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ASSESSMENT FOR MICROALGAE PRODUCTION IN PHOTO-BIOREACTORS FOR VERTICAL FARMING IN URBAN AREAS

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ABSTRACT: In 2050 around nine billion people will live on this planet with the bulk situated in giant cities. Considering the finiteness of resources, highly important for today's agriculture leaves one question open: How can we guarantee food security for the citizens of tomorrow? Key technology for solving this problem could be the artificial eutrophication process triggered by the effluent from urban wastewater treatment plants. Many environments to cultivate microalgae have been developed in the last decades. Photo bioreactors mounted on the claddings of multi-storeyed buildings could continually generate high amounts of biomass under the influence of sunlight and the addition of usually undesired carbon dioxide. The nitrogen and phosphorus share of this biomass could be used as fertilizer, at best in vertical farms thus reducing food production chain to a theoretical minimal volumetric expansion of a few city blocks. Anaerobic fermentation tanks would further form methane out of the algal carbon and hydrogen content to provide energy. In case of Vienna this concept gives an energy self-sufficient nutrient recycling method allowing a city intern food production to be independent from phosphor rocks and fossil fuels.
Keywords: biofertilizer, biogas, centralized, microalgae, recycling

1 INTRODUCTION: TODAYS FOODPRODUCTION

There is no human way to refer to the fact, that nearly one eight of the world population do not have enough to eat [1]. For that reason it should at least be primarily mentioned. The food security of the rest, including us, meanwhile highly depends on three non-renewable resources, fossil fuel, methane (CH_4) and phosphor rocks (PRs). With about 95 EJ a year the food sector accounts for around 30% of the world's total energy consumption [2]. More than one per cent is used solely for the production and distribution of *nitrogen, phosphorus- and potassium-fertilizers* [3]. Burning world's reserves of crude oil and natural gas mostly provides this energy. A simple shift to renewable energies is necessary but would not utterly unbound food production from fossil fuels.

The *Haber-Bosh process* for example was developed in the beginning of the 20th century and was improved over years reaching a today's energy consumption close to the theoretical minimum [4]. The formation of NH_3 asks for a high demand of hydrogen. H_2-stripping out of CH_4 is the best available technology making this resource highly important for fertilizer industries. Dawson and Hilton [3] predict that if all reserves of natural gas would only be used for ammonia production, the demand for millennia could be covered.

Furthermore oil refinery is the mother of many different economic sections. Amongst others it is the main producer of sulphur. Sulphur is further burned to get sulphuric acid, which is "...the 'acid of choice' for the dissolution of PR..." [3]. Next to a high energy demand for the burning process the dependence to the availability of fossil fuels is therefore also shown. FAO-2008 [5] gives a forecast for *phosphate fertilizer* supply by 2011-2012 of about $45*10^6$ tonnes P_2O_5. The origin of this phosphate is mainly PR, thus making world reserves of this mineral highly interesting. About 42% of these reserves are assumed to lie under Moroccan ground [6]. Related to the upcoming *oil peak* a so-called *phosphor peak* is expected in the next decades [7]. Better technologies to dissolve P_2O_5 out of the residues saved from todays PR-mining could prolong the reserves lifespan but would not change the fact that this resource is also finite. According to Cohen, D. [6] and Dawson and Hilton [3] a consumption rate related to todays lifestyle could only be ensured for the next 100-400 years.

29% of the world's total energy consumption is furthermore used for the transportation, processing, retailing and production of food excluding fertilizer industries [2]. Energy is mainly provided by fossil fuels. Summing up with CH_4 released to the atmosphere from livestock farming, food production forms a great share in global green house gas (GHG)-emissions. Growing consumption increases emission as well as the utilization of land and water for food production. To cover the demand of nutrition about 11% of the worlds land surface was used for crop production by irrigating with 70% of all water withdrawn from aquifers, streams and lakes in 2010 [8].

Several concepts to work against these trends have been developed. FAO-2011 [2] predicts that a change to diets including "...the use of more fresh and local foods..." is indispensable. This would also reduce food losses and the demand for energy, water and land. In fact 1/3 of the food is lost during production, processing and distribution today [9]. This does not take into account that only a small share of used fertilizer can be found in food appointed for the consumer. Nitrogen (N) and phosphorus (P) is also lost during farming through erosion into lakes and rivers and finally into the ocean thus causing eutrophication changing former ecological systems.

Alternative methods for the production of high quantities of food are quite common in lower developed countries and strictly forbidden in Europe because of worse impacts on nature and consumer. One is known as the technique of slash and burn: High amounts of forests are slashed every year around the world before the dry seasons. In times with less rainfall the wood can dry and is burned afterwards to release its nutrients into the subjacent soil. This gives a short-term boost of the floors "*nutritiousness*" being exhausted after a few crops because of high erosions. When harvest gets poor the farmer shifts to another sector of the forest to repeat the procedure, leaving behind a field bad suited for reforestation. The bad impact on ecosystems and the often-occurring non-reversibility of the soil condition is well known and still between 3 and 7 per cent of the world population is using this technique [10] most times because of the lack of possibilities.

Another common method is the direct use of human faeces from wastewater streams. According to (WHO, cited in [11]) nearly 700 Million people eat food produced with human faecal fertilizers triggering diarrhoea related diseases such as cholera killing 2.2 Million of them every year. Even this can be seen as a reason for bad conditions in the poorest countries of the world, recycling of nutrients from sewerage could be an opportunity for the worlds food sector. The *International Water Management Institute* (IWMI) argue that "...the social and economic benefits of using untreated human waste to grow food outweigh the health risks." The "...dangers can be addressed with farmer and consumer education..." (IWMI, cited in [11]). **The authors** of this paper predict that an advanced technology for the recycling of essential elements could also reduce 1st worlds dependency from fertilizer industry and in this connection from fossil fuels and PRs.

2 ROOM FOR IMPROVEMENT

The world population prospect of the *UN's Department of Economic and Social Affairs* (ESA) gives different forecasts for this century. Their overall conclusion is that the amount of people living on this planet will increase until 2050 to a value between 8 and 12 billion [12]. About 9 billion people would need a 70% increase of food production compared to 2005-2007 [13]. To meet this demand and to ensure food security for the next generations new food production chains have to be developed. Therefor several factors have to be improved:

2.1 Reducing food miles

From a todays point of few it seems quite impossible to reach the "20/20/20-targets" given from the European Commission [36] in the next eighteen years. The information that a 20% share of renewable resources in the commercially used energy is hard to reach shows us, that the consumption should rather be avoided than substituted. This could largely be achieved by reducing food transportation. Sensitisation of the consumer for the ecological costs of imported luxury goods could do one´s bit as well as logistical improvement or a decrease of the volumetric expansion of the delivery chain for essential nutritions. These changes would have another positive effect:

2.2 Avoiding food losses

Distribution plays a great role in wasting eatable material. Its consequences differ from region to region according to average temperature and availability of cooling systems. Big regional differences can also be found in the "kitchen-related" food wastes as well as in the generally high crop losses [9]. Some of these wastages, including the one generated by post harvesting storage ask for new techniques and models for the food production to avoid them.

2.3 Managing Earths finite surface

That we have to look out about other techniques and models gets also obvious when the increasing need for land is reconsidered. Because of Earths environmental limits this need has the potential to become a limiting factor for the growth of world population and food security.

2.4 Less irrigation

As the SOLAW-report [8] shows, in many parts of the world a high physical water scarcity faces large shares for irrigation. The knowledge of plant physiology helps to decrease watering of the fields by using low budget upgrading ideas and outlines the benefits of higher technologies used for example in green houses.

2.5 Freeze of mineral *N- and P-fertilizer*

Another benefit of more controlled environments like green houses is the lower nutrients run off. This does not only positively effect the surrounding water bodies but also the economics. Reconsidering the entanglement of mineral *N-and P-fertilizer* production and the non-renewable resources motivates the search for alternatives!

3 A CONCEPT TO ENSURE FOOD SECURITY…

3.1 Vertical farms

Despommier, D. [14] discusses the idea for a totally controlled agriculture. In so-called *vertical farms*, food could be produced minimizing cultivated area and shifting production into town. Many models have been developed how such farms could look like, following the same guidelines: Multi-storied buildings sheltering different cultivation methods should produce the nutrient demand of the citizens living within a small radius around the production place. Different well-known techniques could ensure a year-round harvest in perfectly controlled environments. Despommier, D. [14] predicts that *pythotrophologie* is advanced enough to create healthy food in artificial environments. Some of the numerous advantages are listed below (after [14]):

- Year-round crop production
- No weather-related crop failures
- Use of 70-95% less water
- Greatly reduced food miles
- More control of food safety and security

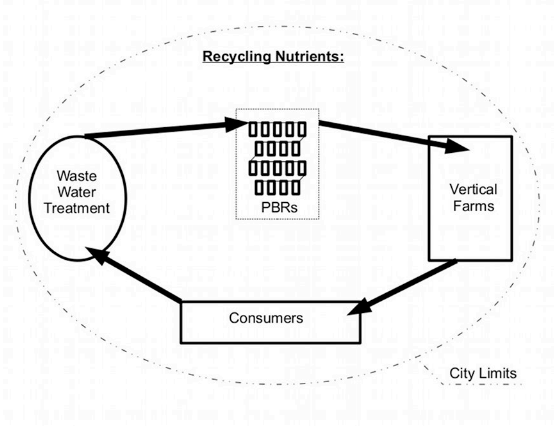
If demand is covered by this indoor agriculture, conventional farms could be left alone allowing the ecosystem to restore. After shrubs and bushes regain territory, growing trees would bind atmosphere's carbon dioxide (CO_2) building a serious opponent against GHG-emissions. Further advantage would be the low consumption of *N-and P-fertilizers* because of the prevented erosion. How to provide vertical farms with the still needed amount of N and P without the use of non-renewable resources will further be discussed:

3.2 Bio fertilizer production in photo-bioreactors

As mentioned in the introduction, recycling of essential elements out of human wastewaters will be necessary in the future. In the context of this paper generally N and P, furthermore labelled as nutrients, are meant. Algae are objects of investigations for this task since the mid of the previous century [15]. Looking at the undesired effects of *eutrophication* in water bodies contaminated with sewage makes the controlled combination of wastewater treatment and algal production for further use self-evident. Modern wastewater treatment plants offer different possible linkages to a commercial production of algae. In general they generate effluents with nutrient loadings, undesired too high to release into water bodies. One example is the "*centrate*" generated when *activated sludge* is dewatered after undergoing an *anaerobic digestion process*. With around 1600mg/L *total Kjeldahl nitrogen* and 53mg/L phosphorus (1) this liquor is rich in nutrients and would be well suited for artificial algal production in a thinned out form. Up to 15% and 4% N and P deposited into canalization could respectively be reused in this way. Therefor bacteria and protozoa have to be reduced. This could be accomplished through several techniques. According to their research Cho et al. [16] suggest a $2*10^{-7}$m-pore size filter rather than *autoclaving* or a high radiation with *UV-C* light.

Different methods for the cultivation of algae have been developed in the last decades. Most of them rely rather on the production of microalgae than macroalgae like seaweed. Depending on the strain, microalgal growth can be accomplished by *photoautotrophic*, *heterotrophic* or *mixotrophic cultivation*. While in *heterotrophic* cultivation, algae are fed a carbon source, such as sugar, and grow without light, *photoautotrophic cultivation* strategies use big surfaces to capture photons for photosynthetic plant metabolism' [17]. In **the authors** opinion only the sun should be considered as a photon source for *photoautotrophic cultivation*. Literature gives plenty of data about this method of algal production in several systems including *photo-bioreactors* (PBRs), *open pond*- and *race way-systems*. In contrast to *immobilized cultures*, where algae grow on a thin film [18] the previous named systems contain high amounts of water in which micro algae can move and are mobile. Because of their architecture, highest values for photoactive volume (PAV) mixed with smallest surface areas can be found in modern flat plate PBRs. This combination supports the highest production rate related to the volumetric expansion of the facility. To further reduce needed ground area **the authors** suggest mounting them vertically on the claddings of cities buildings. This would not only save land but would produce the biomass in the vicinity of its consumption place.

For the production of biofertilizer, primary the N and P content of the algal biomass is of note. This allows applying a harvesting method completely different as normally used in the *biofuel sector* where a high lipid content of the algal product is the ultimate goal. After a simple settlement process *anaerobic fermenters* could extract carbon, hydrogen and oxygen content of the water-algae mixture. This content would form CH_4 and CO_2. The biogas could produce the energy for further centrifugation of the *fermenter effluent* and for other parts of the production chain. After centrifugation the dry part could be used as soil conditioner as predicted in Collet et al. [19]. But also the liquid part should be investigated to be used as common fertilizer for agriculture if produced in a non-N/P-limited way.



Picture 1: A carbon intelligent food production chain

The combination of vertical farming and the recycling of nutrients from wastewater streams through a *controlled eutrophication* in PBRs mounted on the claddings of the cities buildings would result in a truly carbon intelligent food production chain (q.v. **Picture 1**). The impact on traffic, the stability of world's non-renewable resource reserves and the GHG-emissions could be highly positive.

4 … COMPUTED FOR VIENNA

As an example the concept will closer be investigated under the circumstances found in Vienna. Location specific parameters necessary for a profound estimation are only the sunlight irradiance intensity, duration and the temperature of the surrounding air. This data is measured and recorded from meteorology stations. Primarily to provide a tool for the estimation of *photovoltaic* (PV) *energy* generation in European countries Suri et al. [20] collected the data of solar irradiation in an 1km-1km resolution for 30 European and candidate countries. The combination of this data with a *geographical information system* (GIS) can be found as an interactive map on the website of the *photovoltaic geographical information system* (PVGIS) [21]. The radiation power in [W/m^2] is given by the global irradiance (G) and the diffuse irradiance (G_d) hence particle in the atmosphere scatter sunlight and bring solar radiation into corners where no direct light can get. PVGIS provides these values for horizontal surfaces averaged on a fifteen minutes basis under a real sky.

To convert them for a horizontal surface, 50% of these irradiances are lost (after Slegers et al. 2011 [22]). Furthermore direct sunlight irradiance will be avoided because of its negative effect of *photo-inhibition*. This can be achieved by directing flat plate PBRs surfaces always away from sun. Only the façade-reflected light and the diffuse irradiation remain. It can be assumed, that a rough white facade acts like a *Lambertian-scatterer* when radiated. Incident light is being scattered in every direction from -90° to +90° around the surface normal with an average intensity mitigation of 36%. For the average G- and G_d- values in Vienna a sunlight irradiance on the reactors surface of about I_{PBR}≈158W/m^2 can be calculated according to **formula (4.1).**

$$I_{PBR} \approx (0.5 + 0.32)G_d + 0.64(G - G_d) \qquad \textbf{(4.1)}$$

While I_{PBR} consists of *unpolarized* sunbeams with no excellent direction the average intensity of the light reaching the photoactive volume can be estimated. With the *refractive indices* of *Plexiglass*, air and water this share (I_{trans}) accounts to approximately 84% of I_{PBR} [23].

Light after transmission through the reactor walls travel through cultural volume. That is where it can be absorbed by the algal culture. The potential for absorbing light is given by the *attenuation coefficient* (α). Slegen et al. [22] for example give an *attenuation coefficient* of 75m^2/kg. Together with a small reactors cross-section area of d=3cm and a cultural density of C_x=1kg/m^3 the absorbed sunlight (I_{abs}) is given by *Beer-Lambert-Bouguer law.*

The spectrum of more than the half of this absorbed radiation lies beyond the *photosynthetically active band.* Light with a wavelength between 400 and 700nm can be further used for algal photosynthesis hence it is called *photosynthetically active radiation* (PAR). This has to be corrected because of the relatively week absorbance of chlorophyll in the green band. This part forms about 10% of PAR and depletes the amount of energy used for photosynthesis E_{PS} [24]. In summary approximately 39% of the absorbed light intensity can further be used by the photon capturing mechanism of the algae [23].

Assuming that the wavelengths of the light used for photosynthesis are distributed normal still shows a difference to the wavelengths suited for activating algal *reaction centers* which lie at 680nm and 700nm respectively. Fitting PAR, which is accomplished by algal *antenna centers,* consumes another 20% [23]. Coming from an average incident irradiance a quite low value of around I_{PS}=37W/m^2 can now be converted to chemical energy. Too high intensities have been successfully avoided through surrendering on direct sunlight. No *photo inhibition* has to be feared and the energy flux can utterly be used to compute further metabolism of the plant.

To synthesis one mole of sugar in the *Calvin cycle* a minimum of forty-eight moles photons are necessary according to the chemical energy needed for the process [24]. The energy content of these photon moles can be computed through using *Einsteins equation* and the average wavelength suited for the *reaction centers.* One mole of photons, belonging to the 690nm spectrum transport an energy of about 174kJ. Compared to 2808kJ heat energy produced through burning one mole of sugar in a calorimeter [25] a maximum *sugar production efficiency* of 33.7% can be found.

Conversion of sugar to algal biomass provides an upgrade in the calorific value of the biomass. **The authors** assume that this difference equals the mass lost that occurs within this process. For an algal strain with a *calorific value* of 21kJ/g the difference to the calorific value of on sixth of sugar (15.6kJ/g) equals an energy upgrade of 34%. Authentication of this assumption is given by mass loss calculations described by Williams and Laurens [26].

For remembrance the data used for this estimation is obtained from average sunlight irradiances given in [W/m^2]. Energy converted to algal biomass per square meter can now be calculated by multiplying with the total duration of sunlight irradiance [21]. Dividing through the calorific value of the algae gives the specific yield related to the surface. For Vienna a total irradiation durability of 5212.5 hours a year is used. This value leads to an average yearly production of approximately 7.4kg/m^2. The small cross-section area used for the flat plate PBRs in this estimation gives a yearly *algal dry weight* yield of around 245g for one litre PAV.

If calculation is executed with exact values, the energy losses that belong to algal heat production can be summed up and compared to the temperatures of the Viennese air. By doing so the need for heating and cooling to obtain the optimal temperature for algal growth can be computed. According to Schipfer, F. [23] this leads to an energy demand of around 1.3MJ for every kg *algal dry weight* produced in the PBRs.

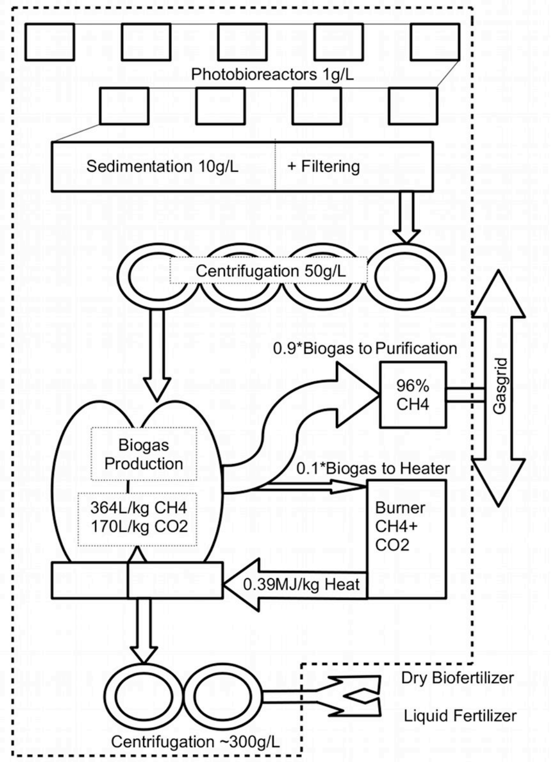
To generate this energy, biogas should be considered as a *joint product*. A theoretical conversion of the algal carbon content to CO_2 and CH_4 can be achieved through high *retention periods* in anaerobic fermentation tanks. After Sialve et al. [27] one half of this carbon (C) could form the CH_4 content in the produced biogas. When one gram algal dry weight contain about 520mgC [28] this amount would produce 458mL CH_4. After washing out the CO_2 –content, the biogas could be burned to produce heat and electrical energy. After subtraction of the heat necessary for the *anaerobic fermentation process*, about 11.53MJ *calorific value* biogas would remain for the processing of a single kg *algal dry weight* [23]. **Picture 2** shows the mass flow of such a harvesting process according to Collet et al. [19].

Further physical and economic values for flat plate PBRs are gained from the Austrian company *Ecoduna* [30]. Their technology is distinguished by a quite small energy consumption for the biomass production process. The following **Table I** shows the *specific net energy* for this process, when the reactors are mounted on the claddings of a Viennese building and biogas is used as a joint-product in the harvesting process.

Table I: Specific net energy [MJ/kg]

	Consumption	Production	Reference
Aeration	3.16		[31]
Infrastructure	2.47		[31]
Heating	1.30		[23]
Harvesting	1.76	11.53	[23]
Overall	8.69	11.53	

The estimation promises an energy-self sufficient biomass production. With the nutrients gained from the cities wastewater treatment facility (EBS-Wien), which will be upgraded with *anaerobic digesters* and a flue gas combustion unit, algal fertilizer production could give an interesting alternative to today's mineral fertilizer industry.



Picture 2: Harvesting algal-fertilizer

The other side of the picture is marked by quite high installation and maintenance costs involved in the presented theoretical concept. According to Mohr, M. [30] the costs of 1.4*10^6 L PAV in flat-plate PBRs could value about 2.240.000€. It is assumed that this volume is the maximum that an 100m*100m façade could tolerate. The installation costs to ensure a mass flow on such a horizontal hectare can be found in **Table II**. References used for calculating these values through up- and downscaling are cited as "Following".

Table II: Estimated and rounded costs

	Costs in €	Dimensioning	Following
PBRs	2.240.000	1,4*10^6L	[30]
Centrifuge1	140.000	4,5m^3/h	[31]
Centrifuge2	28.000	0,9m^3/h	[31]
Gas Wash	29.000	29,5m^3/h	[32]
Connection	33.000	250m	[32]
Fermenters	175.000	700m^3	[32], [37]
$\Sigma_{Installation}$	2.644.000		

Purification of the biogas can be found as "Gas Wash" and "Connection" stands for an access to the commercial gas grid with *coagulants*, *safety system* and *odour addition*.

After Molina Grime et al. [31], yearly maintenance costs of 4% of the above mentioned installation fees are calculated. With an energy self-sufficient biomass production in mind, no further charges for electricity have to be computed. Depreciation is set for 15years and forms together with the maintenance a value that will be compared with the benefits.

Main idea behind the concept is the production of biofertilizer. Theoretical output of the estimation is in one hand dry soil conditioner and in the other hand *liquid algal fertilizer*. For the calculation of the benefits, these two products will not further be distinguished. According to Park et al. [28] the N-and P-share of the produced biomass will be estimated and multi placated with the fertilizer values given by Matzenberger, J. [33].

Methane excess is fed to the gas grid and generates a yearly income related to regional gas prizes. Timmerer and Lettner [32] estimate a value for the year 2004 of 1.63cent/kWh. Furthermore profits for binding carbon dioxide can be calculated according to the certificate prize listed on *BlueNext* [34]. Even if a crisis impacts this market drastically the theoretical profit should be considered. To accumulate the C-content of 1kg algae around 1,9tCO_2 can be bound [28]. The income of this sector is calculated with the averaged prize of 6,99€/tCO_2 from April 2012.

Another profit is generated through facilitating EBS-Wien from wastewater. Disposing 1m^3 sewage in Vienna in 2012 costs 1,89€ appointed from the city [35]. Supposing that the same prize would be paid for absorbing 1m^3 wastewater generates a good salary.

For the profits the averaged algal dry weight production, calculated for this paper was used and multi placated with the theoretical PAV for one vertical hectare. Results are shown in **Table III**.

Table III: Estimated and rounded balance

	Costs in €	Dimensioning	Following
Depreciation	176.000	15 years	
Maintenance	106.000	4% a year	[32]
$\Sigma_{Expenses}$	282.000	a year	
N-fertilizer	25.000	32t	[33]
P-fertilizer	5.000	5t	[33]
WW-boni	46.000	24.000m^3	[35]
CO_2-Certif.	5.000	651t	[34]
CH_4-Excess	4.000	270.000kWh	[32]
Σ_{Income}	85.000	a year	

The estimation of the biomass production with exact values generates benefits 33% lower than given in **Table III** [23]. The reason for the overestimation in this paper mainly lies in ignoring *photo inhibition,* which does play a role for higher irradiances in the summer months. This leads to an overall assumption, that the concept could only become economical feasible, if fossil fuels, fertilizer, wastewater boni and CO_2-certificates undergo a 5-fold price increase.

5 CONCLUSIONS AND OUTLOOK

Except for the CO_2-certificates no price increase can truly be expected in the near future. The only assumption for the economic part of this paper that can be made by pure conscience is that balance will get positive at the latest with expiring natural gas, crude oil or PR-resources. This paper wants to demonstrate an alternative for those who are interested in leaving some of these resources for the following generations. With an energy self-sufficient N- and P- recycling method that can be applied to any vertical surface, every city could fight against GHG-emissions and fossil fuel consumption without exhausting valuable urban area. Combined with the concept of vertical farming, life cycle assessments of the food consumed by tomorrow's citizens could contain no single transport mile thus releasing the inhabitants from a great share of traffic at the same time. Through this more efficient way of using earth's surface food security for a much higher world population could be ensured and atmosphere´s CO_2 could be mitigated through reforestation. Wasting of food, fertilizer and water could highly be reduced. Avoiding nutrient run-off would also contribute to the countless ecological benefits, which have to be further investigated.

The whole process leaves enough room for improvement and further research. Other climates should be computed as well as other harvesting techniques. Wastewater industry has developed many different concepts for reusing essential elements like N and P, which should also be investigated and considered. Another important factor for the presented idea would be to spot the algal strain, best suited for this task. Furthermore a biological and medical point of few would be interesting and is necessary for the development of a closed urban nutrient cycle.

7 NOTES

(1) After an E-mail from Harald Hanssen, Hamburg Wasser, 19.03.2012.

Wastewater treatment in Hamburg gives comparable values to the wastewater treatment in Vienna according to their *population equivalents*.

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