Which is more profitable: a greenhouse or vertical farm?

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Abstract

The demand for hyper-fresh, pesticide-free food (the "local food movement") is driving demand for Controlled Environment Agriculture systems since they can be located in urban centers. Sales from greenhouses is growing at 8.8% while sales from vertical farms is growing at 30%. It is commonly believed that a vertical farm cannot economically compete with a greenhouse due to the high cost of powering the artificial lighting (Shackford 2014). Nonetheless, researchers have yet to analyze the economics underlying a vertical farm (e.g., Eigenbrod et al. 2015) let alone compared the profitability of a vertical farm to that of a greenhouse. This research gap is particularly relevant to Canada, as it is uniquely positioned to be a leader in the vertical farm market.

Below, we report the results of a detailed simulation of the profitability of growing lettuce in a vertical farm and in a greenhouse located near Quebec City. Surprisingly, we find that both the costs to equip and run the two facilities are very similar, while the gross profit is slightly higher for the vertical farm.

Introduction

In 2016, the National Restaurant Association surveyed chefs across the united states and asked them what they thought was the most important food trend of the decade. A plurality of them (44%) said it was peoples' desire to eat local food (National Restaurant Association, 2015). This trend is commonly referred to as the "local food movement", and put simply it is the desire by people to eat pesticide-free, produce that is grown within a few miles of where they live, making it is hyper-fresh and reducing energy used for transportation.[3] It's not niche. Consumer spending on locally grown food has exploded from $4.8B in 2011 to nearly $12B in 2014, and the market is forecasted to exceed $20B by 2019. That growth has caused an increase in the number of suppliers, grocers and restaurants that have added or plan to add locally grown food offerings all year round. This is even true for national chain restaurants, like Chipotle and Subway (Zacka 2014). It is not only about flavor and the joy of knowing where your food came from, it is also about health. The nutritional value of fruits and vegetables degrades during shipping even if they are refrigerated. For instance, even if spinach is stored at 4 C, after 8 days it loses 47% of folate, an important B vitamin required for RNA and DNA synthesis (Pandrangi and LaBorde 2004).

Of course, for most places in the world, growing food outdoors is not possible all year around. In fact, only about 10% of the world's land is arable [4], so demand for local food has helped push the annual growth of the commercial greenhouse market to 8.8%, and it is expected to reach $29.64 Billion by 2020 (Markets and Markets 2016). As a means of increasing yields further, greenhouses are increasingly supplementing

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[3]Obviously, if we changed this definition, our results might change as well. However, given market surveys and trends in food consumption in general (like increases in the demand for organic) we believe this to be a reasonable compromise. Kearney, reports several other characteristics that consumers tend to associated with "local", however many of these wouldn't impact our model's results. For instance, grown in same state, "quality", knowing the farmer, are characteristics that we can assume are the same across both models. The distance and non-pesticide constraints, on the other hand, restrict the possible models.

[4] http://data.worldbank.org/indicator/AG.LND.ARBL.ZS

natural light with artificial light and using hydroponic systems, which in turn is driving 6.5% annual growth for the hydroponic farm market (Manifest Mind 2014).

The *vertical farm* is another way to provide locally grown food year around. In this case, plants are grown indoors using hydroponic systems and only artificial light. Also, the plants are grown in multiple level racks, dramatically increasing the yield per square-meter relative to a greenhouse (see **Figure 1**). A major drawback of greenhouses is that they are often located large distances from city centers, where real-estate prices are lower. Having multiple levels of grow units, reduces the facilities foot-print, reducing the cost of locating closer to urban centers, allowing the farmer to supply hyper fresh produce (Despommiers 2013). The trade-off is that the vertical farm uses lots of energy to power lights rather than taking advantage of the free power of the sun. Nonetheless, the popularity of the vertical farming model is increasing, with annual sales growing at 31% and expected to reach $4B by 2020 (ReportsnReports 2016).

There is a heated debate in the industry regarding which model will prove more profitable for growing plants: A greenhouse, which leverages natural light, or a vertical farm, which has much higher yields per square-meter, but spends much more money powering lights. Moreover, though there have been studies of the economics associated with operating greenhouses in various locations (e.g., Kessler et al. 2006), researchers (e.g., Eigenbrod et al. 2015, Mok et al. 2014) have noted there is a dearth of peer-reviewed research investigating the economic dynamics underlying the operation of a vertical farm. Moreover, though it is commonly believed that a vertical farm cannot economically compete with a greenhouse due to the high cost of powering the artificial lighting (Shackford 2014), no studies have compared the economics underlying the two models when holding production variability and yield equal.

The simple purpose of this paper is to fill that gap. We do so below using a detailed simulation of the profitability of supplying locally grown Boston lettuce, year around in the region of Quebec City, Canada, using a vertical farm and using a greenhouse.

This is a particularly relevant question for Canada since certain characteristics make the country uniquely positioned to be a leader in the market. First, a vertical farm is electricity intensive, and Canada enjoys some of the lowest electricity prices in North America. So, for the same reason Canada is a leading exporter of other electricity intensive products (e.g. aluminum), one would expect Canada to have an advantage when it come to electricity intensive plant production. Second, Canada is already a leader in Controlled Environment Agriculture, and thus has an abundance of expertise (Zahniser and Link 2002). Finally, the country shares a border with the largest market for locally grown produce (and for legal marijuana, which is also predominately grown indoors) in the world.

Model Assumptions

We first need to decide on the type of greenhouse and vertical farm. There are various configurations of hydroponic greenhouses that are capable of delivering locally grown produce. For instance, a *closed* greenhouse uses machines to completely control the greenhouse environment. All natural cooling and dehumidification (i.e. vents) are replaced with refrigeration-based cooling, and CO_2 levels are optimized to increase yields. In practice, the required energy often makes this model unprofitable, which is why closed greenhouses are rare.

So instead, we consider a semi-closed greenhouse, which cools and dehumidifies using vents that are fitted with screens to reduce the likelihood of pest damage. Similarly, the vertical farm could be closed or semi-closed, and plants could be grown vertically or horizontally. To keep the comparison as close as possible, we compare the semi-closed hydroponic-greenhouse (GH) to a semi-close vertical farm (VF) where the plants are grown horizontally, like in a greenhouse, but with multiple level racks. We assume that both the GH and the VF have 1,170 square-meters of growing space, though the foot-print of the VF is much smaller — about 279 square-meters. We also assume the GH and VF produce the same yields per unit of growing space. This requires identical indoor temperature, humidity and artificial lighting to maintain a recommended daily light integral for lettuce of 17 $mol{\cdot}m^{-2}{\cdot}s^{-1}{\cdot}d^{-1}$ — albeit in the GH model the lighting requirements are only supplemental (Brechner and Both 2016).

There are three main differences between a VF and a GH. First, a VF is built inside a structure with no natural light, and all light is provided by LED lighting. Second, plants are grown in multiple level racks, which is not practical in a GH due to shading. Finally, since there is no need for windows, the VF's walls and ceiling are much better insulated. A building's R-value is a measure of how well it is insulated. The higher the value of R, the better the insulation. Since the GH is single-pane glass, we assume it has a relatively low R-value of 0.9. The VF is built inside an insulated warehouse and is assumed to have an R-value of 6.0. [5] Both the VF and the GH use a heating ventilation and air conditioning system (HVAC) comprised of natural gas heating. Cooling and humidity control is done using electrically powered ventilation fans.

[5]http://www.coloradoenergy.org/procorner/stuff/r-values.htm

Our simulation requires a large number of inputs, like the efficiency of an HVAC system, the average *daily light integral* (DLI) for a given month, LED plug efficiency, and many others. We summarize some of the main assumptions in Table 1, but a detailed discussion would make this paper too cluttered for most readers. So the balance we have chosen is to attempt to give readers a deep understanding of the simulation's structure and dynamics and a detailed summary of the results, while making the actual simulation model available to readers who would like to more deeply explore the underlying assumptions and calculations.[6]

The Dynamics Underlying the Simulation

The simulations results are driven by the relationship between the amount of sunlight hitting the earth (DLI), outside temperatures, indoor temperatures, heat created by LED lighting, and indoor heating, cooling and humidity control requirements. In particular, these interactions determine the capital cost to equip a leased facility for hydroponic production (CAPEX) and the operating cost (OPEX) for a facility that's optimized to maximize lettuce yields. For instance, the winter is cold and cloudy, so the GH requires natural gas (NG) to power heaters and electricity to power supplemental LED lighting. The maximum electricity load determines the cost for building the electricity infrastructure, since the infrastructure must be capable of meeting the peak load regardless of how infrequently that peak is reached. At the same time, the waste heat from the LED lights actually helps heat the facility, reducing

[6] The full simulation can be found here.

the NG used by heaters.[7] During the summer months, the GH requires less energy for supplemental lighting, but the supplemental lighting that is required increases the electricity needed to power the vents used for cooling and dehumidification. Similarly

for the VF, waste heat from the LED lights offsets heating bills during the winter, but during the summer the VF's lights produce far more unwanted heat that must be removed using vents.

For both the GH and VF, Tables 2a and 2b show average climatic conditions by month and the resulting electricity required to power lights, heating, and venting. For the year, we see that the GH uses about 348,289 kWh of electricity a year while the VF uses 1,683,239 kWh. But, the GH uses 235,450 m^3 of natural gas a year for heating, while the VF requires only about 289 m^3.

An Example Calculation

Table 3 uses the example of a GH in November to show how we calculate total energy demand. The first section of the table reports underlying assumptions, while the following sections show how we calculated the total amount of energy used for heating, cooling and dehumidification, and LED lighting. To summarize the table, in November, the average outdoor temperature is -0.33 C. Given we want to maintain an indoor temperature of 18.3 C, there are 948 heating degree days. In the LED section, we see that the optimal DLI for growing lettuce is 17 $mol \cdot m^{-2} \cdot s^{-1} \cdot d^{-1}$. But the average DLI for November is 12.5 and only 8.12 of that reaches the plants because the solar

7 In many places, it's rare to use electricity for heating. In Canada, because of the abundance of hydroelectricity, the price of electricity is the lowest in North America. Thus, it's common for large companies and households to heat using electricity.

transmittance ratio (the proportion of light that passes through the glass) is 0.65, meaning there is a DLI deficit of 8.88. To compensate, 84.89 $W{\cdot}m^{-2}$ of LED lighting is used, meaning the total amount of electricity used to power the GH supplemental lighting is 71,480 kWh.

In the "NG required for heating" section of **Table 3**, we see that both the sun and the LED lights generate heat, while there is heat-loss due to both infiltration from the vents and conduction. The net-effect is that the GH requires 23,730 m^3 of NG for heating.

Finally, to maintain humidity control and minimum CO2 levels, the vents maintain a minimum of two air exchanges per hour and require 674 kWh of electricity. In total, the GH requires 72,154 kWh of electricity and 23,730 m^3 of NG in November.

Capital Expenses

Table 4 summarizes our estimates of the capital expense (CAPEX) per growing unit associated with equipping a GH and VF. The first two columns report the CAPEX cost per growing unit. Columns 3 and 4 report each cost as a percentage of total CAPEX. The last column reports the cost difference for that item between the VF and GH models.

The most obvious difference is the cost of buying and installing the LED lights, which is about $155 per growing unit lower for the GH. Similarly, the cost for the electrical distribution equipment for the main power feeds from the utility company is $26.68 lower for the GH. In total, the CAPEX is 23% higher for the VF, $766,400 compared to $633,128 for the GH.

It costs more to equip a VF, but it costs about 10% less a year to operate one. **Table 5** reports total annual operating expense (OPEX) for each farm. We see that a major cost driver for the GH is real-estate, which accounts for 20% of total operating expenses, and that is $36,000 higher than that of the VF. The heating accounts for about 11% of OPEX, and the GH spends about $31,000 a year more on NG. On the other hand, the annual cost of powering the VF's LED lights, including a demand charge, is over $44,000 more than that of the GH's. In total, the GH's annual operating expenses are over $22,000 more than the VF's.

Annual Gross Profit

In order to estimate the gross profit for each farming model, we imagine the farmer leases the GH or VF and borrows all the money necessary to equip the facility for operation (the total CAPEX in **Table 4**). We assume that the loan has a 4.75% interest rate [8], is paid monthly, and is amortized on a straight-line bases over 10 years. In this case, the sum of annual payments is $79,658 for the GH and $96,426 for the VF. So the total annual cost of running each facility (the annual loan payments plus the OPEX) is $347,337 for the GH and $342,533 for the VF.

On the revenue side, we have assumed that each facility grows exactly the same amount and same quality of plant, and each facility loses 5% of each harvest due to shrinkage. The wholesale price of Boston greenhouse-grown lettuce is assumed to be

[8] At the time of writing this paper, this is the average rate on a 10 year loan in the agricultural sector (see http://www.agstar.com/loans/Pages/ag-farm-loans.aspx)

US 7.62 $/kg[9] and each facility sells 62,596 kg/year, implying annual revenues of $476,637. We calculate the gross profit by subtracting OPEX plus the annual loan payments from revenues, implying a gross profit of $129,301 for the GH and $134,105 for the VF.

Conclusion

Sales of locally grown fruits and vegetables now exceed $14B in North America and are growing at 20%. This, in turn, is a driving factor for rapidly increasing demand for greenhouse and vertical farm facilities, which enable year-around supply. Though it is commonly believed in industry circles that, in terms of profitability, a vertical farm can not compete with a greenhouse, no studies have compared the the two models. This is a particularly relevant question to Canada, as low electricity prices, proximity to the U.S., and intellectual capital makes the country uniquely positioned to be a leader in this market.

We compare the profitability of a greenhouse (GH) to that of a vertical farm (VF) when supplying locally-grown lettuce, and each facility has 1,171 m^2 of growing space. We estimate the total capital expenditures necessary to build each facility is about $633,128 for the GH and $766,400 for the VF. The annual costs of operating each facility is about $267,678 for the GH and $246,106 for the VF. More specifically, a VF uses more electricity for lighting, but it costs much more to regulate the internal climate of the GH because of poor insulation. Moreover, more land is required to operate a GH, increasing the cost of the real-estate. In particular, the cost of installing the

[9] This is the average price per kg in 2015 reported by Agro Foods Canada (see https://infohort.agr.gc.ca/IH5_Reports/cognosSubmitter.xhtml?lang=e&report=12&pageMenuId=12)

lighting infrastructure is about $155 higher per grow unit for the VF, while the annual cost of powering those lights is about $37,000 higher. On the other hand, the annual cost of renting space is $36,000 higher and heating costs are $31,000 higher for the GH. Nonetheless, we estimate that gross profits are nearly identical: $129,301 for the GH and $134,105 for the VF.

We believe our results differ from the expectations of many growers for three main reasons. First, growers' expectations are lagging rapid increases in LED lighting efficiency. Second, in cooler environments like Canada (and probably in hotter ones too) the facility's insulation has an important impact on heating and cooling costs. Finally, vertical farms are often assumed to use a refrigeration system for cooling and dehumidification. In this study, we assume each facility uses a lower cost, forced ventilation system.

Finally, our analysis does not consider some other additional benefits offered by a VF that may represent a significant value to growers. For instance, the ability to more precisely control the environment within a VF can increase the quality and consistency of the final product. In particular, de Tourdonne et al. 2001 find that the quality of plants grown in a GH varies significantly as you move from the center of the GH towards the walls, due to changes in temperature and light. The VF is more easily compartmentalized to limit crop loss due to pest infiltration since dividing walls can be installed without loss in light transmittance. Moreover, because the VF's foot print is a fraction of the size of the GH's, a commercial size VF can be much more easily placed close or within an urban area, increasing both the freshness of the delivered product and the working experience for the employees (e.g., a shorter commute) (Despommiers 2013).

Tables and Figures

Figure 1: An illustration of a vertical farm provided by AeroFarms, who is currently building the world's largest vertical farm.

Table 1: General Assumptions

	GH	VF	unit
Electricity			
Electricity cost (0 to 210k kWh)	0.0376	0.0376	$/kWh
Electricity cost (>210k kWh)	0.0279	0.0279	$/kWh
Electricity demand charge	10.77	10.77	$/kW
Internal elect. distribution cap.cost	0.5	0.5	$/W
Utility electricity distribution cap. cost	0.35	0.35	$/W
Real-estate			
Lease/m^2	32.29	64.58	$
Width of facility	18.3	18.3	m
Length of facility	91.5	15.2	m
Height at center	4.9	7.32	m
Height at wall	2.1	7.32	m
Growing space	1,171	1,171	m^2
Growing levels	1	6	
Grow unit size	1.49	1.49	m^2
Sheating R Value	0.9	6	
Labor			
Labor Persons / 10,000 kg yield	0.315	0.315	person
Hourly cost of labor	10.49	10.49	$
Lettuce			
Harvest/year	10	10	
Yield/harvest	5.34	5.34	kg/m^2
Lettuce wholesale price*	7.63	7.63	$/kg
LED Lighting			
LED Price/W	1.75	1.75	$
LED plug efficiency	25	25	%
Heating and Cooling			
Ventilation System	1.092	1.092	$/W
NG Heater Capital Cost	0.0231	0.0231	$/W

* see https://infohort.agr.gc.ca/IH5_Reports/cognosSubmitter.xhtml

Table 2a: Total electricity used by the GH given the monthly climate condition

	Avg. exterior temp. C	Target indoor temp. C	Avg. DLI*	Avg. solar heat input (MJ/m^2)**	NG use m^3	Electricity (kWh)		
						Vents	LED lights	Total electricity
Apr	2.6	21.1	32.5	16.06	20,894	676	0	677
May	9.83	21.1	37.5	17.92	5,916	699	0	699
June	15.33	21.1	42.5	19.95	1	1,376	0	1,376
July	18.28	21.1	42.5	20.01	5	3,145	0	3,145
Aug	16.83	21.1	37.5	17.04	24	2,156	0	2,156
Sep	12.28	21.1	27.5	12.52	4,382	676	0	676
Oct	6.56	18.3	17.5	7.81	13,599	699	46,829	47,528
Nov	-0.33	18.3	12.5	4.16	25,020	676	71,503	72,180
Dec	-8.83	18.3	7.5	3.53	38,451	699	100,943	101,643
Jan	-11.83	18.3	12.5	4.76	48,173	699	73,886	74,586
Feb	-10.61	18.3	17.5	8.22	43,074	631	42,297	42,930
Mar	-4.67	18.3	27.5	12.86	35,914	699	0	700
Total					**219,023**	**12,830**	**335,459**	**348,296**

* Units mol·m**-2·s-1·d-1**(Korczynski et al. 2002)
** (Knapp et al. 1980)

Table 2b: Total electricity used by the VF given the monthly climate condition								
						Required electricity (kWh)		
	Avg. exterior temp.	Target indoor temp.	Avg. Solar DLI*	Avg solar heat input (MJ/m2)**	NG use m^3	Vents	LED lights	Total
Apr	2.6	21.1	0	0	8	654	136,963	137,617
May	9.83	21.1	0	0	5	1,161	141,528	142,690
June	15.33	21.1	0	0	4	2,252	136,963	139,215
July	18.28	21.1	0	0	6	4,751	141,528	146,280
Aug	16.83	21.1	0	0	2	3,176	141,528	144,705
Sep	12.28	21.1	0	0	2	1,461	136,963	138,424
Oct	6.56	18.3	0	0	8	1,082	141,528	142,610
Nov	-0.33	18.3	0	0	134	643	136,963	137,606
Dec	-8.83	18.3	0	0	17	428	141,528	141,956
Jan	-11.83	18.3	0	0	20	372	141,528	141,900
Feb	12.9	18.3	0	0	37	361	127,832	128,193
Mar	23.6	18.3	0	0	24	515	141,528	142,043
Total					**289**	16,856	**1,666,383**	1,683,239

* Zero solar DLI reaches inside of VF, target DLI of 17mol·m-2·s-1·d-1 achieved with artificial lighting
** Zero solar heating input reaches inside of VF

Electricity required for LED lights			
Required DLI (G)	N	17 mol/m^2/s	
Avg. DLI (I)	O	12.5 mol/m2/s	
Solar Transmit (J)	P	0.65	
DLI Deficit (J)	Q	8.88 mol/m2/s	N - O * P
PPFD deficit (K)	R	102.72 mol/m2/s	1,000,000 * Q / O * P
PPFD / W (L)	S	1.21 μmol/m2/s	
Supplemental LED light W/ m^2 (M)	T	84.89 W/**m^2**	R / S
Monthly LED electricity use	U	71,480 kWh	T * C * D * I /1000

Table 3 (continued): Electricity and NG required to power GH in November

NG required for heating			
Heat from LEDs and Sun			
LED plug efficiency	V	25%	
Heat created by LEDs	W	53,610 kWh	U * (1 - V)
Daily solar heat	X	1.155 kWh/m^2	
GH exposed roof area (50%)	Y	873 m^2	A'/2
Heat created by sun	Z	19,662 kWh	X * Y * I * P
Total Heat Input	a	73,272 kWh	W + Z
Heat loss			
Infiltration heat loss	b	87,340 kWh	1.2 * B * H*(F - E) * J * I * 1/L
Sheathing R-value	c	0.9	
Heat loss due to conduction ***	d	183,601 kWh	1/3412 * G * J * A / c * 10.76
Total heat loss	e	270,941 kWh	b + d
Total heat required	f	197,669 kWh	e – a
NG required for heating	g	23,730 m^3	f / M
Electricity required for vents			
Vent fan m^3/min	i	326 m^3/min	H / K * B
Pest screen restriction factor	j	0.6	
Vent fan efficiency	k	0.58 m^3/min/W	
Vent fan power	m	937W	i/k * 1/j
Electricity for vents	n	674 kWh	1/1000 * m * I * J
November electricity demand		**72,154 kWh**	U + n

* Assuming 70% of floor space can be used for growing, then both the GH and VF have 787 grow units. Each requires rack space, electricity distribution, hydroponic components and chemicals, and MISC.
** To maintain humidity control in the Canadian climate, a minimum of two air exchanges per hour is maintained in the GH and VF.
*** Uses conversions factors that allows the use of the english unit based insulation “R value”

Table 4: Total capital expenditures (CAPEX) for a GH and a VF					
	GH	**VF**	**GH**	**VF**	**$GH - $VF**
Lights	$301.69	$422.99	37.5%	43.4%	-$121.30
Internal Wiring for Lights, etc.	$86.20	$120.86	10.7%	12.4%	-$34.66
Utility electricity distribution *	$60.76	$87.44	7.6%	9.0%	-$26.68
Grow unit rack **	$125.00	$125.00	15.5%	12.8%	$0.00
Hydroponics	$108.63	$108.63	13.5%	11.2%	$0.00
NG heat sys.	16.34	$0.05	2.0%	0.0%	$16.29
Vent fan sys.	5.86	$8.86	0.7%	0.9%	-$3.00
Misc. grow unit CAPEX	$100.00	$100.00	12.4%	10.3%	$0.00
Total Cost for facility	$633,128	$766,400	100%	100%	-$133,272

* Rosenquist (2004)
** Based on a price of $803 + $200 for install/ship, single quantity for six grow units, with a 25% discount in high quantity.

Table 5: Total operating expenditures (OPEX) for a GH and a VF

Item	GH	VF	GH	VF	$GH - $VF
Real Estate Lease	$54,000	$18,000	20.2%	7.3%	$36,000.00
Lighting Electricity	$11,321	$48,509	4.2%	19.7%	-$37,188.00
Ventilation Electricity	$433	$491	0.2%	0.2%	-$58.00
Electricity Demand Charge	$17,656	$25,410	6.6%	10.3%	-$7,754.00
NG for Heating	$30,609	$38	11.4%	0.0%	$30,571.00
Water	$995	$995	0.4%	0.4%	$0.00
Nutrients	$17,434	$17,434	6.5%	7.1%	$0.00
Seeds	$11,018	$11,018	4.1%	4.5%	$0.00
Packaging	$34,439	$34,439	12.9%	14.0%	$0.00
Labor *	$89,774	$89,774	33.5%	36.5%	$0.00
Total Op Ex	$267,678	$246,106	100.0%	100.0%	$21,572.00

* We assume each facility requires 1 full-time general worker who is paid minimum wage and a working supervisor who is paid $63k. The cost per m^2 is in-line with costs reported in other studies of the operating costs of GHs.

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