FROM BIOREGENERATIVE LIFE SUPPORT SYSTEMS FOR SPACE TO VERTICAL FARMING ON EARTH – THE 100% SPIN-OFF

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ABSTRACT

The Institute of Space Systems of the German Aerospace Center (Bremen, Germany) conducted a Concurrent Engineering study to apply its know-how of Controlled Environment Agriculture technologies in space systems to provide valuable spin-off projects on Earth and to provide the first Concurrent Engineering study of a bioregenerative Vertical Farm to assess its economic feasibility.

Vertical Farming is an advanced method of agriculture on Earth, where commercially viable crops are cultivated inside multi-story buildings that mimic several aspects of an ecological system.

The conceptualized Vertical Farm of DLR is a building with 37 floors, a square footprint of 44 by 44 meters and a total height of 168 meters. There are 25 plant cultivation floors in the building with multiple stacked plant growth layers on every floor. A total edible biomass output of approximately 13,3 metric tons/day can be achieved with a total grow area of ca. 93.000 m^2.

In this paper the authors present the technical design and economic analysis of the Vertical Farm. Furthermore, advantages and challenges of such a farm together with a comparison to traditional agriculture will be outlined.

1. INTRODUCTION

Hundreds of millions of people around the world do not have access to sufficient food. With the global population continuing to increase, global food output will need to drastically increase to meet demands. At the same time, the amount of land suitable for agriculture is finite, so it is not possible to meet the growing demand by simply increasing the use of land. Thus, to be able to feed the entire global population, and continue to do so in the future, it will be necessary to increase the food output per land area.

One idea that has been recently discussed in the scientific community in the context of “Urban Agriculture” is called Vertical Farming, which cultivates food crops on vertically stacked levels in (high-rise) buildings using so called Controlled Environment Agriculture (CEA) technologies.

These technologies control all essential growth parameters of the plants (e.g. temperature, relative humidity, light quality and quantity). Examples of CEA technologies are advanced aeroponic Nutrient Delivery Systems (NDS), CO_2 injection systems and high-performance PAR-specific LED-lighting systems.

By decoupling plant growth from the natural system, higher yields can be achieved while life-cycle phases can be shortened, which results in faster production batches.

2. ADVANTAGES AND CHALLENGES OF VERTICAL FARMING

Aside from the main objective of conserving agricultural resources and re-developing biodiversity, Vertical Farming as a self-sustaining method of food production will also bring the following benefits:

- Year-round crop production (even during winter- and dry summer periods),
- Faster production and higher crop yields due to the utilization of CEA technologies,
- Worldwide application – Also in areas, where traditional agriculture is not or only partially possible (e.g. desert-, polar regions and mega-cities like Tokyo or New York),
- No weather related crop failures due to hail and heavy rain storms,

- Vicinity of crop production to the consumers → Reduction of transportation time and therefore costs (fresh food),

- Significant reduction of pesticide/ insecticide use → No pollution of soil and ground water.

The Vertical Farm (VF) concept has certain challenges left to overcome. These challenges shall be mentioned below in order to frame the overall scope:

- High initial investment required,

- High energy demand and

- Requires additional CEA technology development.

Additional information on these challenges can be found within [1] [2].

3. RESEARCH INITIATIVE – EDEN

In 2011, the Institute of Space Systems of the German Aerospace Center (DLR) launched a research initiative called EDEN - Evolution & Design of Environmentally-closed Nutrition-Sources. The research initiative focuses on bioregenerative life support systems, in particular greenhouse modules and technologies for planetary research stations or habitats on the Moon/Mars. The focal point is CEA technologies and the transformation and integration of these technologies into space-proven hardware solutions.

The technologies required for a VF are well-known and already being used in conventional greenhouses, as well as in the designs of bioregenerative life support systems for space missions. However, the economic feasibility of a VF, which will determine whether this concept will be developed or not, has yet to be adequately assessed.

Through a Concurrent Engineering (CE) process the research initiative aims to apply its know-how of CEA technologies in space systems to provide valuable spin-off projects on Earth and to provide the first CE-study of a VF to assess its economic feasibility.

This developed VF enables the cultivation of plants and the production of fish in a simultaneous manner. Water is recycled using filtration and recovery systems. The bio-waste resulting from the plant cultivation- and fish farming processes is used for power- and heat generation, fish feed supplement and to generate new bio-fertilizer for the crops.

4. TECHNICAL DESIGN

The conceptualized VF of DLR (see *Fig. 1*) is a building with 37 floors, a square footprint of 44 by 44 meters and a total height of 168 meters (while 5 of these floors are beneath ground level).

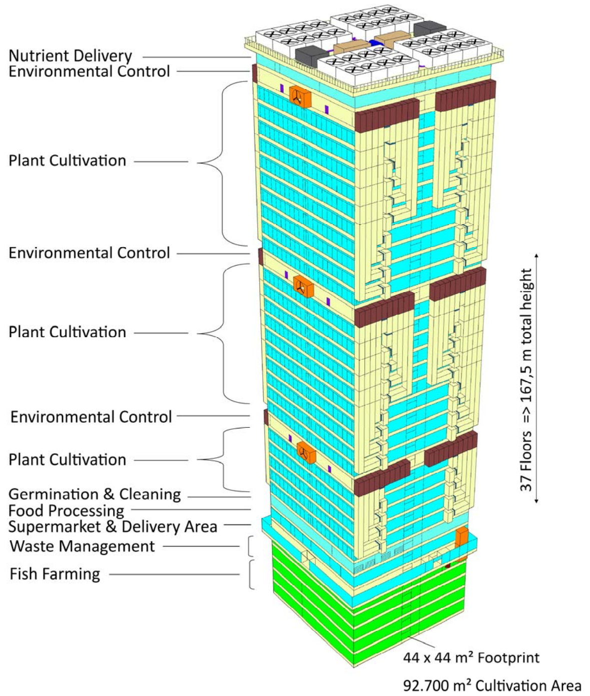

Figure 1: Inner structure of the Vertical Farm

A Germination Floor is used for the initial germination of all seeds. The floor contains twelve controlled environment chambers (Germination Units) which can accommodate several tens of thousands of seeds at a time. Additionally, this floor comprises systems for the cleaning and sterilization of equipment. These machines are used to prevent and, when necessary, destroy contaminants, fungi and other sources of disease that may threaten food production. Finally, a laboratory is located on the Germination Floor for the analysis of samples from the entire VF.

The facility includes 25 Plant Cultivation Floors (see *Fig. 2*) each with multiple stacked plant growth layers. These various floors are used for the cultivation of ten different crop species. A total edible biomass output of approximately 13,3 metric tons/day and about 4.900 metric tons/year can be achieved with a total grow area of ca. 93.000 m^2. Each of the Plant Cultivation Floors is divided into four different sections, and only a single crop type is grown per floor. The sections of one floor are seeded and harvested at a different time, to allow for a more distributed output of food. The plants are grown in special Grow Units, which can hold up to a maximum of six Grow Pallets, depending on the crop type. The Grow Pallets provide a support structure for the plants and house sensors to monitor the local environmental conditions.

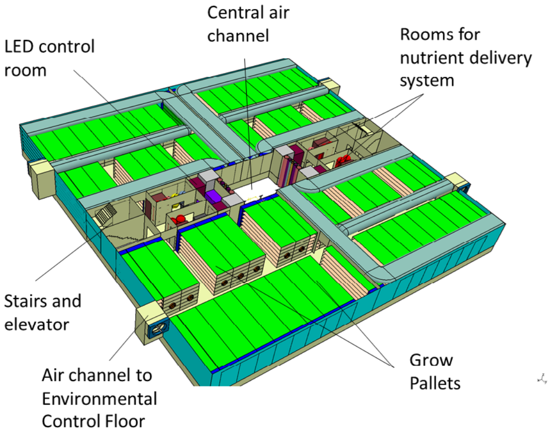

Figure 2: Plant Cultivation Floor

Aside from plant germination and cultivation, three Fish Farming Floors (see *Fig. 3*) are dedicated to the cultivation of tilapia fish. A total of ca. 2.100 tilapia fish can be produced per day, which corresponds to roughly 280 kg/day and 100 metric tons/year of tilapia filet. The fish are kept in circular tanks of different dimensions, according to a pre-defined stocking rate based on the size of the fish. The tanks are connected to water management systems which re-circulate the water, maintaining desired conditions and separating out waste. The fish are fed a mixture of non-edible plant biomass produced in the VF and high-protein fish feed which is bought from an external supplier.

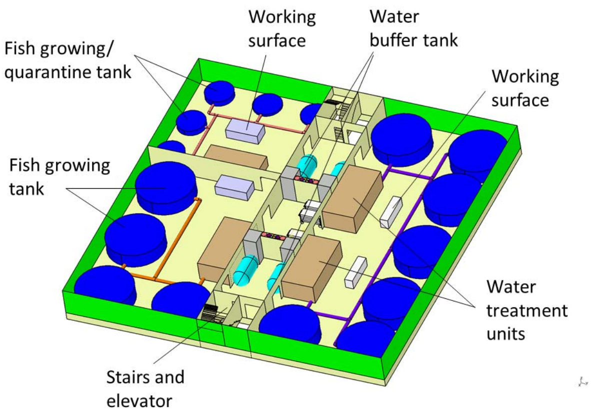

Figure 3: Fish Farming Floor

A total of 225.000 L/day of water is calculated to be required for plant cultivation, along with around 30 L/day of a concentrated commercial nutrient solution. By cooling the air and capturing the condensed water, most of the water can be recovered, leaving a total of 23.000 L/day which needs to be supplied from outside the VF. The water and nutrients are stored on one Nutrient Delivery Floor at the top of the building and are pumped down to the Plant Cultivation Floors as needed. There, the water and nutrients are mixed in the desired quantities, heated or cooled to the desired temperature and delivered to the plants.

To allow precise control over the light spectrum, intensity and duration, LED lighting is used in the VF. The lighting system has a peak power demand of 6.000 kW and an energy consumption of 81.000 kWh/day. To ensure that the LEDs can operate at optimal conditions, each Plant Cultivation Floor is outfitted with two heat exchanger systems to cool the LEDs, each capable of removing 200 kW of heat out of the building. The total peak power consumption of all the heat exchangers needed for the LED system is 2.500 kW. The energy consumption of the LED heat exchangers is 60.000 kWh/day.

To maintain the desired relative humidity for plant cultivation, it was determined that an air flow rate of approximately 850 m^3/s is required for the VF. A total of three Environmental Control Floors (see *Fig. 4*) are assigned to the air management and environmental control system, and each is designed to handle an airflow of 280 m^3/s. Each Environmental Control Floor is divided into four identical sections, similar to the Plant Cultivation Floors, and is connected to eight or nine Plant Cultivation Floors through air ducts running along the sides of the building.

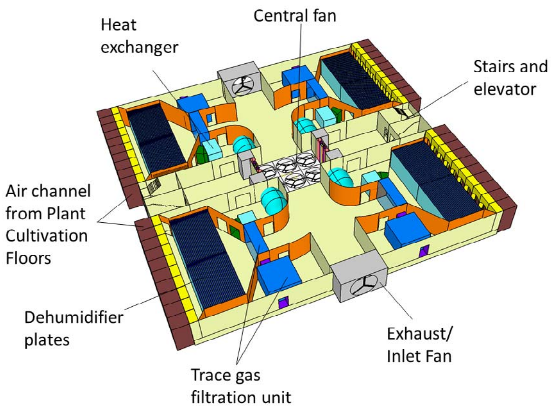

Figure 4: Environmental Control Floor

The used air arrives from the Plant Cultivation Floors and passes through dehumidifier plates connected to a heat exchanger system. The plates cool the air from approximately 25 ºC to about 19 ºC. The resulting condensate is captured and stored in buffer tanks, before being filtered and re-used. After leaving the dehumidifier plates, the air is re-heated to 25 ºC and forced through a filtration system that separates out any unwanted particles and trace gases. Afterwards, the dry, filtered, air is forced down to the Plant Cultivation Floors through a large air channel running down the center of the building. Large exhaust/inlet fans at the sides of the Environmental Control Floors are used to let air in or out of the building when necessary. The heat load from the LEDs and air dehumidification is transferred to the roof through pipes filled with cooling fluid. On the roof 32 heat dissipation units ensure that the heat is rejected from the building. Cooling and re-heating of the air in the VF requires a peak power of approximately 8.500 kW for the operation of the heat exchangers on the Environmental Control Floors and the heat dissipation units on the roof of the building and amounts to a consumption of 202.000 kWh/day. Furthermore, the fans required for the inlet and exhaust of air and the circulation of air through the building, have a peak power demand of 4.300 kW and an energy consumption of 68.000 kWh/day.

Once the fish and crops have matured and have been harvested, it is necessary to process them for shipment to supermarkets and restaurants. For this purpose, one Food Processing Floor in the VF has been devoted to cleaning and packaging of the produced biomass. On this floor, the inedible biomass is separated from the edible biomass and thrown down a waste chute to be processed by the waste management floors. The packaged food is delivered to the ground floor, which acts as a delivery and pick-up area and contains space that can be rented out as a supermarket. The excess space on this floor, which was not needed for cleaning or packaging machines, was turned into office space and a break room. Furthermore, the control room from which the entire building can be monitored is also located on this floor.

The inedible biomass ends up in a large storage container on the upper Waste Management Floor. There are two Waste Management Floors in the VF which are designed to process the waste produced by plant and fish cultivation. The top Waste Management Floor houses five biogas domes which utilize anaerobic microorganisms and bacteria to digest waste and produce biogas. Furthermore, this floor contains a fertilizer facility that utilizes special fermentation tubes filled with lava rock particles in order to produce/ extract nutrients from waste. The extracted nutrients, as well as some water, are then stored in tanks before being used for plant cultivation purposes. The second Waste Management Floor contains another five domes for biogas production. Furthermore, there is a gas separation system which is used to split the biogas into its major components, methane and carbon dioxide, and to remove the unwanted minor components. The methane and carbon dioxide are stored in high-pressure tanks, until needed. The methane is used to run the power generating turbines, while the carbon dioxide is injected in the Plant Cultivation Floors to increase the plant biomass yields. On average the Waste Management Floors process 9,5 metric tons/day of plant and fish waste. This waste can be used to produce up to 3.300 m^3/day of biogas, which corresponds to 2.000 m^3 of methane gas and 1.000 m^3 of carbon dioxide. The methane gas is used to produce up to 7.800 kWh/day of electricity, while the carbon dioxide is used to cover part of the carbon dioxide demand of 1.300 m^3/day. Even with consideration of the carbon dioxide produced by the Waste Management Floors, the VF still requires a total of 300 m^3/day (utilized by the Plant Cultivation Floors) of carbon dioxide from external sources.

5. ECONOMICAL ANALYSIS

Based on a building construction database with cost data [3], the expected cost of the VF building is calculated to be 140 M€ (FY 2012). Then, using best engineering estimate approaches, the cost for the equipment required for the VF is estimated to be 145 M€ (FY 2012). Those numbers contain a 20% margin to account for the inaccuracies inherent in these cost estimates. The total non-recurring cost is then calculated to be 285 M€ (FY 2012). This non-recurring cost (see *Fig. 5*) is amortized over a period of 30 years, resulting in annuity costs of 14 M€/a (FY 2012).

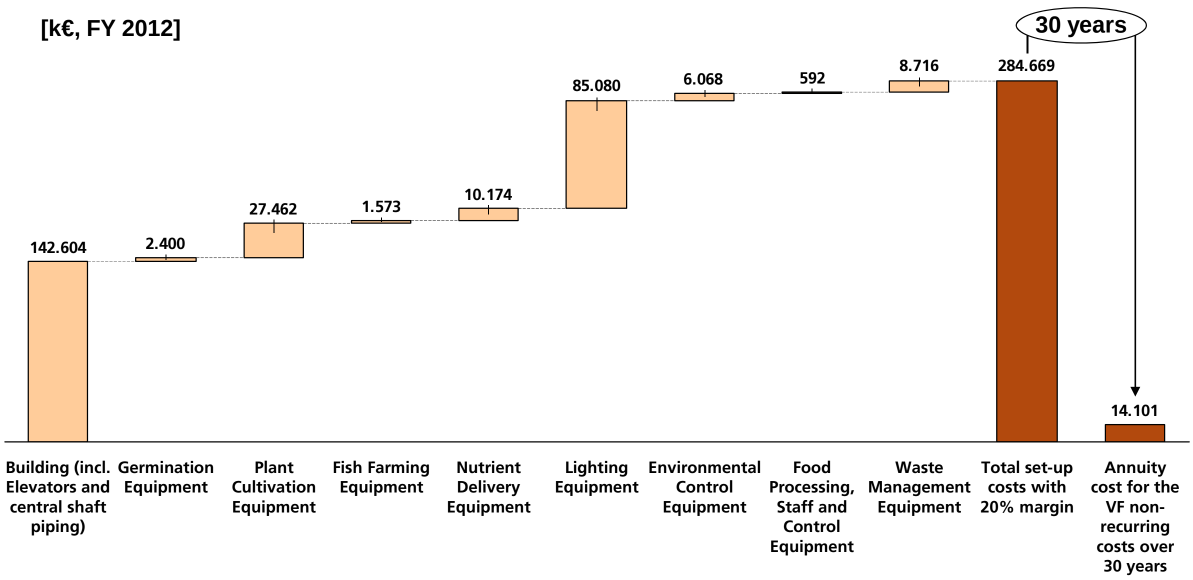

Figure 5: Annuity cost for the entire Vertical Farm non-recurring costs (including 20% margin) [FY12]

Calculations and best engineering estimates are made for the power demands of the different subsystems of the VF. It is found that the peak power consumption is around 21.300 kW and the energy consumption is roughly 405.500 kWh/day. Consequently, the energy cost is calculated to be 28.500 k€ (FY 2012) per year including a margin of 20%.

Each year, 10% of the initial equipment cost is written-off to cover the costs of equipment maintenance and replacement. This amounts to 14,5 M€ (FY 2012) per year including a margin of 20%. The recurring cost of seeds, fish feed, nutrient solution and water is 1.500 k€ (FY 2012) including a margin of 20%. Personnel costs are calculated to be 3,60 M€ (FY 2012) including a margin of 20%, based on 60 employees with an average salary of 50.000 €/year. The total recurring cost is calculated to be 48 M€ (FY 2012) per year.

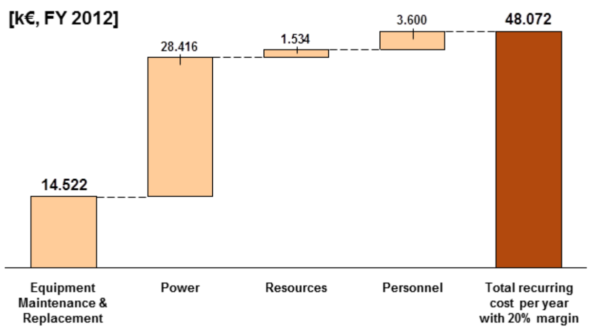

Figure 6: Total recurring cost VF per year (including 20% margin) [FY12]

The combined annual costs for the VF, including write-offs, recurring and non-recurring costs and cost margins is calculated to be roughly 62 M€/year (FY 2012) including a margin of 20%. A cost distribution can be seen in *Fig. 6*. To cover these expenses, an average food price of 12,54 €/kg is required.

6. ALTERNATIVE SCENARIOS

Three different scenarios are examined to determine the most promising VF design for future studies.

Taking into account the changes to the VF which occur when the Fish Farming Floors are removed from the building, leading to a pure crop production VF, the average cost per kilogram of produced food decreases to 12,48 €/kg (Scenario 1).

Removing the Fish Farming Floors and the Waste Management Floors from the VF, reduces the average cost per kilogram of produced food to 12,23 €/kg (Scenario 2).

In the last scenario, the Fish Farming Floors and Waste Management Floors are removed and no water recovery is performed on the Environmental Control Floors. As a result of these changes, the average cost per kilogram of produced food in this scenario drops to 9,88 €/kg (Scenario 3).

Tab. 1 presents the required minimum prices for the food produced in the VF for all scenarios in order to cover all expenses.

Table 1: Vertical Farming scenarios and the corresponding minimum (average) food prices [FY12]

Scenario	Minimum price [€/kg]
Baseline Vertical Farm	12,54
Scenario 1	12,48
Scenario 2	12,23
Scenario 3	9,88

While the estimates and assumptions were quite coarse at times, some conclusions can nonetheless be drawn from the comparison of these scenarios with the baseline design. For example, the low cost of 20 €/ton which was assumed for waste disposal [4] (Scenarios 2 and 3) makes it cheaper to forego waste management in the VF. Furthermore, the high costs of cooling air to recover the water in the VF are significantly higher than the costs of bringing in water from the outside. Based on these scenarios and the corresponding minimum food prices, it is concluded that water recovery and waste management are currently not cost effective in areas with low water prices and low waste removal costs and thus should not be investigated in near-term design studies.

7. COMPARISON WITH TRADITIONAL AGRICULTURE

Traditional field cultivation and closed environment cultivation (protected cultivation) produce different crop yields. Column four of *Tab. 2* provides the required agricultural land area in hectares required to fulfill the VF plant yield, shown in column three for every plant with respect to the baseline scenario.

Table 2: Yield comparison of the Vertical Farm with traditional field cultivation

Crops	Expected yield in field agriculture [metric tons/ha*year], [REF]		Baseline Scenario		Mono-crop Scenarios		
			Yield of VF* [metric tons/year]	Required agricultural land to fulfill VF output [ha]	Yield of VF* [metric tons/year]	Required agricultural land to fulfill VF output [ha]	Area Ratio for Equal Biomass Output
Lettuce	23	[5]	1.478,78	64,29	9.242	401,83	2.075,55
Cabbage	27	[6]	355,49	13,17	4.444	164,59	850,17
Spinach	12	[7]	205,38	17,12	5.135	427,92	2.210,31
Carrots	30	[8]	280,83	9,36	3.510	117,00	604,34
Radish	13	[9]	215,01	16,54	5.375	413,46	2.135,65
Tomatoes	37	[10]	978,12	26,44	8.151	220,30	1.137,90
Peppers	49	[11]	558,94	11,41	6.987	142,59	736,53
Potatoes	20	[12]	493,96	24,70	2.470	123,50	637,91
Peas	3	[13]	68,67	22,89	429	143,00	738,64
Strawberry	22	[14]	219,2	9,96	5.480	249,09	1.286,63
Total			**4.854,37**	**215,87**			

* include conservative aeroponic increase factor 1,4 based upon [15]

There is an increase in yield of all crops in the VF compared with traditional cultivation techniques. To produce an equal amount of edible output as that produced in a VF with a footprint of 1.936 m² (0,19 ha), an area of 216 ha of field cultivation is needed (see *Fig. 7*). This is a required agricultural land increase factor of 1.115.

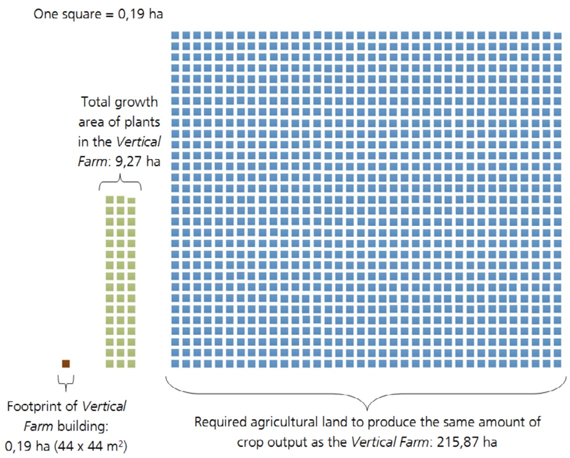

Figure 7: Vertical Farm compared to Traditional Agriculture

The increases in yield of the VF is the result of the protected environment (optimized growth conditions), shortened growth periods, additional numbers of grow cycles and harvests per year (no seasonal restrictions) as well as area utilization optimization (vertical stacking).

Tab. 2 also displays a considered mono-crop scenario (table columns five to seven) whereby the entire VF is utilized for the cultivation of one single crop. The highest area ratio for the mono-crop scenarios is reached in case of spinach. To produce the VF output of 5.135 metric tons of spinach per year, 428 ha of agricultural land is needed. This leads to an agricultural land increase factor of 2.210 times, compared to the footprint of the VF building.

8. CONCLUSION

At the present time, no matter the chosen study scenario, results demonstrate that the price to produce one kg of biomass in the envisioned VF is too high compared to supermarket vegetable and fruit prices e.g. in Germany.

Nevertheless, significant margins were built into the calculations with respect to yield, energy consumption and cost analysis. The following aspects will further enable the general economic feasibility of the VF:

- **Shorter grow phases:** Margins are built into the considered plant life cycles and thus overall the production cycles. For example, the grow parameters from [16] include germination time (ca. 1-2 weeks) into the documented crop growth periods. As this phase is executed within the separate floor (Germination Floor) within the VF, the overall production cycle is in reality shorter than that calculated in this report. This way overall biomass output will be higher and thus result in lower prices per kg.

- **Innovative cultivation recipes:** Recent research suggests that through PAR-specific lighting strategies or so called ‘light recipes’, including inner canopy lighting and maximized day/night illumination schedules, plant yields can be further advanced. Also new plant varieties, specially bred for an implementation within a VF, can have positive impacts on VF yield. Further research in this field can therefore push the biomass output and thus decrease price.

- **Energy savings:** Energy costs represent a major portion of the overall recurring costs. The price of one kWh was set to 0,16 € [17] which already reflects future price development. Present energy prices for the energy intensive production industry such as chemicals, paper, ceramics, cement, iron and steel are lower [18] and could contribute further to cost saving. Power plants also offer time-dependent energy use cost reductions (e.g. if energy is used during the night a reduction in cost can be had). Since the VF is independent from the outside day/ night periods due to the absence of windows in the entire building, this approach can lead to significant cost savings. Also the incorporation of regenerative energy systems like wind turbines on the roof and solar cells as general wall panelling will contribute to a more balanced power budget. Furthermore, light intensity adjustments based on plant maturity were not considered and could permit additional energy savings. The consideration of the described opportunities for energy saving will decrease the total VF energy demand and reduce the price per kg of biomass.

- **VF design adjustments:** Further cost savings can be achieved by designing a VF in a different manner. As stated earlier the present VF concept was designed under a 'show case' agenda, meaning that several functions and floors are not necessary when designing for lowest cost. Also, general cost savings can be achieved by optimizing the overall design of the VF (e.g. instead of one tall building with 37 floors it may be more cost effective to employ a number of smaller buildings of less height (e.g. 5 buildings with 10 floors each). This could result in less complexity and so less cost.

- **Cost analysis:** Several cost items were estimated with high margins and significant savings can be made during future studies. To mention one example, the maintenance cost (10% of the initial equipment cost) accounts as an annual cost item of ca. 14 M€. This factor might be reduced by half or even more.

Considering the above listed aspects, it is suggested that the achievable price for a break-even production within a VF can be reduced to 3-5 € per kg of biomass. A necessity of this, are financial contributions within this research domain over the coming years. Of course a break-even price of 3-5 €/kg is still above present vegetable and food prices e.g. in Germany.

Nevertheless, one has to consider that this price would be:

- Grow season independent (e.g. same price for strawberries in summer as during winter),

- Climate independent (e.g. unpredictable droughts, floods or insects plagues) and

- Location independent, which means the VF could produce fresh crops in any place in the world.

The last point is particularly interesting for three distinct regions on our planet, where traditional agriculture is not or is only to some extent feasible.

The first group is desert countries, for example Saudi-Arabia and United Arab Emirates. These countries are trying to gain food independence for their citizens, while being located in extreme arid regions with almost no fertile land.

The second potential group can be found within colder climates such as Siberia, Canada, Sweden and Iceland. Agriculture limitations include seasonal growth restrictions with short summers and long winters.

The last group can be found within mega cities, where no agriculture land is present but where a large number of consumers reside. Here, VFs can provide in-situ fresh food for the population. The initial target mega cities should be seen within high-income industrial areas such as North America, Europe and Asia.

The calculated VF (baseline scenario) produces on a footprint area of 1.936 m² the same amount of fresh crops as 216 ha of traditional field agriculture. This is an increase factor of 1.115. For mono-crop scenario calculations, this value (in case of spinach) rises even to 428 ha of equal agriculture land (increase factor of 2.210).

From a space-based life support perspective we are required to close the air, water and food resource loops for long duration crewed missions due to constraints on resupply. This requirement results in a 'space technology pull' that can be utilized to benefit terrestrial sectors such as Vertical Farming. In particular, on long duration missions, production yields and reliability must be maximized and all resources utilized in an efficient manner. Incorporating the technologies developed for such space-based bioregenerative life support systems can permit similar results in terrestrial systems.

Investing in the CEA research domain can further push the Technology Readiness Level of space-based life support systems while advancing key technologies applicable to Vertical Farming. This will advance human spaceflight while open-up the door for realizing Vertical Farms in a commercial way and strengthen the international community in facing the global food situation in the coming 50 years.

9. ACKNOWLEDGMENTS

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