# Up, Up and Away! The Economics of Vertical Farming

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## Abstract

With rising population and purchasing power, demand for food and changing consumer preferences are building pressure on our resources. Vertical Farming, which means growing food in skyscrapers, might help to solve many of these problems. The purpose of this study was to construct a Vertical Farm and thereof investigate the economic feasibility of it. In a concurrent Engineering Study initiated by DLR Bremen, a farm, 37 floors high, was designed and simulated in Berlin to estimate the cost of production and market potential of this technology. It yields about 3,500 tons of fruits and vegetables and ca. 140 tons of tilapia fillets, 516 times more than expected from a footprint area of 0.25 ha due to stacking and multiple harvests. The investment costs add up to € 200 million, and it requires 80 million litres of water and 3.5 GWh of power per year. The produced food costs between € 3.50 and € 4.00 per kilogram. In view of its feasibility, we estimate a market for about 50 farms in the short term and almost 3000 farms in the long term. To tap the economic, environmental and social benefits of this technology, extensive research is required to optimise the production process.

**Keywords:** Vertical Farming, Market Potential, System Design, Production Economics

# 1. Introduction

According to the United Nations World Food Programme, nearly 1 billion people worldwide are undernourished (FAO, 2012). About 42% of these chronically hungry people live in India and China, two of the world's most populous nations (FAO, 2008). This already unacceptable situation is going to compound with growing population and therefore requires new approaches towards food production in the coming decades. Transition economies must further adapt to the fast changing dietary pattern towards high protein, vitamin and mineral rich diets demanded by a growing population with gradually increasing purchasing power (Huang et al., 1999). By 2050, our growing global population will require an estimated 60% more food than we produce today (Alexandratos and Bruinsma, 2012; Tilman et al., 2002; Green et al., 2005). All this while 1.3 billion tons of global food production is lost or wasted annually (Gustavsson et al., 2011).

Until 2050, the number of people living in urban areas is expected to rise to more than 6 billion, 90% of them in developing countries (UN, 2013). This unprecedented explosion and growth of mega-cities worldwide may prove unsustainable and ecologically disastrous. In 2000, the world's mega-cities took up just 2% of the Earth's land surface, but they already accounted for roughly 75% of the industrial wood use, 60% of human water use, and nearly 80% of all human produced carbon emissions (UNPD, 2008). It is clear that the human population is not only growing but also concentrating in social agglomerates. This has mixed effects on the environment. From a macro perspective, it means concentration of service industry and less distance to be covered to deliver goods and services, thus cutting on emissions. From a micro perspective, the environment of the cities is suffering a blow, with heightened air, water, light and sound pollution.

Arable land is also finite, with agricultural land covering 38% and arable land covering 11% of the total land area. The global projections show that up to 2040 agricultural land can only be increased by another 2%. (FAOSTAT, 2012) Water is a scarce resource too (Gleick, 1993). From this, the need to minimise the negative environmental effects of agriculture, particularly with regard to greenhouse gas emissions, soil degradation and the protection of already dwindling water supplies and biodiversity arises. Therefore, we need to find agricultural technologies that have a neutral or positive impact on our environment.

Vertical Farming holds the promise of addressing these issues by enabling more food to be produced with less resources use. However, its economic as well as environmental feasibility requires in-depth scientific investigation. Vertical Farming is steadily becoming a subject discussed broadly in industrial and scientific communities (e.g. ThanetEarth, 2011; NewYork-Sunworks, 2012; Cowing, 2011; Omega-Garden, 2012; Levenston, 2011; PlantLab, 2012; VertiCrop, 2011). It is an agricultural technique involving large-scale food production in high-rises. Using cutting-edge greenhouse methods and technologies, like High Density Vertical Growth (HDVG), these buildings would be able to produce fruits, vegetables and other consumables (e.g. herbs, pharmaceutical plants) throughout the year. The concept involves growing and harvesting of a wide range of plants in high density urban areas (mega cities) and the sale of these crops directly within the city community, reducing transportation as opposed

to the standard rural farming model. The advantages of this method are the multiplication of agriculturally productive land (by growing in vertically mounted stacks), the increase in crop yields (by using optimized production methods, such as light exposure variations, or additional $CO_2$ supply), the protection of the crops from weather-related problems as well as pest and diseases (as opposed to outdoor farming), and the minimisation of water requirements (through water recycling).

Therefore, the purpose of the study was to construct a Vertical Farm and conduct a market analysis investigating the potential markets for such a technology. The specific objectives of the study were to: (1) Design and simulate a farm; (2) Identify the costs for feasibility reasons; (3) Identify potential markets through a market analysis.

## 2. Vertical Farming

Defining Vertical Farming (VF), it is a system of commercial farming whereby plants, animals, fungi and other life forms are cultivated for food, fuel, fibre or other products or services by artificially stacking them vertically above each other (Own Definition).

An example for a Vertical Farm stands in Suwan, South Korea (Levenston, 2011). There, the Rural Development Agency is investigating Vertical Farming technology (Fabian and Kollenberg, 2011). The facility is three stories in height totalling an area of 450 m². Almost 50% of the energy requirement is supplied through renewable resources like geothermal and solar arrays, which is mainly necessary for heating, cooling and artificial lighting requirements. Presently lettuce is being cultivated through careful regulation of light, humidity, carbon dioxide and temperature. Researchers project five years of further research before this technology is ready for the market. (Levenston, 2011) The problem is of scale, none of these are big enough to practically demonstrate the scope of this technology.

Hence, in the following section the initial system for a Vertical Farm is presented, big enough to provide around 15,000 people with 2000 kcal of nutrition per day. The study to conceptualise the structural design of the VF was done in collaboration with the German Aerospace Centre in Bremen, through a Concurrent Engineering Study. It is assumed that the VF is built in Berlin as a megacity with enough market potential for implementing such a structure.

### 2.1 General Structure of a Vertical Farm

In order to support 15,000 people with enough food the tower is planned to have the following configuration: A Vertical Farm of 0.93 ha[1] (roughly the size of a city block) with a total of 37 floors, 25 of them solely for the purpose of crop production and 3 for aquaculture. Further, 3 uniformly distributed floors are for environmental regulation and 2 in the basement for waste management. In addition there is one floor for cleaning of the growth trays, sowing and germination, one for packing and processing the plants and fish and one for sales and delivery at the basement (Figure 1). This configuration results to a total building height of 167.5 meters,

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[1] An estimated 28 m² of intensively farmed indoor space is enough to produce food to support a single individual in an extra-terrestrial environment like a space station or space colony supplying him with about 3000 kcal of energy per day (Mitchell, 1994).

with a length (and width) of 44 meters, giving an aspect ratio[2] of 3.81. A freight elevator big enough to allow a forklift truck was planned in the centre of the building, allowing for harvest and waste to be transported down to the respective floors.
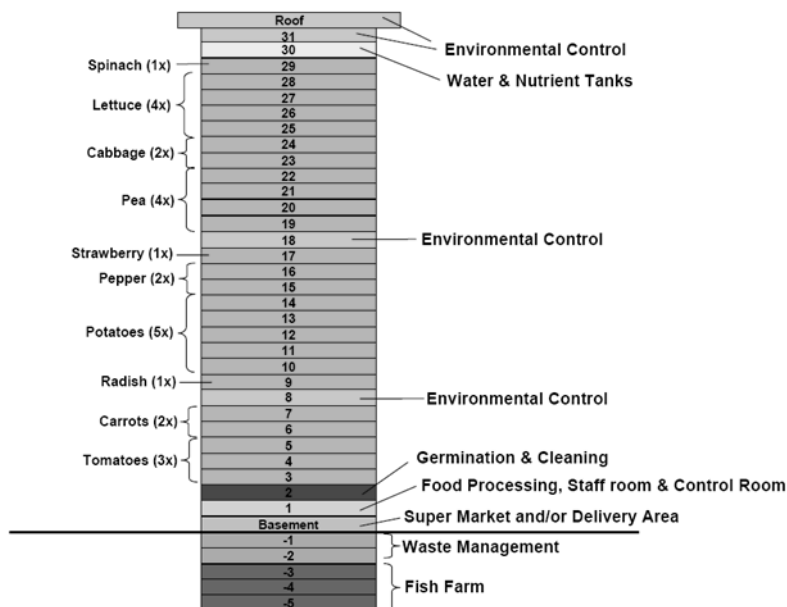


Figure 1. Layout of the Vertical Farm

Source: Designed in a CE Study by the author at DLR Bremen.

LED (Light Emitting Diode) technology is chosen for the artificial lighting as it emits a low level of thermal radiation, has no hot electrodes, and has no high-voltage ballasts. LED also has a long operating life, which makes it a practical alternative for long-term usage involving plant production. Most importantly, it is possible to modify the irradiation output to approximate the peak absorption zone of chlorophyll. The selected plant species have different illumination requirements in terms of PPF (Photosynthetic Photon Flux). Therefore, the panels are not operated at maximum power, but on different power levels depending on the PPF requirements of the plant species. Furthermore, the desired duration of illumination is adapted to the needs of the plants, leading to 12 - 16 hours periods depending on the plant species. Furthermore, to save power, the LED will be operated in a shutter sequence[3].

### 2.2 Agricultural Sub-System

The Vertical Farm has to provide the optimal conditions for the crops to transition from seeds through germination, vegetative, reproductive and harvesting phases. As it is a closed system, a major prerequisite is controlled temperature, and relative humidity in the growth chambers. Additionally, controlled and elevated $CO_2$-levels have been simulated to obtain maximum

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[2] Aspect ratio is the ratio of the height of a building to the width of its shape. Since we assume a square footprint of 44 X 44 m, in this case it is the quotient of 167.5/44.
[3] A shutter sequence means that the LED are frequently turned on and off with a defined frequency. Investigations in plant response showed, that shuttering of LED do not affect the development and growing of plants, but can drastically reduce the required electrical energy (NASA, 2004).

biomass yield. Since the plants grow in aeroponic systems, it is further possible to recycle the excess nutrients from mist in the air. Another major task in such a closed system is filtering out contaminations and trace gases, such as ethylene, which are released into the air by plant. For these matters, three environmental control floors are required, controlling the air quality and recycling the excess nutrients of 8 -9 plant cultivation floors each (Figure 1).

The seeds germinate on a specialized Germination Floor, while the later stages take place on the Plant Cultivation Floors (Figure 1).

In the Cultivation Floors, a plant growth area is segregated into eight zones which can be harvested at different times. These eight zones are sown with a time lag (7 days interval) to facilitate a uniform harvesting pattern, in order to avoid peaks and troughs of labour requirement. This also ensures a steady supply of the products to the centres of demand, bringing down the necessity for storing and refrigeration.

The aforementioned cropping cycle creates a continuous sowing and harvesting loop. The total number of sowing and harvest events is 215 in 365 days in which a total of 68 ha is sown and harvested every year. A weighted average is being made to arrive at the area cultivated on an average. The estimated yield of a Vertical Farm is shown in Table 1.

Table 1. Estimated yield of a Vertical Farm compared to traditional agriculture

| Crops | Yield in VF due to Tech (tons/ha) | Field Yield (tons/ha) | Factor increase due to Tech | Factor increase due to Tech and Stacking |
|---|---|---|---|---|
| Carrots | 58 | 30 | 1,9 | 347 |
| Radish | 23 | 15 | 1,5 | 829 |
| Potatoes | 150 | 28 | 5,4 | 552 |
| Tomatoes | 155 | 45 | 3,4 | 548 |
| Pepper | 133 | 30 | 4,4 | 704 |
| Strawberry | 69 | 30 | 2,3 | 368 |
| Peas | 9 | 6 | 1,5 | 283 |
| Cabbage | 67 | 50 | 1,3 | 215 |
| Lettuce | 37 | 25 | 1,5 | 709 |
| Spinach | 22 | 12 | 1,8 | 820 |
| Total (average) | 71 | 28 | 2,5 | 516 |

Source: Designed in a CE Study by the author at DLR Bremen.

Due to the closed environment and controlled lightning, the land productivity of Vertical Farming is twice as high as traditional agriculture. Taking additionally into account that only 0.25 ha on which the farm is built are needed, the total yield increases 516 fold compared to traditional agriculture through stacking the production. (Table 1) In total this leads to an estimated production of 3,573 tons of edible fruit and vegetables.

To handle a stack area of 403 m² per hour (harvest and preparation of new seed trays) an estimated work force of 6 - 10 workers (based on 8 h work time per day) are required.

The fluid delivery system of this VF has special requirements not only because it must provide

the water necessary for all the subsystems of the building and handle the sewage management as any normal industrial building, but also because it must provide the required nutrients for all the different crops as well as function as an irrigation system. Apart from the growing floors, the rest of the floors require a standard fluid delivery system of any industrial building.

These subsystems are based on the aeroponic system, lately used by NASA for its Greenhouses bio-regenerative growth chambers (Agrihouse, 2011). In short, it involves spraying a nutrient solution (exact solution of the nutrients required by the plant) directly to its roots which remain suspended in the air with no soil. According to AgriHouse, Inc., growers choosing to employ the aeroponics method can reduce water usage by 90%, fertilizer usage by 60%, all while maximizing their crop yields by 45 to 75% (Agrihouse, 2011).

Approximately 217,000 l of water are required by the system per day out of which about 14,000 l are assimilated and leave the tower within products and waste. The extra water that is not absorbed by the plants is directly re-circulated in the water-recycling system to be processed and sprayed again, thereby closing the loop.

*2.3 Aquacultural Sub-System*

The fish farm serves the functions of waste disposal, plant nutrient source and food (fish filet) production within the VF. It will add to the efficiency of the farm by utilizing irrigated water from plants as well as plant waste to create food in the form of edible fish biomass. This process is often called aquaponics.

The design is based on a balanced production cycle, which aims to optimize the production by allocating the different maturity stages in different tanks. To balance production and decrease handling costs, 5 different tanks size are chosen which are optimized to the desired production volume of close to 700 fish per day per floor. It leads to a total estimated production of 341 tons of fish per year, with 137 tons of edible fish fillet. In total, 3 workers are needed.

Tilapia has been chosen as fish species because Tilapia is able to consume a wide range of feed (The Fish Site, 2004); the tropical water temperature required by tilapia is ideal for a VF as heat sink from LED lighting can; Tilapia are very efficient in transforming feed into animal protein, the feed/fish mass ratio ranges from 1.5 to 2 depending on water conditions and feed quality; and due to the moderate taste of tilapia it is widely eaten (The Fish Site, 2004).

*2.4 Food Processing Sub-System*

When plants and fish are full-grown they need to be harvested and readied for delivery to supermarkets and restaurants. This is done on the food processing floor. In the process conceived above one may produce a kg of bio-mass with the composition shown in Table 2.

Table 2. Composition of production

| Crops | Composition (g) |
|---|---|
| Carrots | 56 |
| Radish | 41 |

| | |
|---|---|
| Potatoes | 103 |
| Tomatoes | 197 |
| Pepper | 113 |
| Strawberry | 44 |
| Peas | 14 |
| Cabbage | 72 |
| Lettuce | 284 |
| Spinach | 39 |
| Fish | 37 |

Source: Designed in a CE Study by the author at DLR Bremen.

For processing the food the necessity of 15 workers is estimated.

*2.5 Waste Management Sub-System*

In the process of producing edible biomass, the Vertical Farm generates bio-waste as by-products (e.g. leaves, stems, fibrous roots, damaged fruit and vegetables) from the crops as well waste from the aquaculture system. The annual bio-waste from the plant growth chambers is estimated to be roughly 2443 metric tons. That from the aquaculture systems is estimated to be about 517 tons. Going by the assumption that 1 ton of plant waste is fed to the Tilapia per day, the remainder is roughly 7.11 tons per day on average. Since the Vertical Farm is envisaged to have a closed functional loop, this waste is converted into useful resources, such as liquid fertilizer or bio-fuel. Wastewater is recycled through a nutrient extraction process by pumping it into tubes filled with volcanic rock particles. In the design for the Vertical Farm two Waste Management floors have been incorporated to serve the exact purpose.

## 3. Cost Analysis

In this section, the capital expenditure for constructing a VF as well as the annual variable costs are discussed. Further, different cost scenarios are identified deriving the possible range of costs per kg biomass produced.

*3.1 Production Costs*

An overview of the total construction costs (building plus equipment) as well as the variable costs per year is shown in Table 3. The costs are derived from the structure and equipment described before.

Table 3. Production Costs

| Fixed Costs | Costs (€) |
|---|---|
| Building (incl. Site) | 111 581 994 € |
| Equipment | 90 382 192 € |
| Total Costs | 201 964 186 € |
| Variable Costs | Costs (€/a) |
| Personnel | 2 050 000 € |

| | |
|---|---|
| Power Demand | 5 390 941 € |
| Plant Seeds | 44 406 € |
| Water (recycled) | 0 € |
| Nutrients | 424 919 € |
| Fish Food | 127 020 € |
| Total Costs | 8 037 286 € |

Note: The costs have been inflation corrected to investment year 2012, assuming USD 1.00 = € 1.30. The building and equipment costs are amortised over a period of 30 years. The interest rate is assumed with 3% for the next years.

Source: Designed in a CE Study by the author at DLR Bremen.

The costs are expressed in form of Annuity. Based on average land price in Berlin the cost of building a 37 story high VF is around 111.58 million Euros. Compared with building costs of a couple of randomly chosen high rises in Europe (Post Tower in Bonn -> 207 Mio €; New ECB Headquarter in Ostend -> 500 Mio €; Main Tower in Frankfurt am Main -> 467 Mio €[4]) the building costs for the VF are significantly lower, mainly because it is not meant for habitation. The required equipment cost a total of about 90.4 million Euros. Whereby, the fixed costs sum up to 200 million Euros. (Table 2)

The variable costs include personnel, power, seed, feed and fertilizer costs. A predominantly manual production system with minimal mechanization would require a total of 41 personnel. The cost of labour is taken at an average of 50,000 €/year per personnel. Apparently, the food processing section requires the maximum number of personnel for its daily operations. Power costs sums up to around 5.4 million Euros a year[5] (Table 2). Although this is incurred only when power is obtained from external sources and could hence be considered as one of the constituents of the worst case scenario. Cost saving measures include: lighting at night, when the tariffs are low; use of shutter factor and consideration of development factor (which refers to the fact that a plant does not require full light exposure throughout its life cycle). The exact water costs are difficult to measure as the possibilities are innumerable, from rain water harvesting to deep boring to urban grey water recycling. Therefore, this is kept open for research and inclusion of water costs into the cost analysis has been accounted to be null. As bio-wastes are re-utilised for composting and generation of plant nutrients, for the purpose of cost estimation only 50% of the amount mentioned in section 2 is accounted. A fish consumes 191% of its total body mass as feed in its entire life cycle[6]. However, Tilapia being versatile the non-edible plant biomass can be fed. Therefore only 50% of the total feed requirement is accounted for in the cost estimation. Since a total of 137 tons of fish fillet is obtained from 341 tons of total fish biomass, approximately 651 tons of feed is consumed by the fishes per year. Of this, about 50% of this can be obtained for the bi-products of the VF, while the rest amount of 326 tons is bought at an approximate rate of 0.39 €/kg from the market totalling to an amount of 127,000 €/year (The Fish Site, 2004).

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[4] For more details see CTBUH (2012).
[5] The cost estimation is derived on the basis of information found in
http://www.tengelmann-energie.de/Hochtarif.690.0.html.
[6] This is based on the CE study regarding the aquaponic cycle.

*3.2 Cost Scenarios*

The different cost scenarios vary according to the building parameters, production parameters, production technology, fixed cost and variable cost margin (Figure 2).
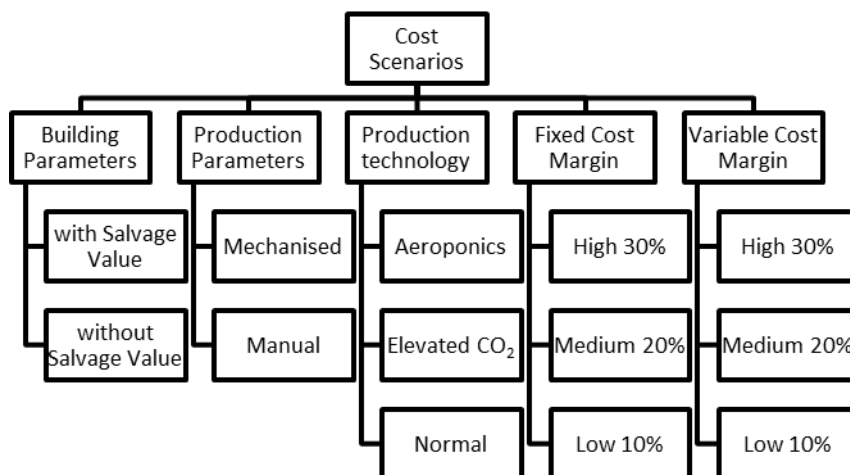


Figure 2. Identified Cost Scenarios

Under the best scenario, which in itself is not a very optimistic one, the cost of producing edible biomass in this system is around 3.17 €/kg. In the worst case, that is with no salvage value, high labour requirement, hydroponic system, and high cost margins, it takes around 6.32 €/kg of organic fruits, vegetables and animal protein. From the results it is possible to calculate a probability distribution as seen in Figure 3.
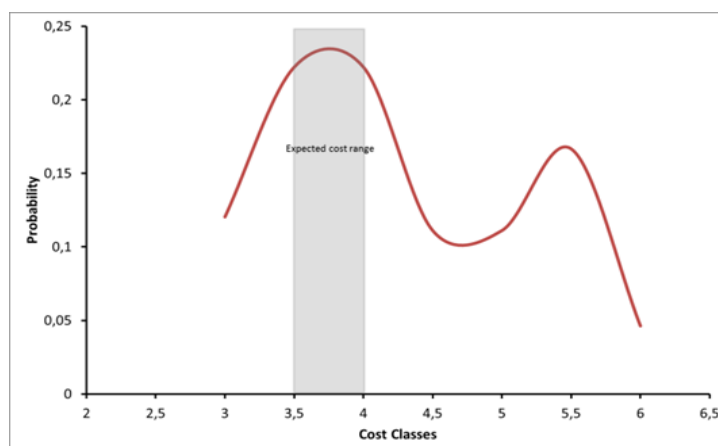


Figure 3. Probability Distribution of Costs per kg Biomass

The simulations show that it is most probable that the costs lie between 3.50 €/kg and 4.00 €/kg (44% of cases), followed by the class between 5.50 €/kg to 6.00 €/kg (17% of cases).

## 4. Market Analysis

A SWOT analysis is being used to analyse different facets of Vertical Farming. It is a simple but systematic framework for appraising the intrinsic and institutional environment of a technology or business proposition. For the process of strategic planning, the SWOT analysis is

an early but important "first step" in business planning. It identifies potential market opportunities.

The environmental scan comprises the analysis of the internal situation as well as the external environment. The internal situation describes the main product advantages and disadvantages, mainly in comparison to the main competing product (conventional agriculture in this case). In other words, the Strengths- Weakness analysis (SW-analysis) looks at the total output of the system as a self-affected good. The external Opportunities-Threats analysis (OT-analysis) examines the external environment. Opportunities and threats are anticipated future pathways and should be described in a dynamic sense, considering the current situations, existing threats, unexploited opportunities as well as probable trends (Checco, 2005).

When analysing VF, it is compared to conventional farming since it is the main competitor to Vertical Farming. In this regard first the internal and the external factors are identified.

*4.1 Internal Analysis*

The intrinsic factors of vertical agriculture that may be controlled within the system are featured in the internal analysis.

**Strengths**

Industrial agriculture has till date used agricultural machinery, advanced farming practices and genetic technology to increase yield. However, it still needs extensive tracts of fertile land for the purpose of food, fuel or fibre production. However, agriculture still largely depends on season, especially in case of fruit and vegetable crops. Socio-economically this renders the farming population under or unemployed for a greater part of the year. While in industrialised nations, higher food prices, greater affordability and government subsidies ease this problem to some extent, in developing countries, where subsistence agriculture is the norm, this translates to poverty and vulnerability (Hansen and Donohoe, 2003).

Vertical Farming provides a paradigm shift in the way we know and do agriculture. In terms of space, abandoned urban properties, abandoned mines or even peripheries of buildings can be converted into food production centres thereby eliminating the need for expensive constructions. Owing to optimum use of vertical space 1 indoor acre is equivalent to 4-6 outdoor acres or more, depending upon the crop (e.g., strawberries: 1 indoor acre = 30 outdoor acres), something that is inconceivable in case of conventional or greenhouse agriculture. This intensifies agriculture instead of extensifying it. Due to provision of artificial light at the required wavelength (380-450 nm in the violet end and 630-700 nm in the red end) for an optimal duration, crop production becomes a year round enterprise, comparable with other manufacturing industries.

It also creates new employment and research opportunities. Technologies developed for VF may prove to be useful not only for remote research stations like in the poles, but also in refugee camps especially in flooded or earth quake affected areas where camp dwellers need to be fed for prolonged period of time.

Agriculture has always been affected by volatilities of weather. Fluctuations in temperature,

water availability, photo-intensity beyond the biological requirements of the plants have persistently lead to diminishing yields. These factors have always remained beyond the control of farmers and could only be prevented through costly chemicals, avoidance of high-risk high-production crops, or purchase of crop insurance. Vertical Farming systems address many of these problems. Like greenhouse agriculture, there is no weather-related crop failure due to droughts or floods as irrigation is artificial and controlled. Temperature and photo-intensity and duration are also artificial and optimal.

Although the balance of energy required for artificial lighting, heating and cooling and that generated by bio-gas is a matter requiring further research, VF dramatically reduces fossil fuel use since there is no agricultural machinery or inorganic fertiliser involved. Furthermore, since food is grown locally or closer to points of consumption, transportation is reduced, thus saving on energy and the environment.

Agriculture especially in developing and transitional economies has often been held responsible for environmental degradation, loss of rainforests like in Amazon basins or desertification and loss of ground water as in Khorezm basin (Martius et. al., 2005). At least high value fruits and vegetables cultivated in Vertical Farms has the potential to take some pressure from agriculture whereby, fertile lands can be utilised for cereal, fodder, fibre and bio-fuel production. VF may additionally create sustainable environments for urban centres purifying the air and providing a positive psychological effect on urban populace, who are often deprived of greenery.

**Weaknesses**

Crops require space, light, carbon dioxide and water, which is available freely in nature. In case of Vertical Farming all these need to be supplied at a cost.

Structures need to be built for the nutrient delivery system and platforms for plant growth along with artificial growing medium, generating additional costs. This could be a weakness compared to conventional agriculture; greenhouse agriculture on the other hand has similar requirements. Taking this into consideration, Vertical Farming is logically viable only in places where agriculture is necessary but agro-climatologically difficult to be practiced in the open, like in desert nations or mountainous nations lacking flat arable land. This might also be justified as a space saving approach in Mega-cities where real estate demands hinder setting up of parks and botanical gardens.

Light in Vertical Farming towers has to be supplied artificially. Although it opens up the opportunity to regulate the wavelengths, intensity and photo-period to optimal levels, and can be held comparable to greenhouse agriculture, it still remains a cost that needs to be taken into consideration. The justification of incurring this extra cost lies in areas where light intensity is too low or the photo-period incompatible for crop cultivation, as in case of   higher latitudes or where the intensity is too high for cultivating sensitive salads, fruits and vegetables, as in sub-tropical deserts.

*4.2 External Analysis*

The exogenous factors which a particular enterprise has no influence upon, but can affect its performance positively or otherwise, are featured in the external analysis.

**Opportunities**

Opportunities include those external factors and conditions which an enterprise should take note of and maximise upon in order to gain success.

There is an increasing demand for protein, vitamin and mineral rich food as more and more countries transition from developing to developed nations. Despite Engel's law of declining share of food related expenditure with increasing income, there is expected to be a change in the consumption pattern in these countries (Rimmer and Powell, 1992). In particular, Cranfield et al. (1998) expect reduced consumption of unprocessed bulk commodities (e.g., grain, rice and cereals) along with an increased consumption of higher valued consumer ready products (e.g., fruit, meat and dairy products). This changing consumer preference is an external factor that might serve as an opportunity for Vertical Farming because it is particularly efficient in producing sensitive crops of high nutritional value away from their native agro-climatic zones.

It is clear that places where population is growing also happen to be places where land is shrinking in terms of arability. Vertical Farming might also find opportunity in this dismal fact. Land management, through ploughing and manuring contributes to almost 78% of the agricultural emissions in the U.S. (AgMRC, 2008). Vertical Farming completely rules out this measure and therefore has an advantage. Global climate change therefore presents an opportunity for Vertical Farming to get greater social and political acceptance. In addition to this there is an increasing controversy regarding the use of arable land for bio-fuels and the later contributing towards rising of food prices (Banse et al., 2008). Vertical Farming can relieve high yielding land, now used for fruit and vegetable cultivation.

Recent decades have seen food sovereignty being sought by many nations and recommended by many think-tanks in view of the volatility of food prices. This is seen especially in geographical regions where purchasing power is high but agro-climatic factors too hostile for conventional agriculture, like in Deserts, Taigas and Tundras (Elhadj, 2005). VF could generate this sovereignty to a certain extend.

The recent developments in the field of renewable energy, like Photovoltaics, Solar-Thermovoltaics, Wind or even Pumped-storage Hydroelectricity, are noteworthy opportunities. Not only because in larger scale they might open doors for cheaper electricity but also because of their location. Since they are mostly located in areas unfit for agriculture, even a small fraction of their generating capacity might be used for the purpose of a VF.

**Threats**

The biggest threat to VF is scepticism from business and academia (e.g. Richard, 2005; Alter, 2010), and it is not entirely unfounded. Till date no project has practically demonstrated the viability of a VF at this scale, most exist in small research initiatives or as concept drawings by architects. Therefore it is imperative that initiation leave alone acceptance would require convincing at different levels and hence requires some serious action research. This work is a

step towards removing these doubts by showing the economic feasibility at least in the drawing board by spelling out all the parameters clearly.

The market opportunity is limited. It is feasible to grow only high value crops for consumers with dispensable money for such products. It has no merit to flourish even in Mega-cities in resource rich nations as long as conventional agriculture can supply food cheaply. The pressure on our resources is still not that high that such costly measures can be taken. This technology might not see mass production in near future but a successful implementation of the technology in potential markets will definitely improve its marketability.

In 2010, the EU spent € 57 billion on agricultural development, of which € 39 billion was spent on direct subsidies. Agricultural and fisheries subsidies form over 40% of the EU budget (EU, 2010). The United States spent around $20 billion per year to farmers in direct subsidies as "farm income stabilization" via U.S. farm bills (USDA, 2011). Although the merits or demerits of these measures may be seen from different perspectives and is debatable, from the point of Vertical Farming prospects, one thing is clear: these subsidies are there for the sole purpose of enabling the farmers to act competitively in a globalised world. This will definitely not serve in favour of Vertical Farming. Due to subsidies conventional agriculture can and will supply food at prices much lower than the real price and therefore present a tough competition for this new technology, where energy cost is a big concern. Therefore, Vertical Farming needs to be merchandised in areas where such subsidies are not present, becoming increasingly difficult in a globalised world. Conversely, one could avoid competition with conventional agriculture by producing niche high value products.

*4.3 Qualitative SWOT Analysis*

Based on the internal and external factors a SWOT matrix can be created (Checco, 2005). It connects different arguments with each other. Strengths should be used to maximize opportunities and minimize threats. Further, weaknesses should be minimized and threats avoided by taking advantage of opportunities. The process of forming relationships between the different findings is, however, subject of personal evaluation.

The first quadrant the strength layer has an intersection with the opportunity layer. The point of convergence where the strength of the enterprise addresses some opportunities is with regard to the Environment. Climate change, increasing $CO_2$ emissions caused by mechanized agriculture as well as transportation and related storage of food are some of the grave issues that can be addressed by VF. In addition to that increasing urbanisation and thereby increasing urban wastes needs environment friendly treatment, which VF offers. Race for food sovereignty is another major issue that can be addressed since VF can grow food in places otherwise hostile for agriculture.

In the second quadrant the weakness layer has an intersection with the opportunity layer. The point where one can minimise weakness by relying on the opportunities is energy. The field of Renewable energy is reanimating itself constantly[7]. Energy balance of the VF is on the other hand extremely skewed. Development of integrated projects where renewable power stations

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[7] Source: http://www.davidtan.org/ and http://www.cleanwindenergytower.com/ respectively

are coupled with VF will not only increase their marketability but also subsidise their costs mutually.

A Vertical Farm as presented in this paper, requires a net total of 3.5 GWh of electricity a year. Monumental as it seems, this is less than the amount of electrical energy generated by a power station of 0.5 MW installed capacity in a year running at full capacity[8]. A wind turbine of 80 m length, for example generates 2.5 MW (Layton, 2006).

The third quadrant shows the intersection of strength and threat layer. This quadrant indicates a possible threat to the enterprise or the product, but it also shows a possible strength of the enterprise in order to prevent this particular threat. A list of possible combinations in this quadrant includes the integration of renewable energy stations with VF. In addition to that is the environmental and ecological services provided by VF that could open new markets in face of market limitations. But above all is its performance against traditional agriculture that could turn the balance in its favour. Plant cultivation in field (with climatic influences) and in closed environment (protected cultivation) creates different amounts of yield. By the application of vertical frames and multiple stacks, the basic ground area of the building (2500 m²) is increased 37 times to an expanded plant area to a total of 92,718 m², comprising of a total of 116 stacks through 25 floors. This results in a total production of 3,573.41 tons of edible plant biomass. However, for this only 2500 m² is being used, so if we grew all those crops proportionately on the same 2500 m² this means multiplication of the yields by a factor of 516. This makes Vertical Farming a viable candidate, at least theoretically for our race to multiplying the food production by 60% by 2050 (Alexandratos and Bruinsma, 2012; Tilman et al., 2002; Greene et al., 2005).

The fourth quadrant, which is also called the dead quadrant, shows the intersection between the weakness layer and the threat layer. In this quadrant the enterprise has to face a threat, but can only oppose a weakness in this field. Therefore, the strategy is to minimise the weakness and avoid the threats. Only through investigating possible methods of optimising space, light, water and energy requirement and maximising yield weaknesses can be minimised. While power costs could be tackled through research into energy efficient production system, the equipment costs are expected to go down once the trend catches up and serial production of these equipment starts. For that matter more research is required, which is possible only if there is a market potential for this technology.

*4.4 Market Potential*

Having discussed the limitations of market potential with regards to areas where traditional agriculture can supply inexpensive products or where the purchasing power of consumers are not high enough, this section discusses the potential of marketing this technology notwithstanding the limitations and reasonable doubts. Presently the biggest markets for this technology according to the SWOT analysis, is in Desert regions, Taiga region and Mega-cities. What it means in terms of numbers can be derived based on some criteria. The criteria are that we consider only those countries or cities where the GDP per capita is USD 20,000 or more and

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[8] Based on the own calculations on power demand.

there is a demand emanating from a population of 5 million or more. The GDP per capita, which is a proxy for the purchasing power of the consumers as well as the population which mirrors the quantity of demand, are the most important factors for assessing market potential, beside the urge for food sovereignty and incompatibility of agro-climatic factors for food production.

**Desert Region**

Desert regions refer to Middle East and North African (MENA) countries. Although there are many other countries like Australia, and the US which have substantial stretches of land that fall under the category of desert, due to other fertile tracts, these nations are not resource constrained and enjoy food sufficiency. The nations shown in Table 4 have been selected because they are resource constrained, do not enjoy food sovereignty, but can financially afford to do so (as shown by the GDP per capita figure being above USD 20,000).

Table 4. Statistics of Middle Eastern Nations

| Country | GDP per Capita | Population | Market potential |
|---------|----------------|------------|------------------|
| Qatar | $ 102,700 | 1,853,563 | 18 |
| United Arab Emirates | $ 42,000 | 8,264,070 | 82 |
| Kuwait | $ 40,700 | 3,566,437 | 35 |
| Israel | $ 31,000 | 7,879,500 | 78 |
| Oman | $ 23,900 | 2,773,479 | 27 |
| Bahrain | $ 21,200 | 1,234,571 | 12 |
| Saudi Arabia | $ 20,400 | 27,136,977 | 271 |

Source: CIA (2012).

Regarding Saudi Arabia as an example for the situation of the desert regions, the non-renewable water will last another 14 years if the average extraction remains at 10 billion cubic meters per annum for traditional desert agriculture (Elhadj, 2008). Conventional farming is out of question with an average rainfall of only 70-100 millimetres a year (Elhadj, 2008). Therefore, technologies with a promise of judicious use of water as well as food sovereignty should be more than welcome despite requirement of higher financial investments. Vertical Farming which undoubtedly is more sustainable than the form of agriculture hitherto practised, might find a market in these countries.

If it is assumed that only 100g of VF products is consumed per head per day, the design presented in this paper, can feed around 100,000 people round the year. Based on this figure the market potential (Table 4) has been calculated, simply as a quotient of the present population and the supply potential of a VF (100,000 people). This is probably not the number of farms that would be built, but it gives us a rough idea of how many could be build and what potential lies ahead for this technology. Assuming for pilot purposes only two Vertical Farms per nation, this would lead to 14 VF in the short term.

**Taiga Region**

The nations lying in the Taiga regions also have a comparable situation. Although other countries like Russia and Canada are located in this region, they have other fertile tracts that offset their food dependency as a nation and hence they were left from the analysis. The Nordic countries do not have suitable conditions for agriculture, enjoy high purchasing power and abundance of renewable energy in the form of hydro-electric or off-shore wind power. In addition to that they strive for food sufficiency which makes them a good market for VF technology. This is also seen in the projects been developed in Sweden (Plantagon, 2011). Table 5 gives us an overview of the same.

Table 5. Statistics of Nordic Nations

| Country | GDP per Capita | Population | Market potential |
|---------|----------------|------------|------------------|
| Denmark | $ 37,151 | 5,543,453 | 55 |
| Norway | $ 53,470 | 5,003,000 | 50 |
| Sweden | $ 40,393 | 9,415,295 | 94 |
| Finland | $ 49,349 | 5,410,233 | 54 |
| Iceland | $ 38,060 | 320,060 | 3 |
| Greenland | $ 37,517 | 56,615 | 1 |

Source: CIA (2012).

Again, at limits one could construct as many VF as shown in the last column although that is unlikely. However, one could safely assume that for pilot purposes, even if two VF are constructed per nation, 12 VF could come up in the short term.

**Mega-cities**

Again, going by the criteria of population of around 5 million and per capita GDP of above USD 20,000, in Table 6 the market potential in Mega-cities have been tabulated examplarily[9].

Table 6. Statistics of Mega-cities

| Country | GDP per Capita | Population | Market potential |
|---------|----------------|------------|------------------|
| London | $ 75,330 | 7,500,000 | 75 |
| Berlin | $ 28,500 | 4,970,000 | 49 |
| New York City | $ 67,700 | 18,900,000 | 189 |
| Los Angeles | $ 57,500 | 12,820,000 | 128 |
| Hong Kong | $ 45,268 | 7,069,000 | 70 |
| Tokyo | $ 40,334 | 36,669,000 | 366 |
| Buenos Aires | $ 27,689 | 13,074,000 | 130 |

Source: CIA (2012).

Piloting in the initial years will be done not only for food production purposes but also to add prestige to the city and provide ecological services, before VF can fully demonstrate its worth.

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[9] Further Mega-cities and their long term market potential are Paris (110), Madrid (58), Barcelona (49), Washington, D.C. (55), Houston (59), Dallas (63), Philadelphia (59), Chicago (94), Atlanta (52), Singapore (48), Osaka (113), Seoul (97), Santiago (59) and Mexico City (194).

These motives can only be expected in comparatively rich cities with high level of environmental consciousness. Although the full market potential is high, assuming one VF per city, we are still looking at around 21 VF that could come up as pilot projects in mega-cities around the world.

**Total Market Potential**

Considering the countries in the desert, the Taiga regions, and the mega-cities, there is a potential of setting up around 2900 VF. Although this projection looks utopian, mass production will bring down costs, research will make production cheaper, as a result of which the market potential will extend to cities and countries not envisaged in this analysis. However, for the starting point, one could just look at the number of VF that could be built as pilot projects. Assuming two for each country and one for each mega-city, a total of 47 VF could be built in the short term. One can project that the greatest potential lies in the systems developed for mega-cities, followed by desert nations. With an increasing threat of desertification caused by climate change, this segment is also going to retain its importance. Nordic countries have the smallest share both in short and long term.

**5. Conclusion**

The intent of this research was to investigate whether the concept of Vertical Farms is feasible financially and economically. A prototype has been planned and discussed, and a cost analysis developed on its basis. Through the analysis of the market potential, different future markets were identified.

A system design for Vertical Farm has been presented with 37 floors totalling a height of 167.5 m. Five of these floors are underground, housing the 3 floors of Aquacultural and 2 of waste management sub-systems the 32 floors above ground comprise of the 25 floors for agricultural production and 2 for food processing sub-systems among others. The building occupies a land area of 0.25 ha, has a footprint area of 1,936 m² and floor area of 1,600 m² giving it an aspect ratio of 3.81. This area is multiplied to 9.27 ha for plant growth due to multiple stacking and to an equivalent of 68 ha due to multiple harvest potential.

The building costs add up to € 111.5 million with additional € 90 million for equipment. It requires 80 million litres of water per year, most of which is recycled requiring only a fraction of that from external sources (since about 4000 l leave the system as sold plant and animal matter). The VF takes in 10,000 l of nutrients, sequesters around 868 tons of $CO_2$, and saves many more due to carbon neutral production and supply chain. However, it also needs roughly 3.5 GWh of power at € 5.3 million and produces 3,573 tons of fruit and vegetables and 137 tons of tilapia fillets per year. The crop production alone is roughly 500 times the yield expected from growing these vegetables in an area of 0.25 ha with the given proportion. By-products are mainly 2,443 tons of biological waste yielding around 3 million litres of bio-gas and recycled nutrients in addition to slurry which can be used as farm manure. Such a system can produce fruit, vegetables and fish at an average cost lying between € 3.50 and € 4.00. Streamlining of this technology and further research could scale down the cost. Based on this, one can conclude that even with conservative assumptions, growing food in Vertical Farms might be a feasible

venture.

Markets for such a technology are found mainly in resource constrained nations and mega-cities with substantially high purchasing power. Given our criteria, the market potential for Vertical Farms is estimated to be around 50 pilot projects in the short term. Regarding the high production costs, even in the identified markets, they might be a factor hindering the building of Vertical Farms. In order to bring that down, further research for more efficient production techniques in addition to integration and customisation of these systems with other enterprises are required.

Around 3000 units could be projected for the long run, provided the building and production costs are brought down through further research and mass production of equipment and input factors.

For fostering Vertical Farms in the future, further research areas can therefore be the optimisation of production process for edible biomass (combination of crop cultivation and fish farming) as well as the optimisation of animal farming. Growing mushrooms actually requires the same growing conditions as the environmental requirements for Tilapia, this might be another prospect worth looking into. The cost of the building, its requisite structural parameters as well as the servicing and transport equipment and power requirements are serious research questions that can be answered only through action research. Optimal growing conditions in the agricultural system, the optimal labour requirement as well as the production plan needs to be worked out. Several LED panels for plant growth exist. Due to the high amount of panels required for the proposed VF concept an innovative panel design specialized for the requirements of Vertical Farming needs to be developed. These questions open an entirely new area of research for Agricultural Economists.

This work started with reasonable doubts that food grown in Vertical Farms might be exorbitantly expensive to ever become a practicable solution. This work has shown, however, that it is a possibility which needs to be further investigated.

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