Circular Aquaponics for Urban Agriculture

for

Master of Applied Science

Environmental Policy and Management: Energy Management & Sustainability

Travis Andren

University of Denver University College

March 8, 2017

Faculty: Jennifer Golightly

Director: John Hill

Dean: Michael J. McGuire
Abstract

Controlled environment agriculture (CEA) and vertical farming (VF) systems have incredible potential to reduce environmental impacts currently associated with geoponic (soil-based) farming practices. These CEA and VF models currently suffer from problematic energy demands, associated carbon dioxide (CO₂) emissions, and questionable nutrient inputs that limit organic certification and occasionally limit marketability based on taste. Existing and theoretical VF systems’ performance was evaluated through literature review and an optimized solution was presented and evaluated on the same comparative parameters. The proposed redesign of the energy system, nutrient system, and distribution methods offers a greater measure of responsibility toward the triple bottom line than existing VF systems.
# Table of Contents

Abstract ................................................................................................................................... ii

Background ............................................................................................................................. 1

Importance ........................................................................................................................................................ 1
Problem Statements ......................................................................................................................... 2
Energy Problems ........................................................................................................................................ 2
Nutrient Terroir ........................................................................................................................................... 3

Approach ................................................................................................................................. 5

Anaerobic Digestion Assumptions .................................................................................................................... 6
Energy Assumptions ......................................................................................................................................... 7
Distribution Assumptions ................................................................................................................................. 7
Nutrient Assumptions ....................................................................................................................................... 8
Revenue Assumptions ...................................................................................................................................... 8
Evaluative Calculations .................................................................................................................................. 9

Literature Review ........................................................................................................................................ 9

Design and Production ................................................................................................................................. 9
Energy ............................................................................................................................................................. 11
Nutrients .......................................................................................................................................................... 13
Distribution ..................................................................................................................................................... 14
Revenue .......................................................................................................................................................... 15
Calculations ..................................................................................................................................................... 15

Solution ......................................................................................................................................................... 17

Stationary Fuel Cells ................................................................................................................................. 17
Hydrogen FCEV ............................................................................................................................................... 19
Nutrient Synergy ............................................................................................................................................. 19
Proposed Scaled Solution ............................................................................................................................... 20

Discussion ..................................................................................................................................................... 21

SWOTT Analysis .......................................................................................................................................... 23
Background

“If the skyscraper farm is the 747 jetliner, we are now at the stage of the Wright brothers” – Dickson Despommier (2010).

The evolution of agriculture has seen a variety of phases from anthropological records dating from before the Neolithic era, to green houses like the Crystal Palace from the 1851 World’s Fair, to plant factories growing medical plants indoors in Japan (Goto 2016). Today’s mainstream agriculture practice is manipulating ancient methods of working the fields, delivered through the inclusion of chemicals and vast amounts of water usage to grow crop species that are now growing in frequency of use of genetic modification (Besthorn 2013, 192). These practices coincide with an increasing acceptance of food that is chemically treated and over-processed, filled with food dyes and preservatives. In a time when climatic change has become a global concern, there are increasingly recognized methods for transitioning our agriculture system toward a more sustainable solution (Besthorn 2013, 195).

Importance

In the United States, agriculture accounts for nine percent of total greenhouse gas (GHG) emissions, especially nitrous oxide (N₂O) and methane (CH₄) from soil fertilization and livestock. This metric does not take into account the GHG emissions associated with distribution of crops, both into and within the borders of the United States (EPA 2016). The United Nations estimates indicate that without improved efficiencies, agricultural water consumption is expected to increase by an estimated 20 percent globally by 2050. During the same period, food demand is estimated to rise by 60 percent (UN Water 2016). As of 2014, nearly 50 percent of U.S. vegetable imports came from Mexico contributing toward the 1,500-mile average
distance that food travels to reach the plate of an American consumer (USDA 2016; Mundler et al. 2016). Can controlled environment agricultural methods be improved to have a greater effect on the triple-bottom line than traditional outdoor agriculture?

**Problem Statements**

Efforts to reduce the impacts of geoponic (soil-based) agriculture, both domestic and imported, has introduced methods of controlled environment agriculture (CEA), specifically vertical farming (VF). VF represents a method of CEA that maximizes land usage by layering and condensing crops, often within each floor of a multi-story building. Typically utilizing hydroponic or aeroponic technologies, these crop growth techniques trade the variable environment of soil for a controllable environment of nutrient enriched water. Various methods of hydroponics, including drip irrigation, ebb and flow, nutrient film technology, deep water culture, and wick systems, along with plant root misting methods known as aeroponics are common practice. The U.S. leader in aeroponic technology is AeroFarms, from Newark, New Jersey. AeroFarms’ aeroponic approach has been cited by Future Foods Farms as using less than one gallon of water per head of lettuce, compared to conventional geoponic methods in California that average ten to fifteen gallons of water per head (Future Foods Farms 2016). Water usage in vertical farming is one of the technologies’ greatest assets, while other inputs associated with energy and nutrients present the critical problems to the technology.

**Energy Problems**

CEA is commonly divided into greenhouses and vertical farms, the differing factor being the use of sun-fed systems versus artificially lit systems. VF is differentiated from CEA greenhouses in that the process of photosynthesis is artificially created through controlled
lighting spectrums, allowing for photoperiods to be maximized in the effort of increasing yields. Although the advent of light emitting diode (LED) technology has reduced VF energy demands compared to prior lighting systems, energy consumption is the significant ecological and economic detriment to every VF installation. The impact of purchasing energy from utilities has drawn strong criticism of VF as being inferior compared to geoponic farming practices. Despite this opposition to artificially lit agriculture systems, artificially lit models of VFs have a greater potential for return on investment (ROI) than sun-fed systems (Shao et al. 2016). Addressing these high energy inputs and their associated environmental impacts is the primary planetary benefit to the triple bottom line in the proposed solution.

Utilizing advanced fuel cell energy technologies that operate at a greater efficiency than traditional utility power options, paired with anaerobic biogas reclamation may provide a superior solution than what has been proposed to date. These technologies have also been configured into tri-generation systems that produce electricity at high efficiency, heat for use in the fuel-reforming process, and purified hydrogen that can be contained under pressure and pumped to localized fueling stations for use in automotive fuel cell electric vehicles (FCEVs) (Leo 2016). These FCEVs emit nothing but pure water and are currently available in variable formats from commuter cars to cargo vans (Hyundai 2016).

Nutrient Terroir

Although not measured, there are sentiments in the agricultural community that indicate that there is a flavor profile difference with some hydroponic farmed products (Collins 2011). These flavors are often the result of the “recipe” of nutrients, their source, and method for extraction. This species specific nutrient recipe may be sourced, like in soil, from natural
means or from chemical means. The French term for this flavor, commonly used in reference to the grapes that make wine, is terroir. Terroir has been expressed as one of the driving factors that traditional agriculture cites as an advantage over CEA. This perception of poor terroir reduces the adoption rate within the market, affecting the uptake from the people within the market, as well as the profit of the company attempting to produce CEA locally. Terroir is derived from the nutrient dynamics of soil, or in the case of hydroponics the profile of the hydrological (water) system and any additives that have been introduced to the system. The selection of nutrients inputs into a hydroponic system defines both the viability of organic certification as well as the terroir derived in the plants.

Similar to how natural decomposition provides nutrient transfer in geoponic systems, anaerobic digestion (AD) of organic plant waste also offers a nutrient transfer process that meets organic certification requirements (Kosseva 2013, 28). The process AD produces three outputs that can be beneficial to a CEA business, biogas for onsite power generation, liquid fertilizer, and solid fertilizer. These fertilizers can be utilized within the CEA process or sold back to the geoponic farming community. The AD process not only provides for the CEA business, but also eliminates a GHG emission source that is commonly landfilled, emitting methane gas into the atmosphere of an extended period of time.

When addressing the effects of agriculture on the people who consume and produce it, the planet from which it is grown and returns to, and the profitability of those who produce it, CEA, specifically VF may pose an advantage over geoponic farming. The use of circular aquaponic nutrient systems and circular energy systems in VF applications are more
advantageous to the triple bottom-line than both traditional geoponic and standard-input VF agricultural processes to date.

**Approach**

As a comparison, a literature review identified inputs and outputs of varying VF system designs, both conceptual and functional, and averaged them over the common species of lettuce, measured per kilogram (kg) of lettuce yield over a one-year period of time. The primary reason for comparing models based on the crop species of lettuce is that it is both a commonly compared crop and has a low inedible biomass ratio. In addition to inputs and outputs associated with lettuce production, the estimated revenue generated per year based on cited production rate of each model was factored to provide clarity of systematic efficiency.

Among three compared designs, the first was an economic estimation system for vertical farming business modeling by Shao et al. (2016). Shao et al.’s proposed software model calculates ROI for Shanghai, London, and Washington D.C. locations and modeled varying building scales, crops, and energy system options. This approach standardized fixed performance metrics across variable area to derive estimated performance of the farming system to forecast ROI models.

Second, a market analysis initiated by the German Aerospace Center for the prospects of vertical farming through the use of advanced bio-regenerative modules in a terrestrial application (Banerjee 2012). Banerjee (2012) theorized a complete VF model including architectural performance, that was based upon an aquaponic system growing tilapia and multiple crop species in a high-rise installation.
Third was Freight Farms’ Leafy Green Machine (LGM) modular CEA system, a commercially available containerized farm with performance calculations published publicly for evaluation by potential customers (Freight Farms 2016). Additionally, Gordon Graff’s “Skyfarming” (Alter 2011) has been cited as a reference for system component design however it has not been compared as a viable peer-reviewed VF model.

The evaluation of the proposed designs presented in the literature review consisted of inputs associated with energy (kilowatt-hours, kWh) and nutrients (fertilizer), and outputs of CO₂ emissions associated with both distribution of product over a fixed distance (300-mile distribution distance) and with the cited energy systems for each model. The inputs and outputs of each model were then factored down to the cited production rate per kilogram of lettuce. The specific metrics associated with each model’s energy source emissions, annual yield, nutrient input, and subsequent design parameters were identified per case study, creating a baseline comparison by which to evaluate proposed solution parameters.

Anaerobic Digestion Assumptions

In models containing AD systems, assumptions on the rate of biogas produced by input were made. The calculation of methane yield from digestion of fruit and vegetable wastes alone was 420l/kg of volatile solids (VS). This rate increased to 611l/kg VS when mixed with abattoir wastewater, that was calculated as gray water coming from an aquaculture system. These rates of methane (biogas, natural gas) production calculate to 14,832ft³/Ton VS and 21,577ft³/Ton VS with abattoir respectively (Khalid et al. 2011). These gas rates were used in place of estimations made by each source featuring AD due to the topic expertise of Khalid et al.. When reviewed
systems featured both aquaculture and anaerobic systems combined, the higher rate of 611l/kg VS was used, for all other models featuring only anaerobic digestion 420l/kg VS was used.

Energy Assumptions

When exact emissions figures were not obtained per energy source, the US Energy Information Administration’s stated figures for carbon dioxide emissions produced per kilowatt-hour per fuel source were used and noted as a substitute for trade knowledge of each power source. For natural gas, a carbon dioxide rate of 1.22 lbs. of CO$_2$ per kWh (.553kg/kWh) was used; for coal the rate of production for bituminous coal was used at a rate of 2.07 lbs. of CO$_2$ per kWh (.939kg/kWh) (EIA 2016). In reviewed systems that did not identify a specific energy source (anaerobic digestion-fed, solar, wind, etc.) the emissions rate for coal was used.

Distribution Assumptions

The distance used for distribution evaluations was set at a constant of 300 miles round-trip. When distribution methods were not identified, the assumption method of distribution was a diesel box truck, based upon Corporate Average Fuel Economy (CAFE) 2012-2025 Light Duty Vehicle Standards for light-duty diesel transportation emissions. The fixed metric that was used for diesel emissions is the 2016 CO$_2$ standard for light trucks of 298 grams/mile (GPO 2012) other metrics associated with sulfur dioxide, nitrogen oxide, lead, ozone, and particulate matter were not measured in this evaluation and were assumed to meet compliance. In order to more accurately determine the impacts of distribution, an assumption of 5,000 heads of lettuce per truck per day traveling at a fixed distance of 300 miles were calculated on an annual rate of distribution (365 days per year). Identified metrics were compared throughout this evaluation and were used to identify the strengths and weaknesses of each design’s
performance. The resulting emissions comparison of reviewed system design are represented in tables 1.1 and 2.1.

**Nutrient Assumptions**

In instances when nutrient input was not clearly identified, assumptions were made based upon the findings of Genuncio et al. in their 2012 study of “Hydroponic Lettuce Production in Different Concentrations and Flow Rates of Nutrient Solution.” In this study the hydroponic nutrient solution was calculated as one liter of nutrient solution per plant. This solution contained 750 mg of calcium nitrate (Ca(NO$_3$)$_2$), 500 mg of potassium nitrate (KNO$_3$), 150 mg of monoammonium phosphate (MAP), and 400 mg of magnesium sulfate (MgSO$_4$). There are additional micronutrients identified by Genuncio et al. that were not factored in this evaluation (Genuncio et al. 2012). In instances when nutrient input was clearly identified in the reviewed system design, these assumptions were discarded in favor of the evidence provided by the source’s nutrient model.

**Revenue Assumptions**

For the evaluation of revenue generation, the USDA National Retail Report of Specialty Crops issued for the week of February 17, 2017 identified the retail cost per head of Boston-Greenhouse lettuce at $1.99/head (USDA 2017). For an equalized comparison of weight-to-head ratio, the calculation of 0.11kg/head of fully grown lettuce was used as an average (Maynard 2013). When achieving organic certification, the USDA has identified that price comparisons in 2013 were as much as 194 percent the price of a non-organic lettuce counterpart (USDA$^2$ 2016). This value of 1.94 was factored in to revenue modeling when systems identified that their selected nutrient streams achieved organic certification.
Evaluative Calculations

For the purpose of a comparative evaluation of the proposed VF systems and the proposed solution of a circular aquaponic system, two sets of tables were generated to compare the inputs and outputs of each system on an annual scale, as well as a per-kilogram of lettuce comparison to more clearly understand the impact per unit of production of each proposed system.

Literature Review

Design and Production

The design of a VF is a blended exercise between architecture and agricultural practices. The scale of VF solutions ranges from a standard forty-foot shipping crate to multi-story skyscraper designs. For comparison of gross floor area, the models evaluated ranged from 31.5m² for a single LGM (Freight Farms 2017) to 7,675m² for a 6-story structure (Shao et al. 2016) to a massive 71,632m² 37-story tower (Banerjee 2012). The gross floor area does not equate to the functional area used for growing crops, as various designs for crop organization exist. When designing a VF system, the default option of relying on utility-provided power and water inputs has been the detriment to the practice. Advancements in optimizing the energy systems pose measurable improvements on performance of the overall VF. Similarly, nutrient system design variations pose outcomes in crop quality that effect marketability.

Designs for crop organization commonly associated with hydroponic or aeroponic growing methods include A-frames, stacked drums, stacked beds, and grow towers. Each of these designs carries unique characteristics relating to land productivity, lighting configurations,
and species capability. For the purpose of continuity, each of these design styles can accommodate the evaluated species of lettuce.

Shao et al. (2016) proposed a side-by-side evaluation of artificial lighted systems and sun-fed systems, evaluating drums, a-frames, and stacked beds among other options with the goal of forecasting ROI. They cited a gross yield of 78.5kg/m²/year as a constant in their evaluation. The gross yield was factored over an 80 percent functional area resulting in a net yield of 481,990kg/year over the cited 7,675m² (Shao et al. 2016, 36).

Banerjee (2012) cited stacked layers as their design specification, indicating that each floor growing lettuce had six stacks per floor equaling an effective growing area of 5,508m² per floor. Banerjee’s design had four floors devoted to lettuce for a total effective area of 22,032m². Banerjee indicated production rates of 47.8kg/m²/year (1,053,130kg/year over the effective area) (Banerjee 2012, 49).

Freight Farm's LGM (2017) publication stated that each LGM contains both nursery and growth areas. Citing the growth area as containing enough space for over 4,500 plants in 256 towers. LGM cited average weekly yields of 500 full sized heads of lettuce (26,000 heads/year, estimated at 0.11kg/head equates to 2,860kg/year) (Freight Farms 2017).
The most recognized detriment to CEA and VF is the massive amount of energy required to power both growing lights and atmospheric control mechanisms. It is this input in system designs that has the most opportunity for both cost savings and environmental impact improvement. Evaluating the energy demands of three CEA systems provided the foundational comparison for the proposed solution to lower annual CO₂ emission profile associated with energy production.

The energy use projection that Shao et al. cite in their ROI model-generator was attributed to lighting alone and was generalized as a real-time usage of 200 W/m² of floor area.
The model for this farm was 7,675m² at this size the annual energy consumption for this model was 13,446,600 kWh/year. Shao et al. did not cite any anaerobic digestion systems, and actually recommended that users of their model “think twice before adding a renewable energy system” (Shao et al. 2016, 46). The estimation for annual CO₂ emissions associated with their farming operation used the rate for coal-produced energy. The coal-power derived CO₂ emissions for this farm was 27,834,462 lbs. CO₂/year (12,625,500 kg CO₂/year).

Banerjee’s (2012) 37-story building had a projected monthly energy demand of 3,176,589 kWh for lighting and environmental demands alone, factoring to 38,119,068 kWh/year. The lettuce portion of this structure (four floors) was accountable for 850,752 kWh/month, that factored to 10,209,024 kWh/year based on a sixteen-hour photoperiod for lettuce (Banerjee 2012, 102). Banerjee does feature an AD system for which the author did not include a means to process the biogas produced by the system however, this system did remove -150,000 kWh/month from the power demand for “miscellaneous needs” citing “waste”. This calculation results in a total “miscellaneous needs” power demand of (negative) -10,440 kWh/month (-125,280 kWh/year) (Banerjee 2012, 102). This figure was factored into the energy demands placed upon the lettuce-producing floors (4 of 37 total floors) to bring the total energy consumption for all lettuce production to 10,195,480 kWh/year. Since Banerjee indicated the inclusion of AD, the emissions rate for this power consumption was factored with the natural gas figure of 1.22 lbs. of CO₂ per kWh (.553 kg/kWh). The resulting total CO₂ emissions associated with the growing of lettuce in Banerjee’s model was 12,438,485.6 lbs. of CO₂/year (5,642,002 kg CO₂/year).
Freight Farms’ LGM was cited as consuming 100 kWh/day per container (Freight Farms 2017, 13). There was no indication as to how this model would pair with an AD system, so the CO₂ emissions associated with this farming model used the rate for coal-produced energy. The annual energy input for a LGM container was 36,500 kWh/year with an associated CO₂ emission factor of 75,555 lbs. CO₂/year (34,271 kg CO₂/year).

**Nutrients**

Critical to every hydroponic system is nutrient enrichment of the water that nourishes the root systems of the plants. This key attribute also dictates whether the resulting crop can be certified as organic or non-organic in the marketplace. The USDA upholds stringent requirements for organic certification, something that many vertical farms have struggled to obtain (GPO 2017; Nanos 2016).

In Shao et al.’s (2016) system, the authors did not indicate specific nutrient inputs, resulting in a calculation of the nutrient solution assumption provided by Genuncio et al. (2012). Based upon Shao et al.’s factored production of 481,990 kg of lettuce at an average of 0.11 kg/head, the nutrient solution recipe was applied to 4,381,727 heads/year of lettuce. The resulting calculation for annual nutrient inputs into this model were 3,286 kg of Ca(NO₃)₂, 2,190 kg of KNO₃, 657 kg of MAP, and 1,752 kg of MgSO₄. Although water consumption was not a compared attribute in this analysis, Shao et al. identified the annual water usage in terms of l/m²/year. For this calculation, their functional growing area of 6,140 m² was calculated for a total annual water consumption of 9,301,100 liters/year.

Banerjee’s solution to the topic of nutrient input set his system apart from the others. Citing the use of BEYOND™ All Natural Plant Amendment (AgriHouse 2014) as the primary
nutrient supplement, combined with the aquaculture element of the system, the ability to obtain organic certification was possible. Banerjee went so far as to indicate that the fish feed would be made up of 50 percent non-edible plant biomass. Banerjee’s calculation for total nutrient supplements calculated to 2,011 l/year of BEYOND™ All Natural Plant Amendment for lettuce production.

Freight Farm’s LGM (2017) identified nutrient requirements however, did not express detail about which nutrient blends are required. For this reason, the evaluation of the LGM system used the nutrient assumption provided by Genuncio et al (2012). Based on LGM’s annual production of 26,000 head (2,860kg at 0.11kg/head), the nutrient requirement calculated to 19.5kg of Ca(NO₃)₂, 13kg of KNO₃, 3.9kg of MAP, and 10.4kg of MgSO₄.

Distribution
One of the perceived benefits in the localization of crop production is the reduction of impacts associate with the distribution of crops. This distribution has the potential to extend far beyond the 300-mile range used in this evaluation. Each of the associated systems compared in this exercise had no mention of an alternative distribution network for this reason, each was modeled after the distribution assumption of a payload capacity of 5,000 heads/truck and the 2016 CAFE CO₂ emissions standard for light trucks of 298 grams/mile. Based on these figures, Shao et al.’s model required three trucks to deliver an average of 12,004 heads/day, accruing 97,893kg CO₂/year. Banjee’’s model required six trucks to deliver an average of 26,230 heads/day, accruing 195,786kg CO₂/year. A single Freight Farms LGM would require only one truck to deliver an average of 71 heads/day, resulting in annual emissions of 32,631kg CO₂/year.
Revenue

The importance of the people and profit branches of the triple-bottom line rely on an equitable revenue stream coming in for the goods produced. A company that cannot sustain economic prosperity won’t have the opportunity to provide employment however, price-gouging practices also position goods and services outside the realm of capability for many consumers. Some consumers may unwittingly view organic crops as an unjustified luxury others recognize the importance of eliminating non-organic chemicals from the food supply. In this comparison, only Banjeer’s system qualified for organic pricing based on the use of the organic-certified nutrient source, BEYOND™ All Natural Plant Amendment. Any proposed solution that addresses the triple-bottom line should incorporate organic certification as a mandate to address people and profit accordingly.

Calculations

The results of annual performance of each CEA system are shown comparatively in table 1.1 Total Annual Performance of CEA Systems. In the interest of comparing the outcomes of these systems on a per-unit scale, the calculations from each system were averaged down to each kilogram of lettuce produced (about 9 heads of lettuce). This calculation intended to represent an equalized comparison between all design parameters and farm scales and is represented in table 2.1 Performance of CEA Systems Averaged to 1Kg Production.
From this direct comparison, it became clear that Banerjee’s system which included anaerobic digestion, aquaculture, and organic nutrients, resulted in significant reductions in emissions and energy demanded per Kg while also commanding a premium price in the market.

These factors paired with the potential for improved terroir through organic nutrient utilization

### Table 1.1 Total Annual Performance of CEA Systems

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Shao et al. 2016</td>
<td>481,990</td>
<td>13,446,600</td>
<td>12,625,500</td>
<td>3,286 kg Ca(NO₃)₂ 2,190 kg KNO₃ 657 kg MAP 1,752 kg MgSO₄</td>
<td>97,893</td>
<td>$8,719,637</td>
</tr>
<tr>
<td>Banerjee 2012</td>
<td>1,053,130</td>
<td>10,195,480</td>
<td>5,642,002</td>
<td>2,011 l/year of BEYOND™</td>
<td>195,786</td>
<td>$36,961,033</td>
</tr>
<tr>
<td>LGM 2016</td>
<td>2,860</td>
<td>36,500</td>
<td>34,271</td>
<td>19.5 kg Ca(NO₃)₂ 13 kg KNO₃ 3.9 kg MAP 10.4 kg MgSO₄</td>
<td>32,631</td>
<td>$51,758</td>
</tr>
</tbody>
</table>

### Table 2.1 Performance of CEA Systems Averaged to 1Kg Production

<table>
<thead>
<tr>
<th></th>
<th>Kg Lettuce</th>
<th>Energy Demand [kWh/kg lettuce]</th>
<th>Emissions Derived From Energy [kg CO₂/kg lettuce]</th>
<th>Identified Nutrient Input per Head [mg/head]</th>
<th>Distribution Emissions [kg CO₂/ kg lettuce]</th>
<th>Annual Revenue [$/kg lettuce]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shao et al. 2016</td>
<td>1</td>
<td>27.89</td>
<td>26.19</td>
<td>6,818 mg Ca(NO₃)₂ 4,543 mg KNO₃ 1,363 mg MAP 3,635 mg MgSO₄</td>
<td>0.20</td>
<td>$18.09</td>
</tr>
<tr>
<td>Banerjee 2012</td>
<td>1</td>
<td>9.68</td>
<td>5.36</td>
<td>703 ml/year of BEYOND™</td>
<td>0.19</td>
<td>$35.10</td>
</tr>
<tr>
<td>LGM 2016</td>
<td>1</td>
<td>12.76</td>
<td>11.98</td>
<td>6,818 mg Ca(NO₃)₂ 4,543 mg KNO₃ 1,363 mg MAP 3,635 mg MgSO₄</td>
<td>11.41</td>
<td>$18.09</td>
</tr>
</tbody>
</table>
provided an opportunity for the Banerjee system to surpass the other two systems in profitability, scale to hire additional people while providing significantly greater crop output, and a planetary impact that is reduced beyond both competitive systems.

**Solution**

Despite an advantageous position of Banerjee’s system over Shao et al.’s and LGM’s in nearly every evaluated category, the ability to optimize vertical farming is not clearly expressed. Banerjee (2016) started to identify various system design parameters to aide in reducing impacts however, an inadequate explanation neglected to reveal the details that enable greater synergy.

The proposed solution closes the loop of energy input by sourcing AD feedstocks from customers such as grocers, co-op markets, and restaurants while also using non-edible biomass from the proposed farm as the source of organic municipal solid waste. This waste stream acts as the fuel source for both onsite energy production and distribution fuel production. Using the energy produced to grow the eventual fuel for the energy system defines the referenced term “closed-loop energy.” Using the same anaerobic digestion system to produce both liquid and solid fertilizer offsets the nutrient input demand by using a source that may also be considered organic as long as the input feedstock to the AD system is closely regulated.

**Stationary Fuel Cells**

Historically, fuel cells have been viewed as a fringe-science based on the requirement of technologies like proton exchange membrane (PEM) fuel cells to accept only purified hydrogen as a fuel source. Advances in technology in the twenty-first century have enabled a new class of stationary (often high-temperature) fuel cells that process incoming hydrocarbon fuel, to
provide electrical efficiencies exceeding 80 percent (Mekhilef et al. 2012). Many of these fuel cells have the ability to operate in both a co-generative heat and power (CHP) format as well as a tri-generation format that produces heat, electricity, and purified hydrogen (H2) as a byproduct (Mullendore 2015).

A leader in the stationary fuel cell market is Fuel Cell Energy that produces both CHP and tri-generation configurations in increments of 1.4MW and 2.8MW (2.3MW tri-gen) sizes. These systems are both electrically efficient and emit significantly less CO2 than a traditional natural gas power system. The DFC® Fuel Cell operated on natural gas in a CHP format has a cited CO2 emission rating of 550 lbs./MWh (0.55lbs/kWh compared to 1.22 lbs/kWh of traditional natural gas power generation) (Mullendore 2015; EIA 2016).

Alternatively, a smaller sized 400kW system provided by Doosan carries a 495lbs./MWh CO2 emission rating (0.495 lbs./kWh or 0.225kg/kWh) when installed in a CHP format. The Doosan PureCell Model 400 has an average electrical efficiency of 41 percent with a peak overall efficiency of 90 percent. The Model 400 has a stated gas consumption rate of 3,961 CFH to reach maximum power output (Doosan 2014). Calculated out, the Model 400 would be supported by an anaerobic digestion system that supported 4.4 Tons of VS/day based on the Anaerobic Assumptions identified in the Approach. That scale of an AD system would prevent atmospheric methane emissions of 34,652,662ft³/year from entering the atmosphere through traditional landfill practices while also providing 3,504,000kWh/year of energy to a farm, with the emissions of 78,675kg CO2/year. The energy produced from one Model 400 would provide enough power to support up to 96 Freight Farm LGM systems (based on calculated 36,500kWh/yr. energy consumption of the LGM system).
Hydrogen FCEV

When a stationary fuel cell is installed in a tri-generation configuration, the cited output for a Fuel Cell Energy DFC-H2 system is 2,350kW and 1,270kg/day H₂ (Mullendore 2015). For a delivery scenario, the Hyundai H350 FCEV van was selected. The H350 has a tank capacity of 7.05kg/H₂, a stated range of 262 miles (while other FCEVs have ranges exceeding 300 miles (Toyota 2016)), and emits nothing but pure water (0.0kg CO₂/year distribution) (Hyundai 2016). Scaling the output ratings of 2,350kW tri-generation system down to the Model 400kW size, the output of H₂ would be 204kg/day, enough for nearly thirty H350 fuel-ups.

Nutrient Synergy

Taking note from Banerjee’s (2012) system of incorporating both AD and aquaculture into the overall system, the proposed solution would leverage the nutrient enrichment capabilities of aquaculture on the hydrological system of the VF to further reduce the nutrient demands. Nutrient recovery in AD has been cited as a commercially viable solution by companies like Magic DiRt™ (2016) to provide nutrient supplement in various stages of crop growth. DVO Digesters has indicated that their recovered nutrient technology can remove up to 90 percent of phosphorus and 75 percent of nitrogen ammonia from organic waste, transforming it into stable fertilizer (DVO 2017).

Another approach to nutrient synergy is to utilize aquaculture to manipulate water enrichment within the hydrological system. By separating the aquaculture from direct plant interaction, the maintenance of food safety standards can be more easily achieved, and nutrient-enriched water can more easily be manipulated to contain the exact nutrient content desirable for each plant species. Pairing this approach with the use of organic-certified nutrient
supplements like BEYOND™ All Natural Plant Amendment aides in marketability while also reducing overall cost and inputs to the system.

Modeling these inputs into the proposed solution, a scaled measure of BEYOND™ All Natural Plant Amendment was calculated at the production rate per LGM system, minus 30 percent input as a conservative estimate for the nutrient replacement strategy of both anaerobic fertilizer processing and aquaculture water enrichment. The purpose of this was to reduce overall nutrient inputs into the system while also maintaining organic-certification to increase marketability. The aquaponic atmosphere and water pumps added an additional 20 percent energy usage to the overall demand for this system (Love et al. 2015). Uncalculated in this comparison was the additional cost and revenue created through additional aquaculture and fertilizer sales.

Proposed Scaled Solution

The proposed solution is scaled to a Doosan PureCell Model 400 fuel cell system installed in a scaled tri-generation configuration that produces 204kg/day of H2, paired with 80 Freight Farms LGM systems, a 4.4T/day AD system, supplemented by aquaculture production. Love et al.’s (2015) 10,300-liter aquaculture system used 19,526kWh/year of energy to produce an estimated 35.3kg (~78lbs.) of tilapia per year. The LGM uses an average of 10 gallons/day (37.8 liters) (Freight Farms 2017). At a scale of 80 LGM modules, the total daily water use is 3,024 liters. The matchup in scale between the aquaculture system and daily water usage enabled a daily exchange of water between fish and crops. The proposed nutrient input for the LGM system utilized the BEYOND™ All Natural Plant Amendment at a scaled rate per kg of lettuce produced. The nutrient input amount was reduced by 30 percent to account for nutrient
replacement by the AD and aquaculture systems. These crops would be delivered by a fleet of Hyundai H350 FCEV vans that produce a cumulative zero net CO₂ emissions since the H₂ production emissions are already calculated into the PureCell Model 400. The energy demand represents 80 LGM systems with a 20 percent increase, but the emissions derived represent the entire 400kW system operating over the span of an entire year.

Discussion

In table 1.2, this proposed system, Andren 2017, was modeled to the same parameters as the other comparative systems. In table 2.2, the findings from table 1.2 are divided down per kilogram of lettuce produced.

The Andren 2017 system of aquaponic vertical farming with closed-loop renewable energy provided by fuel cell technology, does have an increased annual energy demand but at a significantly reduced CO₂ emission output for both energy production and distribution. The revenue generated nearly matched the revenue of the Shao et al. system that produces more than twice the annual yield. In reviewing the per Kg comparison in table 2.2, the Andren 2017 system had an overall CO₂ emission reduction of 60 percent over the Banerjee system, a 660 percent reduction over the Shao et al. system, and a 577 percent reduction over a single LGM system powered by coal fired energy production.
Table 1.2 Total Annual Performance of CEA Systems with Solution

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Andren 2017</td>
<td>228,800</td>
<td>2,939,526</td>
<td>788,400</td>
<td>305 l/year of BEYOND™</td>
<td>0</td>
<td>$8,030,048</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3,286 kg Ca(NO₃)₂</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2,190 kg KNO₃</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>657 kg MAP</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,752 kg MgSO₄</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2,011 l/year of BEYOND™</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19.5 kg Ca(NO₃)₂</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>13 kg KNO₃</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.9 kg MAP</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10.4 kg MgSO₄</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shao et al. 2016</td>
<td>481,990</td>
<td>13,446,600</td>
<td>12,625,500</td>
<td></td>
<td>97,893</td>
<td>$8,719,637</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$97,893</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$8,719,637</td>
<td></td>
</tr>
<tr>
<td>Banerjee 2012</td>
<td>1,053,130</td>
<td>10,195,480</td>
<td>5,642,002</td>
<td></td>
<td>195,786</td>
<td>$36,961,033</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$195,786</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$36,961,033</td>
<td></td>
</tr>
<tr>
<td>LGM 2016</td>
<td>2,860</td>
<td>36,500</td>
<td>34,271</td>
<td></td>
<td>32,631</td>
<td>$51,758</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$32,631</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$51,758</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.2 Performance of CEA Systems and Solution Averaged to 1Kg Production

<table>
<thead>
<tr>
<th></th>
<th>Kg Lettuce</th>
<th>Energy Demand [kWh/kg lettuce]</th>
<th>Emissions Derived From Energy [kg CO₂/kg lettuce]</th>
<th>Identified Nutrient Input per Year [kg]</th>
<th>Distribution Emissions [kg CO₂/kg lettuce]</th>
<th>Annual Revenue [$/kg lettuce]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andren 2017</td>
<td>1</td>
<td>12.85</td>
<td>3.45</td>
<td>1.34 ml/year of BEYOND™</td>
<td>0</td>
<td>$35.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6,818 mg Ca(NO₃)₂</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4,543 mg KNO₃</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,363 mg MAP</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3,635 mg MgSO₄</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shao et al. 2016</td>
<td>1</td>
<td>27.89</td>
<td>26.19</td>
<td>0.20</td>
<td></td>
<td>$18.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4,543 mg KNO₃</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,363 mg MAP</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3,635 mg MgSO₄</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Banerjee 2012</td>
<td>1</td>
<td>9.68</td>
<td>5.36</td>
<td>0.19</td>
<td></td>
<td>$35.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6,818 mg Ca(NO₃)₂</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4,543 mg KNO₃</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,363 mg MAP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LGM 2016</td>
<td>1</td>
<td>12.76</td>
<td>11.98</td>
<td>11.41</td>
<td></td>
<td>$18.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4,543 mg KNO₃</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,363 mg MAP</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3,635 mg MgSO₄</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Not factored into the tables above were the additional benefits to the planet, profit, and people associated with supplementary hydrogen sales and the reduction of 34,652,662ft³/year
of methane emissions associated with anaerobic digestion. A separate analysis on the effects of expanding hydrogen-based transportation systems falls outside the scope of this study however, may indicate further improvements to the triple bottom-line.

**SWOTT Analysis**

The strength of the proposed solution was based on the modularity of the Freight Farms LGM system that separates the atmospheric and growing operations into pre-configured growing containers. Modularity of atmospheric systems adds a level of security to the system in the event of an atmospheric system failure the entire growing operation would not be compromised. From a planetary impact perspective, the low emissions of the Doosan PureCell Model 400 are the greatest strength to the overall emissions output associated with energy inputs. The AD system provided a reliable opportunity to both reduce methane emissions associated with landfilled organic municipal solid waste, as well as produce fuel for the onsite energy system. Producing hydrogen as a byproduct enables further CO₂ reductions while adding a level of stabilization to fuel cost fluctuation potential. The changeover to an organic-certified nutrient supply for the LGM strengthened the marketability of the produced crops, offering a greater opportunity to address impact on people and profit.

Weaknesses of this system are centralized around the dynamic relationships between the various components. Aquaculture specifically is a field of practice that requires an increased level of attention to obtain proper water quality standards and may be more of a detriment in cost than a benefit in nutrient savings. Redundancies for the other systems are available through utility power, public natural gas supply, and diesel truck rental in the event that any of the critical systems experienced failure.
Opportunities to supplement crop revenue with sales of aquaculture, hydrogen, fertilizer, and energy could significantly increase revenue resulting in the potential for higher wages (people) and increased profit margins for the farming company. Utilization of governmental subsidies associated with systematic efficiencies would also pose an opportunity to reduce capital expenditures.

Threats are minimized through the aforementioned redundancies of utility power and natural gas supplies along with the availability of rental distribution vehicles. Freight Farms’ approach to containing a complete growing environment reduces threats to the overall performance of the system. Other existing threats would be any inclusion of pests, fungi, and plant disease associated with traditional agriculture. Water quality also poses a potential threat if not properly monitored and maintained. Zoning restrictions associated with an AD system may restrict installation to specific geographic locations based on proximity to residential areas and the odors commonly associated with AD systems. Organic certification derived from AD-produced fertilizers would require a closely monitored feedstock into the AD system. If this feedstock were to be compromised by chemical inputs, the threat of losing organic certification would be imminent.

Supporting trends associated with vertical farming are rapidly changing and commonly support containerized systems similar to the LGM system. These containers require a lower minimum footprint within an urban setting than many other more permanent structural solutions. Aquaponics (aquaculture paired with hydroponics) is a trending topic, but still remains a challenging endeavor to master on a commercial production scale. Fuel cell
technology has been growing in market acceptance with new models like the Hyundai H350 being explored.

The analysis between the systems identified in the literature review and the proposed solution compared the overall impacts associated with energy and distribution per kilogram of lettuce produced. This analysis intended to bring attention to vertical farming systems and inform readers of energy demands without losing sight of the impact of CO₂ emissions commonly associated with total energy production.

**Recommendations**

In order to truly optimize the solution to address the needs of the people, planet, and profit, associated fair labor practices must be balanced with profitability of the overall farm. Significant attention must be provided to the scientific expertise associated with CEA, aquaculture, AD, and hydrogen fueling. The level of expertise balanced with the capital costs associated with installation of each system may challenge profitability of the overall system. This comparison was not intended to replace a statistical evaluation of the financial implications of a VF installation. The inclusion of revenue in the system comparison aimed to highlight the marketability of organic certified produce over non-organic nutrient selection. Full system evaluation of profit and loss models would need to be created to test market viability of the proposed solution.

**Conclusion**

Evaluating various systems of vertical farming helped to identify significant environmental impacts associated with energy production required to produce lettuce crops over the identified VF systems. Pairing an AD system that recycles organic waste into both
fertilizer and fuel, with a high performance, low CO₂ emission energy system provided the
greatest measured impact over the compared VF systems. Combining this solution with
nutrient producing aquaculture reduced the overall input of plant fertilizer while still promoting
organic-certified crop classification. Transforming the distribution model from diesel trucks to
hydrogen fuel cell electric vans eliminated emissions associated with distribution.

Using these circular waste-to-fuel energy production and nutrient transfer strategies
facilitated by an AD system paired with zero-emissions distribution and aquaculture nutrient
enrichment that promoted organic crop certification, the proposed solution was more efficient,
marketable, and ecologically beneficial over the compared VF systems. These circular strategies
position the proposed solution to better address the triple bottom-line than standard-input VF
solutions and traditional geoponic agriculture.
References


