10 % and accounted for 0.55 EJ for the year 2011.

## *CROPS AND ENERGY SUBSIDIES*

Standardized methods for energy calculations on crops are still lacking in the world today. Compared to mass-produced industrial goods, it is extremely difficult to achieve uniform data standards. „Published energy costs of individual crops are not readily comparable because of the arbitrary and non-uniform choice of analytical boundaries and sometimes substantial differences in input equivalents.“[160] Energy analysis for crop productions sometimes calculate machinery and irrigation, others include embodied energy of macronutrients and pest-control products. The system border is not always precisely described. Some analysis stops at the farmgate, others include transportation energy etc.
„Typical annual rates are 8-15 GJ/ha for dryland cereals, 20-25 GJ/ha for rain-fed, and more than 40 GJ/ha for irrigated Corn Belt corn and California rice. Nitrogen-fixing soybeans need no more than 8-15 GJ/ha, but potatoes, vegetables and tree crops, with heavy fertilization and irrigation, need 50-100 GJ/ha, and orange groves require about 120 GJ/ha and even these rates are dwarfed by hydroponic cultivation.“[161]

## *GREENHOUSES*

Fruit and vegetable production in greenhouses is characterized, when compared to soil based agriculture, above all by the need for seasonal heating. In some cases, especially in rich industrialized countries, seasonal light requirements are partly provided by artificial lighting in order to enlarge the productive season and secure the crop rotation.
„In warm climates operation costs are dominated by irrigation, fertilization, and cultivation needs. Turkish rates (with some supplemental heating range from 2.6 GJ/t of tomatoes to 4.3 GJ/t of peppers[162], but in heated Dutch greenhouses the same crops may consume as much as 40 GJ/t

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[158] SMIL, V. 2008. Energy in Nature and Society, Cambridge, Mass., MIT Press. p. 297

[159] ibid. p.296

[160] ibid. p.296

[161] ibid. p.296

[162] SMIL, V. 2008. Energy in Nature and Society, Cambridge, Mass., MIT Press. p.296

and the heating rate may be several TJ/ha. These subsidies translate to about 3-4 GJ/t of Manitoba spring wheat, 5 GJ/t of Iowa corn, and up to 7 GJ/t of rice. Although vegetables and fruits need much higher energy subsidies per hectare, their high yields translate into GJ/t rates that are similar to those for cereals.“[163]

Volatile fuel prices and increasing demand for greenhouse crops through increasing pressure on food security and food supply on traditional soil based agriculture are caousing a greenhouse explosion in terms of both numbers and the area cultivated. Due to the fact that greenhouses are inherently energy inefficient production entities (U/V-ratio), especially in temperate climate zones, different strategies for energy reduction get applied and developed. Although greenhouses in specific cases need more energy for cultivation than traditional soil based agriculture, their use is inevitable if fresh food is to be provided for certain areas with constraints on the available arable land, disadvantageous climate or water scarcity. Increasing demand for organic and, locally grown food in the past few decades has also prompted a remarkable growth in urban greenhouses.

Energy efficient lighting, the insertion of energy screens, computer controlled greenhouse climates, air leaks reduction and, efficient ventilation systems are required to reduce the energy demand of greenhouses.

Greenhouse crop production is now a swiftly expanding area and a fact of life throughout the world with an estimated 405,000 ha of greenhouses spread over all the continents. The degree of sophistication and technology depends on the specific local climatic conditions and socio-economic environment.[164]

A yield of 300t/ha fruit or vegetables in the Mediterranean countries is not unusual. A fact relevant for the following simulation model, is that by comparing the soil based agricultural yield of tomatos in Austria of 27.2 kg/m2/crop rotation to the yield achieved in greenhouses in the same country with some 43 kg/m2/crop rotation it emerges clearly that a remarkable production increase can be expected from this method.[165]

As a rule of thumb calculation to estimate the total energy requirement for world greenhouses (without embodied energy) the following might apply:

estimation: approx. 40 MJ/kg[166], 405,000 ha = 4,050 km2 of greenhouses[167]:

405.000 ha x 150 t/ha (50% = OECD)[168] x 20 MJ/kg (=50% - high GDP/low GDP) = 60.750.000 t (greenhouse crops world / a) x 20 MJ/kg = 1.215.000.000.000 MJ = **1.215 EJ**[169]

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[163] ibid. 297

[164] FAO Good agriclutural practices for greenhouse vegetable crops.pdf, p.9

[165] www.wien.gv.at/statistik/wirtschaft/tabellen/gemüseernte-anbauflaeche.thml, retrieved 26.10.2104 and www.statistikaustria.at, Ernteerhebung, retrieved 26.10.2104

[166] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 2011.Energy-Smart Food for People and Climate, Issue Paper, Rome:FAO p.15

[167] http://www.fao.org/docrep/018/i3284e/i3284e.pdf, p.vii, retrieved 21.6.2014

An estimated sum of 1.2 EJ is thus defined for operating world greenhouses.

## FOOD AND TRANSPORT

Food and transport is a much discussed and controversial issue, the opportunities or problems of which are completely dependent on the point of view taken. While more and more people (especially the urban population) ask for locally or regionally grown products[170], which are associated with a low CO2-footprint, the findings of several studies and their resulting recommendations for policies ask by contrast, for a stronger food allocation related to the best fitting climatic condition. In fact, in very specific situations, a locally grown food that is consumed could have a larger CO2-footprint than an imported one. Locally produced apples, for example, can do better in terms of ecology. „If an apple, grown in the southern hemisphere, is offered for sale during the spring time in a German supermarket, it will generally appear more appetizing than a local apple from last year‘s crop that has been stored in the interim period.“[171] It is springtime, the local apple was harvested about six month ago. Since then huge amounts of energy have been expended for washing, storing and cooling the apple. This is why regional food is „seriously challenged“[172] from the ecological perspective when compared to the fresh Chilean apple. Harald von Witzke also refers to a detailed environmental assessment of 150 of the most popular products in UK-supermarkets. „A team from the Manchester Business School (...) examined the entire production process end-to-end, from the harvest all the way though to retail packaging.“[173] Key findings are that it is often true that imported goods have a worse CO2-balance, compared to locally grown food.

The other side of the picture, once again in a brief reference to a UK context, is that more than 80% of all food consumed in London is imported from outside the UK. The data in this paragraph summarize major findings of the study on „The Validity of Food Miles as an Indicator of Sustainable Development.“[174] Referring to Harald von Witzke‘s point, we can confirm that

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[168] OECD, 2008. Environmental Performance of Agriculture at a Glance, p.24, http://www.oecd-ilibrary.org/docserver/download/5108091e.pdf?expires=1446819166&id=id&accname=guest&checksum=5CC696AEB345D9B622DE8C6987704E98, retrieved 12.09.2015

[169] own calculation estimation

[170] The terms „local“ or „regional“ are not strictly defined. „Local“ is often described from 100 - 250 miles. „Locavore: A consumer who primarily eats minimally processed, seasonally available food grown or produced within a specified radius from his or her home, commonly 100 or 250 miles“, Local Food SystemsConcepts, Impacts, and Issues vSteve Martinez et al., USDA, May 2010

[171] WITZKE, H. V. 2011. Bananas from Bavaria?, Augsburg, Ölbaum-Verlag. p.17

[172] ibid. p.18

[173] ibid. p.18

[174] WATKISS, P., SMITH, A., TWEEDLE, G., MCKINNON, A., BROWNE, M., HUNT, A., TRELEVEN, C., NASH, C. & CROSS, S. 2005. The Validity of Food Miles as an Indicator of Sustainable Development: Final report produced for DEFRA. AEA Technology.

transport-emissions related to seas (and overseas) only contribute some 12 % to the total CO2-emissions associated with UK food transport.[175]

Likewise we can assume that the higher the dependency on food imports, the bigger the percentage of food miles on land will be. A quarter of all driven miles in the UK are food related. A further point to be underlined here is the strong impact this has on social costs, too. The total costs generated by the UK food transport system, including costs related to CO2-emissions, air quality, congestion, accidents, the infrastructure and its maintenance and also animal welfare are estimated at over 9 billion pounds/a.[176]

There is a strong movement for re-implementing local social and economic interdependencies, related to food production, retail sales and consumption. „The growth of market share of the supermarkets with the associated decline in local shops and markets, and the increase in international food trade, have led to a move away from locally produced food in the UK.“[177] This issue is addressed by several national campaigns (Eat the View), locally run farmers‘ markets, farm shops and, community-led initiatives such as community growing projects, to name only a few. A new culture is rapidly growing - not only in Great Britain - arising from the necessity of urban population of consuming locally grown food.[178]
In the context of FAO‘s Issue Paper transport is included under the heading „processing and distribution“. In order to make an assumption on what the percentages for processing and distribution (transport) are, we make a comparison between a high-GDP-country such as USA and the average statistics for the continent of Africa. (Fig.12) In this we can see that agricultural production in USA has twice the weighting compared to Africa in terms of energy use of the total energy inputs, but it comes in up to a third lower for preparation and cooking.
Processing and packaging is similar, namely 22% (USA) vs. 18% (Africa).[179] Transport and distribution although again has twice the volume in the United States compared to the situation in Africa. Drawing an inference for the world on this basis to the itemization of the overall world energy consumption in the food sector, we thus roughly assume that a third of the 42% related to processing and distribution mentioned falls to transport, and two thirds to processing.

This number might be not far from the real situation, considering the FAO estimate on global food miles.[180] Some 800 million metric tonnes of food were shipped worldwide in the year 2000. In 2011

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[175] ibid. p.iii

[176] WATKISS, P., SMITH, A., TWEEDLE, G., MCKINNON, A., BROWNE, M., HUNT, A., TRELEVEN, C., NASH, C. & CROSS, S. 2005. The Validity of Food Miles as an Indicator of Sustainable Development: Final report produced for DEFRA. AEA Technology. p.41 ff.

[177] ibid. p.15

[178] http://www.theguardian.com/sustainable-business/2014/jul/02/next-gen-urban-farms-10-innovative-projects-from-around-the-world, retrieved 28.08.2015

[179] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 2011.Energy-Smart Food for People and Climate, Issue Paper, Rome:FAO, p.13

[180] Estimates based on the statistics published by FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 2011.Energy-Smart Food for People and Climate, Issue Paper, Rome:FAO, p.16

world food imports- and exports totaled up to 1.2 billion metric tonnes. By using the shares of global t/km as presented here related to different means of transportation and comparing the extrapolated values of total energy consumption based on the sum of the transported food items, and comparing the estimated 33.3% energy related to the 42% share of processing and distribution mentioned by the FAO-Issue Paper, we carrive at a figure of 24.64 EJ (of 550 TPES). This would lead to the conclusion that all transported food, consignments will all have travelled more than 600 km on a global average.

Before we combine the overall data on world energy consumption within the food system, we first wish to highlight and summarize the previously mentioned findings on energy consumption within the farm gate according to the FAO-Issue Paper, which refers largely to the study by Vaclav Smil on „Energy in Nature and Society“[181].

Fig. 12 on the next page shows the overall energy consumption up to the farm gate. The embodied energy involved is also included in this calculation. 7 EJ is used to produce nitrogen, phosphate and potassium, while 6 EJ is required in the food sector consumption directly on on the farm for water pumping, housing livestock, cultivation practices, harvesting, heating, drying and storing crops.

The indirectly consumed 9 EJ refers to tractors, use of additional farm machinery, operating boats and also for fertilizer manufacturing. The energy involved for the total fuel consumption and maintenance is included in the 7 EJ of machinery. 300 PJ (Petajoule) are needed for irrigation and additional 500 PJ for pesticides. Fishery and aquaculture worldwide consume 2.35 EJ, while roughly 2 EJ are needed for breeding, raising and keeping livestock and 1.25 EJ are required for the energy consumption of greenhouses.

In summary the energy consumption of the food sector exceeds 33 EJ before leaving the farm gate. Comparing this with the findings of the FAO Issue paper where 24% of the energy consumed by the food sector is used, we reach a number of 42.24 EJ, by using the number of 550 EJ TPES, representing a difference of approximately 9 EJ.

## *FOOD LOSSES AND FOOD WASTES*

A serious problem of our food system is the fact that we do not produce our food where we consume it. The fragmented food supply chain has the result that calories “leading to edible products destined for human consumption“[182] gare lost or wasted. “Food losses”, as defined by the FAO encompass all losses from the farm to food processing, whereas “food wastes” refer to losses of the consumer – from the retail and catering trades through to private households.[183]

Findings of a representative study for Germany[184] sketch a typical picture for an industrial country, where the percentage – specifically here 25-31% of all the calories lost for human consumption

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[181] SMIL, V. 2008. Energy in Nature and Society, Cambridge, Mass., MIT Press.

[182] GUSTAVSON et al. 2011. „Global food losses and food wastes“, Study conducted for the International Congress ‚SAVE FOOD!‘, at Interpack 2011, Düsseldorf, Germany, FAO,p.2

[183] NOLEPPA, S. & WITZKE, H. V. 2012. Tonnen für die Tonne. Berlin: WWF. p. 20

[184] ibid.

are allocated as “food losses” and the rest (two thirds to three quarters) are assigned to “food wastes“. This study also points out that there is a lack of comparable methodological standards to provide a solid basis for comparison between the different studies relating to this issue.

Some 6.6 million tonnes of food are wasted in Germany, every year, which correspond to approx. 80 kg/capita.[185] In this context the attempt has been made to answer another interesting question: What portion of the total calories lost are inevitable losses, and what portion is system immanent? On a consumer level this study refers to Cofresco[186] a study which estimates that around 59% of all the food waste (which in the case of Germany would amount some 3.6 metric tonnes of food) could be saved from being lost to the food supply chain.

The last study published by the FAO can be referred to for an estimation of “food losses” and “food wastes” statistics on a global scale. This is an ongoing research project in which standardized methodologies are now being developed. Until now questions on how much food is lost or wasted prompted responses such as “impossible to give precise answer, and there is not much ongoing research in the area.“[187]

Nevertheless some assumptions relevant to our work should be presented:

Nearly one third of food produced for human consumption is lost or wasted every year.

The food losses and wastes in the industrialized countries are ten times higher than food losses and food wastes in developing countries.

In low income countries the main drivers of food losses and food wastes are connected to “financial, managerial and technical limitations in harvesting techniques, storage and cooling facilities in difficult climatic conditions, infrastructure, packaging and marketing systems.“[188]

In high GDP countries, however, there are different main reasons cited for the problem. There is also a lack of “coordination between different actors in the supply chain.“[189] Food is wasted because of defined quality standards. Food which is to all appearances healthy and fresh can be thrown away, because it is lacking some pre-defined aesthetic properties.

On a consumer level people tend to buy larger quantities in rich countries, which if not consumed in time tends to be wasted.

The “best-before-date” practice also leads to vast amounts of food waste.

In highly industrialized countries food is also lost “when production exceeds demand.[190]

The diagrams in Fig. 13 on page 82 show exemplary food losses and wastes at different FSC stages for fruit and vegetables in different regions of the world. A striking fact here from comparing

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[185] ibid. p.23

[186] COFRESCO. 2011. Vermeidbare Lebensmittelverschwendung in europäischen Haushalten: Erkenntnisse und Lösungsansätze. Minden: Cofresco

[187] NOLEPPA, S. & WITZKE, H. V. 2012. Tonnen für die Tonne. Berlin: WWF. p. 20

[188] NOLEPPA, S. & WITZKE, H. V. 2012. Tonnen für die Tonne. Berlin: WWF. p. 20

[189] ibid.

[190] Global food losses and food wsastes, executive summary, p.2

industrialized regions with developing areas of the world is how different types of calories get lost from the food supply chain. The same is also the case on a comparisons of the ratio between food losses and wastes based on a consumer level and production/retailing level. The last diagram represents the production volumes of each commodity group per region in million tonnes.

If food is lost or wasted throughout the production and distribution processes in these huge amounts, then as a matter of course energy is also wasted. And considering the quantity of energy consumed in the food sector, it must be pointed out that the issue of food losses and food wastes is also a serious energy problem. In addition to this it is also an ethical problem. Food losses and waste amounting to 30% of the food produced in 2011 could feed some 1.5 billion people, calculating an average consumption of 900 kg/year, and assuming that all the food items required for healthy nutrition are lost or wasted in equal quantities.

## Sketching the Big Picture of World Energy Consumption by the Food System

By bringing the different studies together to sketch the big picture of world energy consumption in the food system, and overlaying it with the world energy consumption for the year 2011 we can come up with the statistics for current end energy consumption. By the end of this chapter the TPES will be generated, but due to the lack of data the percentage of energy consumption within the food sector will be the same as the total primary energy consumption.[191]

29 EJ are used for agricultural production, 24% of the overall consumption of the food sector. The biggest portion is used for crop production, followed by livestock production and fisheries. 14% or 16.6 EJ  has been assigned to transport, as mentioned in the subchapter above and one third of the energy or 33.3 EJ. Is needed for world food processing 40 EJ can be assigned for retail, preparation and cooking.[192]

Fig.15 represent the percentages and energy consumption for the different items of the food supply chain and highlight that portion of the energy consumption which will then be relevant for a direct comparison of the ratio of the total primary energy supply for traditional soil based agriculture (the food supply system currently in operation) and Vertical Farming food production, assuming that the percentage for preparation and cooking is not face with change, although energy supply for retail also could vary as a result of the shorter distances food will be travelling and therefore fewer structural elements for refrigerating, storage or building entities for ethylene-ripening processes would be necessary.

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[191] It is self-explaining, that the numbers of TPES of the food sector are only rough-sketches. E.g. for agricultural production and processing a much higher electricity consumption can be assumed than for transport and distribution, and therefor a deeper breakdown of these items would be necessary to apply the right conversion factor from end-energy to total primary energy supply.

[192] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 2011.Energy-Smart Food for People and Climate, Issue Paper, Rome:FAO, p.11; Numbers in Fig. 15 and ff. are applied in the same percentage to a world energy consumption of 550 EJ

## Landuse, Energy Consumption and Biocapacity - Resumée

The Chapter “Landuse, Biocapacity and Energy Consumption” presents some good news in terms of potential solutions for how to feed the world population in future and specifically in the next few generations – the biocapacity of the earth has the strength and the capacity to provide an adequate agricultural yield to cover the total daily energy requirement of every single human being on the planet.[193]

Urbanization will continue to make strides in coming decades. Some 1% of the total land mass today is defined as built-up land. An area more than ten times the size of this is cultivated to provide the people with food.[194] The past few decades have seen the detachment of the spatial union between food production areas and urban areas and also the implementation of a global food production network, with the consequence that the food supply chain has grown substantially larger, more complex and more energy intensive.

Enough potential remains on different levels for traditional soil based agriculture to provide human kind with food. Furthermore the area for agricultural land can be tripled in size, but with the consequence that natural landscape will diminish further as it is changed into agricultural land. Land conversion releases CO2, especially through slash-and-burn clearing methods applied to wildland and, above all to the rainforests. The latter has provided by far the biggest share of new agricultural land since the 1980s.[195]

There is enough potential in terms of increasing the productivity of existing agriculture land. Looking back to the last century, energy conversion from sun to food increased many times.[196] But we also see the consequences in terms of energy consumption by investing in infrastructure, machinery, macronutrients and other upgrades for the pace of technologization - and a glance at the short history of agricultural practice since the Green Revolution makes the scenario likely that the dependency of agriculture on hydrocarbon energy will also increase many times - a problem of the current situation the FAO wishes to avoid and to reduce.[197]

Only 55% of all the calories in the agricultural process are produced for direct human consumption (Fig. 6 on page 59).[198] The rest is provided for animal feed, biofuel and industrial production. An enormous potential to establish food security is to be found in this ratio.

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[193] FISCHER, G., VELTHUIZEN, H. V. & NACHTERGAELE, F. O. 2000. Global Agro-Ecological Zones Assessment: Methodology and Results. International Institute for Applied Systems Analysis, FAO., Executive Summary, p.xi

[194] FAO Global Forest Resources Assessment 2010, retrieved 28.08.2015

[195] FISCHER, G., VELTHUIZEN, H. V. & NACHTERGAELE, F. O. 2000. Global Agro-Ecological Zones Assessment: Methodology and Results. International Institute for Applied Systems Analysis, FAO., Executive Summary, p. xii

[196] SMIL, V. 2008. Energy in Nature and Society, Cambridge, Mass., MIT Press. p.304

[197] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 2011.Energy-Smart Food for People and Climate, Issue Paper, Rome:FAO. p.3

[198] CASSIDY S. EMILY, WEST C. PAUL, GERBER S JAMES and JOLEY A JONATHAN, 2013. Redefining agricultural yields: from tonnes to people nourished per hectare. Environmental Research Letters, IOP PUblishing, p.1

Unfortunately the trends clearly indicated that this ratio is not going to change in coming decades. Socio-economic changes lead to changes in FBS with a move away from a vegetal to a diary based and a meat diet which will increases the per capita footprint for food.

In the light of these facts producing food there where it is consumed, appears to be a meaningful postulate. A legitimate question can well be asked at the conclusion of this section: can Vertical Farming truly provide a viable remedy for the problems ahead of us in the current situation of world agriculture? Does its potential include bringing an unavoidable increase in energy dependency, in particular on hydrocarbon sources? Is there a potential to drastically reduce the pressure on land and the need to convert natural landscapes, above all the rain forests, for agricultural uses?

One question can already be answered intuitively: producing food at the location where it is consumed will bring about a shrinking of the food supply chain and it will make the infrastructure including buildings for storage, wholesale, refrigeration and packaging tasks (on a large scale) if not redundant, then certainly less essential. A remarkable number of food travel miles will simply vanish. This intuitively answered question comprises highly interesting research fields in many areas which can readily be conceived, but which are beyond the scope of this dissertation.

Quantification of the land area reduction and of the energy demand for Vertical Farming is the focus of the next chapters:

Can Vertical Farming reduce land use and actually increase the overall energy efficiency of cities?

# The Vertical Farm Reference Models

## Goals and Process

This chapter examines the status quo of component availability for food production adaptable for Vertical Farming. In this context Vertical Farming components are defined as elements of an available technology adaptable for food production in vertical, enclosed building systems, which are directing food production away from natural agro-ecological systems and envisaging drastic scaling of biomass output compared to classical greenhouses.[199]

Design proposals for Vertical Farms have been published exponentially over the past few years. The foremost typology applied by architecture studios and students around the world is based on the typology of the skyscraper. The author defines the skyscraper accepted by most of the design proposals, as the most challenging typology in terms of daylight supply for the well-defined reasons explained in Chapter 4.

Irrespective of the typology, however, this chapter will introduce the available production method alternatives, which go beyond using soil as a “physical support system“[200], soil as a “solid base of operations into which they can spread their roots.”[201] Contrary to popular belief, plants do not necessarily require soils. What they need is space for root development and water with “dissolved minerals, and a source of organic nitrogen.”[202]
Of principal interest are systems of different soil-less cultivation methods such as

hydroponic,
aquaponic and
aeroponic systems

and production methods in terms of

horizontal layers (bedding and stacking practices),
horizontal rotating elements (horizontal dynamic systems) or
vertical rotating elements (vertical dynamic systems) and
3D-conveyor belts.

An existing or planned Vertical Farm has been chosen for each of the production method to exemplify and demonstrate the implementation of the cultivation methods. These farms are used for research purposes, e.g. Suwon Vertical Farm in Suwon, South Korea, for animal food production in Devon, UK by the Vertical Farm in Paignton Zoo, United Kingdom and for marketable food production in Singapore by SkyGreens Vertical Farm, Plantagon Vertical Farm in Linköping, Sweden and Vertical Harvest in Jackson, Wyoming, USA.

## Evaluation of components - Modelling a Vertical Farm - Prototype

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[199] MITCHELL, C. 1994. Biogenerative life-support systems. The American Journal of clinical Nutrition 60 (5), p. 820 - 824. Available on: http://www.ajcn.org/content/60/5/820S.abstract 2.2; To produce foot for an individual in space, estimated 28m2 are needed for a daily output of 2.000 kcal. Retrieved 21.03.2014

[200] DESPOMMIER, D. 2010. The Vertical Farm, New York, St. Martin‘s Press, p. 163

[201] ibid, p. 162

[202] ibid, p. 163

Research results and experimental approaches in the practice of several studies and of institutions with a focus on high-tech greenhouses and experimental food production for and in space[203], focusing on optimization of energy efficiency and maximization of edible biomass output compared to traditional soil based agricultural practices have encouraged follow-up work along this route of implementing food production entities, which contribute to relieving the current situation of increasing pressure on land, water and energy consumption. The following subchapters give an overview of the already established practices for industrially optimized food production.

## Cultivation methods - Overview and Evaluation of the advantages and challenges

Hydroponics refers to the cultivation method for plant growing in nutrient solutions. The roots of the plants can grow with or without the use of substrate (gravel, rockwool, peatmoss, cocopeat etc.) Two distinct systems can be differentiated within hydroponic plant growing practice:

Liquid hydroponic systems without a supporting medium for the plant roots and "The roots are hanging into the nutrient solution which can be either in the form of a liquid or a mist."[204]

Aggregate hydroponic systems where plants get supported by a solid growing medium and „irrigated with a complete nutrient solution."[205]

„Historically, water culture has been undertaken in research since the 17th century, with considerable publicity engendered by Gericke in the 1930s."[206] „Hydroponics, developed (...) by Dr. William Frederick Gericke at the University of California, Davis, is the method of Choice used routinely by nurseries to get seeds to germinate and sprout roots before they are transplanted into some form of potting soil."[207]

„The setup for a hydroponic facility is constrained by the crop itself, especially determined by the root system of the plant. „The liquid portion of the operation is pumped slowly through a specially constructed pipe (...)"[208] avoiding or reducing evaporative water loss. Of principal interest are hydroponic production methods in enclosed environments, where evaporated water can be recaptured, recycled and again enriched with nutrients. Furthermore enclosed environments

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[203] http://www.nasa.gov/mission_pages/station/research/experiments/863.html, retrieved 11.02.2015

[204] RORABAUGH, P.A., 2014. Introduction to Hydroponics and Controlled Environment Agriculture. Tucson, University of Arizona, Controlled Environment Agriculture Center, p. 5-4

[205] ibid.

[206] HANAN J.J. 1998. Greenhouses: advanced technology for protected horticulture, Boca Raton, CRC Press, p. 315

[207] DESPOMMIER, D. 2010. The Vertical Farm, New York, St. Martin‘s Press, p. 163

[208] DESPOMMIER, D. 2010. The Vertical Farm, New York, St. Martin‘s Press, p. 165

increase the potential for better control of diseases and pests to the extent of eliminating the necessity for pesticide and herbicide-use.

> *„A major advantage of hydroponics as compared to growth of plants in soil is the isolation of crops from the soil, which often has problems associated with diseases, salinity or poor structure and drainage. Costly and time consuming soil preparation is unnecessary in hydroponic systems and a rapid turnover of crops is readily achieved as replanting can be done within a day or two after harvesting. The principal disadvantages of hydroponics are the cost of capital and energy inputs relative to conventional open-field production. A high degree of competence in plant science and engineering skills is also required for successful operation of the system. Because of its significantly higher costs, successful application of hydroponic technology is limited to crops of high economic value.“* [209]

The following is a summarized overview of basic principles and advantages of using hydroponics, published by Patricia A. Rorabaugh, Ph.D., Arizona University[210]. Some points of this work are not quoted, because they are not relevant to the goal of this analysis, some have been extended and augmented by results of similar papers for the topic of this work.

Hydroponic food production has the capacity to grow food without being dependent on soil fertility. Crops can be grown on land which is unsuitable for conventional soil based agriculture. “Land with poor soils, and contamination (i.e., high heavy metal and salinity levels)“[211], bad climate conditions etc. land, as we defined it in Chapter 2, is an endless resource, whereas land with fertile soil conditions is scarce. Cities with reduced open (and fertile) areas, can benefit from this cultivation method to “make themselves more independent of food imports through a widespread use of hydroponic systems, whether in a climatically fully controlled environment or outdoors.

*Isolation from diseases or insect pests usually found in the soil*

The plant roots are contained in continuous pipes, substrates, bags, etc. and do not grow through soil that might contain diseases or other pests such as insects and nematodes.[212]

*Direct and immediate control over the rhizosphere*

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[209] Arizona University, Gene Giacomelli on hydroponic tomato production; http://ag.arizona.edu/hydroponictomatoes/overview.htm, retrieved 11.02.2015

[210] RORABAUGH, P.A., 2014. Introduction to Hydroponics and Controlled Environment Agriculture. Tucson, University of Arizona, Controlled Environment Agriculture Center.

[211] ibid. p.5-1

[212] RORABAUGH, P.A., 2014. Introduction to Hydroponics and Controlled Environment Agriculture. Tucson, University of Arizona, Controlled Environment Agriculture Center. p.5

Since the roots are either growing in water or growing through an inert medium, whatever is in the nutrient solution is bathing the roots. Therefore, nutrient concentrations and pH can be adjusted quickly.[213]

*High planting densities are possible which minimize use of land area*

A typical planting density for field tomatoes is 4,000 to 5,000 plants per acre [12.500/ha, Ed.). Greenhouse hydroponic tomatoes can be 10,000 to 11,000 plants per acre [27,500/ha, Ed.]. 23,672 tomatoes can be planted by using an optimized bed size of 60 x 70 cm.[214]

Plants can be grown closer together because of the use of indeterminant ("vining") varieties that take up less area than the bush varieties usually used for field cropping. They also need less root room – the plants are "spoon fed" the nutrient and water they need and do not have to grow a large root system to find these, as field tomatoes do in the soil.[215]

For the Vertical Farm Simulation Model the planting bed size will be defined by an accurate study which examined different distances between tomatos (*Lycopersicon Esculentum* (Mill.) aiming the ideal distances between the plants.[216]

*Higher yields are possible*

As a result of higher planting densities, higher yields are also possible. The indeterminant varieties bred for the greenhouse, can also produce over 6-12 months.

Since most commercial hydroponic production takes place within greenhouses (or other CEA[217])production, through the use of interplanting, can continue year around.

Yields are also greater due to better control over water, nutrition, EC, pH and diseases (see above).

The yields for field grown tomatoes are 10-40 tons per acre compared with 300 tons per acre or more for tomatoes grown using greenhouse hydroponics (equates to 75 kg/m2 (750t/ha); this figure has recently risen as high as 90-104kg/m2 [900-1,040t/ha]).[218]

*Efficient use of water and nutrients*

In soil culture water may be lost in wetting the soil beyond the reach of the plant roots or from the surface through evaporation.

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[213] ibid.

[214] LUITEL, B. P., ADHIKARI, P. B., YOON, C.-S. & KANG, W.-H. 2011. Yield and Fruit Quality of Tomato (*Lycopersicon esculentum* Mill.) Cultivars Established at Different Planting Bed Size and Growing Substrates. Horticulture, Environment, and Biotechnology; 53(2), 102-107.

[215] ibid.

[216] ibid.

[217] Controlled environment agriculture, see also „list of abbrevations". For further informations visit http://ceac.arizona.edu/, retrieved 15.08.2015

[218] LUITEL, B. P., ADHIKARI, P. B., YOON, C.-S. & KANG, W.-H. 2011. Yield and Fruit Quality of Tomato (*Lycopersicon esculentum* Mill.) Cultivars Established at Different Planting Bed Size and Growing Substrates. Horticulture, Environment, and Biotechnology ; 53(2), 102-107.

In hydroponic culture, since the nutrient solution is transported within an en-closed pipe system (or similar) water loss and water stress on plants can be drastically reduced if not eliminated.

Nutrients (...) are also not lost to the soil but retained in the root zone and, in closed systems, are replenished and recycled.[219]

*No weeding or cultivation is needed*

This reduces if not eliminating completely the necessity for using all sorts of herbicides.

Transplanting of seedlings is easy – No transplant shock

In soil culture the root mass can be easily disturbed during transplanting causing root breakage, plant stress and stunted growth for up to a week.

In hydroponic culture seeds are started in Rockwool cubes or plugs, and then transplanted into larger cubes with holes made for that purpose. There is no disturbance of the root mass, little or no root breakage and therefore minimal plant stress and transplant shock.

*Fruit of hydroponically grown plants can have more flavor*

Field tomatoes are mostly harvested before they ripen. Long transportation routes make this necessary to dovetail the crop with the buying time. Tomatoes then gas treated with ethylene for lycopene[220] formation.

“Hydroponically grown tomatoes (...) are picked after they have begun to ripen, which includes the typical red color formation of the fruit (lycopene), the formation of gel within the locules and the characteristic taste.“[221]

It‘s not the greenhouse that distroys the taste of tomatoes.

Tasteless tomatoes which nevertheless have an attractive appearance to the buying public are commonly associated with the greenhouse tomato. It is a matter of fact that in the early years of mass-produced tomatoes in Europe, especially in the Netherlands, and also in America fifteen years ago, the greenhouse industry concentrated on aesthetics, especially on the skin-quality of tomatoes. Today after studying specific outdoor cultivation conditions researchers know how and why a tasty vegetable develops, “they concluded that some stress was necessary in order to elicit flavonoids (complex organic molecules specific to plants). These molecules are the essence of why most vegetables have distinctive flavors and aromas. In addition, restricting the water a plant

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[219] RORABAUGH, P.A., 2014. Introduction to Hydroponics and Controlled Environment Agriculture. Tucson, University of Arizona, Controlled Environment Agriculture Center p. 5-2

[220] Lycopene is a chemical compound which gives tomatoes the red color. More detailled information see Nomenklatura

[221] RORABAUGH, P.A., 2014. Introduction to Hydroponics and Controlled Environment Agriculture. Tucson, University of Arizona, Controlled Environment Agriculture Center p. 5-2

receives increases its sugar content, heightening the flavor even more“[222] Electrical conductivity can also be raised within hydroponic production. “This tends to stress the plant and enhance fruit flavor“[223], too.

## ADVANTAGES OF GREENHOUSE CULTURE OVER FIELD CULTURE

*Virtual indifference to the seasons*

Crops can be grown year around in any climate zone, from tropical regions in deserts and on to the Polar regions on earth. This cultivation method enables fresh food production in space, too.[224] The VEGGIE-research program, launched by NASA, will start fresh vegetable production on the International Space Station within 2015.[225]

*More efficient use of space*

Hydroponic production methods reduce the depth for root development compared to soil based agriculture. If light energy supply is guaranteed, supplementary stackings of one plant above another is possible.

*Control over the aerial (upper) portions of the plant to achieve higher yields*

Air temperature and relative humidity can be regulated within enclosed environments. Both can be adapted to the specific crop and to the actual growing- and maturation stage.

CO2 concentrations can be regulated. If light, nutrient, and water supplies are optimal, with higher CO2 concentrations photosynthesis can be boosted. Plant and fruit growth will accelerate and higher sugar concentrations will result. Normal CO2 concentrations of between 330 and 380 ppm the can be doubled or tripled.

“Light levels and quality (wavelengths) can be controlled by choosing an appropriate shade cloth or glazing. In certain high light regions, shade cloth can be used during the summer to protect the crop. Furthermore certain forms of glazing can block UV radiation, which can harm plants and plant productivity.“[226]

## CHALLENGES OF CLOSED ENVIRONMENT AGRICULTURE

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[222] DESPOMMIER, D. 2010. The Vertical Farm, New York, St. Martin‘s Press, p. 166

[223] RORABAUGH, P.A., 2014. Introduction to Hydroponics and Controlled Environment Agriculture. Tucson, University of Arizona, Controlled Environment Agriculture Center, p. 5-2

[224] During the lecturing phase of this Doctoral Thesis nasa pronounced first vegetable consumption of astronauts on ISS, completely grown in space. https://www.nasa.gov/mission_pages/station/research/news/meals_ready_to_eat, retrieved 10.08.2015

[225] http://www.nasa.gov/mission_pages/station/research/news/veggie.html, retrieved 27.02.2015

[226] RORABAUGH, P.A., 2014. Introduction to Hydroponics and Controlled Environment Agriculture. Tucson, University of Arizona, Controlled Environment Agriculture Center, p. 5-3

Regardless of whether hydroponic, aeroponic or aquaponic methods are imple-mented in an enclosed environment, each of these alternatives to soil based agriculture shares similar, if not the same disadvantages.

The following outline can also be read as common challenges of classical greenhouse food production, and, of course for future implementation of Vertical Farms. For the sake of completeness all the different lines of thought are listed here, even though most of the following points influence neither the configuration of the simulation model as defined in Chapters 4 and 5, nor the architecture and design of Vertical Farms. Referring to Rorabaugh, Arizona University[227], the following challenges are listed such as:

*Large capital, energy and labour input*

Any size of commercial operation (including injector irrigation systems, computer controls, etc.) will cost about $600,000 per acre with the land itself costing $1000 - $2000 per acre or more (depending on location).

Energy costs can be high and include those for heating (usually burning natural gas), cooling (usually through use of evaporative cooling) and electricity to run equipment (injectors, computers, motors, sorting/packing/storage equipment, etc.).

Labor is essential on a daily & intensive basis with significant wage costs for year-around workers plus associated benefits.

*The grower needs a high level of competence in plant science, engineering, computer control systems and marketing*

If not available, experts in these fields needs must be hired. This is an intensive form of agriculture where a small problem can very quickly escalate into a major disaster.

*The technology is limited to crops of high economic value*

Since the initial cost of a large commercial facility is so high it would not be profitable to grow anything but crops of high economic value including tomatoes, colored bell peppers, cucumbers and even lettuce which, in a hydroponic greenhouse, can yield multiple crops per year.

*Plant diseases and insect pests may prove more difficult to control*

Root pathogens that produce water-borne spores (e.g., zoospores of Pythium) can be devastating to plants growing in a recirculating system since infected solution could circulate to all plants. For treatments see Chapter 4.

The greenhouse, with its controlled environment, is a perfect habitat for many types of insects, good (beneficials) and bad (white flies, aphids, thrips, spider mites, shore flies and fungus gnats). Although IPM [integrated pest management, Ed.] and biological control are available, the plants will require constant vigilance and swift action.

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[227] RORABAUGH, P.A., 2014. Introduction to Hydroponics and Controlled Environment Agriculture. Tucson, University of Arizona, Controlled Environment Agriculture Center, Chapter 5, p.3

In summary the following plant needs can be listed, as the requirements which are critical for implementing hydroponic systems within a controlled environ-ment:

"Water – Critical for metabolic processes, for transport of substances throughout the plant body (phloem and xylem) and for transpirational cooling.
Light – Critical for photosynthesis. (Where you put your system is important.)
Inorganic mineral nutrients – at the correct concentrations (EC[228]) and pH levels.
Carbon dioxide – Critical for photosynthesis (needed at the leaf surface).
Oxygen – Critical for respiration (needed by all parts of the plant including the roots, as a result aeration of the nutrient solution may be required).
The appropriate temperatures and relative humidity (specific to type of plant).
The proper temperature and relative humidity (specific to type of plant)
Support systems for the roots and shoots. For plants where the roots hang directly into the nutrient solution and do not provide any support for the plant, mechanical support may be needed. For an indeterminant tomato plant, support for the stem will be needed in the form of hooks, twine and vine clips."[229]

## *AEROPONICS*

"The aeroponics systems allow the growth of plants in an air/mist environment without the use of soil or an aggregate media. This high performance food production technology will rapidly grow crops using 99% less water and 50% less nutrients in 45% less time."[230]

Richard Stoner[231] invented this technology in 1982. In principle it is an advanced hydroponics technology, soilless with water and nutrient supply for the plant. By contrast with standard to hydroponics, the roots of the plants no longer "swim" (or are planted in a substrate, Ed.) in a nutrient solution, but are sprayed with a "nutrient-laden mist onto the roots, supplying them with everything they need (...)."[232] Small nozzles cover the plant roots with a continuous mist.

Enclosed root systems which are supplied with water and nutrients with a mist system have now been under observation for decades. The technical requirements for aeroponics are far more advanced than those for classical hydroponics. This might be one of the principal reasons why

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[228] Electrical Conductivity of Water estimates the solids dissolved in water. See List of Abbrevations.

[229] RORABAUGH, P.A., 2014. Introduction to Hydroponics and Controlled Environment Agriculture. Tucson, University of Arizona, Controlled Environment Agriculture Center, Chapter 5, p.4

[230] http://sbir.gsfc.nasa.gov/SBIR/successes/ss/10-026text.html, retrieved 12.10.2014

[231] Also visit http://www.nasa.gov/offices/ipp/centers/kennedy/success_stories/Inflatable_Aeroponic_System_BBlinds_prt.htm, retrieved 15.08.2015

[232] DESPOMMIER, D. 2010. The Vertical Farm, New York, St. Martin‘s Press, p. 165 - 166

aeroponics have so far failed to gain widespread use. “Water quality requirements are very high, and the system must be very reliable. The method (...) is not applicable to products sold that require a substrate. For (...) vegetables, the supporting system must be rearranged. As a rule, the method has been used mostly for research. (...) Apparently the improvement in net return makes it difficult to warrant the initial investment and operating costs.“[233]
The advantage of drastic water (and therefor weight) reduction facilitates food production in space. Research with aeroponic systems is thus strongly supported by NASA. This cultivation methods provides “clean, efficient and rapid food production. Crops can be planted and harvested in the system all year round without interruption, and without contamination from soil, pesticides and residue. Since the growing environment is clean and sterile, it greatly reduces the chances of spreading plant disease and infection commonly found in soil and other growing media.“[234]

## *AQUAPONICS*

The intent of aquaponics is to create a symbiotic relationship between classical aquaculture and hydroponics. Basically it is a hybrid of hydroponics (plants in growing substrates, without soil) and aquaculture[235]. Aquaponics enables the possibility to grow food by creating an “ecosystem in which the wastes of one process become resources for another. Fish waste feeds the plants, and plants clean the water which is returned to the fish tanks. Beneficial bacteria in our filters break down fish waste so that it is easily absorbed by the plant roots, and beneficial insects and organic foliar feeding help control pest populations naturally and safely.“[236]

A promising implemented concept within the context of this doctoral thesis is “The Plant“, an aquaponic Vertical Farm in Chicago with a production area of roughly 2.500 m2 where the aquaponics farm also houses its own breeding system. The main fish cultivated is the tilapia. Additional aquaponics systems will be installed in the next future with prawns. For more information in the Appendix “The Plant” is described and classified in more detail.

The biomimicry of nature can be defined as a helpful cultivation method to change the principle of cradle to grave by traditional industrial farming to the principle of cradle to cradle. Nutrient delivery by fish for plants has the potential to additionally reduce necessary macronutrients for plant cultivation within fully controlled environments. In addition to other operations the conversion of ammonia released into water in the excreta of fish, into nitrates, is the central one.

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[233] HANAN J.J. 1998. Greenhouses: advanced technology for protected horticulture, Boca Raton, CRC Press, p.339-340

[234] http://www.nasa.gov/vision/earth/technologies/aeroponic_plants.html, retrieved 12.01.2015

[235] Also known as aquafarming, is the production of aquatic organisms in both sweet- and saltwater under controlled conditions. The Food and Agriculture Organization (FAO) defines aquaculture the „farming of aquatic organisms including fish, molluscs, crustaceans and aquatic plants. Farming implies some form of intervention in the rearing process to enhance production, such as regular stocking, feeding, prodtection from predators, etc. Farming also implies individual or corporate ownership of the stock being cultivated.“, http://www.fao.org/fishery/statistics/global-aquaculture-production/en, retrieved 12.01.2015

[236] http://www.plantchicago.com/non-profit/farms/plantaquaponics/, retrieved 12.01.2015

The byproduct of fish metabolism becomes the nutrient supply for crops. Plants are able to absorb ammonia from water to some degree, but nitrates are assimilated more easily. This drastically reduces the toxicity of the water for the fish.[237]

## Production methods - Building footprint, cultivation area and soil-based-area-equivalent

Food production within a fully controlled environment aims to maximize yields in order to compete with the traditional food production system. Beyond the economic pressure on food prices it is of central interest due to the potential it offers for relieving the current and future stress situation on available additional farmland. The Vertical Farm “design must make optimum use of its internal space by accommodating the largest possible growing area. (...) It is also of vital importance that the building design allows for the most efficient method for workers to tend the plants (...).” But considering the different production methods explained in more detail below and based on existing or planned Vertical Farms, the ratio between the production footprint and the horizontal circulation on the ground floor level is of basic interest and as a consequence in order to make different production methods in Vertical Farms comparable one must consider the ratio between the production volume to the circulation volume (horizontal and vertical).[238]

Different design strategies using specific production methods aiming a maximization of yield, lead to a maximization of operation costs. The high light requirements of most plants s an issue of central interest. The higher the plant density per level or building volume, the lower the light accessibility of plants will be. This means, “[t]he dense growing configurations distributed throughout a Vertical Farm’s multiple floors create far too many physical barriers for sunlight to penetrate. (...) [E]ven if sunlight could somehow bend around these obstacles, the sum of solar energy cast on a particularly dense Vertical Farm may be less than the farm‘s total energy needs.“ [239]

> Greenhouses using technology adaptable for future Vertical Farms, but also Vertical Farms in construction mostly implement high technology to maximize yields. Great efforts are being made in this to ensure sunlight reaches the crops. These two competing targets are crucial in design and have to lead to new Vertical Farm typologies[240]

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[237] For more information on the nitrogen cycle visit: http://www.britannica.com/EBchecked/topic/416271/nitrogen-cycle, retrieved 01.04.2015

[238] For an advanced building analysis additional information for construction and HVAC must be considered.

[239] ibid.

[240] Gordon Graff stated the problem in a similar way: „The battle between maximizing yields and maximizing solar penetration thus becomes the most important design consideration for architects, and ultimately will be the

We can differentiate typologically between four different food production methods within conventional or stacked greenhouses:

horizontal layers
  - single layer
  - multiple layer

horizontally rotating elements
vertically rotating elements and
3D-conveyor belt.

## *SINGLE HORIZONTAL LAYERS*

Single horizontal cultivation layers are used by all greenhouses, irrespective of whether the unit is for soil-based or soil-less cultivation. Greenhouses for food production, are a “support in controlling temperature, sunlight and [the, Ed.] availability of water during the growing season. To increase the fertility of an ecosystem, one can also act on the temperature (possibly with heated greenhouses), on sunlight (providing shade), on the water supply and its organization (irrigation, drainage, windbreaks, soil covering that minimizes evaporation), and even on the carbon dioxide content of the air (...).[241] Today, artificial lighting enables an additional increase in yield output per square-meter: Stacking the crop. By stacking the growing substrate automatically the available sunlight for plants decreases.

Multiple, stacked non-moving layers are possible and dependent on specific plant- and greenhouse heights, as on light requirements for plant growth, photomorphosis and photosynthesis. The smaller the light requirement of plants is, the easier it is to additionally stack the cultivation footprint within a greenhouse. Specially designed troughs for plant cultivation already enable an optimization of the light supply, and can be used both for greenhouses and outdoor cultivation. This could be achieved by perforating the horizontal substrate supporting element for enabling light to pass through the structure or simply by stacking only the hydroponic substrate and watering pipes. By contrast with the other three production methods, this one can be considered as the only static, non-moving production method. The plants continue in the same position throughout crop rotation. The main advantage of this is in the greatly reduced material and investment cost for additional technical, mechanical and computerized elements.

Single horizontal layer-cultivation is used today in classical greenhouses for crops ranging from tomatoes with their high light dependence, to mushrooms with their low-light requirement. The very low light requirement for mushrooms enables use of a cultivation principle on multiple layers. The low height of the mushrooms also makes multiple stacking possible. The cultivation method for most mushroom production is hydroponic with the use of a growing substrate by adding water and nutrients, or is soil-based using fertile soil.

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primary criteria from which the efficacy of a design will be determined.“ GRAFF, G. 2011. Skyfarming. Master of Architecture, Waterloo, Ontario, Canada, p.76

[241] MAZOYER, M. & ROUDART, L. 2006. A History of World Agriculture, London, Earthscan, p. 63-64

## *MULTIPLE HORIZONTAL LAYERS*

This second practice for multiple horizontal layer-cultivation is in ever more extensive use for greenhouse production, but is also adaptable for outdoor farming. One product is thus quoted here: the hydrostacker. The stacked trays used in this are all combined vertically, interrelated and connected by a vertical watering system which leads water and nutrients to the substrate. The system can be applied in principle for the cultivation of most vegetables and fruits depending on root length and the plant height.

Based on the statistics of Despommier who cites a Florida farmer, “one single acre of greenhouse-grown strawberries using hydrostackers, replace some thirty acres of outdoor farmland.“[242]

Extending beyond classical greenhouses and approaching closer to the typology of a Vertical Farm, the Research Center in Suwon, South Korea (next page) located just outside the capital Seoul (ca. 32 km from center to center), should to be mentioned for the purpose of this work.
Here computers and robots are cultivating leafy crops within a fully controlled environment using LED light and reducing the time to harvest by half. The aim is to identify the optimum wavelength for specific crops in order to reduce necessary artificial lighting. “With a plant factory the environment can be artificially controlled.
The operator can change conditions such as temperatures, humidity and carbon dioxide to provide an optimal environment for plants to grow in.“[243]
The Vertical Farm, built in 2010 can now look back to four years of empirical data. Although specific statistical data has still not been published, the main challenge that is being faced is, as expected, high energy costs. “This factory consumes a lot of energy and electricity. (...) In particular you need to cool the temperature down for some plants through air conditioning. Technological development to reduce energy is [the key for] success of plant factories.“[244]
Compared to the following examples, this kind of stacking is fixed and non-rotational. This cultivation and production method as currently implemented in Suwon, South Korea, is thus classified as a production method that is suboptimal for Vertical Farms having crop productions with high light re-quirements.

The Suwon Vertical Farm is fully dependent on artificial lighting, although it can conceivably be used for cultivation of crops with low or no light requirements within a potentially fully controlled environment and with the potential for heating, ventilation and cooling. The methods for use here are hydroponic, aeroponic, aquaponic or soil-based cultivation.

## *HORIZONTALLY ROTATING ELEMENTS*

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[242] DESPOMMIER, D. 2010. The Vertical Farm, New York, St. Martin‘s Press., photodocumentation from p.146

[243] Lee Sang-Woo, Gyeonggi Province Agricultural Research, In a June 5 report entitled “South Korea moving towards Vertical Farming,” Al Jazeera‘s Wayne Hay described the scene at a Vertical Farm in Gyeonggi-do (Gyeonggi Province). http://www.korea.net/NewsFocus/Sci-Tech/view?articleId=103942, retrieved 03.11.2015

[244] ibid.

In the Southwest of England, Devon[245], Paignton Zoo Environmental Park[246], a combined zoo and botanical garden is producing vegetables to feed the animals within a specially constructed greenhouse on 120 m2. It has now been running since 2009.
While horizontal layers are the cultivation method used in most greenhouses producing food hydroponically, horizontally rotating elements are used at Paignton Zoo for production by the horticultural company Valcant. The columnar design enables the stacking of plants within the entire floor height of 3m. The plant columns are connected to a conveyor track and are turned around the z-axis along the conveyor belt on top of the trays to equalize the available daylight coming through the transparent building skin. A pair of eight layers (or trays) is moved along the conveyor reaching the starting point in 40 minute cycle.

This production unit for Paignton Zoo began pilot operation with VertiCropT™ [247] at Paignton Zoo in Devon. „The pilot project grows 11,200 plants in a greenhouse of 1[2]0 square meters, using a conveyor driven stacked growing system various micro greens, lettuce and salad mixes have been planted sequentially to provide a regular supply of fresh green leaves (...) to improve animal feeding regimes at the zoo.“[248]

The production method consists of horizontally rotating elements, which make use of the full floor height. The rotation enables to equal distribution of the available natural light to all the plants - principally leafy vegetables – on the production line. The trays are “suspended from an overhead track and rotate on a closed loop conveyor.“[249] The principle advantage of this production method consists in allowing “centralized locations for irrigation and the loading and unloading of crops“[250] The environment is fully (computer) controlled providing plants with ideal growing conditions. The plants get provided with water and nutrients at regular interval by the trays. “(...) [I]ntegrated advanced hydroponic technology supplies water and nutrients at the correct pH and EC levels automatically via a central feeding station.“[251] A monitoring operation controls the environmental temperature, humidity, water and nutrient solution composition. “UV filters ensure the re-circulated water is clean and free from potential plant pathogens.“[252]

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[245] The following daylength and sunlight hours got taken from the weatherfiles from Kiev, Ucraina, for unavailability of Devon‘s weather files. Devon‘s latitude is the closest to a city available from the official energyplus weather file-site (http://apps1.eere.energy.gov/buildings/energyplus/).Latitude comparison: 50°43′18″N Devon and Kiev 50°27′13″N.

[246] Paignton Zoo Environment Park Totnes Road Paignton Devon TQ4 7EU

[247] http://www.verticrop.com/, retrieved 12.03.2015

[248] IHC 2010 Lisbon S10 220 verticrop 1Fin 2011 (SHS Acta Horticulturae (3)-2.pdf, retrieved 12.01.2015, p.1

[249] IHC 2010 Lisbon S10 220 verticrop 1Fin 2011 (SHS Acta Horticulturae (3)-2.pdf, retrieved 12.01.2015, p.2

[250] http://www.zoolex.org/publication/frediani/feeding_time_frediani_horticulturist2010.pdf, p.14, retrieved 12.01.2015

[251] ibid.

[252] ibid.

The production method used by Paignton Zoo, implemented by VertiCropTM is adaptable to all existing and new stacked building typologies. It must be accepted that the high density of plants in the z-axis behind the facade drastically reduces light penetration in the deeper zones of the levels and makes artificial lighting necessary. The construction of the horizontally rotating elements also reduces the Choice of crop types. Only those vegetables and fruits can be considered that have a low growth in the z-axis.

A much higher output per m2 compared to traditional soil-based agriculture or greenhouse practice is certainly conceivable. “Scaling up, a 6 m high VertiCropTM requires 87% lower land and building footprint than conventional hydroponic systems to grow the same quantity of plants.“[253]

This cultivation and production method in Devon is thus classified as a Vertical Farm within a potentially fully controlled environment with the potential for heating-, ventilation and cooling. The cultivation method used is hydroponic. The greenhouse construction and the production method is optimized for natural sunlight, but artificial light, if necessary, could be adapted without negatively influencing the production procedure. The production volume is a monovolume with potential for additional level stacking.

## *VERTICALLY ROTATING ELEMENTS*

Two additional relevant Vertical Farms should be mentioned at this point:

SkyGreens Vertical Farms in Singapore.
Vertical Harvest, a Vertical Farm in Jacksonville, Wyoming.

One of the most efficient and economically relevant Vertical Farms is managed by SkyGreens in Singapore, specialized on lettuce production. The chosen production method is thus a vertically rotating system.[254]

## *SKY GREENS, SINGAPORE*

This unit is typologically a tall greenhouse (9 meters high) with growing troughs mounted on an aluminum form. This form consists of a modular structure which is customizable and scalable, it allows different heights (in absolute terms) and between the troughs. Different crops can thus be cultivated. Troughs are currently optimized and produced for the following medium- to high PPFD requirement plants xiao bai cai, naibai, cai xin, Chinese cabbage, mao bai, bayam, kai lan kang kong, spinach.[255]

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[253] http://www.zoolex.org/publication/frediani/feeding_time_frediani_horticulturist2010.pdf, p.14, retrieved 12.01.2015

[254] http://www.skygreens.com/technology/, retrieved 01.02.2015

[255] ibid.

The plants rotate twice a day following an A-shaped path (cross section), which guarantees the same light exposure for each plant. The rotation itself is powered “by a unique patented hydraulic water-driven system which utilizes the momentum of flowing water and gravity to rotate the troughs. Only 60W electricity (...) is needed to power one 9m tall tower.“[256] Hydroponics is the cultivation method used, although this system would also work with a soil-based cultivation method.

While passing through different points in the structure, the troughs are irrigated by a nutrient solution. According to information from SkyGreens, the yield output is ten times higher per unit land area equivalent. Higher yields through the control of the enclosed greenhouse environment are not declared.
The SkyGreen production method is to work with natural light. The principle of the rotating trough-construction is based on using natural light, although this system makes it possible to apply artificial light fixtures.

Water usage, according to SkyGreens, depends on an underground reservoir system and all the water is fully recycled and reused. The drainage system is based on the flooding method (which drains and fertilizes the plants). This eliminates electricity wastage from sprinkler systems as well as water run-offs.[257]
The specific water amounts data per m2 of cultivation area or per crop rotation for this work were not available and it is thus difficult to make comparisons with soil-based equivalents.
The patented and modular A-shape-production method allows an expansion in the x- and y-axis. The distance between the production structures allows an optimization of the horizontal circulation area, which are necessary in every greenhouse. The ratio between the crop growing area and the horizontal circulation area is reduced approx. tenfold compared to other greenhouses with the same crops.

This cultivation and production method in Singapore is thus classified as a Vertical Farm in a potentially fully controlled environment with the potential for heating, ventilation and cooling. The cultivation methods that can be used are hydroponics and soil-troughs. The greenhouse construction and the production method are optimized for natural sunlight, but artificial light could be adapted without negatively influencing the production procedure if necessary. The production volume is a monovolume.

## *VERTICAL HARVEST, JACKSON, WYOMING, USA*

The Vertical Farm in Jackson, Wyoming, USA, was initiated by the architect Nona Yehia and environmental consultant Penny McBride.

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[256] http://www.skygreens.com/technology/, retrieved 01.02.2015

[257] ibid.

Vertical Harvest is designed for natural daylight use. The facade was developed to include the highest daylight transmission possible. It is oriented to the south.
“This natural lighting not only keeps our energy use down, but is a free source for photosynthesis. As a result of our preliminary feasibility report, we determined that in our location there are periods of the year where the natural daylight is not sufficient for growing certain produce. For example, it is impossible to grow tomatoes in the heart of winter in Jackson Hole without the use of supplemental artificial lighting.“[258]

Supplemental growing lights were fixed due to cope with the long winter periods with low light availabilities, based on provided information of operators of Vertical Harvest. The company calculates that it must use approx. 3,000 artificial lighting hours per year to meet the production targets. HPS (high pressure sodium) - lightbulbs are used for tomato production and LED- fixtures for lettuce varieties, microgreens and for the propagation areas of the vertical greenhouse.

## *3D-CONVEYOR BELT - PLANTAGON, LINKÖPING, SWEDEN*

The most advanced and promising production method is the 3D-conveyor belt. The most developed system is patented by Plantagon . Information on this has been comprehensively published and the system is thus investigated in greater depth for this doctoral thesis. Furthermore the author participated at the GUA-Summit[259]in Linköping, Sweden, organized by Plantagon, at the end of January 2013 and thus had the opportunity to discuss in greater detail the state of the art in Vertical Farming using this very specific production method.
Besides different urban and Vertical Farm typologies Plantagon International[260] is also developing, a project which is of particular interest for this doctoral thesis: this is the Vertical Farm project for Linköping, Sweden. The ground-breaking ceremony for this was on February 9th 2012.[261]

A continuous movement from the top of the helix to the bottom (from the top to the ground floor of the building) of the growing crop throughout its crop rotation guarantees a similar amount of sun exposure. Light penetration is certainly less the more distant the plants are positioned from the facade. Additional LED lighting equalizes the differences.
The plant begins the journey as a seedling or a young plant at top of the building and throughout the growing- and ripening phase it moves to the building entrance level, ready to be harvested.

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[258] www.verticalharvest.org, retrieved 12.02.2015

[259] http://www.urbanagriculturesummit.com/summits/urban-agriculture-summit-2013

[260] To their own description Plantagon International „is the global innovation leader in the sector urban agriculture. Plantagon’s resilient food systems minimize the need for land, water, energy and pesticides. The environmental impact is very low, and if the products are delivered directly to consumers in the city, the transportation costs are also minimized. The Plantagon concept is simple and appealing: fresh, local vegetables delivered daily directly to consumers. No middle hands, no yesterday’s food. We develop innovative solutions to meet the rising demand for locally grown food in cities all around the world. We minimize the use of transportation, land, energy and water – using waste products in the process but leaving no waste behind..“, http://plantagon.com/about, retrieved 13.03.2015

[261] In addition information exchange and discussions between the author and Prof. Dickson Despommier, one of the keynote-speakers on that Summit, was possible.

“Food is harvested in batches using an automatic harvesting machine. After the harvest the trays and pots are disinfected, and the pots are then sorted, separated and replanted with a fresh seed for the next round in the cultivation loop. After germination, the pots are recombined with the trays and elevated to the top of the growing helix to repeat the process.“[262]

„The trays are equipped with a light sealed nutrient solution reservoir, and the pots are irrigated about three times per day using an ebb-and-flow technique. A capillary mat at the bottom of each tray protects the individual plants from drought. Excess nutrient solution is collected and reused after disinfestation.“[263] Regardless the system design of the Vertical Farm, conceived by Plantagon, this production method by using the 3D-conveyor belt with moving trays from the top to the basement level, follow the same production flow.

The depth of the trays used at the farm in Linköping is three meters and can be increased to six meters for use in other projects. The multifunctional structure in Linköping is a combination of the vertical greenhouse with an office building, which is situated to the north of the building. In addition the production unit contains spaces for germination, processing, washing and packaging. A restaurant, a visitor‘s area and a conference room are also planned.

The greenhouse volume of this Vertical Farm has a truncated form, developed for optimizing sunlight penetration of the cultivation surface for Pak Choi[264] (also known as bok choy) production.

This patented conveying system moves the trays (containers) on an inclined track and a conveying device. This device is “arranged to travel down the track and comprises a container moving unit which after passage below a container moves the container one step up the track. (...) The invention also relates to a tower structure comprising a container conveying system and a method for conveying containers (...)“.[265] The railing or the “inclined track“, inspired by the structural logic of roller coasters, allows the implementation of this production method in principle to theoretically all the potential geometric forms of three dimensional greenhouses.

„Plantagon integrates the building on site and adapts it to site specific light conditions which vary from location to location in the existing urban fabric of cities. The verticality is important in order to optimize the production of food and the functionality of the building.Plantagon Greenhouse. The patented transportation helix (also referred to as the spiral or the ramp) is the most important concept behind the industrial process of all Plantagon systems. It has been developed based on three main optimisation factors: 1. maximise the footprint usage ratio of the helix; 2. minimize the use of water; 3. minimise the demand for artificial lighting and to gain as homogeneous light levels as possible.“ [266] The principle of the helix, beyond the implementation into the Vertical Farm in

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[262] http://plantagon.com/urban-agriculture/cultivation-systems, retrieved 07.04.2015

[263] ibid.

[264] Brassica rapa chinensis is a Chinese cabbage, very popular in Southern China and Southeast Asia. This winter-hardy vegetable is increasingly grown in Northern Europe. Due to its tolerance to colder temperatures and relatively low light requirements (220 µmol/m-2/s-1) this product presumably got chosen as crop in Linköping with harsh climate and low light intensities.

[265] Excerpt from the patent of Ake Olsson, registered 27.05.2009, published 15.03.2012, „Conveying system, tower structure with conveying system, and method for conveying containers with a conveying system, US 20120060414 A1“, http://www.google.je/patents/US20120060414, retrieved 07.04.2015

[266] http://plantagon.com/urban-agriculture/vertical-greenhouse, retrieved 13.03.2015

Linköping, with all its geometrical (and climatic) limitations, was conceptually developed strictly for use in two standalone Vertical Farms, as published on the organization website.

The example here mentioned (Fig. 27) shows a closed basement, for industrial process and HVAC and a vertical circulation element, containing additional building services in the North (or the South)[267]. The building geometry with leaning extrusion axis of the greenhouse thus permits full sunlight penetration throughout the day and the year, based on the initial premise that the Vertical Farm in this picture is based on a concept devised for equatorial regions.

## Typological comparison of existing Vertical Farms

Should it prove true that the biocapacity of the earth no longer is able to compete with world population growth; urban agriculture (especially Vertical Farm farming) is an issue of greatly increased relevance today. If cities are in most cases dependent on food imports with all the consequences this entails[268], then food markets and the food supply chain also need to be rearranged. Food supply of city dwellers from traditional agriculture as we now have it, which has long been completely dependent on hydrocarbon energy, should be expanded by food production practices which release the current food provision system fundamentally and in three ways from the pressures to which it is subjected:

by increasing the food independencies of cities,
by decreasing the (economic and political) pressures and stresses resulting from the exploitation of natural habitats[269],
decrease the dependencies of hydrocarbon energy.

A closer look at the five Vertical Farms, presented in Chapter 3.2 shows that food production (which is one item within the food supply chain) is the focal task here and it currently not only obtains its components from outside the system but also demands extensive structures for dealing with the tasks that follow-on after the harvest. At the present time a Vertical Farm, should it happen to be embedded in an existing system (urban, infrastructure, program), is an idiosyncratic building and the following typological comparison clearly indicates the differences the concept brings into the food provision arena, based on the primary design decisions it incorporates, all of which have the background aim of making cities more independent and resilient.

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[267] Dependent on the location wether it's on the Northern or Souther Hemisphere.

[268] WATKISS, P., SMITH, A., TWEEDLE, G., MCKINNON, A., BROWNE, M., HUNT, A., TRELEVEN, C., NASH, C. & CROSS, S. 2005. The Validity of Food Miles as an Indicator of Sustainable Development: Final report produced for DEFRA. AEA Technology.

[269] BRUINSMA, J. 2009. The Resource Outlook to 2050. By how much do land, water and crop yields need to increase by 2050? [Paper presented at the FAO Expert Meeting, 24-26 June 2009, Rome on „How to Feed the World in 2050".] [Online]. Available: ftp://ftp.fao.org/agl/aglw/docs/ResourceOutlookto2050.pdf.

The issues of fundamental interest here are the production output, or the output of edible biomass by the Vertical Farms, as also the ratio between the building footprint and the equivalent of traditional soil based agriculture production, the A/V-ratio, the ratio between transparent and opaque facade area of the greenhouse and the embodiment of additional programs to reduce the spatial impact on the food supply chain.
Before we go into detail, the production types of the quoted Vertical Farms up to here must be classified more precisely to make the comparison replicable.

The world map on the next page provides an overview of selected relevant world Vertical Farm types (existing buildings, high-tech-greenhouses with stacked production methods or design proposals, relevant for this discussion) . The geographic position of the buildings compared in this chapter can be found by reference to the numbers.

5 for Vertical Harvest, Jackson, Wyoming, United States,
10 for Plantagon Vertical Farm in Linköping, Sweden,
11 for Paignton Zoo, Devon, United Kingdom,
15 for Suwon Vertical Farm, Suwon, South Korea and
20 for SkyGreens, Singapore.

## *SUWON Vertical Farm, SUWON, SOUTH KOREA*

This facility uses high-technology within a fully controlled environment. It is run specifically on an electric light dependence concept using LEDs, the indoor climate is fully computer controlled, all production spaces are either heated or cooled on demand and the facility is artificially ventilated. The research function of this facility means it is not intended to produce marketable food and thus no additional program for the food supply chain is considered. Linear programmatic expansions such as research spaces are likewise not considered in in this case as with of the Plantagon Vertical Farm in Linköping.
This production type is thus is classified as a Vertical Farm.

## *PAIGNTON ZOO, DEVON, UNITED KINGDOM*

Although feed production within this type proceeds in a stacked manner, the classification for this building is thus as a Vertical Farm. The building envelope takes the same form as a foil tunnel of the kind that is well known and widely distributed in Central Europe. The production method with its horizontal conveyor system, the computer controlled watering and plant nutrition provision, temperature and humidity control are considered in the light of their potential for possible implementation in Vertical Farms. The production type is thus not classified as a Vertical Farm, but as a greenhousePRO.

## *SKYGREENS, SINGAPORE*

SkyGreens produces food in tall greenhouses. Vertically rotating troughs make full use of the total height of the greenhouse and the exposure to natural sunlight, entering from all sides of the building envelope. No additional programs other than food production take place within the building volume. Computer controlled indoor climate such as temperature and humidity and the rotation of the vertical rotating elements make this a high-tech-greenhouse that achieves remarkable increase in the biomass output per m2. SkyGreens is classified as greenhousePRO.

### *VERTICAL HARVEST, JACKSON, WYOMING*

Vertical Harvest not only produces fresh food, but also enlarges its program linearly to include those spaces, which are normally separated by the current food supply chain such as preparation, retail and offices. In addition public spaces are implemented for guided tours and educational purposes. Lighting fixtures and computer controlled HVAC-systems are implemented. These components make a Vertical Farm + out of this production type, which is functionally comparable with the next Vertical Farm.

### *PLANTAGON, LINKÖPING, SWEDEN*

The Vertical Farm in Linköping combines an office building with a monovolumetric vertical greenhouse. This design decision enables an energetic optimization in terms of the synergy potential resulting from the combination of the two different uses. Additional spaces are integrated within the Vertical Farm for those functions which are normally separated spatially by transport routes within the food supply chain such as washing, preparation and packaging of the harvested. In addition, the computer controlled 3D conveyor belt and building systems make a Vertical Farm+ out of this production type.

CLIMATE DATA, Suwon, South Corea: 37°15′4″N 37°15′48″W

| | |
|---|---:|
| hours/year | 8,760 |
| dayhours | 4,392 |
| sunshine hours | (49,24%) 2,163 |
| kWh/m2/a | 1,156.64 |
| diffuse sunlight (kWh/m2/a) | 702.69 |
| direct sunlight (kWh/m2/a) | 453.95 |

| | |
|---|---|
| GJ/m2/a | 4.16 |
| kCal/m2/a | 994,531 |
| l Oil Eq./m2/a | 112.19 |
| av. kWh/m2/a | 0.26 |
| av. MJ/m2/a | 0.95 |
| av. kCal/m2/a | 226.44 |
| av. l Oil Eq./m2/a | 0.03 |

The climate, similar to Seoul, is a humid continental/subtropical transitional climate with strong differences between relatively cold winters (daily mean -2,4°C in January) and hot summer month (daily mean 25,7°C in August). Winters generally are dry and summer month have a high relative humidity. Two thirds of the total radiation are diffuse light, and approximately 50% of the dayhours are sunshine hours.

### ***SUWON Vertical Farm, SUWON, SOUTH KOREA***

This Vertical Farm in Suwon, South Korea, is mentioned here, because it embodies the principle of completeness. Regrettably the author found it was not possible to obtain sufficient information regarding the dimensions of the building and the biomass output yield to contribute significantly to the typological comparisons made within this doctoral thesis.[270]

Nevertheless this Vertical Farm is of central interest. The Korean government, particularly the Rural Development Administration, RDA, have paid close attention to urban and Vertical Farming since 2009 when this research institution was established with the primary focus on optimization of the light supply for crops by investigating the ideal individual wavelength for the specific growing periods.

This Vertical Farm produces primarily leafy vegetables on multiple layers in a horizontal stacking manner. The building itself keeps natural light out. Crops are grown completely through use of artificially light provided by LED fixtures, which produce primarily red and blue light.

The cultivation method is hydroponics with nutrient enriched water.

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[270] http://www.korea.net/NewsFocus/Sci-Tech/view?articleId=103942, retrieved 31.10.2015

The building itself requires an enormous amount of energy. Since within the climatic differences between day and night and throughout the seasons it must be heated, ventilated and also air conditioned in summer.[271]

CLIMATE DATA, Devon, England, Great Britain: 50°43′18″N 3°32′01″W

| | |
|---|---|
| hours/year | 8,760 |
| dayhours | 4,387 |
| sunshine hours | (33,37%) 1,464 |
| kWh/m2/a | 1,004.90 |
| diffuse sunlight (kWh/m2/a) | 586.71 |
| direct sunlight (kWh/m2/a) | 418.19 |
| GJ/m2/a | 3.62 |
| kCal/m2/a | 864,058 |
| l Oil Eq./m2/a | 97.48 |
| av. kWh/m2/a | 0.26 |
| av. MJ/m2/a | 0.82 |
| av. kCal/m2/a | 196.96 |
| av. l Oil Eq./m2/a | 0.02 |

Devon‘s climate is influenced by the North Atlantic Drift. Its relatively mild climate for its latitute is relatively seldom, only compareable e.g. with Vancouver, Canada. The temperature throughout the year change between 8°C and 20°C. Only a third of the dayhours in Devon are sunshine hours. The total solar radiation is around 1.000 kWh/m2/a, the diffuse and direct part are roughly 50% to 50%.

## *PAIGNTON ZOO, DEVON, UNITED KINGDOM*

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[271] http://www.spiegel.de/international/zeitgeist/vertical-farming-can-urban-agriculture-feed-a-hungry-world-a-775754.html, retrieved 13.03.2014

In the same year 2009, the Vertical Farm in Devon started to produce leafy vegetables for zoo animals. In the context of food production within enclosed environments this typology is defined as GPRO, and classified as a high tech greenhouse with crop stackings[272]. The building envelope is the same as that used for foil tunnels (steel construction with transparent and translucent foils), but the production method is conceived for horizontal tray stackings moving along a conveyor belt. For this reason alone it is of basic interest. This production method also can be adapted to existing buildings with stacked levels, which light only reaches from the side. The horizontal transportation offers all the plants an equal exposure to natural light.

With this 3m-pilot system Paignton Zoo produces around 112 lettuces/m2/p.a. Soil-based yielded lettuces can reach up to 500g/head. Greenhouse lettuces normally reach between 100 to 250g/head. Based on studies by VertiCrop, however, the forecasts for this model “suggest annual yields of lettuce around 50 times higher than typical for field grown crops (...).”[273]

Based on average central European data for biomass output, the production per m2/a is roughly ten times higher than for soil based agriculture according to the author‘s calculation.[274] . Considering that lettuce in a non-protected environment can be cultivated only six month in the year, and Paignton Zoo produces for 365 days, the ratio between soil-based and greenhouse output can be doubled, the ratio is therefore 1/20.

In absolute numbers, the 79.35 m2 cultivation area guarantees an output where 1,587.00 m2 of soil based agricultural land would be needed, or compared to the GFA-building footprint the land requirement is 10.8%.

The VertiCrop[275] conveyor system was developed to support heights up to 6m with 250 lettuces/m2/a. Based on these figures the yield would be 29. 20 times higher compared to soil-based agriculture, or calculated throughout the year, 58.40 times higher. This result comes very close to the estimates of Bayley et al. for the system involved. In this case the GFA of Plantagon‘s greenhouse would be 2.45% of traditional soil based agriculture land equivalent.

The building footprint for the greenhouse is 69.76%. A visitor‘s and educational area is situated together with an area for packaging the crops for immediate distribution is located to the west and the north. HVAC facilities are situated under the 0-level. Due to the fact that the crops are fed to animals immediately after harvesting, the plants do not have to be prepared as with a subsequent conventional food supply chain.

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[272] This system, developed by VertiGrow, is currently implemented at the center in Vancouver, Canada, on the rooftop of a building which is ten times the area of the greenhouse building footprint in Devon.

[273] BAYLEY J.E. 2010. Sustainable Food Production Using High Density Vertical Growing (VertiCropTM), Valcent Products EU Ltd., Cornwall, BAYLEY SUSTAINABLE FOOD PRODUCTION PAIGNTON ZOO.pdf, p. 4

[274] Considering that one lettuce weighs 250g at the time when it is harvested and the expectation is 2,14kg/m2/a during a 6month season in middle-Europe of traditional soil based agriculture land equivalent.

[275] http://www.verticrop.com/, retrieved 31.10.2015

CLIMATE DATA, Jackson Hole, Wyoming, USA: 43°29′39″N 110°45′54″E

| | |
|---|---:|
| hours/year | 8,760 |
| dayhours | 4,363 |
| sunshine hours | (68,98%) 3,010 |
| kWh/m2/a | 1,568.18 |
| diffuse sunlight (kWh/m2/a) | 545.70 |
| direct sunlight (kWh/m2/a) | 1,022.48 |
| GJ/m2/a | 5.65 |
| kCal/m2/a | 1,348,392 |
| l Oil Eq./m2/a | 152.11 |
| av. kWh/m2/a | 0.36 |
| av. MJ/m2/a | 1.29 |
| av. kCal/m2/a | 309.05 |
| av. l Oil Eq./m2/a | 0.03 |

There are extreme differences not only between day and night temperatures, but also through the seasons (-46°C to 37°C). The high elevation above sea level (1.901 m) results in high total radiation. More than two thirds of the day hours throughout the year are sunshine hours.

## ***VERTICAL HARVEST, JACKSON, WYOMING, USA***

In the classification of this doctoral thesis, this building is a Vertical Farm +. An existing multi-storey car park has been spatially enlarged by adding an enclosed greenhouse structure. The three-storey Vertical Farm has the cultivations of different plants are implemented on each storey. A largely educative public growing-showroom is on the ground floor, while above this the first floor is used mainly for the production of leafy vegetables. The third floor is covered with a glass and tomatoes are produced on this level.
Produce is sold directly from the retail area within the building, after it is got washed, prepared and packaged.

The varied usage involved here means that besides embodying a locally disconnected program of the traditional food supply chain in this production entity, Vertical Harvest also has the additional objective of involving the community with a dual approach: offering visitor spaces within the building for guided tours and education and also involving people from the community with physical or mental disabilities in the work of growing food. Sensitizing people to the potential local food production and involving the community distinguishes this Vertical Farm from the other examples mentioned in this chapter.

> *„Vertical Harvest has a dedicated central public atrium that is physically separated by glass walls from the major growing areas in the building to encourage visitors to visually experience the greenhouse without risk of contaminating the crops. On the ground floor Vertical Harvest will have a small but functional 'living classroom' where we can grow a limited amount of specialty crops while at the same time incorporating educational initiatives. Here, because there is no soil used and we will growing in mobile containers that are up off the ground, making potential pests and diseases much easier to avoid.“*[276]

The chosen cultivation method is hydroponics. The climate in Jackson Wyoming makes heating the glasshouse necessary. No air conditioning is needed. The greenhouse is naturally ventilated.
Additional artificial lighting is required, although the exterior facade „is specified to include the highest light transmission possible (...)“[277] Approximately 3,000 hours/a are expected to support the growing- and ripening process of the chosen crop. HPD (high Pressure sodium lamps) are used for tomatoes and LED fixtures for "lettuce varietals, microgreen and propagation areas.“[278]
Tomatoes are cultivated throughout the year on a 216,91m2 area. A comparison to traditional soil based agriculture is most likely irritating, because the months with the right temperature for tomato growth are too few for the necessary crop rotation in Jackson. But we can approach using estimates for an expected yield output. Greenhouse tomatoes can be sold at a profit for cultivation values above 45 kg/m2/a. An ordinary greenhouse season in central Europe is about 9 months long. Calculating on an estimated 50 kg/m2/a of tomatoes within the nine month period and adding 25% for a year-round crop we reach 62,5 kg/m2/a under controlled conditions. For Vertical Harvest this would mean that a yield of 13.55 t throughout the year can be expected. When compared with the average data for central Europe once again, this would mean an area equivalent of 595.60 m2 would be needed.
For leafy vegetables like lettuce and other microgreens Vertical Harvest with its growing carousel of 5,486.4 m2 (=18.000 sq.ft.) with an estimated 6kg/a output the annual yield is about 32,918.4 kg. The equivalent area needed for soil based agriculture with the same output, calculated for central Europe would be 15.382,42 m2. Adding the tomato and leafy yield the edible biomass output of Vertical Harvest is 46.46 t/a.
Comparing these data to the building footprint the resulting ratio is 468,44 m2 GFA building footprint to 6.082,00 m2 or 1/13. Compared to the actual greenhouse footprint of Vertical

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[276] http://www.verticalharvestjackson.com/faq-2/, retrieved 01.04.2015

[277] ibid.

[278] ibid.

Harvest[279] we reach a ratio of 229,48 m2 to 6.082,00 m2 or 1/26. This value comes close to the estimated values from Vertical Harvest, which is: „Although Vertical Harvest is situated on a site that is 1/10 of an acre, the greenhouse will be able to produce the equivalent of 5 acres of traditional agriculture.“[280]

## CLIMATE DATA, Singapore, 1°17′N 103°50′E

| | |
|---|---:|
| hours/year | 8,760 |
| dayhours | 4,417 |
| sunshine hours | (44,82%) 1,980 |
| kWh/m2/a | 1,631.92 |
| diffuse sunlight (kWh/m2/a) | 1,127.05 |
| direct sunlight (kWh/m2/a) | 504.87 |
| GJ/m2/a | 5.87 |
| kCal/m2/a | 1,403,198 |
| l Oil Eq./m2/a | 158.30 |
| av. kWh/m2/a | 0.37 |
| av. MJ/m2/a | 1.33 |
| av. kCal/m2/a | 317.68 |
| av. l Oil Eq./m2/a | 0.04 |

Singapore has a tropical rainforest climate. Temperature, pressure and humidity are relatively constant, moving between 22°C and 35°C and 73% (morning) to 79% (evening) of relative humidity. More than two thirds of the total solar radiation are diffuse light. Roughly the half of dayhours are sunshine hours.

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[279] The area was calculated as follows: greenhouse area groundfloor + greenhouse area 1st floor + greenhouse area 2nd floor/3 including horizontal circulation area within the greenhouse zones

[280] http://www.verticalharvestjackson.com/faq-2/, retrieved 01.04.2015

## ***SKYGREENS, SINGAPORE***

The first prototype was installed in 2009 and a research collaborative agreement was signed between Sky Greens and the Agri-Food and Veterinary Authority of Singapore (AVA) in April 2010. The multi-layer troughs in a rotating A-frame vertical structure, referred to as “A-Go-Gro” was then commercialized in 2012. Since then Sky Greens has been expanding and continuously installing additional Vertical Farms in Singapore, all of which are GPRO .in our classification.

The cultivation method used is hydroponics. The A-frame within the greenhouse can reach up to 9 meters with 38 growing troughs. Similar to the idea of VertiCrop for Paignton Zoo, a conveyor belt was installed to ensure uniform light exposure for the plants and this not in a horizontal circuit, but in a vertical one. The greenhouse receives sunlight also from above. This is made necessary by the production method.

Rainwater and recycled water are collected in overhead tanks and used not only for watering the plants via micro-sprinklers three times a day, but are also to support the patented Water Pulley System, which relies on flowing water and gravity to rotate the racks.

Considering an average crop cycle of 8 weeks[281] and considering that on one A-Go-Gro-System 20x38 lettuces (=780) are growing, and using the same average yielded weight of one lettuce, namely 250 g, the output per year (considering a 365 days-production) would be around 1.267,5 kg. The prototypical greenhouse with four A-shaped production systems then would produce around 5.070,0 kg or ca. 5 t/a on a building footprint of 196.16 m2.

The author was unable to obtain reliable data on food production output in Singapore. One reason might be that only 0.5% of the area of Singapore is currently in use for agricultural production.[282] [283]

To keep up with comparisons for output data in central Europe an area equivalent of 2.369,15 m2 would be needed. The building footprint in this case is the same as the area of the greenhouse. The resultant ratio between the footprint of the built envelope and the potentially needed soil based agricultural land then is 1/12. This value is close to the official comparison published by Sky Greens on its website. “When compared with traditional monolayer farms, the Sky Greens patented Vertical Farming system intensifies land use and can result in at least 10 times more yield per unit land area.“[284]

CLIMATE DATA, Linköping, Sweden: 58°24′39″N 15°37′17″E

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[281] SÄCHSISCHE LANDESANSTALT FÜR LANDWIRTSCHAFT, FACHBEREICH GARTENBAU 2004. Salate im Gewächshaus. Hinweise zum umweltgerechten Anbau. Managementunterlage. [Dresden]: Sächsische Landesanstalt für Landwirtschaft, Fachbereich Gartenbau. p.3

[282] http://www.commonwealthofnations.org/sectors-singapore/business/agriculture/, retrieved 02.04.2015

[283] This means that the population of Singapore (531 million) is completely dependent on food imports.

[284] http://www.skygreens.com/technology/, retrieved 03.04.2015

| | |
|---|---|
| hours/year | 8,760 |
| dayhours | 4,385 |
| sunshine hours | (33,52%) 1,470 |
| kWh/m2/a | 916.94 |
| diffuse sunlight (kWh/m2/a) | 517.62 |
| direct sunlight (kWh/m2/a) | 399.32 |
| GJ/m2/a | 3.30 |
| kCal/m2/a | 788,426 |
| l Oil Eq./m2/a | 88.94 |
| av. kWh/m2/a | 0.21 |
| av. MJ/m2/a | 0.75 |
| av. kCal/m2/a | 179.80 |
| av. l Oil Eq./m2/a | 0.02 |

Cold winters and mild summers determine the climate in Linköping from monthly minimum temperatures of -8°C in January to maximum temperatures of 20°C in July. The precipitation is distributed equally throughout the year between 10 and 15 days/month. Global total horizontal radiation is below 1000 kWh/m2/d. Only a third of the day hours are sunny.

## *PLANTAGON, LINKÖPING, SWEDEN*

Plantagon‘s proposal for a Vertical Farm in Linköping is the most holistic project of the greenhouses and projected Vertical Farms analyzed in this paper. In terms of the classification table it is a V+, a Vertical Farm with an additional program, which enables the use of synergy potentials on an energetic level. In addition the production entity embodies most of the necessary functions of the food supply chain, which is spatially divided here in sectors such as germination rooms, washing, preparation and storage.

The project was developed together with the city of Linköping, Tekniska Verken, the energy provider for Linköping and Sweco, a globally active sustainable engineering firm. An issue of primary interest in the project was to implement and optimize energy circuits between the Vertical Farm, the biodigester, run by Tekniska Verken and the district heating with an internal exchange of CO2, excess heat and green waste.[285]

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[285] http://plantagon.com/urban-agriculture/industrial-symbiosis, retrieved 03.04.2015

Typologically the building consists in a slender north-facing office building with a monovolumetric vertical greenhouse in the south, containing the 3D conveyor belt based on the form of a helix.

> *„The different system designs basically all have the same production flow and location of equipment. The machinery is located in the basement on one or two floors and the trays are transported to the top of the helix by a special tray elevator. The crops grow during the slow transport down the helix and are ready for harvesting when they reach the end of the helix at the basement level. Food is harvested in batches using an automatic harvesting machine. After harvest, the trays and pots are disinfected, and the pots are separated and replanted with another seed for the next round in the cultivation loop. After germination, the pots are recombined with the trays and elevated to the top of the growing helix to repeat the process.“*[286]

The helix itself transports the trays from top to the basement level. The cultivation area it provides is 1,999.20 m2[287] when pak choi is planted. Calculated with the expected edible biomass of 1.300 kg/d (=4.000 plants/d), as reported at the Urban Agriculture Summit by Sweco-Horticulturist Susanna Hultin, and assuming the non-edible portion of this to be 10% of the total weight, the annual biomass output is 521.95 t. For reasons of comparison in this calculation an optimized assumption of a greenhouse pak choi yield is used of 5.25 kg[288]/ready of harvested tray[289]. the resulting effective all year-cultivation area within the Vertical Farm in Linköping would be seven times higher than the cultivation area of all the trays within this system, namely 14,592.40 m2 or 1.45 ha[290].

A tray moves along the helix in 50 days or 142.64m or 2.85m/d. By dividing all the trays by 50 (3.331 trays) we get the daily number of harvest trays ready for harvest. With 66.6 trays ready to harvest a day each with 15 plants of 350g each, the daily biomass output (marketable and non-marketable) is 349.65 kg or 127.62 t/a. Even by calculating with a shorter crop rotation (35 days) and a higher weight of the plant, this result is far less than the calculated expected year-round harvest communicated by Plantagon. For this diagram the author takes the verifiable data from the above listed empirical data of greenhouse cultivation: On an effective area of 1.45 ha 127.62 t is produced. This is 88.01 t/ha or 5.8 times more than the average pak choi yield per hectare in central Europe.

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[286] http://www.handelskammer.se/files/2011404_ps_en_plantagonsweco.pdf, retrieved 03.04.2015

[287] own calculation: helix length = 999,48 m; distance from tray to tray = 30 cm; resulting trays on helix: 3.331,6 trays 300 cm x 20 cm = 0,6 m2.

[288] 350 g/Pak Choi; 90% (318,18g) is edible biomass

[289] 15 Pak Choi plants per 325g/head; http://www.lel-bw.de/pb/site/lel/get/documents/MLR.LEL/PB5Documents/lel/pdf/a/Alternative%20Herbstkulturen%20-%20Heike%20Sauer%20LVG%20Heidelberg.pdf, retrieved 07.04.2015

[290] If every tray needs 50 days from seed to harvest, every tray it is used 7.3 times a year.

14.592,40 m2 or 1,45 ha Pak Choi[291] soil based cultivation in a climate zone like Linköping could take place for maximum 8 month/year. The expected biomass output can reach up to 15t/ha[292]. The ratio between the building footprint (1,005.70 m2) and the agricultural land needed is 1/29, the ratio between the greenhouse footprint (376.02 m2) and the agricultural land needed is 1/77.

Even though the numbers communicated on the Urban Agriculture Summit seem way too optimistic, it can still be pointed out here that this production method with the robotic 3D-conveyor belt changes the basic cultivation surface available here into one with an effective cultivation area throughout the year which is seven times higher.
This Vertical Farm, with a building footprint of 1,005.70 m2 a cultivation surface of 1,999.20 m2 was implemented to illustrate the benefits this patented production method brings for the reduction of arable land use while maintaining the same edible biomass output. Due to its continuous movement and the seed- and cultivation intervals this cultivation surface is effectively seven times higher, throughout the year at 14,592.40 m2. To obtain the total (edible and non-edible) biomass with pak choi as calculated above, based on an average central European yield, an area of 84,635.92 m2 of soil based agriculture was compensated by this Vertical Farm.

# Vertical Farm - Substitution of Natural Growth Factors

## Goals and methods

The amount of light plants need for growth in closed conditions is examined in this chapter. A brief review of the basic physics of light will be useful here to distinguish between light for humans and light for plants, or light in photosynthesis and in architecture. Differentiation between the quality and the quantity of light, between photometry and radiometry are necessary to build up the Simulation Model in Chapter 5.

Assumptions on the overall energy value the sun offers for plant growth already tell us that lighting power for Vertical Farms will be the significant energy consuming system within the

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[291] Pak choy is a cool season crop that prefers moist and uniform conditions in full sunlight. High temperatures with long days will induce bolting, especially in the white-stemmed varieties. The ideal temperature during growth is 15-20°C and, while best grown in spring and autumn, it can be grown all year round. Most varieties of Pak choy can tolerate light frosts., https://www.daf.qld.gov.au/plants/fruit-and-vegetables/vegetables/asian-vegetables/Pak-choy, retrieved 08.04.2015

[292] Roughly 50% of greenhouse yields. https://researcharchive.lincoln.ac.nz/bitstream/10182/670/3/Fu_Magrsc.pdf, retrieved 08.04.2015

building. This assumption is also based on the results of two Master theses by Chirantan Banerjee[293] and Gordon Graff [294], although both these works only touch on the complexities of light use in plant growth, nevertheless both of these works highlight the relevance of lighting within the energy performance of the Vertical Farm.

This work, however, aims to go beyond interpolating estimations of light needs of plants to an overall energy consumption for artificial lighting, and thus deepened the scope for the question of which quality and quantity of light is necessary for the production of a specific vegetable or fruit plant.
*Lycopersicon esculentum* (Mill.) (solanaceae), commonly known as tomato, stands in the spotlight of this research.

Firstly an introduction in the physics of light will be given, the difference of perception of light between humans and plants will be explained. Subsequently a picture of the state of the art in research about PPFD (Photosynthetic Photo Flux Density), DLI (Daylight Integral) and PAR (Photosynthetically Active Radiation) will be given.

In addition the different growth stadiums of the *L. esculentum* will be examined and specified for its lighting-, temperature and water requirement. Lastly the edible biomass-output per year can be calculated, related to the energy-consumption/kg and compared to soil-based *L. esculentum* and greenhouse *L. esculentum*.

Research and statistics on horticulture and plant physiology necessary for this thesis, in addition, got supported by the Institute for Plant Sciences at the University for Natural Resources and Life Sciences, Vienna. To evaluate statistics and numbers they got discussed and compared with empirical data provided by „Zeiler“-greenhouses in Vienna across excursions and interviews . It is one of the largest companies in Eastern Austria and, to this day, the only year-round producer of tomatos.

## Introduction and basics

Translation of light to sugar is crucial factor in food production. Not only the available light diminishes on Earth as one moves from the equator to the poles, but also the length of temperate seasons. The practice of greenhouse production has been increasing in most countries ever since the 17th century in an effort to prolong the food production seasons. But greenhouses reach their limits as they encounter power demands for temperature heating and light at the feasibility threshold for food production in energy and economic terms. The greenhouse skin must generally be optimized for maximum light transmittance and to minimize heat transmission.

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[293] BANERNJE, C. 2012. Market Analysis for Terrestrial Application of Advanced Bio-Regenerative Modules: Prospects for Vertical Farming. Master of Science Masterarbeit, Rheinische Friederichs-Wilhems-Universität, Hohe Landwirtschaftliche Fakultät.

[294] GRAFF, G. 2011. Skyfarming. Master of Architecture, Waterloo, Ontario, Canada.

Enlarging the photoperiod and the length of crop rotation calls for supplementing or substituting natural growth factors, such as photosynthetically active radiation. This makes it necessary to investigate in more detail which part of the total solar radiation actually is crucial for sugar production and plant growth.

## Photometry and Radiometry

Radiation from the sun can be distinguished by its quality or quantity. Quality, the waveband of the light or the distribution of the wavelength within the waveband, is central to distinguish the energy content of photons by measuring wavelengths and frequency and for defining whether it is visible or invisible radiation. The quantity, or intensity or the amount of energy of specific wavebands enables the differentiation between useful and non-useful, essential and harmful energy, both in photometry and radiometry.

Photometry is the science of measuring light. The reference is the sensitivity for brightness of the human eye. Radiometry is concerned with the measurement of radiant energy in terms of power. “In modern photometry, the radiant power at each wavelength is weighted by a luminosity function that models human brightness sensitivity.“[295]

A difference in radiometry today, especially for plant physiology, is that the perceived brightness of light is no longer relevant, but the focus is now on the energy content of photons within PAR (Photosynthetic Active Radiation), and more specifically the quantity of photons between 400 nm and 500 nm (blue light) as well as photons between 600 nm and 700 nm (red light) and their energy content. “This quantity can be measured as the number of photons, or as a total energy value. Whenever a number of radiation quantity (intensity) is given, the wavelength(s) involved must also be given (quality), or else the number has little useful value“[296]

Photometric measurements are of central significance for architecture. The wavelength 555 nm is that most relevant for luminance and illumination. The average human eye is most sensitive at 555 nm, or a frequency of 540 THz. “Photometry describes lighting conditions with the human eye as primary sensor.” “The spectral responsivity curve of the standard human eye at typical light levels is referred to as the CIE Standard Observer Curve (photopic curve), and covers the waveband of 380 - 780 nm. The human eye responds differently to light of different colors and has maximum sensitivity between yellow and green. In order to make accurate photometric measurements of various colors of light, or from differing types of light sources, a spectral responsivity curve for a photometric sensor must match the CIE photopic curve very closely.“[297]

Photometry is therefore concerned with visible light (from the perspective of the human eye); the corresponding quantities are as follows:

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[295] http://en.wikipedia.org/wiki/Photometry_%28optics%29, retreived 03.08.2014

[296] GIACOMELLI, G. 1998. Components of Radiation Defined: Definition of Units, Measuring Radiation Transmission, Sensors. CCEA, Center for Controlled Environment Agriculture, rutgers university, Cook College.

[297] http://www.licor.com/env/pdf/light/Rad_Meas.pdf, p. 3. Retrieved 03.11.2015

*Luminous flux: radiation coming from a source per unit time (cd x sr), where sr is the solid angle, expressed in lumen (lm).*

*Luminous energy: or quantity of light is not the same as radiant energy. The quantity of light referrs only to the amount of visible light (from 380 to 780 nm), expressed in lumen per second (lm s). This entity sometimes is expressed also in talbots.*

*Luminous intensity: is the luminous flux in a particular direction per unit solid angle. The SI unit of luminous intensity is candela (cd).*

*Illuminance is the density of the luminous flux, incident at a point on a surface. In architecture the density of the luminous flux is one of the prior entities. Illuminance gets measured by Luxmeters which have the highest spectral response on a wavelength of 555 nm or a frequency of 540 THz.*

The visible spectrum for human eye sensitivity ranges from approx. 380 nm (violet) to approx. 780 nm (dark red). Luxmeters to measure illuminance are calibrated to exactly this wavelength. Illuminance is thus the key value for light in architecture.

By contrast with photometry, radiometry focusses on the totality of electromagnetic light, including the range from $3^{11}$ and $3^{16}$ Hz corresponding to wavelengths from 0.01 and 1000 micrometers and therefore includes UV light, visible and infrared light.

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It is necessary to divide electromagnetic radiation into the visible and invisible range. The differentiation between radiometry and photometry is essential for sensitizing to different qualities of light measurements in architecture intended for human use and also in architecture provided for plants.

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The electromagnetic spectrum summarizes total solar radiation. In contrast to photometry, where only the spectrum visible to the human eye is taken into account.

Radiometry measures radiant energy (SI unit is J [Joule]), an interchangeable form of energy. The radiant energy flow rate in form of specific electromagnetic waves is called radiant flux (W). „Radiant flux can be measured as it flows from the source (sun, natural conditions), through one or more reflecting, absorbing, scattering and transmitting media (the Earth‘s atmosphere, a plant canopy) to the receiving surface of interest (a photosynthetizing leaf).“[298] Total solar radiation is measured by the solarimeter between the wavelengths from 300 nm and 3000 nm.

Plants need a very specific range of solar radiation from 400 nm to 700 nm; this is the so called Photosynthetic Active Radiation (PAR)[299]. Although plants also use a very small percentage beyond 400 nm and 700 nm, the essential radiation for photosynthesis lies in the range between

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[298] http://www.licor.com/env/pdf/light/Rad_Meas.pdf. p.1, retrieved 13.08.2014 - This article is referring to LANG, O.L. et al. 1981. Physiological plant ecology. Chapter: Photosynthetically active radiation. Springer-Verlag. Berlin, Heidelberg, New York

[299] SCHOPFER, P. & BRENNICKE, A. 2010. Pflanzenphysiologie, Heidelberg, Spektrum Akademischer Verlag, p.167

400 nm and 500 nm (blue light) and between 600 nm and 700 nm (red light). Chlorophyll A and B and carotenoids are most sensitive to these very specific ranges. This means that the sensitivity of the human eye and the sensitivity of plants for photosynthesis are not congruent.[300]
„Although photometric measurements have been used in the past in plant science[301], PPFD and irradiance provides the preferred measurements in advanced plant and greenhouse research. The use of the word ‚light‘ is inappropriate for plant re-search. The terms "ultraviolet light" and "infrared light" clearly are contradictory.“[302]

The quantities corresponding to photometric units are as follow:

Radiant flux: the amount of radiation coming from a source per unit of time (W [Watt]).

Radiant Energy is the radiant flux leaving a point on the source per unit of time. Like all forms of energy, this SI unit is the joule (J). This term is usually used if emitted radiation is measured in the surrounding environment. This entity is also interchangeable with Watts, because a Joule per second equals one Watt (Js = W).

Radiance is the radiant flux emitted by a unit area of a source or scattered by a unit area of a surface (W m-2 sr-1 [Watt per m2 steridian]).

Irradiance is the radiant flux incident on a receiving surface from all directions (W m-2 [Watt per m2]).

Within the scope of this fact it also emerges that lux (lumen/m2) as the SI unit for illuminance and luminous emittance to measure luminous flux/m2, a basic measuring procedure in architecture can no longer be used in lighting analysis of the production facility for Vertical Farms. The Lux meter must be substituted with the quantum sensor, which is limited to the PAR (photosynthetic active radiation from 400 nm to 700 nm) with its output value of (μmol/$m^{-2}$/$s^{-1}$) and the spectroradiometer, an instrument which splits the incoming light into separate wavelengths or wavebands and then measures the irradiance of the photons in these wavelengths. It measures the spectral irradiance (SI) in the units μmol/$m^{-2}$/$s^{-1}$ or W/ m2.

## Light for plants - Light for humans

### *THE SOLAR CONSTANT*

"(...) [is] the total radiation energy received from the Sun per unit of time per unit of area on a theoretical surface perpendicular to the Sun's rays and at Earth's mean distance from the Sun. It is

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[300] ibid. p.445

[301] ATANAS, G.D. 2005. Integrierte Produktion von Tomaten (*Lycopersicon esculentum* Mill.) im Gewächshaus unter besonderer Berücksichtigung der integrierten Bekämpfung der Weissen Fliege), Dissertation, Humboldt-Universität Berlin., p.889

[302] ibid.

most accurately measured from satellites where atmospheric effects are absent. The value of the constant is approximately 1,366 kilowatts per square meter.[303] The “constant” is fairly constant, increasing by only 0.2 percent at the peak of each 11-year solar cycle. Sunspots block out the light and reduce the emission by a few tenths of a percent, but bright spots, called plages, that are associated with solar activity are more extensive and longer lived, so their brightness compensates for the darkness of the sunspots. Moreover, as the Sun burns up its hydrogen, the solar constant increases by about 10 percent every billion years.“[304]

„The solar irradiance is measured by satellite near the outer surface of Earth‘s atmosphere.“[305]

The energy content of the solar constant, calculated per year and m2 of solar irradiation, unfiltered by the atmosphere, is equivalent to more than 43 GJ.

## ***SOLAR OR GLOBAL RADIATION - DIFFUSE AND DIRECT RADIATION***

“Solar radiation is also known as global radiation, meaning that it is the sum of direct shortwave radiation from the sun and diffuse sky radiation from all upward angles.“[306] “(...)[R]adiation has two distinct directional properties when it reaches the ground. Direct radiation arrives from direction of the solar disk and includes a small component scattered directly forward. The term diffuse describes all other scattered radiation received from the blue sky (including the very bright aureole surrounding the sun) and from clouds, either by reflection or by transmission.“[307]

It is also necessary to state that light transmission is the same in both direct and diffuse radiation. “Direct or diffuse light does not have different PAR values. This means that our eyes perceive differences in lumens between direct and diffuse light. Diffuse light appears dimmer to us even though the total light transmission is not decreased.“[308]

Recent findings in the Netherlands even prove that diffuse light increases photosynthesis up to 25 %. This point will be highlighted below: light is not uniformly distributed in greenhouses, but this can be improved if the light is diffuse. To determine the effect of diffuse light on crop growth and development, an experiment with *L. esculentum* crop was conducted from December 2010 to November 2011 under commercial crop management. Three kinds of glass were used as greenhouse covering: standard glass (no diffuse light, 0% haze) and two types of diffuse glass which transformed an increasing fraction of the direct irradiation into diffuse irradiation (45% and 71% haze).

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[303] 1361 watts per squaremeter per second

[304] http://www.britannica.com/EBchecked/topic/552889/solar-constant, retrieved 10.09.2014

[305] Kopp, G.; Lean, J. L. (2011). „A new, lower value of total solar irradiance: Evidence and climate significance“ (PDF). Geophysical Research Letters 38: n/a. Bibcode:2011GeoRL..38.1706K. doi:10.1029/2010GL045777.

[306] http://www.fao.org/docrep/x0490e/x0490e07.htm, retrieved 10.09.2014

[307] John L. Monteith et.al „Principles of Environmental Physics: Plants, Animals and the Atmosphere“, AP, fourth edition, p. 58 - 59

[308] http://www.greenhousecatalog.com/greenhouse-light, retrieved 11.09.2014

„As presented by Dueck et al.[309] yield increased by 7.8% under 45% haze and by 9.4% under 71% haze, compared to the reference. During the experiment we performed measurements in order to understand these effects. Diffuse light penetrated deeper and more homogeneously into the canopy, which led to higher photosynthesis rates in the middle and bottom canopy layers. Furthermore, less photoinhibition was measured under diffuse light treatment when the outdoor irradiation was high. Under sunny conditions the temperature of upper leaves in the canopy was 3 to 5 °C lower in the greenhouses with diffuse glass compared to the control, while greenhouse air temperatures were comparable. The leaf anatomy, canopy structure , total nitrogen and chlorophyll contents of top, middle and bottom canopy layers were also studied in order to further explain the increased production under diffuse light. The results showed that diffuse glass on greenhouses is one way to improve the light use efficiency of greenhouse crops.“[310]

## ***PHOTOSYNTHETICALLY ACTIVE RADIATION - PAR***

“The PAR, Photosynthetically Active Radiation, comprises the waveband 400 to 700 nm, which are the limits of wavelengths that are of primary importance for plant photosynthesis. The PPFD, Photosynthetic Photon Flux Density is the number of photons in the PAR waveband that are incident on a surface in a given time period (μmol/m$^{-2}$/s$^{-1}$). The quantum sensor will measure this value. A very clear sky value will approach approx. 2000 μmol/m$^{-2}$/s$^{-1}$ PAR.“[311]

The PPFD number for a clear sunny sky differs by up to 15% in different studies, from 1700 μmol/m$^{-2}$/s$^{-1}$ (also used by Gene Giacomelli) to 2000 μ mol/m2/d. Most conversion calculators online use the factor 0.018 to convert lux to μmol/m$^{-2}$/s$^{-1}$ and the factor 0.219 from Photons to W (sunlight) or 4.57 from WPAR to Photons.[312]

„Radiation can either be reflected, absorbed or transmitted once it impacts a surface. The properties of the material will determine what proportion of the three will be; however, the sum of

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[309] DUECK, T., JANSE, J., LI, T., KEMPKES, F. & EVELEENS, B. 2012. Influence of Diffuse Glass on the Growth and Production of Tomato. VII International Symposium on Light in Horticultural Systems, 75-82.

[310] https://www.wageningenur.nl/en/Publication-details.htm?publicationId=publication-way-343239373835, retrieved 14.09.2014

[311] GIACOMELLI, G. 1998. Components of Radiation Defined: Definition of Units, Measuring Radiation Transmission, Sensors. CCEA, Center for Controlled Environment Agriculture, rutgers university, Cook College. p.5 ff

[312] 1. GIACOMELLI, G. 1998. Components of Radiation Defined: Definition of Units, Measuring Radiation Transmission, Sensors. CCEA, Center for Controlled Environment Agriculture, rutgers university, Cook College. p. 5 ff
2. http://www.skyeinstruments.com/wp-content/uploads/LightGuidanceNotes.pdf, retrieved 12.11.2014
3. http://www.licor.com/env/pdf/light/Rad_Meas.pdf
4. http://www.controlledenvironments.org/Growth_Chamber_Handbook/Plant_Growth_Chamber_Handbook.htm, retrieved 10.10.2013
5. http://www.egc.com /useful_info_lighting.ph, retrieved 10.10.2013

the energy reflected, absorbed and transmitted must be 100%. The properties are often abbreviated by the Greek symbols α, ρ and τ, which represents reflectance, absorbtance and transmittance. There are standard test procedures for determining each. The leaf will typically absorb nearly 95% of wavelengths between -400 - 700 nm, while only 5% of the 700 - 800 nm waveband is absorbed. Of the remaining 95% of the 700-850 nm waveband, approximately 45% is reflected, and 45% is transmitted.“ [313]

The ratio of PAR [W] within the total solar radiation [W] changes during the day and the year. In horticulture and agriculture the quantity of PAR [W], is usually calculated, depending on the location, by using factors from 0.44[314] to 0,50[315] [316].

Based on the definition of units and measurements of Giacomelli’s paper[317] gives us the possibility to calculate the photons and therefor the energy content of the color within the light spectrum which is most effective for photosynthesis.

## ***PHOTOSYNTHETIC PHOTON FLUX DENSITY - PPFD***

The PPFD, Photosynthetic Photon Flux Density is the number of photons within the PAR - waveband that is incident on a surface in a give[n] time period (μmol/m$^{-2}$/s$^{-1}$). The quantum sensor will measure this value.

When considered as a photon it may be expressed in energy terms, Watts per square meter (W/m2), or as the number of photons (moles of photons) μmol/m$^{-2}$/s$^{-1}$ . Wavelength as units of meters, typically nanometers (nm) [...] or micrometers (μm). Frequency (f, A/N) has units of cycle per second. Together they are related as parameters of a photon of light by the constant c, the speed of light (299.792.458 m/s, A/N). The frequency of the photon is equal to the speed of light divided by wavelength of the photon. The energy of a wavelength of light is equal to Planck’s constant (h = 6,626·10-34 Js, A/N) multiplied by the speed of light and divided by the wavelength. From this relationship, an important fact is determined. For radiation (light), as its wavelength

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[313] GIACOMELLI, G. 1998. Components of Radiation Defined: Definition of Units, Measuring Radiation Transmission, Sensors. CCEA, Center for Controlled Environment Agriculture, rutgers university, Cook College. p.6

[314] GIACOMELLI, G. 1998. Components of Radiation Defined: Definition of Units, Measuring Radiation Transmission, Sensors. CCEA, Center for Controlled Environment Agriculture, rutgers university, Cook College.

[315] http://www.landwirtschaftskammer.de/gartenbau/beratung/technik/artikel/lichtwerte-umrechnen.htm, retrieved 12.05.2015

[316] „Tomaten Zeiler“ for its greenhouses use this factor to get PAR-values from its solarimeter-sensors placed on the rooftops. S. appendix „Excursion Tomaten Zeiler.

[317] ibid, referring to G.H.M. Kronenberg and R.E. Kendrick, in: 1986: R.E. Kendrick and G.H.M. Kronenberg (Eds.), „Photomorphogenesis in Plants, Nijhoff, Dordrecht, pp.99-114

increases, its energy decreases, and as the wavelength decreases, the energy increases. Thus short wave blue light has more energy than longer wave red light."[318]

„Mol is a unit of measurement used in physics and chemistry to express amounts of elements, defined as the amount of any substance that contains as many elementary entities (e.g. atoms, molecules, ions, electrons) as there are atoms in 12 grams of pure carbon-12 (12C), the isotope of carbon with relative atomic mass of exactly 12 by definition. This corresponds to the Avogadro constant, which has a value of $6.02214129(27) \cdot 10^{23}$ elementary entities of the substance."[319]
A mole of photons, therefore consists in 602 trillion light particles. This entity is used to define the Daylight Integral (DLI) and is described in more detail on the next page.

## *DAYLIGHT INTEGRAL - DLI*

„ (...) DLI, the daylight integral, is the cumulative amount of photosynthetic light that is received each day. The DLI is measured as the number of moles of light (mol) per square meter (m2) per day (d1), or mol/m2/d. The DLI can have a profound effect on root and shoot growth of seedling plugs, root development of cutting and finish plant quality attributes such as stem thickness, plant branching and flower number."[320]

DLI is measured by the cumulative amount of rain or light received during a 24-h-period. It is dependent on the time of the year (sun‘s angle), location, latitude and cloud cover and the daylength (photoperiod).

In the context of greenhouses or Vertical Farms this is additionally nfluenced by the glazing type, the structure and all obstructions, hanging baskets, etc. Generally we can assume that on earth DLI varies from 5 to 60 mol/m2/d. In greenhouses DLI rarely exceeds 30 mol/m2/d, because of shading applied to prevent excessive temperatures. Target minimum DLI inside a greenhouse should be from 10 to 12 mol/m2/d. On this point it is necessary to highlight the difference of minimum DLI found in the literature. Cultivars used for outdoor (soil based agriculture) tendentially need a higher number in the context of DLI supply. Most greenhouse plants, especially F1-hybrids of *L. esculentum* are optimized to germinate, grow and ripen best with lower temperatures and lower light measurements. This explains a DLI-range, e.g. for *L. esculentum* from 10 mol/m2/d to 20-30 mol/m2/d.[321]

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[318] GIACOMELLI, G. 1998. Components of Radiation Defined: Definition of Units, Measuring Radiation Transmission, Sensors. CCEA, Center for Controlled Environment Agriculture, rutgers university, Cook College.

[319] International Bureau of Weights and Measures (2006), The International System of Units (SI) (8th ed.), pp. 114–15, ISBN 92-822-2213-6

[320] RUNKLE, E. 2006. Do you know what your DLI is? Available: http://www.hrt.msu.edu/energy/Notebook/pdf/Sec1/Do_you_know_what_your_DLI_is_by_Runkle.pdf.

[321] JONES J. Benton, 2007. Tomato Plant Culture : In the Field, Greenhouse, and Home Garden, Second Edition, Edition 2, CRC Press, p.58

## The Tomato - *Lycopersicon esculentum* (Mill.)

The simulated Vertical Farm will use *L. esculentum* for the following primary reasons:

*L. esculentum* is the most widely produced vegetable in the world.[322]

*L. esculentum* is a vegetable with a strong growth in production quantity worldwide.[323]

Huge landfills consumed for *L. esculentum* Production, for soil based agriculture and greenhouses. (Fig.59 with numbers retrieved from FAO)

*L. esculentum* is probably one of the best researched vegetable, ideal for data availability for growing conditions.

*L. esculentum* is one of the plants with the highest daylight needs for photosynthesis.

“While *L. esculentum* continues to be one of the most widely grown plants, the production and distribution of *L. esculentum* fruits have been changing worldwide. Smaller, flavorful *L. esculentum* are becoming more popular than beefsteak *L. esculentum*, greenhouse-grown *L. esculentum* cultivars are one of the most researched and developed vegetables, optimized for greenhouse production and, as a consequence a potential product for Vertical FarmVertical Farming. Its high daylight needs for photosynthesis will sharpen the potential limits of a stacked greenhouse type in plant production. Its high daylight needs for photosyntesis will sharpen the potential limits of a stacked greenhouse type in plant production.

## General Data - Origin and Distribution

*L. esculentum* is one of the major crops and main vegetables consumed in many countries. It has its origins in South America, where the “xitomatl” was cultivated by the Aztecs.[324] The earliest known reference in Europe is a description by Pietro Andrea Matthioli[325] who classified the „golden apple“[326] as a nightshade plant and a mandrake, a category of food known as an aphrodisiac. This may be one of the reasons why the Catholic Church defamed the fruit and called it as the “fruit of the devil”; it was forbidden and the successful distribution of the fruit was stopped for at least 200 years.[327]

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[322] http://faostat3.fao.org/browse/Q/QC/E, retrieved 31.10.2015

[323] ibid.

[324] http://www.epicureantable.com/articles/atomatohis.htm, retrieved 19.09.2014

[325] McCue, George Allen. „The History of the Use of the tomato: An Annotated Bibliography.“ Annals of the Missouri Botanical Garden (Missouri Botanical Garden Press) 39, no. 4 (November 1952): p.291

[326] In Italy the *L. esculentum* is called pomodoro, literally translated the golden apple.

[327] LUNDY, R. 2006. In Praise of tomatoes, New York, Lark. p.42

Since the fifties of the last century, the *L. esculentum* increased in its popularity in Europe at great speed until it became the one of the most widely produced and consumed vegetables all over the world.[328]
The world primary production of food and food manufacturing is currently 6,824,143,000 t or 996 kg/cap/a. Tomatoes are cultivated on a surface area of 4.731.999 ha. The world average *L. esculentum* production is 158,019,580.71 tonnes or 23 kg/cap/a or 2.3% of the world's total food and food manufacturing production.

## *L. ESCULENTUM - WORLD PRODUCTION*

From all vegetable produced worldwide the *L. esculentum* is on top of the list. 16,58% or 158.019.580,71 t of all vegetable produced (953.272.659 t) are *L. esculentum*.[329]
Comparing the different food zones of Kastner (Fig. 59) we see a huge difference in yield/ha. Depending on energy input, level of technology, mechanization and climate *L. esculentum* crop yield varies from 6.57 t/ha in Western Africa to 97.39 t/ha in Northern Europe.The ten biggest *L. esculentum* producing countries of the world produce more than 76% of the total global *L. esculentum* crop. 30,7% of it are produced in China, followed by India (10,6%), USA (7,9%), Turkey (6,9%), Egypt (5,1%), Iran (3,5%), Brazil (2,8%), Italy (3,7%), Iran (3,5%), Spain (2,4%) and Uzbekistan (1,7%) as seen in the diagram the page before.

## *ITALY AND AUSTRIA*

Some of the production and consumption data for Austria is related to data from Italy for reasons of comparison. Italy is the biggest *L. esculentum*-producer in Europe and also the biggest per capita consumer of this vegetable. Italy produces 5,950,215 tons of fresh tomatoes a year on an area three times that of Vienna, on 103,858 ha. The yield calculated by FAO is 57.29 t/ha/a. The per capita consumption is about 60.5 kg/a or 30 kcal/cap/day are covered by *L. esculentum* consumption.

In Austria *L. esculentum* cultivation started intensively after the Second World War and since then it is has been increasing continuously. Austria is at place 90 among world *L. esculentum* producers. The per capita consumption ranges between 16 kg/cap/a (FAO-data) to 27,7 kg/cap/a (Statistik Austria)[330]. The per capita consumption ranges between 16 kg/cap/a (FAO-data) to 27,7 kg/cap/a (Statistik Austria) The per capita consumption is much lower than in Italy. On 185 ha in Austria in 2012 52,032 tons were produced. This is explained by the cultivation method. More than 94 % of all crop yield is cultivated in greenhouses or plastic tunnels.[331]

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[328] FAOSTAT, world tomato production, area harvested and yield, retrieved 26.09.2014

[329] ibid.

[330] STATISTIK AUSTRIA, Ernteerhebung. Erstellt am 29.11.2012. - 1) Anbaufläche lt. Auskunft der Landwirtschaftskammern und Erzeugergenossenschaften; retrieved 26.10.2014

[331] http://www.wien.gv.at/statistik/wirtschaft/tabellen/gemueseernte-anbauflaeche.html; Koordinationsstelle der Landwirtschaftskammer Wien, Mag. Doris Reinthaler et al. retrieved 26.10.2014,

## *PRODUCTION IN AUSTRIA AND VIENNA*

*L. esculentum* production in Austria in 2012 was 52,032 tons/a. *L. esculentum* production in Austria is steadily increasing. Official data from Statistik Austria show an increase from 2011 to 2014 of more than 8 % and reached a production weight of 54.469 tons.[332] An interesting point in this context is, that even Austria is strongly shaped by intense agriculture, 37,5% of the overall *L. esculentum* production comes from the agricultural area within the city border of Vienna. Some 15 % of the city‘s surface is used for agricultural production. In 2012 Vienna has produced 19.385 tons of *L. esculentum* on a surface of 45 ha. There is no soil based *L. esculentum* production outside of greenhouses or foil tunnels in Vienna.
Crop yield in Vienna‘s greenhouses per year is 430 t/ha or 43 kg/m2 compared to Austria with 272 t/ha or 27,2 kg/m2.[333] Vienna could deliver to its inhabitants 50% of per capita *L. esculentum* consumption - during the the period of ideal climate conditions. Actually Austria is producing 16 % of its *L. esculentum* consumption. Most of its imports come from Italy, Spain and the Netherlands.[334]

## ***L. esculentum* and Light**

Lighting will be the significant energy consuming system within the building, this work decided to concentrate on a product which is intensively PAR-light-dependent throughout the whole crop rotation. The results should thus take into account and present a certain worst case scenario.

Different crops differ from each other enormously in regard to the needed PPFD they need for photosynthesis and do so up to a factor 150, e.g. *L. esculentum* largely needing around 300 $\mu mol/m^{-2}/s^{-1}$ , while strawberries make do with a mere 2 $\mu mol/m^{-2}/s^{-1}$ [335] [336]. The specific cultivar the author will examine is *L. esculentum*, a F1-hybrid[337] Furthermore it is an economically important cultivar.[338]

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[332] http://www.wien.gv.at/statistik/wirtschaft/tabellen/gemueseernte-anbauflaeche.html; Koordinationsstelle der Landwirtschaftskammer Wien, Mag. Doris Reinthaler et al. retrieved 26.10.2014,

[333] ibid. retrieved 27.10.2014,

[334] ibid.

[335] Künstliche Beleuchtung im Gartenbau, Philipps, AEG

[336] http://www2.produktinfo.conrad.de/datenblaetter/100000-124999/101861-an-01-ml-PRONOVA_LUX_QUANTUM_METER_de_en.pdf, retrieved 12.11.2014

[337] Crossing two genetically different plants produces a hybrid seed. This can happen naturally, and includes hybrids between species (for example, peppermint is a sterile F1 hybrid of watermint and spearmint). In agronomy, the term “F1 hybrid” is usually reserved for agricultural cultivars derived from two parent cultivars. These F1 hybrids are usually created by means of controlled pollination, sometimes by hand-pollination. For annual plants such as *L. esculentum* and maize, F1 hybrids must be produced each season. http://en.wikipedia.org/wiki/F1_hybrid, retrieved 04.08.2014

Certain requirements are necessary for optimal *L. esculentum* growth. “The key requirements are light, carbon dioxide (CO2), water, adequate temperature, and sufficient and proper nutrients.“[339]

Plant physiology within controlled environments is a complex matter. Integrating all of the components which affect the photosynthesis and morphogenesis of plants would go beyond the scope of this dissertation. It is thus necessary to concentrate on the most important parameters for plant growth which directly is interlinked with space and energy.

This chapter outlines space and energy influencing parameters for *L. esculentum*, namely lighting conditions, temperature, water supply, cultivation method and plant heights.

Lighting conditions, the ratio between available daylight and best PPFD-density for photosynthesis directly influence the production method and the building shape. These two parameters in turn directly influence the overall energy need for lighting. The optimum temperature for plant growth and maximum crop yield is directly influenced by the orientation of the plants, the shape of the facade and the A/V-ratio of the Vertical Farm. Water supply and bed sizes are needed for a schematic arrangement of the production method in line with the expected plant height through the cultivation period.

Photosynthesis is a complex physical and chemical process and a full presentation of this subject would extend beyond the constraints of this dissertation. In order to establish estimates for energy consumption or additional lighting needed by plants to a useful standard of accuracy, it is essential to explain the basic process of photosynthesis.

Also noted on this point should be that morphogenesis, “the shaping of an organism by embryological processes of differentiation of cells, tissues, and organs and the development of organ systems according to the genetic ‚blueprint‘ of the potential organism and environmental conditions“[340], will not be treated in this work. Of course specific light qualities lead to differences in plant growth, e.g. the blue spectral range leads to compact, red spectral range to elongated plant bodies.[341] But several other parameters influencing morphogenesis of plants cannot be identified as space-influencing factors.

## *L. esculentum* and Photosynthesis

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[338] HENDRICKS Patrick, 2012. Life Cycle Assessment of Greenhouse Tomato (Solanum lycopersicum L.), University of Guelph, Thesis

[339] HENDRICKS Patrick, 2012. Life Cycle Assessment of Greenhouse Tomato (Solanum lycopersicum L.), University of Guelph, Thesis

[340] http://www.britannica.com/EBchecked/topic/392779/morphogenesis, retrieved 11.09.2014

[341] Künstliche Beleuchtung im Gartenbau, Philipps, AEG

Light, or more precisely PAR wavelengths, are absorbed by the pigment chlorophyll. In more developed plant species we find Chlorophyll A and Chlorophyll B. The ratio between Chlorophyll A and Chlorophyll B is 3:1. Carotene and xanthophyll are also pigments and play an important role in photosynthesis (Fig. 58 on page 168). But in contrast to Chlorophyll a and b, carotene and xanthophyll act like transporters after absorbing the energy of photons of a specific wavelength, and they send the chemical energy to the chlorophyll. The task carotene and xanthophyll perform is to enlarge the assimilation spectrum or in other words the plant-sensitivity-curve for photosynthesis.

Photosynthesis: $6CO_2 + 6H_2O = C_6H_{12}O_6 + 6O_2$

The spectrum where photosynthesis occurs was first recorded and published in 1973 by K.J. McCree. The sensitivity curve of 22 different plants was observed (e.g. barley, soya and *L. esculentum*). These results show that there is a marked decrease of photosynthetic reaction the closer the wavelength comes to the blue light range.

Recent publications in the Netherlands from the Institute for Horticulture in Wa-geningen show that there is evidence that the role of blue light for the photosynthesis was underestimated by McCree. The results suggest that light within the waveband from 530 to 670 nm is the most effective, light waves shorter than 400 nm and longer than 700 nm is virtually insignificant.

Respiration: $C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6\ H_2O$

## Factors affecting the rate of Photosynthesis

### *Light Compensation Point*

There is a break-even point when the plant is producing as much sugar as it needs for respiration. This point is defined as the light compensation point. As light increases (and water is available) carbon production also increases. The plant thus exceeds its carbon production, the surplus is transformed into glucose. Exceeding the light compensation point, is the main goal in food production as a fundamental principle.

By increasing brightness and intensity within PAR the photosynthesis-rate also increases, “but only up to a certain point, beyond which increasing the brightness of light has little or no effect on the rate of photosynthesis. (...) The light intensity at which the net amount of oxygen produced is exactly zero, is called the compensation point for light.“[342] At this point the consumption of oxygen

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[342] http://Tomatosphere.org/teachers/guide/grades-8-10/plants-and-light, retrieved 12.09.2014

by the plant due to cellular respiration is equal to the rate at which oxygen is produced by photosynthesis.
"The compensation point for light intensity varies according to the type of plant, but it is typically 40 - 60 W/m2 for sunlight. The compensation point for light can be reduced (somewhat) by increasing the amount of carbon dioxide available to the plant, allowing the plant to grow under conditions of lower illumination."[343]

## *Light Saturation Point*

On the other side of the "photosynthesis activating point" of what we could call the light compensation point, is another point essential in plant cultivation: the light saturation point.

Photosynthesis continues to produce sugar from CO2 and H2O until it reaches the saturation point. At this point carbon production can no longer occur.[344]
„The saturation point describes the amount of light that is beyond the capability of the chloroplast to absorb. Photosynthesis still occurs, but the amount of light has exceeded the amount of pigments that are available for absorption."[345] This saturation point is different for every plant. "Different plants have different saturation points, determined by the number of pigments in their chlorophyll cells. Plants that typically grow in shaded areas have lower saturation points, while those that grow in areas more exposed to light have higher saturation points. The integrated photon flux, CO2 concentration, and atmospheric humidity are critical parameters, with a photon flux, of 20 to 30 mol/m2/d being optimum for most plants, including *L. esculentum*."[346] This high value is referred to *L. esculentum* growing on soil under a free sky.

Evaluating the light compensation point and the light saturation point for a specific plant type is crucial for all plants grown under artificial conditions in greenhouses or Vertical Farms. Due to the fact that solar radiation and therefore the amount of PAR also decreases within a built environment, electric lighting is essential for plants which need high amounts of light, both in greenhouses and in Vertical Farms.

As already noticed in the beginning on this chapter, every plant is different, has individual needs of PPFD, CO2 and water. On this point of the work it is necessary to limit research results on lighting on cultivars of *L. esculentum* argued as follows:t

*L. esculentum* is a fruity vegetable with one of the highest light density needs for photosynthesis, morphogenesis and fruit development.

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[343] ibid.

[344] SCHOPFER, P. & BRENNICKE, A. 2010. Pflanzenphysiologie, Heidelberg, Spektrum Akademischer Verlag. p.445 ff.

[345] http://www.ehow.com/about_6535863_definition-plant-light-saturation.html, retrieved 12.09.2014

[346] JONES J. Benton, 2007. Tomato Plant Culture : In the Field, Greenhouse, and Home Garden, Second Edition, Edition 2, CRC Press, p.58

*L. esculentum,* as a developed F1-hybrid , has already been optimized and adapted to conditions with less light and lower temperature compared to soil-based *L. esculentum*

*L. esculentum* needs a remarkable amount of water for its growth and fruit development in soil based agriculture.

*L. esculentum* is one of the most extensively researched vegetables, especially in the Netherlands, where considerable data are available.[347]

## *LIGHT FOR L. ESCULENTUM - A RESUMÉE*

We have seen that data about PPFD for *L. esculentum* in greenhouse production differ greatly from study to study. There are more than 5000 cultivars of *L. esculentum*. Most greenhouse *L. esculentum*, however, are F1-hybrids already optimized for greenhouse production, where sunlight is the determinant. Every cultivar is different and therefore has its own individual “ideal” PPFD-curve during crop rotation. The author also has seen that sometimes there is still confusion even in horticulture “about behavior and terminology dealing with radiation more than almost any other factor.” (...) In the control of plant growth (...) there are at least five types of information that may be derived from the radiation en-vironment:

1) radiation quantity [W/m2, Ed.]
2) radiation quality [spectral distribution, PAR, Ed.]
3) direction of radiation
4) duration of radiation (timing of light-dark transition) [time or DLI, Ed.] and
5) polarization.

Of these five groups, industry has utilized only 1) and 4) to any significant extent in design and management decision.“[348] But numerous published papers and the lively scientific activity focused on this area carried out over the past few years has put us in a position to apply approved data, e.g. the ideal PPFD for F1 hybrids of *L. esculentum* optimized for greenhouses during the phase of fruit development. PPFD during the establishment, vegetative growth, flowering and fruit-set from different studies are averaged out. The diminishing PPFD-factor through the crop rotation period is an assumption, based on discussions the with “Zeiler“. These values subsequently were evaluated at the Department of Crop Sciences at the University for Natural Resources and Life Sciences. The result is an ideal lighting demand curve throughout the whole crop rotation of *L. esculentum*, representing sigmoid growth curve visible in diagramatic form on the next page. The establishment period (seeding and transplanting) is excluded within the simulation model. Low light and space requirement in the first weeks of the crop rotation led to this decision. Crop rotation and lighting analysis within the simulation model therefor starts after transplanting with the start of the vegetative growth.

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[347] On this point although it is necessary to claim that data about PPFD, DLI, photoperiodism etc. are not coherend, but can be used as a fan of data which enable assumtions for the simulation model, starting below.

[348] HANAN Joe J. et al.1998. Greenhouses, Advanced Technology for Protected Horticulture, Boca Raton, Kondon, New York, Washington, D.C., CRC Press, p.91

For the sake of completeness it must be said that the needed PPFD can be maximized or minimized by reducing or rising the CO2-level within the Vertical Farm. Water supply and nutrient composition are also directly interconnected with the ideal PPFD-curve. On this field intensive research is going on and more need of research can be assumed. Considering all these factors would go beyond this doctoral thesis.
Four PPFD-amounts, following a sigmoid growth curve, now get defined for *L. esculentum* production within the Vertical Farm:

50 µmol/m$^{-2}$/s$^{-1}$ during the establishment (seeding, (trans-)planting)[349]

150µmol/m$^{-2}$/s$^{-1}$ during the vegetative growth (development and photomorphogenesis)

150 - 300 µmol/m$^{-2}$/s$^{-1}$ during the flowering period to the first fruit-set (blossoms, pollination, first fruits and fruit growth)

300 µmol/m$^{-2}$/s$^{-1}$ during ripening to first harvest (fruit growth, lycopene production)[350] [351]

300 - 100 µmol/m$^{-2}$/s$^{-1}$ along the rest of the crop rotation

## Temperature and other Growing Conditions

TEMPERATURE

All phases within the lifetime of the *L. esculentum* plants, from germination, to plant growth, flowering and pollination, fruit-set, photosynthesis and yield - are all influenced by temperature.

“A day temperature from 70 to 82°F [approx. 21°C to approx. 28°C] is optimum, while night temperature from 62 to 64°F [approx. 16,5°C to approx. 17.5°C] is optimum for greenhouse *L. esculentum*. During cloudy weather, a temperature closer to the lower end of these ranges is preferred, while in sunny weather, temperatures closer to the higher end are better.“ “[352]
These ranges were compared to differend studies and experiments with greenhouse *L. esculentum* and, by the end of the chapter, compared with the production practices of „Zeiler“.

MINIMUM AND MAXIMUM TEMPERATURES

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[349] http://www2.produktinfo.conrad.de/datenblaetter/100000-124999/101861-an-01-ml-PRONOVA_LUX_QUANTUM_METER_de_en.pdf, retrieved 29.04.2014; A range from 45 to 55 µmol/m-2/s-1 is recommended.

[350] HANFORD, A. J. 2004. Advanced Life Support. Baseline Values and Assumptions Document. Houston: National Aeronautics and Space Administration. p.59

[351] Researches from LumiGrow (http://www.lumigrow.com/) who supported calculations of this work, calculate with a range of 300 - 380 µmol/m-2/s-1

[352] SNYDER, R. G. [2010]. Greenhouse Tomato Handbook. Mississippi: Mississippi State University Extension Service.

The ideal temperature is dependent of direct and diffuse solar radiation, the rela-tive air humidity, water and CO2 concentration in the air. An overview of different findings will be given below. But there are physiological limits beyond the ideal temperature for the best and biggest yield.

*L. esculentum* plants prefer warm weather. Temperatures below 10°C or below delay seed germination and vegetative development are inhibited. The consequences are a reduction of fruit-set and an impairment of fruit ripening.[353] *L. esculentum* can scarcely absorb nutrients at all when temperatures sink below 12°C. Below 10.5°C the degree of growth is negligible. The reduction of nutrient uptake starts below 14°C. Beyond 32.5°C the evaporation cooling through leaf transpiration starts to diminish and so called water stress begins. Beyond 35°C lycopene, a carotenoid which gives the fruit its characteristic red color no longer develops. This situation thus inhibits the development of normal fruit color and it also reduces fruit-set.

Beyond 36°C blossom drop (flower abortion) starts, especially if these temperatures already occur in the early morning period and last for a number of consecutive hours.[354] Temperature differences of between 4°C to 8°C in daytime and nighttime improves germination, growth and development, and also flowering and yield.[355]

The range within the minimum and maximum temperature, where *L. esculentum* production should take place for high quality yield is between 20 and 24°C.[356]

Through the crop rotation of the *L. esculentum* plants the following approximate temperature values can be defined:

Establishment, from seedlings to (trans-)planting:
    19,5 - 21,5°C[357]
Vegetative growth - development, photomorphogenesis
    19,5 - 21,5°C[358]
Flowering to fruit set - blossoms, pollination and first fruit set
    18,5-20°C[359]
Fruit growth

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[353] JONES J. Benton, 2007. Tomato Plant Culture : In the Field, Greenhouse, and Home Garden, Second Edition, Edition 2, CRC Press p.18

[354] JONES J. Benton, 2007. Tomato Plant Culture : In the Field, Greenhouse, and Home Garden, Second Edition, Edition 2, CRC Press. p.18

[355] Voican, V., Lăcătus, V. and Tănăsescu, M. 1995. GROWTH AND DEVELOPMENT OF TOMATO PLANTS RELATED TO CLIMATIC CONDITIONS FROM SOME AREAS OF ROMANIA. Acta Hort. (ISHS) 412:355-365

[356] ibid. p.18

[357] LANDESANSTALT FÜR LANDWIRTSCHAFT, FACHBEREICH GARTENBAU 2004. Gewächshaustomaten. Hinweise zum umweltgerechten Anbau. Managementunterlage. [Dresden]: Sächsische Landesanstalt für Landwirtschaft, Fachbereich Gartenbau.

[358] ibid.

[359] ibid.

18-22°C[360]

Ripening to first harvest - fruit growth, lycopene production, sugar production

22-24°C[361]

Full harvest to the end of the crop rotation

22-24°C[362]

Taking into consideration the rate of truss production, the opening rate during flowering, the fruit development /time, the number of flowers and set-fruits, the best values lie at 22°C.[363] The only higher value compared to other temperatures we find at the mean fruit size (g) at 18°C.
„Air temperature can have a marked affect on the atmospheric demand (moisture requirement) of the *L. esculentum* plant, increasing with increasing air temperature."[364] Water requirements for soil based *L. esculentum* can increase fivefold between ideal and extreme temperatures. „However, the relationship between air temperature and relative humidity can moderate the transpiration rate, reducing the atmospheric demand with increasing humidity."[365]

Comparing these data with the interview at "Zeiler" we see the following analogies. Zeiler maintains a maximum temperature between 20 and 24°C during the heating period in a greenhouse in the south of Vienna,. In summer the greenhouse is not cooled as temperatures increase. The roof of the greenhouse is covered with a special color on a chalk basis instead, to increase the reflection of direct solar irradiation. The greenhouse is naturally ventilated, air exchange takes place through openings in the glass roof.

During the heating period, again the temperature ranges from 24°C to a minimum of 14°C. The reduction from 24 to 14°C occurs rapidly after sunset, when all the ventilation dampers are immediately opened. The findings of this practice are an increase in blossom-production and fruit-set, a fact which is also confirmed by studies in greenhouses from Sachsen, Germany, where the night-temperature rated value of approx. 15°C for approx. 4 hours is reduced for 1 to 2 K. This supports the generative plant growth and also has positive effects on fruit-set.[366] At the Zeiler greenhouse, the temperature increase from 14 to 24°C takes place slowly supported by the daylight after the respiration-phase.

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[360] 2001, S.R.Adams et al. „Effect of Temperature on the Growth and Development of Tomato Fruits", Horticulture Research International, Wellesboune, Warwick CV35 9EF, UK, Annals of Botany 88: 869-877, 2001, p.869-877

[361] Excursion Report, see „Appendix"

[362] ibid.

[363] ADAMS, S. R., COCKSHULL, K. E. & CAVE, C. R. J. 2001. Effect of Temperature on the Growth and Development of Tomato Fruits. Annals of Botany ; 88, 869-877. The experiment was made with the Tomato „Liberto" with constant temperatures at 14, 18, 22 and 26°C.

[364] JONES J. Benton, 2007. Tomato Plant Culture : In the Field, Greenhouse, and Home Garden, Second Edition, Edition 2, CRC Press, p. 18

[365] ibid. p.18

[366] SÄCHSISCHE LANDESANSTALT FÜR LANDWIRTSCHAFT, FACHBEREICH GARTENBAU 2004. Gewächshaustomaten. Hinweise zum umweltgerechten Anbau. Managementunterlage. [Dresden]: Sächsische Landesanstalt für Landwirtschaft, Fachbereich Gartenbau. Chapter 1.7.2

## WATER

Water is a scarce resource in most parts of the world. The amount of precipitation falling on the world land surface of 150.000.000 km2 is about 110.000 km3/a. Two thirds of this is evapotranspirated by vegetation on the land surface. The remaining volume “feeds” rivers and lakes and aquifers. These are the renewable freshwater resource of the world. The water withdrawal for municipal, industrial and agricultural purposes is returned to the environment after a certain time period.[367]
In this context the percentage of water withdrawal by traditional agriculture, how much water a *L. esculentum* plant needs to produce high quality and high quantity yield are important questions for the for the Vertical Farm and so too is the issue of estimating to what extent Vertical Farms can reduce the water consumption in agricultural production.
On a global average use 70% of fresh drinking water is used worldwide for soil-based agriculture[368]
This value, of course varies greatly between different countries where the values of water withdrawal for agricultural use range from 91% to 2%.[369]
Especially *L. esculentum* have a vaste water content, up to 96%[370]. The plant absorbs water by its roots and through irrigation and fertigation.
Irrigation is the technical term for artificial application of water in non or low rain-fed agricultural areas. In greenhouses and Vertical Farms irrigation is an intrinsic subsystem with a central advantage to soil-based outdoor agriculture: Through drip irrigation the plant gets its water and nutrients exactly where it absorbs it.

Moisture requirements on the field vary from 2.000 to 10.000m3/ha/a. „A mature *L. esculentum* plant may wilt during an extended period of high air temperature if the plant is not able to draw sufficient water through its roots, a condition that can occur if the rooting medium is cool or the rooting zine is partially anaerobic. Also the size of the root system may be a factor. Just how large the root system must be to ensure sufficient rooting surface for water absorpiton is not known.“[371]
In this context we talk about evapotranspiration, which is the sum of evaporation of water from the soil and the transpiration from the plants. The amount of water required can thus be drastically minimized compared to conventional soil-based agriculture because of eliminating water losses through evaporation and water dissipation to root areas of the growing crop.[372]

The high-tech-greenhouse and the Vertical Farm are conceived as closed environmental systems where water recovery is possible. The aim of implementing closed water cycles in Vertical Farms

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[367] http://www.fao.org/nr/water/aquastat/water_use/index.stm, retrieved 24.09.2014

[368] http://www.fao.org/nr/water/aquastat/water_use/index.stm, retrieved 24.09.2014

[369] ibid.

[370] „Nutrient composition and antioxidant activity of eight Tomato (*Lycopersicon esculentum*) varieties, J.L. Guil-Guerrero, M.M. Rebolloso-Fuentes Article

[371] JONES J. Benton, 2007. Tomato Plant Culture : In the Field, Greenhouse, and Home Garden, Second Edition, Edition 2, CRC Press, p.18

[372] ibid.

thus makes sense and to a certain extent, has also been an actively pursued objective in a number of dif-ferent projects.[373] [374] [375]

“In greenhouse vegetable crops, the irrigation water-use efficiency (WUE), expressed as the ratio between marketable crop production and total crop irrigation supply, is much higher than in open field crops due to the low evaporative demand inside the greenhouse that reduces water requirements and the higher productivity of greenhouse-grown crops. (...) In unheated plastic greenhouses in the Mediterranean Basin, WUE was similar between crops grown in soil or substrate, and increased under the following conditions:

improved greenhouse structure
increased length of growing season
recirculation of nutrients in substrate-grown crops

The highest WUE values of 45 (substrate-open system) and 66 kg m3 (sub-strate-closed system) were for *L. esculentum* grown in the Netherlands with glass-houses.“[376]
An enormous improvement in efficient water consumption results in the change-over from soil based agriculture to closed systems such as greenhouses or Vertical Farms.

Water requirements for *L. esculentum* are normally the sum of the water lost for evaporation of the soil, transpiration of the plant and the “incorporated” water of the plant itself. A rule of thumb exists to calculate the amount of the daily water supply needed for greenhouses [ml/m2]: when the daily radiation [J/cm2] is multiplied by the factor 3, e.g. with a radiation of 1,000 J/cm2 three liters of water are needed. This approximate value is only valid for mature indeterministic *L. esculentum* plants[377]. The following calculations are for media and calculating 2.5 plants per m2.

During the crop cycle there is a steady increase in water requirement until a peak at the harvest, when the plant reaches its maximum fruit output and after which the water requirement shrinks again.

During the establishment and vegetative growth phases for *L. esculentum* plants 0.75 l/m2 are required. During the flowering to the first fruit-set through the pe-riod of fruit growth the plant water needs are doubled from 1.65 l/m2. 3.15 l/m2 of water from the weeks of ripening to the first harvest while 7 l/m2 are needed during the period of full harvest. After the plant reduces its fruit

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[373] http://plantagon.com/urban-agriculture/industrial-symbiosis, retrieved 24.09.2014

[374] http://urbanfarmers.com/projects/basel/, retrieved 20.09.2014

[375] http://www.plantchicago.com/non-profit/farms/plantaquaponics/, retrieved 20.09.2014

[376] W.BAUDOIN et al. 2013. Food and Agriculture Organization of the United Nations, Plant Production and Protection Division. „Good Agricultural Practices for greenhouse vegetable crops - Principles for Mediterranean climate areas“, p.130

[377] Indeterministic *L. esculentum* plants normally are used in greenhouses, while deterministic plants are used for soil based agriculture outside of protected environments. The main difference between these two types are that indeterministic plants can reach a height up to 3m while deterministic plants from their morphology are bushy and reach a maximum height of approximately 80 to 90 cm.

development, the water requirement shrinks from 7 to 5 l/m2 within four weeks and diminishes water uptake until the end of the cropping season with 2 l/m2 of water.[378]

Similar can be found in the Greenhouse Tomato Handbook[379], where 50 ml per plant are given for new transplants and reach an amount of 3 quarts (2.7l) for a mature plant on a sunny day. “Generally, 2 quarts per plant per day are adequate for fully grown or almost fully grown plants. Monitor plants closely, especially for the first couple of weeks following transplantation, so that the volume of water can be increased as needed. (...) Most growers use from 6 to 12 waterings per day once plants are established.”[380]

These figures are also comparable with the practical experience of the “Zeiler” greenhouse in Vienna, with a daily water supply of 8l/m2. Per m2 on average 2.75 plants are produced, and every plant needs approx. 2,96 l of water/day.
We find a higher value of water quantity per plant in fertigation studies of the University of Arizona where an average of 4 l/plant/day is mentioned. On average of 2,5 plants/m2 (2.5 heads on one stem) the amount of water as nutrient solution reaches a value of 10 liters/m2/day. The “water needs may be doubled!” in desert areas if evaporative cooling is used.[381]

## Growing media and plant density

Industrially grown greenhouse *L. esculentum* are on the increase around the world, especially in Europe, North America and China. The most extensively used growing medias today are rockwool, perlite, media containing peat moss and coconut coir.

Recent studies at the University of Arizona, focusing on the influence in crop yield of *L. esculentum* clearly show that differences in crop output between the different medias is negligible. Water consumption and nutrient distribution, however, have an altogether different priority pattern and their effectiveness depends directly on the substrate. In order to achieve comparable results regarding water consumption, evapotranspiration of plants, which are an important influencing factor of the indoor climate control, the author chose to use coconut coir for the following reasons:

Coconut coir is abundantly available at low cost and compared to rockwool, it is a renewable material. The water holding capacity (and the bond of macronutrients) are also better compared

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[378] 3 SÄCHSISCHE LANDESANSTALT FÜR LANDWIRTSCHAFT, FACHBEREICH GARTENBAU 2004. Gewächshaustomaten. Hinweise zum umweltgerechten Anbau. Managementunterlage. [Dresden]: Sächsische Landesanstalt für Landwirtschaft, Fachbereich Gartenbau. Chapter 15

[379] SNYDER, R. G.2010. Greenhouse Tomato Handbook. Mississippi: Mississippi State University Extension Service.

[380] ibid.

[381] http://ag.arizona.edu/ceac/sites/ag.arizona.edu.ceac/files/pls217nbCH10_0.pdf, retrieved 17.09.2014

with other media. Coconut coir is “far less costly than rockwool and any media containing peat moss.“[382]

Recent findings in horticulture research by comparing different planting bed sizes and growing substrates illustrate an additional advantage from the use of co-copeat. “Plants grown in cocopeat produced the highest marketable fruit quantities (56.2%) per plant and yielded the greatest (445.6 g) marketable yield per plant. Plants grown in a cocopeat substrate produced higher fruit quantities (5.2%) and total yield (0.7%) than those with a rockwool substrate.“[383] In this experiment it was also observed, that *L. esculentum* grown within cocopeat growing substrate produced the highest fruit weight.

In this study four F1-*L. esculentum* were used: Campari, Temptation, Annamay and Adoration, four cultivars with a similar fruit weight than the four F1-*L. esculentum* cultivated by “Zeiler“-greenhouse. “Two sets of experiments were conducted simultaneously under the same climate-controlled greenhouse. For the first experiment, planting beds were arranged parallel in a north-south direction and with a bed width of 20cm, 40cm, 60cm and 80 cm constructed by laying a wooden plank along both sides of the bed.“[384] The bed height was 8 cm and the distance between the cultivation rows was 70 cm. The optimum distance between the plants with the highest (marketable) fruit yield is 60 cm.

In the second experiment, these cultivars as mentioned above were bedded in cocopeat, rockwool and masato.[385]All plants were drip irrigated, supplied with a standard nutrient solution and treated according to recommended cultural practices.
The results of this study will be the basis for the following simulation model in terms of plant density and rasterization. The cocopeat slabs used in this study were 95 cm x 15 cm x 8 cm and placed over a Styrofoam slab (as the truss) with similar dimensions. At “Zeiler“-greenhouse the truss-slab was made of rockwool.

Cocopeat is a renewable organic natural material, with its low bulk density and obvious advantages for plant growth and development it can be considered a suitable substrate for the simulation model. Plant distances of 60 x 70 cm will be applied to configure the ground floors and plant arrangements.

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[382] http://ag.arizona.edu/ceac/sites/ag.arizona.edu.ceac/files/Comparing%20Media%201996%2097.pdf, p.1, retrieved 15.10.2015

[383] LIUTEL B.P. et al., „Yield and Fruit Quality of Tomato (*Lycopersicon esculentum* (Mill.) Cultivars Established at Different Planting Bed Size and Growing Substrates“, Department of Horticulture, kangwon National University, Chuncheon 200-701, Korea, Hort.Environ.Biotechnol. 53(2):102-107.2012, ISSN (print): 2211-3452, ISSN (online): 2211-3460

[384] ibid.

[385] Unfortunately it wasn‘t possible to find any material about substrate „masato“. To my knowledge it must be a specific soil, used in South-eastern Asia.

## Setting up Vertical *L. esculentum* - Farm

### Light availability in Vienna and Greenhouse Practises

The photosynthetically active radiation (PAR) represents from 44%[386] to 50%[387] of the visual light spectrum depending on different research results. Even though also PAR can vary by some percentage points, use of the factor 0.5 to obtain PAR from the total radiance in the eastern region of Austria has become established practice. To obtain the photon flux density and the daylight integral it is necessary to evaluate the exact amounts involved by using spectrometers on top of the greenhouse or the plant canopy. These values are dependent on geography, the latitude and longitude, the climate zone and also the influence of specific conditions the plant is growing under (air quality, microclimate etc.).

It is therefore necessary to work with specific climate data in order to achieve further precise estimates. For this purpose we continued our calculations with data from Vienna, Austria. For various reasons: *L. esculentum* cultivation in eastern Austria has a relatively short but successful tradition. Vienna has a high density in glasshouses which cultivate *L. esculentum*. As a result of the climatic conditions here with very substantial variations of temperature and humidity between summer and winter, glasshouses are largely in use to extend the cultivation time throughout the year. Most of the greenhouses stop *L. esculentum* production in October due to the low sunlight levels.

Vienna is located in northeastern Austria, on the foothills of the Alps in the Vienna basin. According to the Köppen-Geiger-Classification, Vienna lies within the Cfb-climate and the humid continental climate. Its summers are warm to hot with average temperatures between 24 - 31,7 degrees (dry bulb temperature). It has not been uncommon in recent years for temperatures to reach 40°C.

Winters are dry and cold with average temperatures around freezing point. In January and February very low temperatures are possible (down to - 18,30°C). Spring and autumn are mild. The average precipitation is relatively modest at around 600 - 620 mm annually. Snow is relatively uncommon compared to southern and western Austria. The elevation of the city ranges from 156,68 m.o.A (meters over the sea-level of the Adria) to 484 m (Kahlenberg).

Global irradiation in Vienna reaches around 1.120 kWh/m2/a whereas the ratio between direct and diffuse light is about 56.5% (direct irradiation) and 43.5% (diffuse irradiation). The annual distribution of global total radiation shows that the month with the highest total solar irradiation is July with 172.62 kWh/m2 or 621.42 MJ/m2 (dir=68.35%, diff=31.65%). The month with the lowest total solar irradiation is December with 18.93 kWh/m2 or 68.14 MJ/m2 (dir=72.58%, diff=27,42%).

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[386] GIACOMELLI, G. 1998. Components of Radiation Defined: Definition of Units, Measuring Radiation Transmission, Sensors. CCEA, Center for Controlled Environment Agriculture, rutgers university, Cook College.

[387] http://www.landwirtschaftskammer.de/gartenbau/beratung/technik/artikel/lichtwerte-umrechnen.htm, retrieved 12.05.2015

The month with the most daylight hours is July with 248 hours, followed by August and May with 244 hours, respectively 238 hours. The month with the lowest daylight hours is December, followed by November and January with 52, 64 and 67 hours.

No statistics are currently available from ZAMG[388] or other institutions to provide the average DLI data for Vienna. To my knowledge there is only one single large-scale graphic available to evaluate DLI. The Institute of Floriculture from Michigan State University, Jim Faust, Clemson University, developed an "Outdoor Daily Light Integral (DLI) Map for the United States. Daily light integrals (mol/m2/d) are visible here from 5 to 60 DLI throughout all the climate zones from January to December. In Chapter 5.6 DLI is calculated on the basis of daylight availability taken from the annual solar radiation simulation from Vienna.

DLI for Vienna for the simulation model got calculated as follows: W(solar radiation)*0.5[WPAR]*4.57[µmol/m$^{-2}$/s$^{-1}$]*seconds[daylength]/1,000,000[389]

The photosynthetically active radiation (PAR) in Vienna ranges from 8.33 kWh/m2 in December to 75.95 kWh/m2 in July. In springtime and autumn goes from 36.47 kWh/m2 in March to 71.06 kWh/m2 in June and from 42.33 kWh/m2 in September to 12.10 kWh/m2 in November respectively. The following photosynthetic photon flux densities (PPFD) were evaluated (using the factor 4.57/W from Gene Giacomelli, Arizona University) in relation to the photosynthetically active radiation (PAR). The PPFD value is the quotient of the daylight integral (DLI) and the average length of the day in seconds. The values in µmol/m$^{-2}$/s$^{-1}$ range from 720.82 in July to 188.23 in January with an average of 459.78 µmol/m$^{-2}$/s$^{-1}$ throughout the year.

By overlaying the climate data and the average solar irradiation with specific responses of *L. esculentum* on sunlight we receive the time with enough sunlight for plant cultivation. The light compensation point for most of C3-plants ranges from 40 - 60 W/m2 sunlight or ca. 90 - 135 µmol/m$^{-2}$/s$^{-1}$ respectively. The light saturation points of *L. esculentum* ranges from ca. 260 W/m2 to 350 W/m2 sunlight or 600 - 800 µmol/m$^{-2}$/s$^{-1}$.[390]

## ***DIMINISHING FACTORS AND CURRENT RESEARCH TENDENCIES FOR GH***

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[388] Zentralanstalt für Meteorologie und Geodynamik (Central Institution for meteorology and geodynamics), Austria

[389] Table 25 (Appendix): DLI, µmol/m-2/s-1 for Vienna

[390] JONES J. Benton, 2007. Tomato Plant Culture : In the Field, Greenhouse, and Home Garden, Second Edition, Edition 2, CRC Press, p.58

Several universities, firms and horticulturists are currently working on the “low energy greenhouse“ [391] [392], focusing on the reduction of heat loss and the optimization of photoperiods and light quality to reduce the energy requirement for artificial (supplemental) lighting. In the context of characteristics for greenhouse glazing, or better covering, materials, glass is still the material with the highest PAR-transmittance-capacity.[393] Current calculations minimize outside PAR through greenhouse covers up to 30%, taking the age of the glass, impurities and pollution, profiles and construction into account.

The objective of “ZINEG“[394] is to increase energy efficiency within the greenhouse-industry. Its system approach is to operate greenhouses “without fossil energy, without fossil CO2-emissions”. One of the solutions lies in developing new covering materials. The fundamental requirements for a greenhouse-cladding-material are to obtain high light transmittance plus good insulation.

## Artificial Lighting - General Data

Assuming that artificial lighting is the key energy consumer in Vertical Farms, the choice for lamp types with a high luminous efficiency[395] is mandatory. Most lamps are produced to illuminate indoor or outdoor spaces for people. The measurement for color, temperature, light intensity and luminous flux are all calibrated on a wavelength of 555 nm. Complete datasets are available for these lamp types, including the emitted light spectrum and the light angle.

This is diminished by 10% for classic greenhouses due to the reflections from the building envelope.

Additional diminishment of daylight availability can be expected with stacking plant production in a Vertical Farm, conceived to the skyscraper typology.

Photosynthesis is at its most effective with blue and red light. The choice of lamp types in which the blue and red light spectral components are highest is necessary, not only for reasons of efficiency, but also to reduce operating costs.

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[391] „Low Energy Greenhouse and the Hot-Box Approach, kamer van Koophandel Haaglanden, Den Haag, 27.01.2009, Prof.Dr. hans-Jürgen Tantau, Institute of Biological Production Systems, Biosystems and Horticultural Engineering section, Leibniz Universität Hannover

[392] https://www.wageningenur.nl/en/show/Three-fruitful-years-of-experience-in-low-energy-greenhouses, retreived 15.09.2014,
2006, Jon Kristinsson, „The Energy-producting Greenhouse, em.Prof. Faculty of Architecture, Delft University of Technology, Netherlands and
http://www.dhlicht.de/fileadmin/Downloads/pflanzenbroschuere.pdf, retreived 09.08.2014

[393] https://hrt.msu.edu/Energy/Notebook/pdf/Sec1/AJ_Both_Greenhouse_Glazing.pdf, retreived 13.09.2014

[394] http://www.zineg.de/, „Gesamtziel des Verbundvorhabens ist es, für die Pflanzenproduktion in Gewächshäusern den Verbrauch fossiler Energie für die Heizung und damit die (fossilen) CO2-Emissionen möglichst auf Null zu reduzieren. Zur Erreichung dieses Ziels ist ein systemorientierter Ansatz durch Kombination technischer und kulturtechnischer Maßnahmen erforderlich.“ , Laufzeit: 01.05.2009 - 30.04.2014, retreived 12.08.2014

[395] Luminous efficiency is the percentage of lumen per Watt compared to the luminous efficiency of sunlight. Per Watt the sun has a luminous flux of 683 lm.

By contrast with lamps conceived with the human eye luminous efficiency factor in mind, the choice here is for the photo efficiency µmol/J [Ws]. The following diagrams show the spectral distribution of the most common lamp types used in greenhouses. Additional lamp types and their spectral distribution ae listed in the Appendix.
The lamp types referred to in this work for in the Vertical Farm are LED types and this for the following reasons:

LEDs have the highest photon efficiency of all growth promoting lamps.

LEDs are produced to emit the ideal spectrum for photosynthesis.

LED technology has “rapidly advanced over the past decade (...) [. A] similar significant advances throughout the coming decades can be expected. (...) [LED] technology (...) progresses under what is known as Haitz’s Law, which observes and predicts that the cost per (...) useful light emitted) of LEDs falls by a factor 10 every decade.“[396] [397] [398]

LEDs produce much less excess heat than any other lamp types used for plant growth[399] and therefor the lamp itself can be placed closer to the canopy without overheating leaf surfaces, which leads to water stress in the plant, and these lamps are thus ideal for plant production within the skyscraper building typology with lower floor heights.

Incomplete and difficult to compare descriptions and data for LED  lamp types made it necessary to contact several manufacturers in order to obtain a precise data pattern, not only concerning photo-efficiency, but also about the light angles and the photon flux densities along the light radiation.
Two lamp types were initially considered for the simulation model setup, both produced by LumiGrow, Novato, California, USA. The support from the manufacturer side was required to define the optimum distance between the LED fixture and the plant canopy for supplying *L. esculentum* with the necessary PPFD on one hand, and to define a raster for the fixture to cover the complete cultivation area on each of the different levels on the other.

## Artificial Lighting - LED LumiGrow 325 and LumiGrow 650

LumiGrow, Inc. is one a provider of horticultural lighting solutions, “enabling commercial growers and researchers to achieve operational efficiencies, reduce energy consumption and improve crop yields.“ [400]

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[396] GRAFF, G. 2011. Skyfarming. Master of Architecture, Waterloo, Ontario, Canada. p.94

[397] http://www.nature.com/nphoton/journal/v1/n1/full/nphoton.2006.78.html, retrieved 12.01.2015

[398] This is necessary to consider, because even though LEDs have the highest photon efficiency of all lamp types produced nowadays for plant growth, fixture costs are five to seven times higher.
see: NELSON, N. 2009. Planning the productive city. Available: http://www.nelsonelson.com/DSA-Nelson-renewable-city-report.pdf.

[399] Zeiler for instance within his greenhouse uses HPS-lamps (High Pressure Sodium Lamps). Excess heat within the greenhouse is not considered as waste heat, but while enlarging the photoperiod during the day and enlarging crop rotation throughout the year, heat can be used and additional heat costs therefor can be diminished.

[400] www.lumigrow.com, retrieved 12.02.2015

The LumiGrow Pro-series (325 and 650 [W, Ed.] are developed to “output more red and blue in the essential PAR range than the industry’s most powerful conventional lighting systems, including any high-intensity discharge (HID) fixture. Peerless in the industry, the Pro 650 light delivers 2X the red and blue PAR of a 1000 Watt HID light while it consumes 40% less energy. The Pro 325 provides a red and blue PAR equivalent to that of a 1000 Watt HID light while it reduces energy consumption by a whopping 70%.“ [401]

The LumiGrow Pro-series lamps have a light angle of 120°. The PPFD for the plant is dependent on the distance of the lamp to the canopy of the *L. esculentum*. The PPFD output of LumiGrow 325 can thus be considered adequate for the simulation model. The table below shows the dependency of PPFD to height-distance between fixture and plant canopy. Furthermore the list highlights the amount of blue and red light from the overall PPFD within the PAR range and the amount of green and yellow light (between 500 nm and 600 nm). It is an extended table of values provided by the author, based on official data taken from the LumiGrow website. The following data were verified by the corporate research department of the LumiGrow. The DLI was added and calculated for a photoperiod of 16 hours, or 57,600 seconds with a constant of 300 μmol/m$^{-2}$/s$^{-1}$ of PPFD.

It is important to mention, that μmol/m$^{-2}$/s$^{-1}$ listed in Tab.10 must be defined as adjusted PAR-values. PAR weights the entire spectrum between 400 nm and 700 nm equally. The norm DIN-5031-10 defines the photobiological and thermal effect of optical radiation.[402] Based on this spectral sensitivity curve (DIN-5031-10) every wavelength gets absorbed differently from the leaves. This explains why the effective output of 81 μmol/m$^{-2}$/s$^{-1}$ [403] provided by Lumigrow Pro 325 is sufficient for optimum plant growth.

The specific conversion factor for Lumigrow Pro 325 from lux to μmol/m$^{-2}$/s$^{-1}$ is 2*0.081. Simulation results provided by Lumigrow to evaluate the simulation results in Chapter 5 can be seen in the Appendix. Lighting schedule, developed in Chapter 5, therefor, is based on Adjusted PAR.

The operating frequency is from 50 - 60 Hz
Power consumption is 325 Watts
Power Factor is 0.95
Operating temperature from -20 to 60°C
Dimensions: 254 mm x 279 mm x 140 mm)

Tab. 11 shows the photon emmission of Lumigrow PRO 325. The table got generated based on official data retrieved by the company[404] and compared to results of the study on the „Economic

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[401] http://www.lumigrow.com/products/pro-series-greenhouse-lights, retrieved 05.01.2015

[402] DIN 5031-10:2013-12 (D) „Strahlungsphysik im optischen Bereich und Lichttechnik - Teil 10: Photobiologisch wirksame Strahlung, Größen, Kurzzeichen und Wirkungsspektren“ http://www.beuth.de/de/norm/din-5031-10/195406448, retrieved 29.10.2015

[403] See Appendix - Simulation provided by Lumigrow to evaluate simulation results in Chapter 5

[404] http://www.lumigrow.com/products/pro-series-greenhouse-lights, retrieved 05.01.2015

Analysis of Greenhouse Lighting: Light Emitting Diodes vs. High Intensity Discharge Fixtures".[405] Micromoles, here, are interpolated to correspond to adjusted PAR-values (400 nm to 700 nm). These values are used for building up the lighting schedule used for tracing lighting demand of the Vertical Farm Simulation types.

## *L. esculentum* - Organization of the vertical cultivation area

The results of chapter 4 now provide enough data to set up a generic arrangement of the cultivation area for *L. esculentum* suitable for *L. esculentum* cultivars which produce small to medium sized fruits and grow on and along trusses.[406] [407]
The planting bed size is 60 cm x 70 cm, the growing substrate chosen for the theoretical model is "cocopeat".[408]

The maximum PPFD for fruit production will be 300 μmol/m$^{-2}$/s$^{-1}$ (=65.64 W), starting with 150 μmol/m$^{-2}$/s$^{-1}$ (=32,82 W) and ending with 100 μmol/m$^{-2}$/s$^{-1}$ (=21.88 W) by the end of crop rotation.[409] Considering that daylight availability (average PPFD) for soil-based agriculture-*L. esculentum* in Vienna is only given from March to October, supplementary light will be needed for the photoperiod.

LED-light types will be used to cover the lacking PAR availability within the building.[410] The performance analysis has shown that LumiGrow PRO 325 is an LED lamp type which is useful for *L. esculentum*-Production within the stacked greenhouse, the Vertical Farm.[411] LED-fixture will be placed 80 cm upon the *L. esculentum* plant canopy.

All the *L. esculentum*-cultivars mentioned are indeterministic plant types and will grow in the z-axis until they reach -1.00 m from the under-edge of the room height (20 cm height of LED-lamp + 80 cm distance between the light and the plant canopy).

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[405] NELSON, J. A. & BUGBEE, B. 2014. Economic Analysis of Greenhouse Lighting: Light Emitting Diodes vs. High Intensity Discharge Fixtures. PLOS ONE ; 9/6, 1-10. retrieved 15.01.2015

[406] LUITEL, B. P., ADHIKARI, P. B., YOON, C.-S. & KANG, W.-H. 2011. Yield and Fruit Quality of Tomato (*Lycopersicon esculentum* Mill.) Cultivars Established at Different Planting Bed Size and Growing Substrates. Horticulture, Environment, and Biotechnology ; 53(2), 102-107.
Within this work the following cultivars were planted: „Campari", „Temptation", „Annamay" and „Adoration.

[407] see Appendix: Tomaten Zeiler - Exkursionsbericht; „Zeiler" produces the following cultivars: „Avalantino", „Juanita", „Sunstream" and „Vesuvius San Marzano"

[408] LUITEL, B. P., ADHIKARI, P. B., YOON, C.-S. & KANG, W.-H. 2011. Yield and Fruit Quality of Tomato (*Lycopersicon esculentum* Mill.) Cultivars Established at Different Planting Bed Size and Growing Substrates. Horticulture, Environment, and Biotechnology ; 53(2), 102-107.

[409] see chapter 4

[410] ibid.

[411] ibid.

The raster of the LED-fixtures is defined in such a manner that the overall surface of the plant canopies are completely covered with the photon flux given by the light angle of 120°.

Placement of the construction support, height of the growing substrate, placement of the CO2-pipes, drainage and additional support construction shown the next page are based on recommendations experienced during the excursion to „Tomaten Zeiler“ and by the „Sächsische Landesanstalt für Landwirtschaft, Fachbereich Gartenbau“.[412] Based on findings within this chapter, recommendations of “Zeiler” and discussions at the Department of Crop Sciences at the University of Natural Resources and Life Sciences, Vienna three essential schedules for the simulation model can be implemented:

**LIGHTING SCHEDULE:**
16 h photoperiod, 8 h respiration phase

**HEATING HIGH SCHEDULE / HEATING LOW SCHEDULE.**
16 h photoperiod, 8 h respiration phase

Fig. 28 on page 208 represents the total solar radiation in Vienna for 8760 hours, the percentage of Photosynthetically Active Radiation, the needed radiation in PAR for *L. esculentum* with its saturation point - all these values overlapped by the individual crop rotation phases throughout a whole year in closed conditions.

Corresponding to Fig. 83, 84 and 85 on this page, Tab. 12, 13 and 14 visualize the procedure and method for creating csv-schedules to create the lighting schedule for the simulation model for specific days based on EnergyPlus epw-weather files.

The first column of the figures represented on these two pages shows the specific annual hours of the selected day, HOY (Hour Of the Year). The next two columns contain the specific hour or the time step. Wh/m2 are the retrieved solar radiation results of a specific zone at this hour. Detailed annual radiation results of representative levels and zones can be found in the Appendix (Additional Simulation Results).
Wh/m2 is then converted to WPAR/m2. This corresponds to the average available daylight penetration of a specific zone. Hourly data of WPAR/m2 needed are retrieved from DLI needed for the specific period of the crop rotation (p.208-209 and also see Appendix p.401 average DLI/week).

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[412] SÄCHSISCHE LANDESANSTALT FÜR LANDWIRTSCHAFT, FACHBEREICH GARTENBAU 2004. Gewächshaustomaten. Hinweise zum umweltgerechten Anbau. Managementunterlage. [Dresden]: Sächsische Landesanstalt für Landwirtschaft, Fachbereich Gartenbau. p. 33 ff.

Lighting demand for December 21st: 6.33 [DLI needed in mol/m2/d]
* 1,000,000 [mol to µmol] / 4.57 [µmol to WPAR] / 57,600 [photoperiod in seconds] = **24.074 WhPAR/m2 needed**

The difference between WPAR/m2 needed and WPAR/m2 (daylight availability) is the hourly lighting demand supplied by LED. Power demand for Lumigrow LED PRO 325 is 325 W. The csv-schedule now controls and dims LED power supply based on the difference between the demand for photosynthesis for optimum plant growth (WPAR/m2 needed) and the solar radiation results for each specific zone.
*L.esculentum* requires most light during the period of ripening to first harvest. A DLI of 17.28 mol/m2 has to be provided, which corresponds to 65.54 WPAR/m2 within a photoperiod of 57,600 seconds a day. What we see in Tab. 13 and 14, although DLI required is much higher compared to the end of the crop rotation (Tab.12), DLI achieved through the facade and the rooftop of the top level of VF32 comes close to the light quantity needed for the specific period of the crop rotation. In June, where the needed quantity of the light is already diminishing and daylight availability is the highest, only around 25% of the light has to be supplied artificially with LED compared to March 21st, or less than 50% compared to December 21st. On typical summer days with 0-10% coverage, csv is turned to 0 when DLI available exceeds DLI needed.

# Conclusio

## From Modernism to Sustainism

Little imagination is needed to perceive that numerous essential conditions of human life are based on limited resources: food or space for living, matter and energy, space and time. But this fact alone is not enough to explain the phenomenon of scarcity or shortage. Shortage can entail the potential to enable social decisions and regulations when considered in the context of social perception.[413]

And it would appear that awareness of scarcity is also social awareness - above all in some of the most highly developed countries. The twentieth century and the birth of modernist ideas and values, with all their consequences for architecture, urbanism and economic interdependencies,

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[413] LUHMANN, N. 1994. Die Wirtschaft der Gesellschaft, Frankfurt/Main, Suhrkamp., p. 177 ff.

has become modernist culture. At present “we can see a new era emerging, one that embraces more sustainable ways of living and an interconnected world. (...) [N]e w approaches to both local and global issues (...)”[414] simultaneously emerging on many cultural levels, overcoming modernist and postmodernist ideas - a perspective that “promises a networked, globalized, sustainable future.” .”[415]

This dissertation has shown the complete dependency of today’s world agriculture on hydrocarbon energy. With all those many actions during the course of the twentieth century, which have led to an increase in productivity of soil based agriculture, when expressed euphemistically, have caused an ease of the pressure on the necessity for agricultural land expansion.

But there has been a high price to pay: an estimated 176 EJ of TPES (32% of global energy production) is needed every year to keep this practice up and running effectively. The need for new agricultural land is growing exponentially in the contemporary world, primarily as a result of world population growth and changes in diets that are taking place in countries with emerging economies. Water scarcity and land erosion and other environmental impacts of conventional agriculture, problems which have not been delved into in this work, are additional challenges that add their weight in making a necessity of land expansion for crop production. But urban expansion has reached a point where it has become evident “that the ecosystems on which the city depends have a limited capacity.“[416]

The definition of scarcity, though, is always dependent on the perspective, or “scale” [417]. Chapter 2 also has highlighted that potential does exist:

The biocapacity of the earth is entirely adequate for the supply of future generations. But land conversion is needed to supply the additional food needs, and if all suitable land were converted for agriculture, the result would be an intolerable CO2 burden for the planet.

There is enormous potential, however, to increase productivity on existing agricultural land in many regions of the world, but this too will increase our dependency on hydrocarbon energy sources.

Changes in diets, above all reducing the consumption of meat and dairy products, can reduce the per capita footprint. In order to achieve this, rigorous political decisions must be made – supported and carried by broad social acceptance.

Food losses and food waste must be reduced, although it is not possible for all food that is lost from the food supply chain to be eliminated from the statistics, since our globally expanded food supply chain makes losses and wastes immanent.

Food used for energy production (e.g. biofuels) could be reduced to bring it back into the range of consumable calories for humans. But the trends clearly show movement in a different direction.

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[414] SCHWARZ, M. & ELFFERS, J. 2010. Sustainism is the New Modernism, New York, D. A. P. p.3

[415] ibid.

[416] GAUSA, M., GUALLART, V., MÜLLER, W., SORIANO, F., PORRAS, F. & MORALES, J. 2003. The Metapolis Dictionary of Advanced Architecture, Barcelona, Actar. p. 580

[417] german: „Maßstab“ also could be translated by using „standard“, „point of view“

As a global average, we need some 1,700 m2 to produce our daily food to cover on average 2,700 kcal/day by consuming over 16,000 kcal of hydrocarbon energy to produce, distribute and prepare our food. For every calorie we consume, we need six calories of hydrocarbon energy to produce it.

The Neolithic Revolution implemented a nucleus of agricultural land and built-up land. Settlements, emergence of societies, creation of cities and rising of civilizations were first made possible as a result of this development. This practice was first interrupted some decades ago. A food production- and cultivation method, which has been in discussion for the past decade, would re-establish the practice of food being produced where it is consumed – that is the use of the Vertical Farm.[418] [419]

The results of this work have shown the limits of Vertical Farming. Crops with a high lighting and heating demand within a stacked greenhouse with intermediate floors simply cannot compete with the already inefficient energy consuming food sector. Bomford's estimations and calculations[420] clearly highlight the risks that Vertical Farms, instead of easing cities from the dependency on hydrocarbon energy for food supply, rather aggravate the situation.

But this thesis also outlines a way to make Vertical Farms, as structural elements of a city, competitive with energy numbers compared to the today's world agriculture practice.

The principle of the Vertical Farming and the value and meaning it contains – its raison d'être – is primarily dependent on five factors:

### *TO WHAT EXTENT VERTICAL FARMING REDUCES THE NEED FOR ADDITIONAL LAND CONVERSION*

VF7, 14 and 32 each produces the same amount of crops what more than 60 greenhouses would yield. This reduces land use already by a factor of approximately 15. Comparing the yield to soil based agriculture, a reduction of up to 50 times can be achieved.

In Chapter 2, we have seen that since the 1980s roughly 80-90% of the additional land for agriculture came from forests (Chapter 2). Today, this is still an ongoing practice. A ha of forest every year binds more than 11 t of CO2[421] and it would release up to 737 t of CO2[422] which, by

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[418] DESPOMMIER, D. 2010. The Vertical Farm, New York, St. Martin's Press.
First releases of findings at the Institute of Microbiology and Public Health, headed by Dickson Despommier, Columbia University, were published in the early years of the millenium.

[419] DANIEL PODMIRSEG, 2008. The Vertical Farm Project for London - SPUROPE 2050, Diploma, Akademy of Fine Arts, Vienna, Prof. Markus Schäfer

[420] https://energyfarms.wordpress.com/2010/12/02/energy-and-vertical-farms/, retrieved 20.10.2015

[421] SMIL, V. 2008. Energy in Nature and Society, Cambridge, Mass., MIT Press. p.69

[422] http://pubs.iied.org/pdfs/16023IIED.pdf. p.10

converting it into agricultural land, would be released by current slash-and-burn practices. Yield of VF7, for example, could keep untouched some 1.3 ha with a building footprint of roughly 260 m2.

***CONSIDERING THE TOTAL ENERGY BALANCE, IF THE SELECTED CROP WERE PRODUCED VERTICALLY, THIS WOULD EASE THE CURRENT SITUATION WITH REGARD TO HYDROCARBON ENERGY DEPENDENCE***

With its high demand on light, *L.esculentum* challenges the typological development of a Vertical Farm to an extent that it is very difficult to achieve an energy consumption comparable to practices in soil based agriculture, as long it is connected to a conventional energy grid. It is the crop that determines energy consumption. Crops with lower light and temperature requirements can drastically reduce TPES of a Vertical Farm, e.g. lettuce, strawberries or tropical starchy roots typically require a low amount of light for photosynthesis.

***IF THE BUILDING TYPOLOGY AND PRODUCTION METHOD IS OPTIMIZED FOR LIGHT PENETRATION***

Lighting demand of Vertical Farms is the key energy consumer. What results in Chapter 5 have shown is that the skyscraper, or a similar building typology with intermediate floors is most likely inadequate to reach an energy efficiency that would make cities more independent of hydrocarbon energy for food production, regardless of all the positive impacts through the spatial implosion of the food supply chain.

Solar altitude, climate data and light availability are key strategic design components to develop the Vertical Farm building typology with a positive impact for the urban system.

***IF THE VERTICAL FARM WERE IMPLEMENTED, SEEN AS AN URBAN OPERATION OR A STRUCTURAL ELEMENT, IT WOULD ENABLE AN ECOLOGICAL SYMBIOSIS BETWEEN AGRICULTURE, SOCIETY AND ARCHITECTURE***

The Neolithic Revolution implemented a nucleus of spaces for food production and cities. This development has drastically changed within the last decades. The city has to be understood as a system, and the Vertical Farm as an integrative structural element of it. Energy and material flows within the future city have to be redrawn from linear to circular.

***THE VERTICAL FARM WITH A LINEAR PROGRAMMATIC ENLARGEMENT WOULD ENABLE SYNERGY POTENTIALS IN ADDITION TO FOOD PRODUCTION***

by adding items inside the systemic borders of the food sector using synergy potentials on an energetic level (compare Fig. 156 and Fig. 157). Besides energy consumption, DEFRA[423], highlight negative effects of the global food supply chain and its impacts on cities.

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[423] WATKISS, P., SMITH, A., TWEEDLE, G., MCKINNON, A., BROWNE, M., HUNT, A., TRELEVEN, C., NASH, C. & CROSS, S. 2005. The Validity of Food Miles as an Indicator of Sustainable Development: Final report produced for DEFRA. AEA Technology.

Three Vertical Farms with similar volumes have each been simulated with three different building envelopes. Daylight availability and heating demand were at the center of the interest. Simulation results for *L. esculentum*, though, show that the simulated Vertical Farms for L. esculentum cannot compete with energy intensive soil based agriculture-practices. Total primary energy supply and energy land needed to supply Vertical Farms with renewable energy are higher compared to today's traditional agricultural practice.

Economic pressure on maximizing yields within agriculture (and as a consequence, in greenhouse and Vertical Farm production) automatically leads to an intensification in plant density. This, in addition, reduces daylight penetration of plants moving away from the facade to the inside of the production level. To find the balance between the optimum density of crops and the necessary daylight availability is an interesting topic for future research. Maximizing yield and optimizing the building type for daylight gain "becomes the most important design consideration for architects, and ultimately will be the primary criteria from which the efficacy of a design will be determined." [424]

Results of three VF volumes with different A/V ratios show a TPES need ranging from 398.28 kWh/m2/a to 842.50 kWh/m2/a. Whereas the influence of different VT-values for each VF-type are negligible, heating demand strongly differs between the different U-values of each building envelope.
Lighting demand of the different types varies up to 25%, clearly showing the necessity of the potential of precise typological studies for a verticalized cultivation practice. Opaque levels between the cultivation spaces must be substituted.[425]

By considering these values we see that vertical production is more energy intense than the actual practise in world agriculture. Around 1.50 GWh/a (400 kWh/m2/a TPES) are needed for annual production of *L. esculentum*. The actual world average of energy supply for the food sector per square meter of agricultural land is 11.73 MJ/m2/a or 3.25 kWh/m2/a. Subtracting the energy for retail, preparation and cooking, this number is reduced to 7.80 MJ/m2 or 2.16 kWh/m2/a.[426] Energy intensive cultivation practices focused on vegetable production is some 6.5 MJ/m2/a[427] (1.81 kWh/m2/a) up to the farm gate, or 27 MJ/m2/a (7.50 kWh/m2/a), when considering the whole food supply chain.[428]
The aim therefor for future Form Follows Energy[429]-studies for Vertical Farms is to optimize the building shape to reduce TPES, and secondly, to read urban food production as a structural entity

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[424] GRAFF, G. 2011. Skyfarming. Master of Architecture, Waterloo, Ontario, Canada. p.76

[425] http://plantagon.com/urban-agriculture/vertical-greenhouse, retrieved 29.10.2015

[426] see Chapter 2.4.4, Landuse, Energy Consumption and Biocapacity

[427] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 2011.Energy-Smart Food for People and Climate, Issue Paper, Rome:FAO, p. 13

[428] We assuming the ratio that 24% of TPES of the food sector is related to the energy consumption until the farmgate. See Chapter 2.

[429] CODY, B. 2012. „Form follows Energy - Beziehungen zwischen Form und Energie in der Architektur und Urban Design, DBZ Deutsche BauZeitschrift, Bauverlag BV GmbH, Gütersloh, p.48 ff.

of the system “city”, i.e. the city as an ecosystem. “The one characteristic they all [Ecosystems, Ed.] share is that primary productivity (the total mass of plants produced over a year in a given geographically defined region) is limited by the total amount of energy received and processed.”[430]

Research projects such as “Hyper-Building-City”[431], where building typologies for vertical structures (spatially, temporally and digitally densified) entailing all necessary infrastructural elements of a society, including industry and agricultural use, visualize the potential of future cities, when synergy potentials between functions really become activated and systemic borders are rearranged to reduce the spatial dimension between the links of the FBS.

## Vertical Farming and Land use

The effect of reducing land use for agricultural production based on the above mentioned simulation models and considering the assumptions of other Vertical Farms[432] results in the emergence of a clear picture: Land use can be reduced to 30%, when comparing the cultivation area of the production entity to the alternatively needed area for traditional soil based agriculture, or referring to the three simulated building types, by 12.08%, 4.53% and 2.26%, when comparing the building footprint to the soil based area equivalent.[433]

Compared to traditional greenhouse practices, VF 32’s ratio is 1/6.5, for VF14 1/16 and VF7 1/33 for land use.

This strong image is relevant for two reasons: Land in urban areas is more expensive and the virtual area made available by Vertical Farms can be used in various ways. On this issue it is necessary to point out that Vertical Farming need not necessarily be seen as the complete substitution of all current food production practices. But it will bring relief to the current situation in which natural land is being converted into agricultural land.

On a small, (peri) urban scale, agricultural area made available by implementing Vertical Farms, can be used for alternative practices such as the intensification of socially highly desirable areas for urban farming (still soil-based) activation of area for practices with yields that tend to be lower, such as permaculture restoring natural land by abandoning agricultural land with eroded soils (a consequence of conventional agricultural practices) and capturing CO2.

## Final Considerations

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[430] DESPOMMIER, D. 2010. The Vertical Farm, New York, St. Martin‘s Press. p.19

[431] CODY, B. 2014. Form Follows Energy - Die Zukunft der Energie-Performance, energy2121, Bilder zur Energiezukunft, Klima- und Energiefonds, Vienna, omninum, p. 121 ff.

[432] Chapter 3

[433] Chapter 5

Vertical Farming has a notable impact on urbanism at many levels. For example, the ground level strongly reshapes modernist cities, developed on the drawing table and optimized for private transport.[434] On a human scale, market and trade areas, and communal spaces can be implemented again. Of great importance at a social level is the acceptance that Vertical Farms achieve within a dense city.

Although refusal was noticeable during the public presentations and discussions organized by the author, there is also strong interest in public perception: There is no doubt that "[t]he public is no longer convinced that big agriculture has its best interest at heart, and this has resulted in a deep mistrust of mass-produced food."[435] To make this statement plausible we should add that the mistrust primarily comes from the fact that agricultural production is not visible and therefore not perceptible for the urban population. In terms of acceptance for Vertical Farms within a city, it must assert high aspirations in terms of architectural aesthetics extending beyond mere functionality to increase the potential for identification, as well as to provide an urban ground floor level that is carefully planned as public space with integrated market and trade areas.

The Vertical Farm might contribute to make cities more resilient and to reduce environmental impacts, if energy- and material flows are interconnected with the urban system. Research on agricultural sciences, financed by public funding, which has been drastically reduced within the past few decades, must be re-established.[436] Public private partnerships[437] are needed to continue the process of establishing the experimental Vertical Farms, which were started in 2009.[438]
This doctoral thesis aims to contribute to the debate by summarizing the status quo of the situation in world agriculture today and to release impulses for future investigations of crop production using a verticalized cultivation method. The sustainability and energy efficiency discussions in architecture are mostly reduced to the narrow confinements of living, office and retail spaces. When considering that the per capita area for Austria (similar to Germany) is 45m2 living, 10m2 office[439] and 2 m2 retail[440] space, , it should be recalled that the area needed to meet the daily energy requirement for a person is 2,300 m2, a contrast which clearly shows how great the potential is for adding momentum to this discussion.

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[434] Daniel Podmirseg, IMDP, Exhibition, 2012. „Dio Nero - Aesthetics of Disease - Rebuilding local social and economic interdependencies, with Lucas Kulnig and Maria Huber. Venice

[435] DESPOMMIER, D. 2010. The Vertical Farm, New York, St. Martin‘s Press. p.125

[436] Wiederaufbau der öffentlichen Agrarforschung, Conclusion of the lecture „Ist die Herkulesaufgabe lösbar?" held by Prof. Dr. Harald von Witzke, on „Getreidehandelstag" on June 17th and 18tz 2014, Warberg, Germany

[437] DESPOMMIER, D. 2010. The Vertical Farm, New York, St. Martin‘s Press. p.252 ff.

[438] Suwon Vertical Farm, Chapter 3

[439] https://www.wko.at/Content.Node/branchen/k/sparte_iuc/Immobilien--und-Vermoegenstreuhaender/tabellenband_wohnen_2013_079206.pdf, retrieved 13.09.2015

[440] https://www.dghyp.de/fileadmin/media/dg_hyp_deutsch/downloads/broschueren_marktberichte/marktberichte/Immomarkt_Deutschland_2011_DRUCK.pdf, p.3 ff. retrieved 13.09.2015

Results clearly show that the building type, mainly related to natural light gain, the building envelope with respect to heating demand reduction, and the specific physiological needs of the cultivated crop require very careful investigation. These three main drivers determine whether Vertical Farming has a positive impact on the energy demand of urban agglomerations.

Simulation results clearly show how high the expected TPES is when captured by Vertical Farms adopting Skyscraper typologies, and enveloped for completely different purposes. The design of a new typology for Vertical Farming not only needs to enable light penetration within the vertical cultivation space, but use potentials for the production of renewable energy in addition.

From the perspective of an architect, “[t]he end of cheap oil for architecture carries the possibility to move away from the representation of abstract, non-spatial processes and identities back to the presentation of current, local relationships.”[441]
As plant needs are internalized and sensitivity for the potential of Vertical Farming is considered to make cities more resilient, accepting “trends that are transforming our living urban (and rural) space on a massive and unstoppable scale” , a fascinating opportunity arises: the development of a new architectural typology, the typology of the Vertical Farm.
**To conclude, this dissertation presents findings primarily on energy consumption. It also seeks to discuss Vertical Farming in a broad context by opening the following perspectives on the subject:**

Cities and water: as urban populations increase, megacities are today already suffering severe water shortages in terms of both quality and quantity. Vertical Farming and other greenhouse practices, with their system-immanent water control practices, may well contribute to minimizing this problem. World agriculture is responsible for more than 70% of annual global water withdrawal. Cultivation methods such as hydroponics in closed environments drastically reduce water consumption for crop production.

City and land use: with every m2 the urban area increases, agricultural land inevitably increases ten times. Central urban areas are expensive. In most Asian megacities, the settlement density is much higher than in old established European cities. These circumstances are influential on two levels: the light gain for Vertical Farms in an area of high density might decrease by such an amount that the power demand required may well increase drastically. On an urbanistic level, investigations could well prove interesting on whether Vertical Farms in peri-urban zones, still connected to the existing traffic network, might have a positive effect for a typologically different redensification of the low-density peri-urban belt compared to the city center.

City, land use and carbon: Results of Chapter 5 show average soil based area equivalents for achieving the same yield of 13,000 m2 or 1.3 ha. It might be interesting to follow the concept of “carbon sink” to achieve more precise data for evaluating the advantage of reducing the conversion of natural land (over all forests) into agricultural land. The aforementioned area potentially stores from 1.45 to 3.2 t C/ha[442] .
This value corresponds to a CO2eq. from 5.3 to 11.7 t CO2eq.

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[441] Prof. Markus Schäfer for DANIEL PODMIRSEG, 2008. The Vertical Farm Project for London - SPUROPE 2050, Diploma, Academy of Fine Arts, Vienna, Guest-Prof. Markus Schäfer

[442] Raw assumption based on numbers retrieved from SMIL, V. 2008. Energy in Nature and Society, Cambridge, Mass., MIT Press. p.69

Cities and carbon: private and public transport, industry and the urban dwellers themselves release enormous quantities of CO2, which is essential for photosynthesis. The extent to which CO2-capturing could be possible, e.g. by enabling CO2-cycles between different urban uses and plant growth, should be investigated in greater depth. The concept of Vertical Farming developed by Plantagon and Sweco in Linköping must be quoted here. CO2 from the biodigester is delivered to the production greenhouse, as well as excess heat. The concept of “industrial symbiosis” adds weight to this idea.[443]

Cities and employment: “Vertical Harvest” in Jackson, Wyoming[444] follows the concept of working together intensively with the community, also ensuring meaningful employment opportunities for disabled people. Vertical Farming will undoubtedly be more labor intensive than soil based practices. “Large dimensioned farm machinery will not be an option”[445] To what extent Vertical Farming could contribute to the widespread issue of underemployment in urban areas must be investigated.

Cities and politics: developing and developed countries and their cities in particular are vastly dependent on agricultural production areas outside their national borders. Food politics leads not infrequently, to geopolitical conflicts on both a domestic and an international scale. If cities reduce their dependency on agricultural land outside their national borders, the question arises of achieving a stabilization of (inter-)national relationships.

Cities and real estate: urban voids are expensive. Additional feasibility studies are necessary to determine what conditions are necessary to make Vertical Farming a profitable business proposition. It is estimated that only 20% of the money spent on food finds its way to the farmers. The differences in the food price this imbalance represents have their roots in the long food chain. Vertical Farms could sell their produce directly in the city areas where they are located. The question of whether this will result in a balance with the investment costs out is worth examining in further studies.

World population will continue to grow, and changes in diets are most likely to be expected. Agricultural land most likely will continue to expand and change natural habitat into productive land. World agriculture is dependent on hydrocarbon energy sources and world transport is run almost entirely on oil.

Although Vertical Farming per se is not the solution to these problems, we have seen that this production method comprises the potential to relieve the pressures of the current situation. The right design strategies defined by architects entail the potential to drastically reduce the energy demand. Furthermore, if the implementation of the building is understood as an urban operation, i.e. as an integration of a structural element into a system, Vertical Farms could contribute to change urban material and energy flows from linear to circular.

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[443] http://plantagon.com/urban-agriculture/industrial-symbiosis, retrieved 03.11.2015

[444] http://verticalharvestjackson.com/our-team/, retrieved 03.11.2015

[445] DESPOMMIER, D. 2010. The Vertical Farm, New York, St. Martin‘s Press. p.171 ff.

# List of Abbreviations

| | |
|---|---|
| ASHRAE | America Society of Heating, Refrigerating, and Air-Conditionio ning Engineers |
| ASPO | Association for the Studies of Peak Oil and Gas |
| A/V | Area divided by volume - ratio |
| BMR | Basal Metabolic Rate |
| CIE | Commission Internationale de l‘Eclairage |
| DG | Double Glazing Facade |
| DGE | Deutsche Gesellschaft für Ernährung |
| DLI | Daylight Integral |
| EC | Electric Conductivity |
| EE | Embodied Energy |
| EJ | Exajoule |
| ETFE | Double-ETFE-layered Facade |
| F1 | Filial 1 hybrid |
| FAO | Food and Agriculture Organization of the United Nations |
| FBS | Food Balance Sheets |
| FSC | Food Supply Chain |
| GAEZ | Global Agro-Ecological Zones |

| | |
|---|---|
| GDP | Gross Domestic Product |
| GFA | Gross Floor Area |
| GH | Greenhouse |
| GHG | Greenhouse Gas |
| GW | Gigawatt |
| ha | hectare |
| HID | High Intensity Discharge |
| HPS | High Pressure Sodium Lamps |
| HVAC | Building services, heating, ventilation and air conditioning |
| IEA | International Energy Agency |
| IFPRI | International Food Policy Research Institute |
| IIASA | International Institute for Applied Systems Analysis |
| J | Joule |
| K | Kelvin |
| kW | Kilowatt |
| LED | Light Emitting Diode |
| LUC | Land-use change |
| MJ | Megajoule |
| MW | Megawatt |
| Mt | Metric tonne (1000 kg) |

| | |
|---|---|
| NFA | Net Floor Area |
| nm | Nanometer |
| PAL | Physical Activity Level |
| PAR | Photosynthetically Active Radiation |
| PJ | Petajoule |
| Pcal | Petacalorie |
| PPFD | Photosynthetic Photon Flux Density |
| RDA | Rural Development Administration (South Korea) |
| SG | Single Glazing Facade |
| SI | International System of Units |
| THz | Terahertz |
| TPES | Total Primary Energy Supply |
| UNCED | United Nations Conference on Environment and Development |
| UNDP | United Nations Development Programme |
| UNFCCC | United Nations Framework Convention on Climate Change |
| UNO | United Nations Organizations |
| UV | Ultra Violet |
| VF | Vertical Farm |
| VF7 | Simulation Model Vertical Farm 36m x 7.2m x 61m |
| VF14 | Simulation Model Vertical Farm 36m x 14.4m x 33m |

| | |
|---|---|
| VF32 | Simulation Model Vertical Farm 36m x 32m x 12m |
| W | Watt |
| WPAR | Watt within the range of 400 - 700 nm |
| WHO | World Health Organization |
| OECD | Organisation for Economic Cooperation and Development |
| ZINEG | Zukunftsinitiative Niedrigenergiegewächshaus |

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# Nomenclatura

**AVOGRADO‘S NUMBER:** „number of units in one mole of any substance (defined as its molecular weight in grams), equal to 6.02214129 × 1023. The units may be electrons, atoms, ions, or molecules, depending on the nature of the substance and the character of the reaction (if any). See also Avogadro’s law.“[446]

**BASAL METABOLIC RATE:** „Basal metabolic rate (BMR), index of the general level of activity of an individual’s body metabolism, determined by measuring his oxygen intake in the basal state—i.e., during absolute rest, but not sleep, 14 to 18 hours after eating. The higher the amount of oxygen consumed in a certain time interval, the more active is the oxidative process of the body and the higher is the rate of body metabolism. The BMR has been used in measuring the general metabolic state during therapy. It was formerly widely used to assess thyroid function, since the thyroid hormones are prime regulators of tissue oxidation and metabolism; but, since the advent of radioactive-isotope tests and thyroid-hormone studies, BMR measurements have fallen into disuse. (...) Energy is needed not only when a person is physically active but even when the body is lying motionless. Depending on an individual’s level of physical activity, between 50 and 80 percent of the energy expended each day is devoted to basic metabolic processes (basal metabolism), which enable the body to stay warm, breathe, pump blood, and conduct numerous physiological and biosynthetic activities, including synthesis of new tissue in growing children and in pregnant and lactating women. Digestion and subsequent processing of food by the body also uses energy and produces heat. This phenomenon, known as the thermic effect of food (or diet-induced thermogenesis), accounts for about 10 percent of daily energy expenditure, varying somewhat with the composition of the diet and prior dietary practices. Adaptive thermogenesis, another small but important component of energy expenditure, reflects alterations in metabolism due to changes in ambient temperature, hormone production, emotional stress, or other factors. Finally, the most variable component in energy expenditure is physical activity, which includes exercise and other voluntary activities as well as involuntary activities such as fidgeting, shivering, and maintaining posture. Physical activity accounts for 20 to 40 percent of the total energy expenditure, even less in a very sedentary person and more in someone who is extremely active.“[447]

**DAYLIGHT INTEGRAL:** „(...)the daylight integral, is the cumulative amount of photosynthetic light that is received each day. The DLI is measured as the number of moles of light (mol) per square meter (m2) per day (d1), or mol/m2/d. The DLI can have a profound effect on root and shoot growth of seedling plugs, root development of cutting and finish plant quality

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[446] http://www.britannica.com/EBchecked/topic/45889/Avogadros-number, retrieved 11.09.2014

[447] http://www.britannica.com/EBchecked/topic/54585/basal-metabolic-rate, retrieved 06.12.2014

attributes such as stem thickness, plant branching and flower number.“[448] DLI is measured by the cumulative amount of rain or light received during a 24-h-period. It is dependent on the time of the year (sun‘s angle), location, latitude and cloud cover and the daylength (photoperiod).

**ETFE** „stands for Ethylene Tetrafluoroethylene, a transparent polymer that is used instead of glass and plastic in some modern buildings. Compared to glass, ETFE: tansmits more light, insulates better, costs (...) less to install, is only 1/100 the weight of glass.“[449]

**EVAPOTRANSPIRATION:** „Loss of water from the soil both by evaporation from the soil surface and by transpiration from the leaves of the plants growing on it. Factors that affect the rate of evapotranspiration include the amount of solar radiation, atmospheric vapor pressure, temperature, wind, and soil moisture. Evapotranspiration accounts for most of the water lost from the soil during the growth of a crop. Estimation of evapotranspiration rates is thus important in planning irrigation schemes.“[450]

**F1 - HYBRID VARIETIES:** „The development of hybrid varieties differs from hybridization in that no attempt is made to produce a pure-breeding population; only the F1 hybrid plants are sought. The F1 hybrid of crosses between different genotypes is often much more vigorous than its parents. This hybrid vigour, or heterosis, can be manifested in many ways, including increased rate of growth, greater uniformity, earlier flowering, and increased yield, the last being of greatest importance in agriculture.“[451] LED or LIGHT EMITTING DIODES: „in full light-emitting diode, in electronics, a semiconductor device that emits infrared or visible light when charged with an electric current. Visible LEDs are used in many electronic devices as indicator lamps, in automobiles as rear-window and brake lights, and on billboards and signs as alphanumeric displays or even full-colour posters. Infrared LEDs are employed in autofocus cameras and television remote controls and also as light sources in fibre-optic telecommunication systems. (...) By varying the precise composition of the semiconductor, the wavelength (and therefore the colour) of the emitted light can be changed. LED emission is generally in the visible part of the spectrum [from 400 to 700 nm (A/N)] or in the near infrared [from 700 to 2.000 nm (A/N)]. The brightness of the light observed from an LED depends on the power emitted by the LED and on the relative sensitivity of the eye at the emitted wavelength. Maximum sensitivity occurs at 0.555 micrometre, which is in the yellow-orange and green region. The applied voltage in most LEDs is quite low, in the region

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[448] RUNKLE, E. 2006. Do you know what your DLI is? Available: http://www.hrt.msu.edu/energy/Notebook/pdf/Sec1/Do_you_know_what_your_DLI_is_by_Runkle.pdf.

[449] http://architecture.about.com/od/construction/g/ETFE.htm

[450] http://www.britannica.com/search?query=evapotranspiration; retrieved 14.09.2014

[451] http://www.britannica.com/EBchecked/topic/463294/plant-breeding/67745/Hybrid-varieties; retrieved 14.09.2014

of 2.0 volts; the current depends on the application and ranges from a few milliamperes to several hundred milliamperes. (...)“[452]

**GREENHOUSE:** „also called glasshouse,  building designed for the protection of tender or out-of-season plants against excessive cold or heat. In the 17th century greenhouses were ordinary brick or timber shelters with a normal proportion of window space and some means of heating. As glass became cheaper and as more sophisticated forms of heating became available, the greenhouse evolved into a roofed and walled structure built of glass with a minimal wooden or metal skeleton. By the middle of the 19th century, the greenhouse had developed from a mere refuge from a hostile climate into a controlled environment, adapted to the needs of particular plants. A huge increase in the availability of exotic plants in the 19th century led to a vast increase in glasshouse culture in England.[453]

**HAITZ‘S LAW**: In 2000 Dr. Roland Haitz on the converence „Strategies in Light“ presented his observation that every ten years costs per Lumen decreases by factor 10, while the amount of light LEDs are producing increases by the factor 20 (for a certain wavelength). Meanwhile this observation is defined as Haitz‘s law.[454] [455]

**HYDROPONICS:** „also called Aquaculture, Nutriculture, Soilless Culture, or Tank Farming,  the cultivation of plants in nutrient-enriched water, with or without the mechanical support of an inert medium such as sand or gravel. Plants have long been grown with their roots immersed in solutions of water and fertilizer for scientific studies of their nutrition. Early commercial hydroponics (from Greek hydro, “water,” and ponos, “labour”) adopted this method of culture. Because of the difficulties in supporting the plants in a normal upright growing position and aerating the solution, however, this method was supplanted by gravel culture, in which gravel supports the plants in a watertight bed or bench. Various kinds of gravel and other materials have been used successfully, including fused shale and clay and granite chips. Fertilizer solution is pumped through periodically, the frequency and concentration depending on the plant and on ambient conditions such as light and temperature. The solution drains into a tank, and pumping is usually automatic.The solution is composed of different fertilizer-grade chemical compounds containing varying amounts of nitrogen, phosphorus, and potassium—the major elements necessary for plant growth—and various trace, or minor, elements such as sulfur, magnesium, and calcium. The solution can be used indefinitely; periodic tests indicate the need for additional chemicals or water. The chemical ingredients usually may be mixed dry and stored. As the plants grow, concentration of the solution and frequency of pumping are increased. A wide variety of vegetables and florist crops can be grown satisfactorily in gravel. The principal advantage is

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[452] http://www.britannica.com/technology/LED, retrieved 13.03.2014

[453] http://www.britannica.com/topic/greenhouse, retrieved 09.08.2014

[454] http://www.nature.com/nphoton/journal/v1/n1/full/nphoton.2006.78.html

[455] http://www.ledsmagazine.com/articles/2015/08/in-tribute-recognizing-the-life-and-work-of-led-pioneer-roland-haitz.html

the saving of labour by automatic watering and fertilizing. The disadvantages are high installation costs and the need to test the solution frequently. Yields are about the same as for soil-grown crops.“[456]

**LIGHT COMPENSATION POINT:** There is a break-even where the plant is producing as much sugar as it needs for respiration. This point is defined as light compensation point. As light increases (and water is available) carbon production also increases. The plant therefor exceeds its carbon production, the surplus is transformed into glucose. Principally, exceeding the light compensation point, is the main goal in food production. By ncreasing brightness and intensity within PAR, of photosynthesis-rate also increases, „but only up to a certain point, beyond which increasing the brightness of light has little or no effect on the rate of photosyntesis. (...) The light intensity at which the net amount of oxygen produced is exactly zero, is called the compensation point for light.“[457] At this point the consumption of oxygen by the plant due to cellular respiration is equal to the rate at which oxygen is produced by photosynthesis.[458]

**LIGHT SATURATION POINT:** On the other side of the „photosynthesis activating point“ we could call the light compensation point an other point is essential in plant cultivation: the light saturation point. „The saturation point describes the amount of light that is beyond the capability of the chloroplast to absorb. Photosynthesis still occurs, but the amount of light has exceeded the amount of pigments that are available for absorption.“[459] This saturation point is different to every plant. „Different plants have different saturation points, determined by the number of pigments in their chlorophyll cells. Plants that typically grow in shaded areas have lower saturation points, while those that grow in areas more exposed to light have higher saturation points.

***LYCOPERSICON ESCULENTUM* (MILL.):** flowering plant of the nightshade family (Solanaceae), cultivated extensively for its edible fruits. Labelled as a vegetable for nutritional purposes, tomatoes are a good source of vitamin C and the phytochemical lycopene. The fruits are commonly eaten raw in salads, served as a cooked vegetable, used as an ingredient of various prepared dishes, and pickled. Additionally, a large percentage of the world’s tomato crop is used for processing; products include canned tomatoes, tomato juice, ketchup, puree, paste, and “sun-dried” tomatoes or dehydrated pulp.[460]

**MOL:** „is a unit of measurement used in physics and chemistry to express amounts of elements, defined as the amount of any substance that contains as many elementary entities (e.g.,

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[456] http://www.britannica.com/EBchecked/topic/279000/hydroponics, retrieved 13.03.2015

[457] http://Tomatosphere.org/teachers/guide/grades-8-10/plants-and-light, retrieved 12.09.2014

[458] ibid.

[459] http://www.ehow.com/about_6535863_definition-plant-light-saturation.html, retrieved 12.09.2014

[460] http://www.britannica.com/plant/tomato, retrieved 26.09.2015

atoms, molecules, ions, electrons) as there are atoms in 12 grams of pure carbon-12 (12C), the isotope of carbon with relative atomic mass of exactly 12 by definition. This corresponds to the Avogadro constant, which has a value of 6.02214129(27)·$10^{23}$ elementary entities of the substance.“[461] A mole of photons, therefor consists in 602 trillion light particles.

**PAR, PHOTOSYNTHETICALLY ACTIVE RADIATION:** „is the waveband 400 to 700 nm, which are the limits of wavelengths that are of primary importance for plant photosynthesis. The PPFD, Photosynthetic Photon Flux Density is the number of photons in the PAR waveband that are incident on a surface in a give time period (μmol/$m^{-2}$/$s^{-1}$). The quantum sensor will measure this value. A very clear sky value will approch approx. 2000μmol/$m^{-2}$/$s^{-1}$ PAR.“[462] The PPFD-number for a clear sunny sky differs up to 15% regarding differend studies, from 1700 μmol/$m^{-2}$/$s^{-1}$ (also used by Gene Giacomelli) to 2000 μmol/$m^{-2}$/$s^{-1}$. This work uses 1800 μmol/$m^{-2}$/$s^{-1}$ for a clear sunny day. Most conversion calculators from horticulturalist and grow lamp manufacturers use the factor 0,018 to convert lux to μmol/$m^{-2}$/$s^{-1}$ and the factor 0.219 from Photons to W (sunlight) or 4.57 from W (sunlight to Photons.[463] „The term PAR and its units (...) [are] an important concept to understand and use.(...) Clearly, the human eye cannot even begin to respond to many of the wavelengths before 500 nm and beyond 600 nm. The plant leaf response, however, extends beyond the PAR waveband of 400 - 700 nm. (...)“[464]

**PEAK OIL, PEAK OIL THEORY:** „a contention that conventional sources of crude oil, as of the early 21st century, either have already reached or are about to reach their maximum production capacity worldwide and will diminish significantly in volume by the middle of the century. “Conventional” oil sources are easily accessible deposits produced by traditional onshore and offshore wells, from which oil is removed via natural pressure, mechanical walking beam pumps, or well-known secondary measures such as injecting water or gas into the well in order to force oil to the surface. The peak oil theory does not apply to so-called unconventional oil sources, which include oil sands, oil shales, oil extracted after fracking “tight rock” formations, and oil found in deepwater wells far offshore—in short, any deposit of oil that requires substantial investment and labour to exploit.“ Proponents of peak oil theory do not necessarily claim that conventional oil sources will run out immediately and create acute shortages, resulting in a global energy crisis. Instead, the theory holds that, with the production of easily extractable oil peaking and inevitably declining (even in formerly bounteous regions such as Saudi Arabia), crude-oil prices are likely to remain high and even rise further over time, especially if future global oil demand continues to rise along

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[461] International Bureau of Weights and Measures (2006), The International System of Units (SI) (8th ed.), pp. 114–15, ISBN 92-822-2213-6

[462] GIACOMELLI, G. 1998. Components of Radiation Defined: Definition of Units, Measuring Radiation Transmission, Sensors. CCEA, Center for Controlled Environment Agriculture, rutgers university, Cook College.

[463] ibid.

[464] GIACOMELLI, G. 1998. Components of Radiation Defined: Definition of Units, Measuring Radiation Transmission, Sensors. CCEA, Center for Controlled Environment Agriculture, rutgers university, Cook College.

with the growth of emerging economies such as China and India. Although peak oil theory may not portend prohibitively expensive gasoline any time soon, it does suggest that the days of inexpensive fuel, as were seen for more than a decade after the collapse of OPEC cartel prices in the mid-1980s, will probably never return. [465]

**PHOTOPERIODISM:** „is another attribute of plants that may be changed or manipulated in the microclimate. The length of a day is a photoperiod, and the responses of the plant development to a photoperiod are called photoperiodism. Response to the photoperiod is different for different plants; long-day plants flower only under day lengths longer than 14 hours; in short-day plants, flowering is induced by photoperiods of less than 10 hours; day-neutral plants form buds under any period of illumination. There are exceptions and variations in photoperiodic response; also, it is argued that the truly critical factor is actually the amount of exposure to darkness rather than to daylight. Temperature is intimately related to photoperiodism, tending to modify reactions to daylength. Photoperiodism is one determining factor in natural distribution of plants throughout the world. The phenomenon has many practical applications. Selection of a plant or a variety for a given locality requires knowledge of its interaction with the photoclimate. Artificial illumination is used to control flowering seasons and to increase production of greenhouse crops. In plant breeding, such stimulation of flowering has greatly reduced the time span from germination to maturity, shortening the time necessary to develop new varieties. In sowing field crops, photoperiodism can be used to select the date of sowing to produce optimum harvest size. Crop yield is reduced both by planting in a season that will cause plants to flower early and by planting at a time that will cause very late flowering. In Sri Lanka (formerly Ceylon), certain rice varieties with a vegetative period of five to six months may extend their life to more than a year when planted in the wrong season, causing almost complete loss of yield. Cowpeas in Nigeria will flower early and produce many seeds only when planted in daylengths of 12 hours or less.[466]

**PLANCK‘S CONSTANT:** (symbol h), „fundamental physical constant characteristic of the mathematical formulations of quantum mechanics, which describes the behaviour of particles and waves on the atomic scale, including the particle aspect of light. The German physicist Max Planck introduced the constant in 1900 in his accurate formulation of the distribution of the radiation emitted by a blackbody, or perfect absorber of radiant energy (see Planck’s radiation law). The significance of Planck’s constant in this context is that radiation, such as light, is emitted, transmitted, and absorbed in discrete energy packets, or quanta, determined by the frequency of the radiation and the value of Planck’s constant. The energy E of each quantum, or each photon, equals Planck’s constant h times the radiation frequency symbolized by the Greek letter nu, ʋ, or simply E = hʋ. A modified form of Planck’s constant called h-bar ($\hbar$), or the reduced Planck’s constant, in which $\hbar$ equals h divided by 2π, is the quantization of angular momentum. For example, the angular

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[465] http://www.britannica.com/topic/peak-oil-theory, retrieved 26.09.2014; also see M.King Hubbert, Colin J. Campbell, ASPO (Association for the Studies of Peak Oil and Gas“.

[466] http://www.britannica.com/EBchecked/topic/9620/agricultural-technology/67813/The-degree-day, retrieved 16.03.2015

momentum of an electron bound to an atomic nucleus is quantized and can only be a multiple of h-bar. The dimension of Planck’s constant is the product of energy multiplied by time, a quantity called action. Planck’s constant is often defined, therefore, as the elementary quantum of action. Its value in metre-kilogram-second units is 6.62606957 × 10−34 joule · second, with a standard uncertainty of 0.00000029 × 10−34 joule · second.“[467]

**PPFD:** Photosynthetic Photon Flux Density is the number of photons within the PAR -waveband that is incident on a surface in a give[n] time period (λmol m2/s). The quantum sensor will measure this value. When considered as a photon it may be expressed in energy terms, Watts per square meter (W/m2), or as the number of photons (moles of photons) μmol/m$^{-2}$/s$^{-1}$. Wavelength (λ, A/N) has units of meters, typically nanometers (nm) [...] or micrometers (μm). Frequency (f, A/N) has units of cycle per second. Together they are related as parameters of a photon of light by the constant c, the speed of light (299.792.458 m/s, A/N). The frequency of the photon is equal to the speed of light divided by wavelength of the photon. The energy of a wavelength of light is equal to Planck’s constant (h = 6,626·10-34 Js, A/N) multiplied by the speed of light and divided by the wavelength. From this relationship, an important fact is determined. For radiation (light), as its wavelength increases, its energy decreases, and as the wavelength decreases, the energy increases. Thus short wave blue light has more energy than longer wave red light.”[468]

**RHIZOSPHERE:** is the area (...) [volume, Ed.] around the root (soil in near contact with roots) which is rich in nutrients and directly influenced by the secretions of plant root exudates and microorganisms.[469]

**SOLANUM / SOLANACEA or NIGHTSHADE:** genus of about 2,300 species of flowering plants in the nightshade family (Solanaceae). The term nightshade is often associated with poisonous species, though the genus also contains a number of economically important food crops, including tomato (Solanum lycopersicum), potato (S. tuberosum), and eggplant (S. melongena). Nightshades are annuals or perennials and range in size from small herbs to small trees. The alternate leaves can be simple or pinnately compound and usually feature glandular or nonglandular trichomes (plant hairs). The leaves and stems are sometimes armed with prickles. The flowers have five petals that are often fused. The flowers usually are white, yellow, or purple and are borne in clusters. The fruit is a berry. The species usually called nightshade in North America and the United Kingdom is S. dulcamara, also known as bittersweet and woody nightshade. Its foliage and egg-shaped red berries are poisonous, the active principle being solanine, which can cause convulsions and death if taken in large doses. The black nightshade (S. nigrum) is also generally considered poisonous, but its fully ripened fruit and foliage are cooked and eaten in some areas. A number of plants outside the genus Solanum are also known as nightshades. The aptly named deadly nightshade, or

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[467] http://www.britannica.com/EBchecked/topic/559095/planck constant, retrieved, 11.09.2014

[468] GIACOMELLI, G. 1998. Components of Radiation Defined: Definition of Units, Measuring Radiation Transmission, Sensors. CCEA, Center for Controlled Environment Agriculture, rutgers university, Cook College., p.2

[469] http://www.researchgate.net/post/What_is_the_best_definition_of_rhizosphere, retrieved 27.09.2015

belladonna (Atropa belladonna), is a tall bushy herb of the same family and the source of several alkaloid drugs. Enchanter’s nightshade is a name applied to plants of the genus Circaea (family Onagraceae). Malabar nightshade, also known as Malabar spinach, refers to twining herbaceous vines of the genus Basella (family Basellaceae).

SPEED OF LIGHT: „speed at which light waves propagate through different materials. In particular, the value for the speed of light in a vacuum is now defined as exactly 299,792,458 metres per second. The speed of light is considered a fundamental constant of nature. Its significance is far broader than its role in describing a property of electromagnetic waves. It serves as the single limiting velocity in the universe, being an upper bound to the propagation speed of signals and to the speeds of all material particles. In the famous relativity equation, E = mc2, the speed of light (c) serves as a constant of proportionality linking the formerly disparate concepts of mass (m) and energy (E).“[470]

**TOMATO**: see *LYCOPERSICON ESCULENTUM* (MILL.)

**TPES or TOTAL PRIMARY ENERGY SUPPLY:** „equals production plus imports minus exports minus international bunkers plus or minus stock changes. The International Energy Agency (IEA) energy balance methodology is based on the calorific content of the energy commodities and a common unit of account. The unit of account adopted is the tonne of oil equivalent (toe) which is defined as 107 kilocalories (41.868 gigajoules). This quantity of energy is, within a few per cent, equal to the net heat content of one tonne of crude oil. The difference between the “net” and the “gross” calorific value for each fuel is the latent heat of vaporisation of the water produced during combustion of the fuel. For coal and oil, net calorific value is about 5% less than gross, for most forms of natural and manufactured gas the difference is 9-10%, while for electricity there is no difference. The IEA balances are calculated using the physical energy content method to calculate the primary energy equivalent.“[471]

**VERTICAL FARMING:** Vertical Farming is defined as a highly industrialized year round cultivation method for food production, adaptable for multiple crop types, where the verticalized building typology, its programme and functions primarily focus on optimium plant growth. The building is seen as a structural element of the urban ecosystem. In addition to food production, the Vertical Farm must incorporate elements of the food sector which, at present, are spatially detached from each other on a global scale, something which has a severe impact on energy consumption and the environment.

## *CONCEPTS AND DEFINITIONS - RETRIEVED FROM FAO:*

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[470] http://www.britannica.com/EBchecked/topic/559095/speed-of-light; retrieved 11.09.2014

[471] http://www.oecd-ilibrary.org/sites/factbook-2013-en/06/01/01/index.html?containerItemId=%2Fcontent%2Fserial%2F18147364&itemId=%2Fcontent%2Fchapter%2Ffactbook-2013-41-en&mimeType=text%2Fhtml

**FOOD BALANCE SHEETS:** „(FBS) provide essential information on a country's food system through three components: 1. Domestic food supply of the food commodities in terms of production, imports, and stock changes, 2. Domestic food utilization which includes feed, seed, processing, waste, export, and other uses and 3.per capita values for the supply of all food commodities (in kilograms per person per year) and the calories, protein, and fat content. Annual food balance sheets show the trends in the overall national food supply, disclose changes that may have taken place in the types of food consumed, and reveal the extent to which the food supply of the country is adequate in relation to nutritional requirements. Food balance sheets provide other relevant statistics that can be used in designing and targeting policies to reduce hunger in countries. The import dependency ratio for food, that compares the quantities of food available for human consumption with those imported, indicates the extent to which a country depends upon imports to feed itself. The amount of food crops used for feeding livestock in relation to total crop production indicates the degree to which primary food resources are used to produce animal feed which is useful information for analyzing livestock policies or patterns of agriculture. Data on per caput food supplies are an important element for projecting food demand, together with such other elements as income elasticity coefficients, projections of private consumption expenditure and population."[472]

**PRODUCTION:** „For primary commodities, production should relate to the total domestic production whether inside or outside the agricultural sector, i.e. including non-commercial production and production in kitchen gardens. Unless otherwise indicated, production is reported at the farm level for primary crops (i.e. excluding harvesting losses for crops) and livestock items and in terms of live weight (i.e. the actual ex-water weight of the catch at the time of capture) for primary fish items. Production of processed commodities relates to the total output of the commodity at the manufacture level (i.e. it comprises output from domestic and imported raw materials of originating products). Reporting units are chosen accordingly, e.g. cereals are reported in terms of grains and paddy rice. As a general rule, all data on meat are expressed in terms of carcass weight. Usually the data on production relate to that which takes place during the reference period. However, production of certain crops may relate to the harvest of the year preceding the utilization period if harvesting takes place late in the year. In such instances, the production of a given year largely moves into consumption in the subsequent year. In the sample Form II of the food balance sheet, located at the end of this document, a distinction is made between „output" and „input". The production of primary as well as of derived products is reported under „output". For derived commodities, the amounts of the originating commodity that are required for obtaining the output of the derived product are indicated under „input", and are expressed in terms of the originating commodity."[473]

**CHANGES IN STOCKS:** „In principle, this comprises changes in stocks occurring during the reference period at all levels from production to the retail stage, i.e. it comprises changes in government stocks, in stocks with manufacturers, importers, exporters, other wholesale

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[472] http://www.fao.org/economic/ess/fbs/en/, retrieved 12.08.2014

[473] http://www.fao.org/economic/ess/fbs/en/, retrieved 12.08.2014

and retail merchants, transport and storage enterprises, and in stocks on farms. In practice, though, the information available often relates only to stocks held by governments, and even this is, for a variety of reasons, not available for a number of countries and important commodities. It is because of this that food balance sheets are usually prepared as an average for several years as this is believed to reduce the degree of inaccuracy contributed by the absence of information on stocks. Increases in stocks of a commodity reduce the availability for domestic utilization. They are therefore indicated by the - sign and decreases in stocks by the + sign since they increase the available supply. In the absence of information on opening and closing stocks, changes in stocks are also used for shifting production from the calendar year in which it is harvested to the year in which it enters domestic utilization or is exported."[474]

**GROSS IMPORTS:** „In principle, this covers all movements of the commodity in question into the country as well as of commodities derived therefrom and not separately included in the food balance sheet. It, therefore, includes commercial trade, food aid granted on specific terms, donated quantities, and estimates of unrecorded trade. As a general rule, figures are reported in terms of net weight, i.e. excluding the weight of the container."[475]

**SUPPLY:** „There are various possible ways to define „supply" and, in fact, various concepts are in use. The elements involved are production, imports, exports and changes in stocks (increases or decreases). There is no doubt that production, imports, and decreases in stocks are genuine supply elements. Exports and increases in stocks might, however, be considered to be utilization elements. Accordingly, the following possibilities exist for defining „supply". (a) Production + imports + decrease in stocks = total supply. (b) Production + imports + changes in stocks (decrease or increase) = supply available for export and domestic utilization. (c) Production + imports - exports + changes in stocks (decrease or increase) = supply for domestic utilization."[476]

**GROSS EXPORTS:** „In principle, this covers all movements of the commodity in question out of the country during the reference period. The conditions specified for gross imports, under 3. above, apply also to exports by analogy. A number of commodities are processed into food and feed items. Therefore, there is a need to identify the components of the processed material exported in order to arrive at a correct picture of supplies for food and feed in a given time-reference period."[477]

**FEED:**"This comprises amounts of the commodity in question and of edible commodities derived therefrom not shown separately in the food balance sheet (e.g. dried cassava, but excluding

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[474] ibid.

[475] ibid.

[476] ibid. http://www.fao.org/economic/ess/fbs/en/, retrieved 12.08.2014

[477] http://www.fao.org/economic/ess/fbs/en/, retrieved 12.08.2014

by-products, such as bran and oilcakes) that are fed to livestock during the reference period, whether domestically produced or imported.“[478]

**SEED:**“In principle, this comprises all amounts of the commodity in question used during the reference period for reproductive purposes, such as seed, sugar cane planted, eggs for hatching and fish for bait, whether domestically produced or imported. Whenever official data are not available, seed figures can be estimated either as a percentage of production (e.g. eggs for hatching) or by multiplying a seed rate with the area under the crop of the subsequent year. In those cases where part of the crop is harvested green (e.g. cereals for direct feed or silage, green peas, green beans) an adjustment must be made for this area. Usually, the average amount of seed needed per hectare planted in any given country, does not greatly vary from year to year.“[479]

**FOOD MANUFACTURE:** „The amounts of the commodity in question used during the reference period for manufacture of processed commodities for which separate entries are provided in the food balance sheet either in the same or in another food group (e.g. sugar, fats and oils, alcoholic beverages) are shown under the column Food Manufacture. Quantities of the commodity in question used for manufacture for non-food purposes, e.g. oil for soap, are shown under the element Other Uses. The processed products do not always appear in the same food group. While oilseeds are shown under the aggregate Oilcrops, the respective oil is shown under the Vegetable Oils group; similarly, skim milk is in the Milk group, while butter is shown under the aggregate Animal Fats. Barley, maize, millet and sorghum are in the Cereals group, while beer made from these cereals is shown under the Alcoholic Beverages group. The same principle applies for grapes and wine.“[480]

**WASTE:** „This comprises the amounts of the commodity in question and of the commodities derived therefrom not further pursued in the food balance sheets, lost at all stages between the level at which production is recorded and the household, i.e. losses during storage and transportation. Losses occurring during the pre-harvest and harvesting stages are excluded (see note on „Production“). Technical losses occurring during the transformation of the primary commodities into processed products are taken into account in the assessment of respective extraction/conversion rates.Post-harvest losses in most countries are substantial owing to the fact that most of the grain production is retained on the farm so as to provide sufficient quantities to last from one harvest to the next. Farm storage facilities in many countries tend to be primitive and inadequately protected from the natural competitors of man for food. Losses become even more serious in countries where agricultural products reach consumers in urban areas after passing through several marketing stages. In fact, one of the major causes of food losses in some countries is the lack of adequate marketing systems and organization. Much food remains unsold because of the imbalances of supply and demand. This is particularly true of perishable foods, such as fresh fruit and vegetables.

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[478] ibid.

[479] ibid.

[480] http://www.fao.org/economic/ess/fbs/en/, retrieved 12.08.2014

Post-harvest losses of fruit and vegetables of between 25 and 40 percent occur in many countries, mainly as a result of untimely harvesting and improper packing and/or transport. The waste of both edible and inedible parts of the commodity occurring in the household, e.g. in the kitchen, also is excluded.“[481]

**OTHER USES:** „In order not to distort the picture of the national food pattern, quantities of the commodity in question, consumed mainly by tourists, are included here (see also „12. Per Caput Supply“) as well as the amounts of the commodity in question used during the reference period for the manufacture for non-food purposes (e.g. oil for soap). Also statistical discrepancies are included here. They are defined as an inequality between supply and utilization statistics. The food balance sheets are compiled using statistics from various sources. Where no official data are available, other sources of information may be used. Many of the supply and utilization elements compiled from available information will not balance. Bringing together data from different sources would almost always result in an imbalance. Beyond the problem of data sources, imbalances usually fall into one of the following three situations: those occurring mainly in developed countries where there is no shortage of official statistics but the information is not internally consistent; cases in which the data are consistent but incomplete; and situations where data are both inconsistent and incomplete.“[482]

**FOOD:** „This comprises the amounts of the commodity in question and of any commodities derived therefrom not further pursued in the food balance sheet that are available for human consumption during the reference period. The element food of maize, for example, comprises the amount of maize, maize meal and any other products derived therefrom, like cornflakes, available for human consumption. The food element for vegetables comprises the amount of fresh vegetables, canned vegetables, and any other products derived therefrom. But the element food of milk relates to the amounts of milk available for human consumption as milk during the reference period, but not as butter, cheese or any other milk product provided for separately in the food balance sheet. It is important to note that the quantities of food available for human consumption, as estimated in the food balance sheet, reflect only the quantities reaching the consumer. The amount of food actually consumed may be lower than the quantity shown in the food balance sheet depending on the degree of losses of edible food and nutrients in the household, e.g. during storage, in preparation and cooking (which affect vitamins and minerals to a greater extent than they do calories, protein and fat), as plate-waste, or quantities fed to domestic animals and pets, or thrown away.“[483]

**PER CAPUT SUPPLY:** „Under this heading estimates are provided of per caput food supplies available for human consumption during the reference period in terms of quantity, caloric value, and protein and fat content. Per caput food supplies in terms of quantity are given

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[481] ibid.

[482] http://www.fao.org/economic/ess/fbs/en/, retrieved 12.08.2014

[483] ibid.

both in kilograms per year and grams per day, calorie supplies are expressed in kilo-calories (calories) per day, while supplies of protein and fat are provided in grams per day. It is proposed to retain the traditional unit of calories for the time being until such time as the proposed „kilojoule“ gains wider acceptance and understanding (1 calorie = 4.19 kilojoules).“[484]

## *FOOD LOSSES AND FOOD WASTES*

**FOOD LOSSES:** „refer to the decrease in edible food mass throughout the part of the supply chain that specifically leads to edible food for human consumption. Food losses take place at production, postharvest and processing stages in the food supply chain (Parfitt et al., 2010). Food losses occurring at the end of the food chain (retail and final consumption) are rather called “food waste”, which relates to retailers’ and consumers’ behavior. (Parfitt et al., 2010).“[485]

**FOOD WASTE OR LOSS:** „is measured only for products that are directed to human consumption, excluding feed and parts of products which are not edible. Per definition, food losses or waste are the masses of food lost or wasted in the part of food chains leading to “edible products going to human consumption”. Therefore food that was originally meant to human consumption but which fortuity gets out the human food chain is considered as food loss or waste even if it is then directed to a non-food use (feed, bioenergy…). This approach distinguishes “planned” non-food uses to “unplanned” non-food uses“[486]

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[484] ibid.

[485] http://www.fao.org/fileadmin/user_upload/suistainability/pdf/Global_Food_Losses_and_Food_Waste.pdf, retrieved 12.08.2015

[486] Global Food losses and food waste FAO p.2