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ABSTRACT

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

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Abstract

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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[1] *and changes in diet*[2] *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*[3] *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.

1 http://www.un.org/esa/population/publications/longrange2/WorldPop2300final.pdf, p.1, retrieved 10.09.2015
2 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.
3 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

FOOD AND ENERGY

World total primary energy supply (TPES) was around 550 Exajoule (EJ) in 2014.[1] A third of this energy is required by the food sector.[2] 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 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[3] and PNAS[4] 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 male requires 11.3 MJ, or 8.82 MJ for a sedentary female.[5] 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.[6] 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 food pro-

1 http://www.iea.org/publications/freepublications/publication/KeyWorld2013.pdf, retrieved 05.04.2014
2 FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 2011.Energy-Smart Food for People and Climate, Issue Paper, Rome:FAO
3 International Institute for Applied Systems Analysis, Vienna
4 Proceedings of the National Academy of Sciences of the United States of America
5 http://ajcn.nutrition.org/content/51/2/241.abstract, retrieved 12.06.2014
6 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.

duction. 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. [1]
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.[2] By assuming a per capita food supply of 900 kg/a which corresponds to FBS[3] 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.[4] From the total primary production of animal feed (for a world livestock of 57,064,502,778 animals)[5], 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.[6] 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 bio-capacity 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.[7] 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%.[8] 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 for food processing.[9] 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.

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1 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
2 http://faostat3.fao.org/download/Q/*/E
3 Food Balance Sheets, http://faostat.fao.org/site/354/default.aspx, retrieved 14.09.2015
4 http://www.fao.org/docrep/018/i3434e/i3434e.pdf, p.4 retrieved 13.08.2015
5 faostat3.fao.org/ live animals, 2011, retrieved 28.08.2015
6 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
7 FISCHER, G., VELTHUIZEN, H. V. & NACHTERGAELE, F. O. 2000. Global Agro-Ecological Zones Assessment: Methodology and Results. International Institute for Applied Systems Analysis, FAO
8 SMIL, V. 2008. Energy in Nature and Society, Cambridge, Mass., MIT Press., p.304
9 FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 2011.Energy-Smart Food for People and Climate, Issue Paper, Rome:FAO

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 north side of the productive greenhouse, enabling synergy potentials in terms of energy flows, oxygen- and CO_2-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[1], 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.“[2] To set up the simulation parameters, requirements for greenhouse tomatoes, Lycopersicon esculentum (Mill.), was chosen. This cultivar has a high requirement in terms of light and a relatively high requirement in terms of temperature.

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

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1 FAO Good agriclutural practices for greenhouse vegetable crops.pdf, p.9

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

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[1] 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 CO_2-emissions of 311.17 t/a or 0.51 kg CO_2/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.[2]

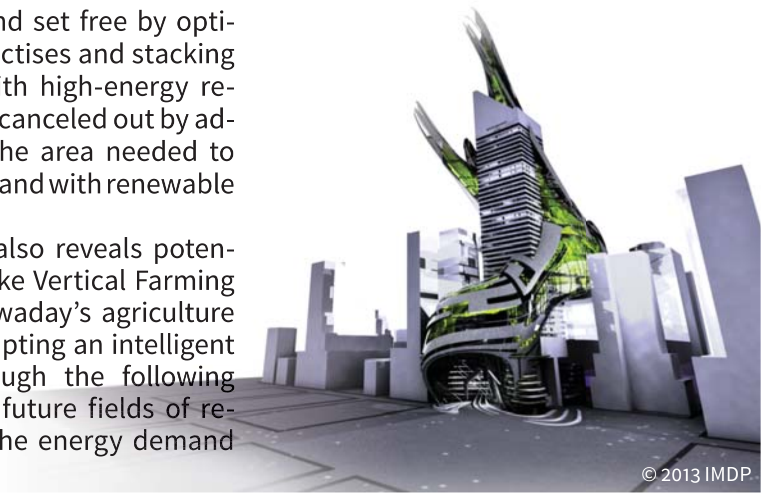
1 We assume the ratio that 24% of TPES of the food sector is related to the energy consumption until the farmgate. See Chapter 2.

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

The effect on reducing land use for agricultural production based on the upmentioned simulation models and considering the assumptions of other Vertical Farms 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. 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 [1]
- 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.[2]
- 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.



The aim therefor for future Form Follows Energy[1]-studies for Vertical Farms is to optimize the building shape to reduce TPES, secondly reading urban food production as a structural entity of the urban system, and furthermore 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."[2]

The strategic design decisions have shown that energy consumption can be reduced significantly. Furthermore, seeing the Vertical Farm as a structural element of a system, within an urban context, enables the potential to reduce the overall energy consumption by activating synergy potentials with other programmes and functions of the city.

1 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.

2 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

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