Integration | Construction | Mechanical | Electrical | Structural

GROWING POWER

VERTICAL FARMING FACILITY

TOTAL BUILDING DESIGN

ENGINEERING

Architectural Engineering Institute, Annual Student Competition
Registration Number: 04-2015

GROWING POWER INC.

EXECUTIVE SUMMARY

The client, Growing Power, is a national nonprofit organization which educates the community on sustainable farming, specifically vertical urban farming. The organization's goal is to provide those communities with high quality, healthy, safe, and affordable food.

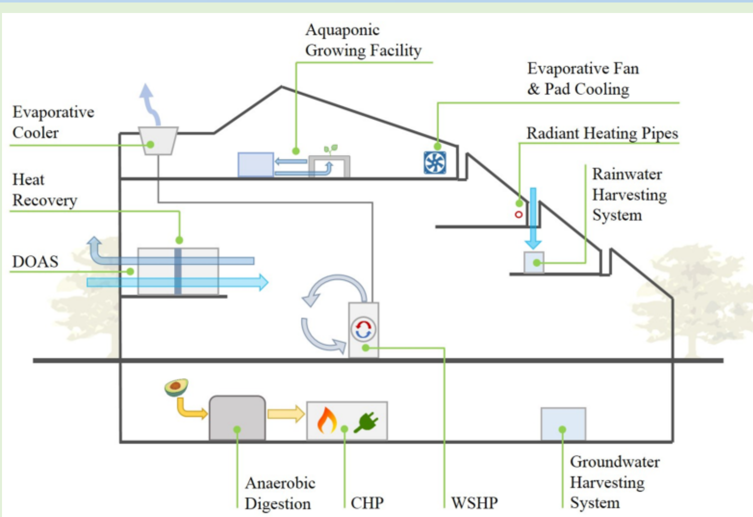
The design team of Total Building Design (TBD) Engineering was asked to develop and submit plans for the new Growing Power headquarters in Milwaukee, WI. The headquarters will be a five-story vertical farm that composes of greenhouse facilities, a market space, offices, and educational spaces for the community. Growing Power has also stressed that they planned to use the developed design as a prototype for future Growing Power facilities in other locations in the United States. The TBD design team investigated what makes a vertical farm successful and aligned that with Growing Power's goals to establish the goals for the project:

Community Outreach – The vertical farm should be an integral part of the community in which it is placed. The design team paid close attention to how decisions affected the community and how the community can benefit from the design of the systems.

Sustainability – The success of a vertical farm system relies heavily on the concept of self-sustaining technologies in order to justify the energy use associated with indoor farming. The design team therefore introduced renewable energy strategies as well as focused on a closed energy loop design.

Flexibility – In order for the facility to successfully impact other communities throughout the country, the design implements technologies that are easily relocated and conscious of the surrounding resources. TBD strives to produce a building that will give Growing Power a strong identity.

Closed Loop Mechanical Design



[PROJECT HIGHLIGHTS]

Combined Heat and Power Facility (CHP):
A CHP system provided the necessary heating and electric demand for the vertical farm.

86% CO_2 Emissions Reduction

On Site Primary Fuel Production:
Primary fuel is produced on site using anaerobic digestion and soybean oil alternatives reducing community emissions.

22 ton reduction in CH_4 produced in landfills per year

Water Source Heat Pumps (WSHP):
WSHP condition the building saving **11%** in energy use compared to the baseline model.

Dedicated Outdoor Air with Heat Recovery (DOAS):
A **29%** savings in energy use is achieved through heat recovery of ventilation air.

Aquaponic Growing Facility:
Aquaponic farming techniques are used to reduce water demand and educate the community.

98% Water Efficiency

Rainwater and Groundwater Harvesting System:
Rainwater and groundwater is collected to offset the water demand of the facility.

99% Reduction in Overall Domestic Water Demand

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GROWING POWER VERTICAL FARM

BUILDING DESCRIPTION

The client, Growing Power, is a national nonprofit organization that prides itself in providing communities with healthy, high quality, safe, and affordable food. The mission of Growing Power is to promote sustainable food producing systems throughout the communities they are a part of, helping to establish food security.

Figure 1. Growing Power Milwaukee, WI

The Growing Power Vertical Farm is a proposed five-story building located in the surrounding area of Milwaukee, WI. The building will have 9,000 S.F. of south facing greenhouse space and 42,000 S.F. of mixed use office, educational, and retail space. As a national nonprofit, Growing Power has a long term vision of using this vertical farm as a prototype for future locations. The TBD team considered Miami, FL as another possible Growing Power location. The challenge of the Total Building Design (TBD) team is to provide Growing Power with a facility that will enable them to carry out their goals, utilizing best engineering practices.

The mechanical design team of TBD Engineering hopes to model the self-sustaining goals of the client by focusing on closed loop energy strategies. A closed loop energy system minimizes loss from the facility by reclaiming end product energy, which in other systems would be lost to the environment. The design focus of the mechanical systems will focus on utilizing renewable energy and on-site energy production. At the same time the intent of the mechanical partners is to provide the community with a building that acts as a teacher in the benefits of urban farming. The greenhouses will incorporate closed loop strategies by utilizing aquaponic systems to educate the community on efficient and sustainable farming strategies.

PROJECT INITIATIVES

Flexibility

The ability for the facility to be used as a prototype for other possible sites across the country, while meeting the changing needs of Growing Power by providing options for continuous improvement.

Community

Strengthen the community outreach by providing ample space for education and enabling the surrounding population to participate in the growing methods used within the vertical farm.

Sustainability

Create a facility with a manageable lifecycle cost aided by the use and optimization of renewable energy, renewable resources, and sustainable practices in design and construction.

Economy

Provide the best product for the budget developed by Growing Power while continuously providing cost savings and exploring funding expansion.

BUILDING ANALYSIS

WEATHER STUDY

The weather data was analyzed using IES Virtual Environment software. From these predictions it can be seen that Milwaukee faces cold stresses during a large portion of the year. On the contrary, the Miami site faces hot stresses for half of the year while the winter months are relatively comfortable. The mechanical design considered the differences between each climate zone so that building loads could be met at both locations. According the ASHRAE Standard 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings*, the Milwaukee climate is considered a 6A zone, while the Miami climate is considered 1A.[3] These zones were used to establish the baseline buildings for the Vertical Farm load and energy simulation. The IES VE software was also used to analyze the solar stress on the building and was used in conjunction with electrical design team to design an appropriate greenhouse façade (Elec|2).

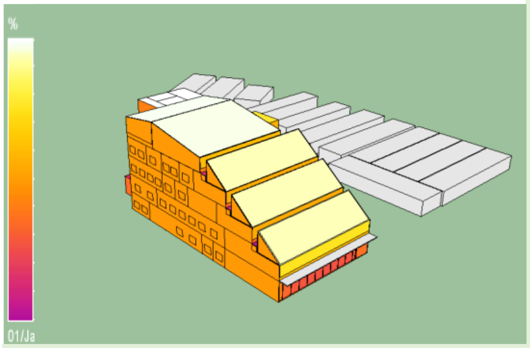

Figure 2. Solar Exposure Study

[DESIGN WEATHER DATA]

★ Milwaukee, Wisconsin

Summer DB/WB (ºF): 86.2/72.3

Winter DB (ºF): 0.0

Min/Max. Rainfall (in.): 1.4/3.5

★ Miami, Florida

Summer DB/WB (ºF): 86.2/72.3

Winter DB (ºF): 0.0

Min/Max. Rainfall (in.): 1.4/3.5

* ASHRAE Design Condition 1% cooling and 99% heating values

CALCULATED LOADS

The mechanical design team used Trane TRACE 700 software to perform an 8760 energy simulation to determine the loads seen by the facility and determine the yearly energy profile of the building. The following data on Table 1 shows the loads seen by the vertical farm after envelope enhancements were made to the baseline construction. Determination of the optimum envelope for the building was an integrated process that involved the entire TBD design team.

The Rainscreen façade technology was chosen for its thermal performance as well as for its flexible application to other parts of the country and economic solution. Low-e glazing was used to reduce solar heat gain to the building interior.

INTEGRATED SOLUTIONS: RAINSCREEN FAÇADE

Desiring to meet the goal of flexibility, the Rainscreen system gives Growing Power the option of relocating a similar building anywhere in the country without major façade changes (Int|10).

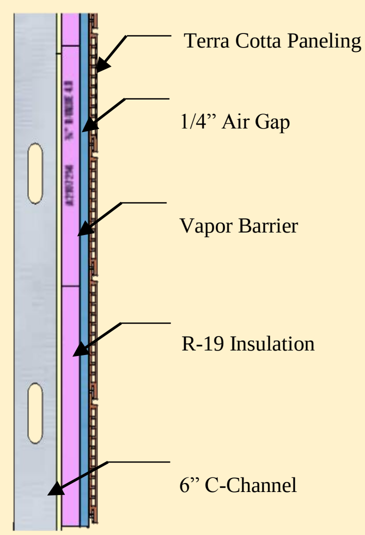

Table 1: Growing Power Facility Loads				
Location	Milwaukee, WI		Miami, FL	
ASHRAE Zone	6A		1A	
	Building	Greenhouse	Building	Greenhouse
Cooling Load	88 Tons (1.2 CFM/SF)		121 Tons (1.6 CFM/SF)	
Heating Load	1,168 MBH	808 MBH	285 MBH	226 MBH

GREENHOUSE

The primary goal of Growing Power is to produce food for the community and this goal cannot be reached without a successful food production system in the vertical farm. The greenhouses in the vertical farm consist of an aquaponic growing system as well as its own HVAC system to maintain optimal production conditions.

Table 2: Aquaponic Growing System Sizes per Floor

Growing Space Level	Aquaculture Raceway Volume [gal]	Grow Bed Area [sf]	Sump Tank Volume [gal]
2	6604	832	132
3	6604	832	132
4	3302	416	66
5	14794	1872	296
Total	**31,304**	**3,952**	**626**

AQUAPONIC GROWING SYSTEM

An aquaponic growing system is placed in the greenhouse spaces to promote and educate the community on sustainable farming techniques, produce food products to bring profitability to Growing Power, as well as to demonstrate the reduced consumption of water for farming. An aquaponic system is a soil-free agriculture system that delivers necessary nutrients and water to plants by means of a closed water loop connecting plant grow beds and aquaculture tanks. Not only does this system produce crops, but it also produces fish for the market.

The aquaponic growing system at the vertical farm will primarily produce tilapia and lettuce. These products will be sold at the market on the ground floor of the building. Table 2 above outlines the sizes of the aquaponic growing system by growing space level in the vertical farm.

THE AQUAPONIC PROCESS

As shown in Figure 3 below, water continuously flows through an aquaculture raceway. Fish waste is removed at the end of the raceway and collected in a sediment collection tank, after which the water is pumped to the grow beds. The plants then absorb the nutrients and the water is sent into a sump tank. The sump tank is atmospheric, such that it ensures that the water levels in the system remain constant.

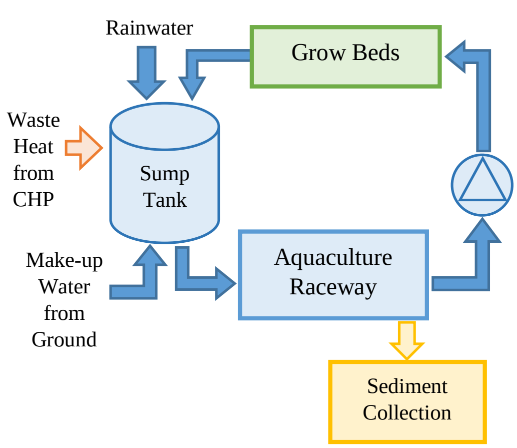

Figure 3. The aquaponic growing system creates a closed loop of water

Aquaponics: An Age Old Idea

The concept of producing crops using fish to provide nutrients has been around for centuries, in fact being a critical element to the survival of North America when the Wampanoag tribe first introduced the technique to the Pilgrims, as seen in Figure 4 below. Today, the cultivation of crops is once again aided by aquaculture, but this time through an aquaponic growing system.

Figure 4. The first Thanksgiving 1621, Jean Leon Gerome Ferris depicts the Wampanoag tribe teaching the pilgrims how to plant crops with fish.[7]

Tilapia require a water environment between 72°F and 90°F for optimal growth. [27] Growth slows when the water temperature falls below 70°F, and tilapia will die when the water temperature drops below 55°F.[27] This indicates that the aquaponic system requires a constant heat source to maintain maximum growth. Waste heat from the combined heat and power (CHP) facility is injected in the sump tank to maintain a setpoint of 78°F (SD|10).

The benefit of aquaponic growing systems is their water loss efficiency. Only 2% of circulated water is lost to evaporation and transpiration per day.[20] This is a vast compared to a traditional farming system, in which 50% of water is lost.[19] The aquaponic system in the vertical farm requires approximately 626 gallons of make-up water per day, which will be fed by the treated rainwater system (SD|6).

Greenhouse Systems in Action

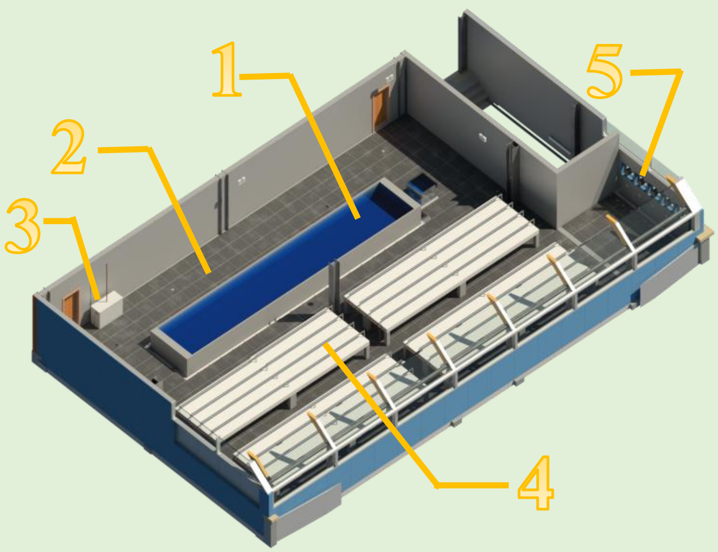

Figure 5. A typical layout of the greenhouse consists of growing beds, aquaculture tank, destratification fans, water collection, and evaporative fan and pad cooling systems.

The greenhouse system used in the facility consists of the following components, shown in Figure 5, on left.

1. Aquaculture raceways provide quality tilapia which in turn produce nutrients for the plants grown.

2. A grated floor system allows for easy maintenance and reduction of tripping hazards without a loss to food production capabilities.

3. A rainwater collection tank will provide supplementary water for the aquaponic growing system as well as the evaporative cooling fan and pad system.

4. Horizontal grow beds will produce lettuce on raft beds which float on a continuous flow of aquaponic water.

5. An evaporative cooling fan and pad system provide cooling and air circulation throughout the space.

Ceiling mounted destratification fans help reduce the humidity in the space generated by the aquaculture raceways. (not pictured)

GREENHOUSE HVAC SYSTEM

The greenhouse indoor environment is controlled by several independent components: cooling, heating, and automatic timing and controls (ATC). The greenhouses meet the thermal and electric demand for the day by using rejected heat and electricity generated from the Combined Heat and Power (CHP) plant.

EVAPORATIVE COOLING SYSTEM

An evaporative fan and pad cooling system maintains the greenhouse temperature and air velocity across the space during the summer months. If overheated, lettuce produces a flower stalk to seed in a process called *bolting*. Bolting will make lettuce unmarketable, and is most likely to occur between temperatures of 80 and 85°F.[26] Therefore, it is critical that the temperature of the greenhouse maintain a setpoint of 78°F so that any temperatures exceeding this setpoint would trigger the evaporative cooling fans to turn on. The fan and pad system will be in operation when natural ventilation through the roof is incapable of meeting this setpoint.

Air exchange rates within the space must be between 0.75 and 1 air change per minute in order to control temperature rise in the greenhouse.[1] An air exchange rate greater than this range can potentially damage plants.

RADIANT HEATING SYSTEM

A benefit to a vertical farm is that crops may be produced throughout the year and not limited to seasonal selections. This benefit is only obtained if the greenhouse maintains the same temperature setpoint at nighttime and during colder winter months. Finned tube radiation will maintain the temperature in the greenhouse at a minimum of 70°F. Hot water will be supplied from the CHP plant through the use of thermal storage. Hot water treated by the exhaust will be stored and accessed during hours in which a heating is called for.

HUMIDITY CONTROL

Due to the increased humidity from the aquaculture tanks, auxiliary fans are located near the aquaculture tanks to reduce the humidity in the growing spaces. When the ventilated roofs and temperature controls are insufficient to reduce the relative humidity in the greenhouses, these auxiliary fans will provide additional air circulation in the space to remove excess humidity.

ATC

The greenhouses include automated control for temperature and humidity regulation as well as the operation of the aquaponic system. The goal of implementing a controls systems is to minimize dependence on manual maintenance. The aquaponic system can fail if not monitored correctly, resulting in the loss of an entire crop of both tilapia and produce. Because Growing Power may rely on community members and not necessarily facility managers to maintain the building, it is necessary for the system to be designed to automatically mitigate any adverse conditions. Because the building is designed to act as an educational tool for the community, instrumentation controlling environmental conditions and plant growth will be synchronized with user interfaces that will show the community how the design of the greenhouses affects both plant growth and building energy use.

GREENHOUSE HVAC OVERVIEW

Cooling:
An evaporative fan and pad cooling system is coupled with a ventilated roof system

Heating:
Radiant piping keeps the temperature of the greenhouse optimal for plant growth

Humidity Control:
Destratification fans eliminate excess humidity generated from aquaponics.

Temperature Constraints:
Min. GH Temperature: 70°F
Max. GH Temperature: 80°F
Min. Aquaculture Temperature: 70°F
Max. Aquaculture Temperature: 90°F

INTEGRATED SOLUTIONS: GRATED FLOORS

A successful greenhouse is also a functional one. The mechanical partners worked with the structural partners to develop a grated floor system to facilitate daily maintenance of the greenhouse space without the hazards of tripping over piping, shown in Figure 6 below (Int|13).

Figure 6. An elevated grate floor system in the greenhouse prevents piping from causing tripping hazards.

INTEGRATED SOLUTIONS: FAÇADE AND GROWTH OPTIMIZATION

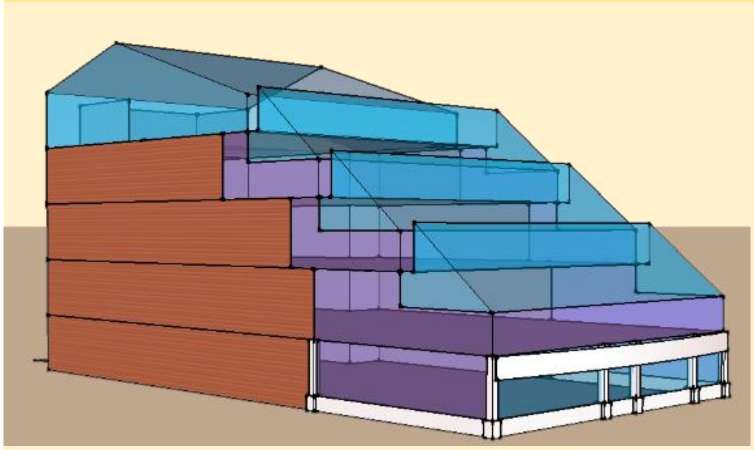

Figure 7. The amount of glazing of the greenhouses depended greatly on the PAR levels calculated.

Photosynthetically Active Radiation, or PAR, is a measure of light in a certain wavelength range that is optimal for the photosynthesis of plants.[18] A specific plant's optimal PAR level can determine if the plant will receive the amount of sunlight required to grow successfully.

A study done on DAYSIM concluded that the East and West walls did not produce adequate PAR levels to effectively grow plants. Therefore, the glazing on those surfaces were replaced with the Rainscreen system for its improved insulation characteristics. The areas of the building highlighted in violet in Figure 7, on left, represent the greenhouse glazing area replaced by the Rainscreen façade based on PAR level analysis (Elec|6) (Int|12).

A SELF SUFFICIENT WATER SUPPLY

The vertical farm relies heavily on closed loops such that water levels must remain stable throughout the aquaponic growing system. Greenhouse water demand for the aquaponic system as well as the evaporative fan and pad cooling system are controlled by their respective sump tanks. As water is lost in the aquaponic system through transpiration and evaporation, make up water is supplied by its sump tank. The evaporative fan and pad system similarly relies on its sump tank for makeup water. The sump tanks are atmospheric such that the float within the sump indicates that there is not enough water. This triggers the pump in the basement to send water to the rainwater collection tank, which then supplies the additional water to the sumps to a satisfactory level.

Due to the daily water demand to provide make-up water for the aquaponic growing system, the mechanical design partners developed a system in which the water demands were met by both rainwater and groundwater.

RAINWATER COLLECTION

A biofilter is necessary to ensure that the water sent to the greenhouses is healthy for both the plants and fish in the aquaponic system. The trough between the roofs of the greenhouse spaces of the building effectively serve as individual biofilters. The pipes entering the building through the biofilters are made visible in the greenhouses so that the educational value of rainwater harvesting can be visibly recognized by visitors on a rainy day. The incoming rainwater collects in individual rainwater storage tanks on each greenhouse level which distributes rainwater to both the aquaponic make-up sump and evaporative cooling pad sump.

Water Utilization Overview

Average Monthly Rainfall in Milwaukee

15,380 gallons

Water Lost in Aquaponics

626 gallons/day
18,780 gallons/month

Average Flushing Water Demand

1,498 gallons/month

Average Water Pumped from Groundwater Collection to Aquaponics and Toilets

4,898 gallons/month

Water Demand Met for Aquaponics and Toilets

100%

99% Reduction in Overall Domestic Water Demand

INTEGRATED SOLUTIONS: BIOFILTER ROOF SYSTEM

Pumice rock traps particles as rain enters the trough, effectively filtering the rainwater as it drains into the rainwater storage system. Having this biofilter in the roof eliminates the need to have another biofilters at the greenhouse level.

In order to allow rainwater to enter the greenhouse areas below, the mechanical design partners collaborated with the structural design partners to create an efficient solution (Struc|12).

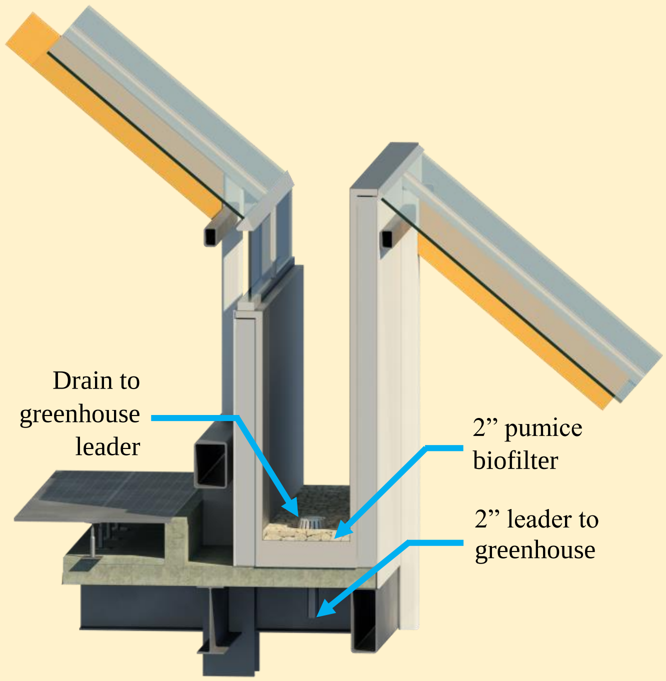

Figure 8. The trough in between the roofs of the greenhouses act as a biofilter which both collects and cleans water for greenhouse makeup water use.

GROUNDWATER COLLECTION

The high water table at the Milwaukee site creates an opportunity for the Growing Power Vertical Farm facility to intentionally draw well water into the building. The water is pumped through the foundation and into a groundwater collection tank. A float tank in the groundwater collection tank will indicate when there is a sufficient water supply and will halt the groundwater pump and send excess water to storm water.

COMBINED HEAT AND POWER

The Growing Power site will be equipped with a combined heat and power facility. This facility will incorporate a closed energy loop as the main energy source and supply the building generator. The greenhouse will use energy to produce food and educate the community. In order to produce this required energy for the site, the food waste will be collected from the Growing Power market and the surrounding restaurants and grocery stores in the area. An anaerobic digestion system will turn the Growing Power and community food waste into biogas which will be used by the internal combustion engine to produce electricity and heat needed to offset the demand of the building.

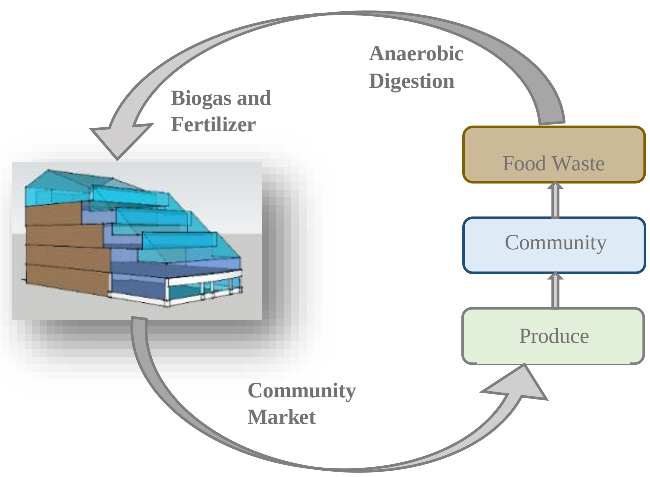

Figure 9. Closed energy loop created by food production and community waste.

CLOSED ENERGY LOOP

The overall success of the vertical farm lies within its ability to reclaim wasted energy. The vertical farm will consume energy in order to provide healthy, high quality, safe, and affordable food for its community. Unlike traditional farming methods, the vertical farm uses its stacked greenhouses to produce food and minimize its footprint. Using the collected food waste from the site and surrounding area in an anaerobic digestion system will provide multiple benefits to Growing Power and the community. The biogas created from the anaerobic process will help power and heat the facility and offset costs associated with the greenhouses. In addition, the byproduct of anaerobic digestion will be nitrogen-rich effluent that can be used to increase the value of Growing Power's already successful fertilizer production.

FOOD WASTE COLLECTION

The food waste potential of the site and the surrounding area was considered in determining the capacity of the anaerobic digestion system. In order to stay in line with Growing Power's goal of community outreach, the anaerobic digestion process will gather food waste from its own site as well as from restaurants and grocery stores in the surrounding area. The decision to reach out to the surrounding stores will not only connect the facility to the community but enhance its ability to offset the vertical farm's peak energy demands with increased waste capacity. An analysis of the surrounding area established potential facilities that might contribute to the collection of food waste. Figure 10 shows the surrounding area of the Growing Power including Milwaukee, which lies in a seven mile radius of the site, highlighting the dense population of restaurants and grocery stores surrounding the Milwaukee site and suggests a large food waste potential. An analysis of the greenhouses was performed in order to determine how much waste would be generated on site. It was found that the weekly waste collected from the site would be 85 lbs. assuming it will be collected weekly at the market. This total is less than 1.0% of the food waste needed to meet the demand of the anaerobic digester system making the rest of the capacity dependent on collected waste from the surrounding area.

BIOGAS FROM FOOD WASTE – ANAEROBIC DIGESTION

The anaerobic digestion process uses the breakdown of food waste to collect biogas. The biogas produced from the process is around 60-70% methane gas which will be used to power the vertical farm's internal combustion engine. The anaerobic digestion

[CHP HIGHLIGHTS]

On Site Heat Generation:
7660 MBH/Day

On Site Electric Generation:
2,115 kWh/Day

Biogas Produced:
8580 ft^3/Day

CO_2 Emission Reduction:
86%
22 Tons CH_4 Removed from Landfills per Year

CHP PEUF / SHP PEUF:
0.78 / 0.47

CHP and Anaerobic Payback Period:
6 years: without Wisconsin Incentives
3 years: with Wisconsin Incentives

Figure 10. Community Partner – Growing Power will work with the Community to gather waste and lower their CO_2 emission.(8)

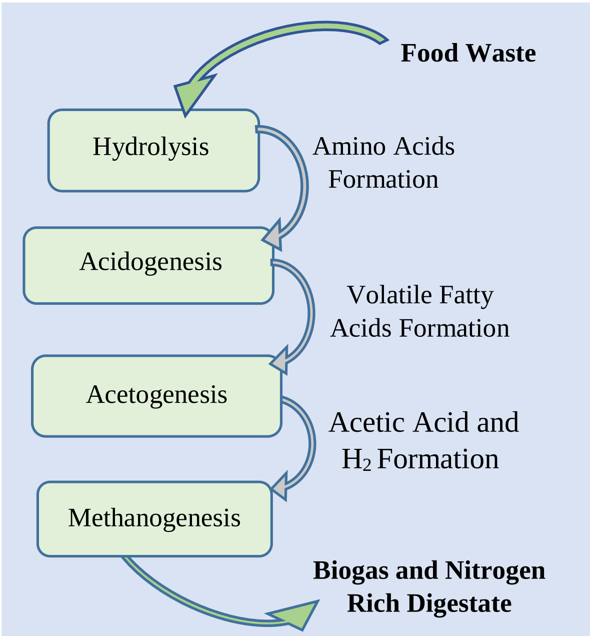

Figure 11. Biogas and nitrogen-rich digestate are produced from food waste.

process takes place in the absence of oxygen and is a biological process in which microorganisms break down organic matter. During the breakdown of organic matter biogas is formed as a byproduct which has a methane content suitable for combustion. In addition to biogas the anaerobic process leaves behind a digestate which is rich in nitrogen and suitable for Growing Power's fertilizer production.[30] The process consists of four separate phases: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. During the last phase; methanogenesis, methane producing microorganisms are at their most stable population and the majority of the biogas is produced. Due to the large variation of food waste quantity that can be assumed to be delivered to the site, extra precaution was taken to design the anaerobic system around day to day variable loading. In order to provide a more stable process for the vertical farm, a mesophilic two phase anaerobic digestion process was used. The mesophilic two phase process operates at a constant temperature of 98º F (37º C) while separating the hydrolysis, acidogenesis, and acetogenesis phases of digestion from the methane-producing methanogenesis phase.[30] Figure 11 demonstrates the steps of anaerobic digestion in which biogas and nitrogen-rich digestate are created from food waste.

ANAEROBIC DIGESTION SIZING AND LAYOUT

The biogas yield and sizes of the anaerobic digestion system were based on the assumed organic loading rate (OLR) of 3 kgVS/m^3/day. This assumes that the mass of volatile solids available for biogas production will be 3 kg per cubic meter of waste added to the system. Figure 12 shows the data gathered from pilot and large scale MSW.[28] It concluded that the biogas yield was greatest for food waste at this OLR and at the mesophilic temperature range. The OLR was compared to the available space of anaerobic plant and biogas demand of the building to determine what capacity was available at the plant.

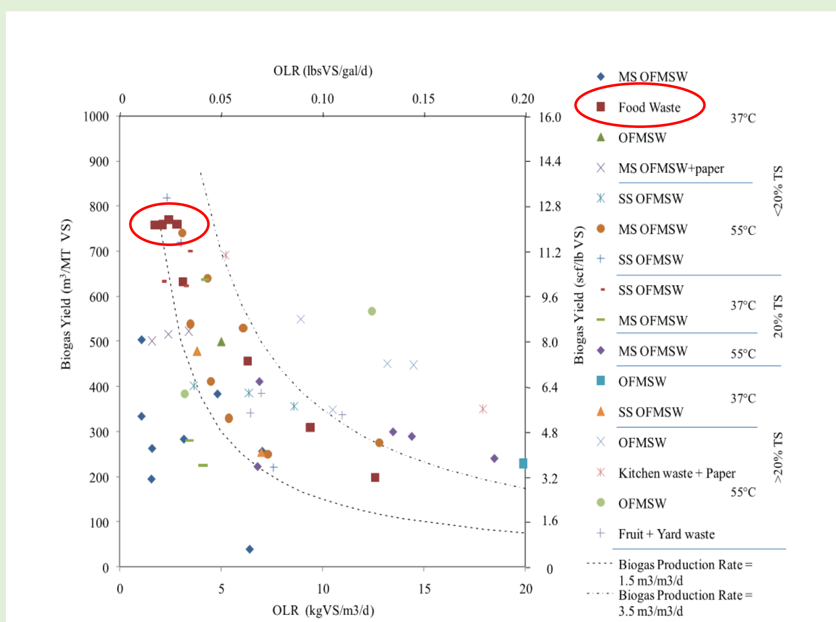

Figure 12. Organic loading rates vs. biogas yield for food waste and other common wastes

The size of the anaerobic digestion plant was limited to the available space within the building footprint. The decision to keep the anaerobic plant inside the building was driven by the desire to move the building concept to different locations around the country. Keeping the plant inside the building allows Growing Power to pursue anaerobic digestion in locations like downtown Miami, where food waste potential is high while building site area is limited. The TBD design team worked early in the project to maximize mechanical space in the building's basement to allow for a large anaerobic plant. The final plant design allowed for 940 square feet of anaerobic digestion. This allowed for six 4,450 gallon anaerobic digesters for the system. This size system will have the potential to handle 1.90 tons of food waste per day and produce 5,580 cubic feet of biogas for the facility and help offset the natural gas demand of the building's combined heat and power facility.

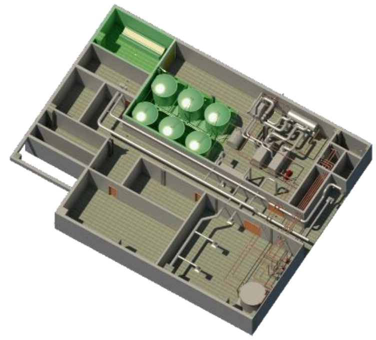

Figure 13. Anaerobic digestion plant located in building mechanical room.

[Anaerobic Digestion Plant]

Square Footage: **940 SF**

Tank Volume: **26,700 Gal.**

Food Waste Consumption:

1.9 Tons/Day

Biogas Yield: **8,580 ft^3/Day**

Equivalent Emissions Reduced:

22 Tons CH_4/yr

53 Tons CO_2/yr

Although the anaerobic digestion plant will not completely offset the natural gas demand, the facility was kept to encourage Growing Power's connection to the community and the environmental benefits that anaerobic digestion presented versus typical landfill disposal. By managing the release of biogas in the anaerobic system, the EPA suggested that the anaerobic site will reduce CH_4 emissions by 22 tons per year and CO_2 emissions by 53 tons per year.[(37)] Using the food waste from the surrounding area will make the emissions reduction a community effort and strengthen the relationship it has with Growing Power.

COMBINED HEAT AND POWER (CHP)

Coupling the facility's anaerobic digestion plant with a CHP plant will help complete the closed energy loop for the building. The internal combustion engine will use the biogas produced from the anaerobic digestion process as well as natural gas from the utility to meet the building demand. The electrical power generation is provided by two 55 kW internal combustion engines. The engines produce an additional 114 kW_{th} of useful heating output that is used to meet the building heating demand. The overall efficiency of the CHP facility is 87% (Elec|4). The exhaust heat and jacket water heat will both be recovered by heat exchangers to meet the hot water demand in the building. A hot water storage tank will also be used to meet peak heating demands in the greenhouses that do not coincide with peak electrical demands. To address the flexibility goal and the need to be able to construct the facility in multiple locations, the mechanical partners used the Milwaukee site as a template to develop a process to analyze the feasibility and requirements of a CHP facility around the country.

[CHP Components]

(2) 55 kW IC Engines

Thermal/Electric Ratio (λ): **1.30**

Total Electrical Output: **110 kW**

Total Useful Heat Output: **389 MBH**

Overall Efficiency: **87%**

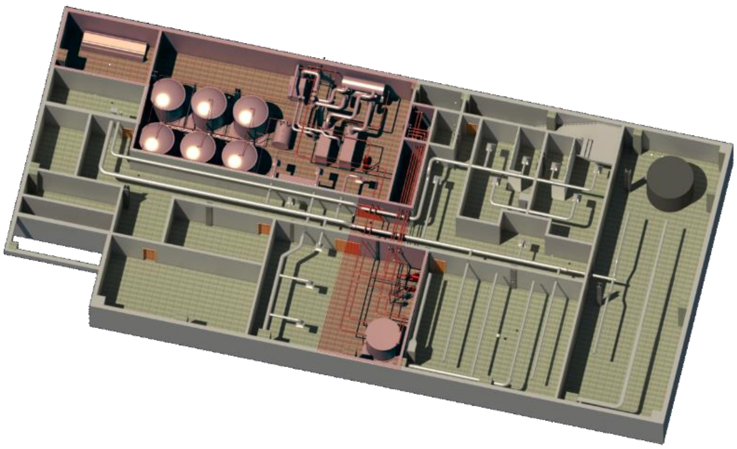

Figure 14. CHP mechanical room layout

Components Needed to Determine Feasibility of CHP at the Growing Power Site

(λ) Thermal to Electric Demand of the Site:
Milwaukee Average Annual λ: ***1.37***

(λ_{CHP}) Thermal to Electric Output of CHP Facility:
Milwaukee IC Engine λ_{CHP}: ***1.32***

(PEUF) Primary Energy Utilization Factor of CHP:
Milwaukee Average Annual $PEUF_{CHP}$: ***0.78***

(PEUF) Primary Energy Utilization Factor of SHP:
Milwaukee Average Annual $PEUF_{SHP}$: ***0.47***

CHP ANALYSIS AND ECONOMIC STUDY

In order to determine the proper size and the feasibility of the CHP facility for the Milwaukee site the yearly thermal load and electrical loads were analyzed. The annual thermal to electric ratio (λ) could be determined and compared the thermal to electric ratio of the CHP system. The duration curve in Figure 15 allowed the TBD mechanical partners to investigate how well an internal combustion engine CHP facility would respond to the λ of the building. In addition, the primary energy utilization factor (PEUF) of the CHP facility was compared to the PEUF of a traditional separate heat and power (SHP) facility to determine how often the CHP facility would outperform the SHP facility. The feasibility analysis shows that The CHP facility for Milwaukee has a higher PEUF than a SHP facility throughout the year and had a similar λ for 40% of the hours throughout the year making the CHP facility a feasible solution in Milwaukee. A study of the carbon dioxide emissions also showed that using the biogas produced from the building, as well as natural gas from the utility, the carbon dioxide emissions created to meet the building demands could be reduced by 86% by consuming less fossil fuels compared to a traditional central power plant.

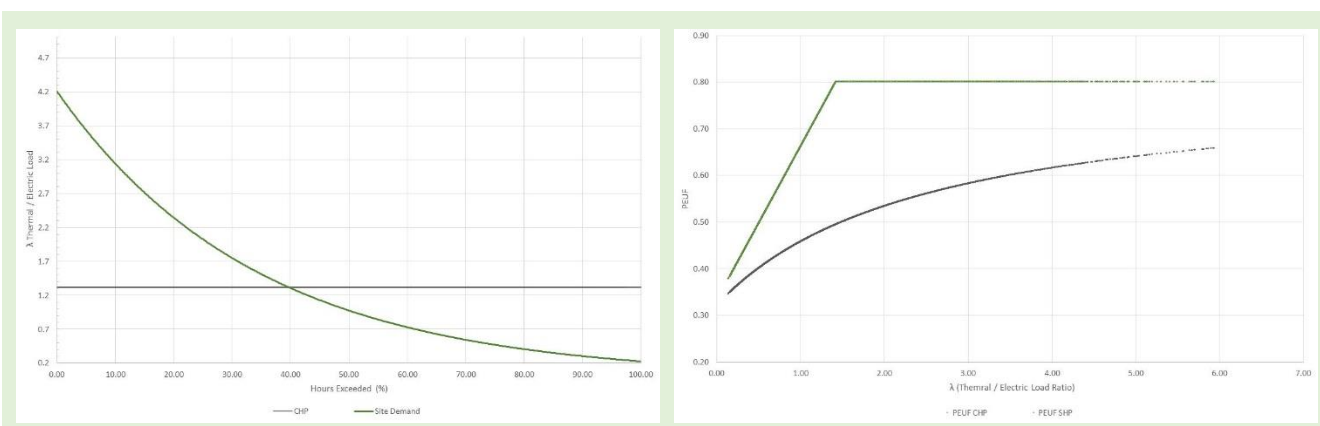

Figure 15. (Left) Duration curve showing the site λ at the Milwaukee facility compared to the λ_{CHP} *of the CHP facility. (Right) PEUF vs. site λ for the CHP and SHP facility.*

Table 3: Emission Reductions from Growing Power CHP

	Unit	lb. CO_2 Produced / Unit	Total CO_2
ft³ of CH_4 / year for CHP	724,153	0.12037	87,166
kWh / year produced at Power Plant	540,763	1.18	638,1000
		% CO_2 Reduction	**86%**

Knowing that the heating and electric demands will differ according to the Growing Power building location, the components used to understand the Milwaukee CHP system should be reinvestigated when site location is changed. The TBD mechanical partners also considered how the CHP system would interact with the rest of the building system and chose systems accordingly. Water source heat pumps were chosen to condition the building due to their ability to utilize the CHP thermal or electrical generation based on climate (p.14)

ECONOMIC STUDY

An economic study was performed in parallel with the CHP feasibility study to ensure that the system selection was economically viable for Growing Power. A spark spread was calculated for the Milwaukee area to determine the difference in electric and gas rates in the area. The spark spread for the on-peak and off-peak hours in Milwaukee are shown in Table 4. The spark spread during on-peak hours suggest a large difference in electric and gas costs and indicates that using natural gas instead of electricity during on-peak hours would benefit the owner. A net present value calculation was also performed to determine the payback on the CHP investment for Growing Power. State and local incentive programs were searched in the Milwaukee area and should be considered at other potential Growing Power sites. The payback period for the Milwaukee CHP facility was 6 years without pursuing the local incentives and 3 years if the Wisconsin incentives were used.

Table 4: Spark Spread Analysis for Milwaukee, WI.

	Electric Rate (Per kWh)	Gas Rate (Per Therm)	Spark Spread
On-Peak (9AM-9PM)	$ 0.08	$ 0.77	$ 15.31
Off-Peak	$ 0.06	$ 0.77	$ 8.80

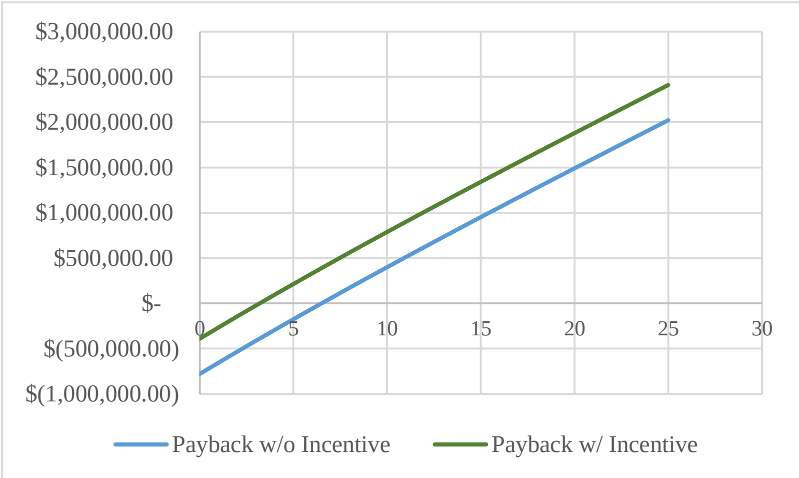

Figure 16. Net present value calculation showing the payback period with and without local Wisconsin incentives.

Based on the feasibility analysis and economic study the CHP facility was determined to be a viable solution for the Milwaukee Growing Power site and a similar analysis would be performed for future sites. Another determinate that ultimately made CHP a viable option for the Milwaukee site was its reduction in environmental impact and its ultimate ability to be used as a community educator in the success vertical farming. CHP also provided the potential for Growing Power to become a greater part of the community network if future communities were designed to utilize the power and heat production of the vertical farm, as well as its food production.

ALTERNATE FUEL SOURCE – SOYBEAN OIL

The future of environmentally friendly building construction relies on a reduced impact on nature through the use of renewable resources and lowering greenhouse gas emissions. Soybean oil biodiesel production is an alternative renewable energy source that can be used by Growing Power in future locations. If the potential future sites of the vertical farm are limited in food waste collection, soybeans may be a reliable source of renewable energy.

An added benefit of soybean oil biodiesel production is its potential reduction in greenhouse gas emissions compared to a gas generator. According to Hill, et. al, biodiesel from soybeans emit approximately half of the greenhouse gases of a comparable gas generator, while using a 90% less pesticides in soybean harvesting than required for corn to create corn grain ethanol.[40]

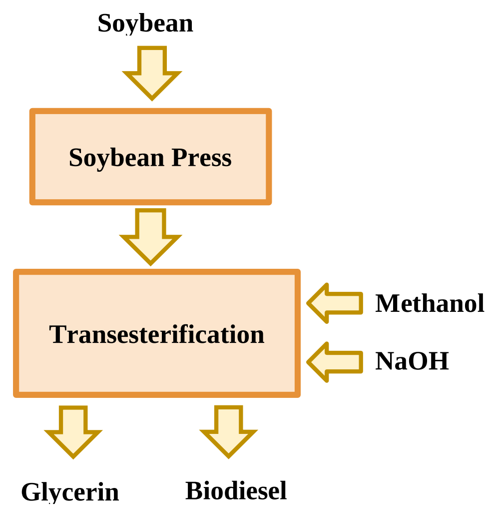

Figure 17. Soybeans can be used as an alternative renewable energy source for the Growing Power Vertical Farm.

Soybeans are cleaned and dried before being converted to soybean oil through a mechanical press. This soybean oil is then processed into biodiesel through transesterification. During transesterification, soybean oil combines with methanol and sodium hydroxide to be converted into biodiesel. The biodiesel can be coupled with a biodiesel generator for CHP use. A co-product of transesterification is glycerin, which is used to create a soybean mush that can be used as fish feed for the aquaponic system. This creates its own renewable of resources consistent with the closed loop design while offsetting operational costs for fish feed. A simplified schematic of the soybean oil biodiesel production process is shown in Figure 17.

This system relies heavily on the availability of soybeans in proximity of the facility. Figure 18, on right, illustrates the availability of soybean per state. Based on this graphic, it can be deduced that a soybean oil biodiesel powered facility may not be feasible in a potential Miami location, while the possibility is much higher for the Midwest. Other factors to consider when looking into this option is cost of soybean and cost of fish feed (SD|12).

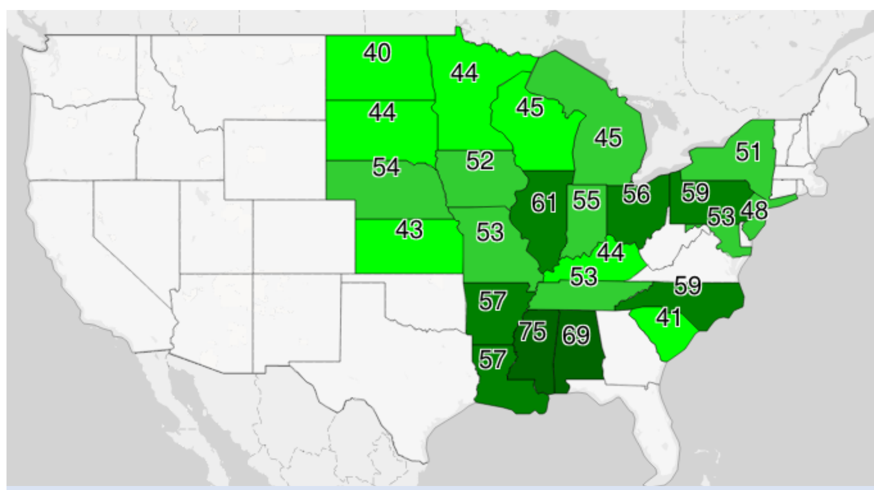

Figure 18. The map above shows the average bushels per acre of soybeans harvested in each state in 2014 courtesy of AgWeb.[9]

BUILDING HVAC

Every mechanical system in a functional building needs to provide a comfortable environment for its occupants, and the Growing Power Vertical Farm facility is no exception. The building relies on a water source heat pump (WSHP) system coupled with a dedicated outdoor air system (DOAS) to condition occupied spaces and provide occupant comfort.

WATER SOURCE HEAT PUMPS

An analysis of mechanical system energy usage was necessary to choose a functional and economically reasonable solution to service the Growing Power Vertical Farm. Using an 8760 hour simulation of building energy usage on Trane TRACE 700, WSHP was compared to an ASHRAE baseline VAV system and determined to meet the thermal comfort conditions of the facility at a lower energy consumption than the baseline by 11%.

WSHPs will provide recirculated heating and cooling to the areas of the building not including the greenhouse spaces. These units can be located near each space, eliminating the need for large mechanical ductwork shafts. With the ability to be oriented vertically or horizontally, the water source heat pumps are easily located within closets and plenums, respectively. Excess heat from the WSHP units will be rejected by an evaporative cooler using variable speed drives to minimize fan energy use.

Building HVAC Overview

Water Source Heat Pumps

Quantity: 25
Energy Savings Compared to ASHRAE VAV Baseline: 11%

Dedicated Outdoor Air Units with Heat Recovery Ventilation

Quantity: 2
Energy Savings: 29%

The WSHP system provides a conditioning mechanism that is reliable and easily maintained. The control sequence for the WSHPs provides consistent conditioning that allows Growing Power to focus on its goals of sustainable farming and education without the need to worry about maintenance. In addition, the WSHP utilizes reverse return piping to eliminate the need for balancing valves.

The system selection also allows the building to be decoupled from a central system. Traditional centralized systems may require the entire HVAC system to be shut down during maintenance, whereas this decoupled system allows other parts of the building to remain in operation while one unit is being maintained.

INTEGRATED SOLUTION: DESIGN COORDINATION

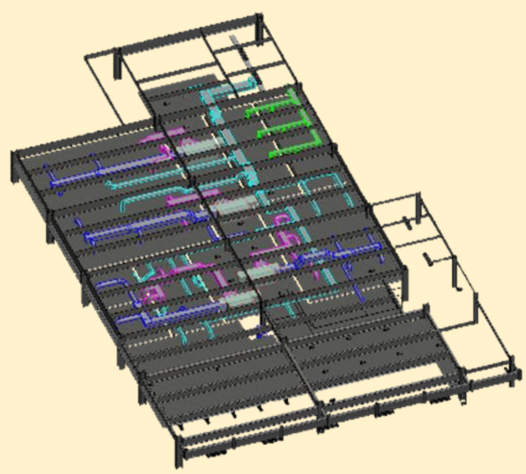

Figure 19. Level 3 3D coordination view

The mechanical design partners worked with the structural design partners early on in the design process to avoid coordination issues in the field. Figure 19 on left is a Revit 3D coordination view of the 3rd level of the Growing Power Vertical Farm facility (CM|SD|8).

The choice to use WSHP allowed the mechanical design to fit within the budget allotted for this project. Choosing a more economical technology such as WSHPs for HVAC allows the budget to focus on more critical design elements such as greenhouse spaces and combined heat and power (CM|6).

For higher heating demands, particularly those seen in Milwaukee, the WSHPs obtain reject heat from the CHP system. Using the waste heat from the CHP allows the design to recycle products created within the vertical farm and reinforces the closed-loop design which makes a vertical farm successful. The electrical generation from the CHP helps meet compressor and fan loads in the building.

DEDICATED OUTDOOR AIR SYSTEM

The WSHPs work in conjunction with two dedicated outdoor air systems (DOAS) that provide the minimum outdoor air required for each space as specified by ASHRAE Standard 62.1. Decoupling the outdoor air from recirculated air minimizes ductwork sizes used throughout the building. The DOAS units each feature a heat recovery wheel to lower the energy required to condition air entering from the outside. Implementing a heat recovery wheel saved 29% of energy in the Milwaukee site as compared to a DOAS unit without heat recovery. Humid climates like Miami could also utilize CHP heat with a desicant wheel for more energy savings. Figure 20, on right, shows the DOAS units located in the auxiliary mechanical rooms on the 2nd and 4th levels.

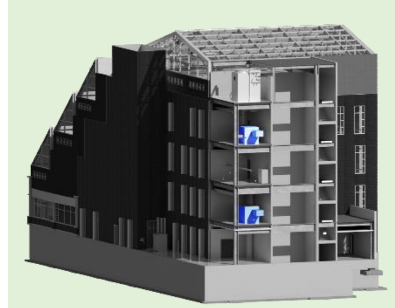

Figure 20. The DOAS units, highlighted in blue, are located on the 2nd and 4th levels.

CONCLUSION

Humans put a large strain on natural resources both out of necessity (to eat) and out of carelessness (landfills). An increase in population indicates that more land must be allotted for food production to meet a growing demand for food.[(17)] The solution to meeting the food demand of a growing population while limiting the area of land taken to construct buildings is the vertical farm.

A thorough investigation into vertical farming led to the conclusion that the success of the vertical farm relies on a constant recycling of materials and resources. The mechanical design of the new Growing Power Vertical Farm Facility in Milwaukee utilizes closed loops in order to provide Growing Power the opportunity to reach its goal of educating and providing the community with healthy, accessible food sources using sustainable farming techniques.

The Growing Power Vertical Farm Facility in Milwaukee is a prominent 5-story building that features four levels of growing space each housing 100% self-sustaining closed water loop aquaponic growing systems. Through the use of anaerobic digestion of food waste to produce methane to fuel an on-site CHP facility, the vertical farm successfully generates heat and electricity for the building without distribution losses from purchasing from separate plants. Therefore the CHP facility operates with a PEUF value which is 1.66 times better than that of a separated system.

Using food waste as an input to the CHP plant closes the energy loop by implementing a resource which is produced by man, digested or wasted by man, and then used once again to produce more food at the vertical farm. Growing Power's CHP plant allows it to become a community leader in power generation, food production and waste management in future communities. The anaerobic digestion process can be implemented at future Growing Power sites as long as the food waste is available for collection surrounding the new site. Coupling the anaerobic digester with CHP use reduces the emissions of the building by 86%.

The Growing Power vertical farm facility implements a building HVAC system compatible with CHP such that waste heat supplements the heating load for the water source heat pump units throughout the building. In addition, waste heat is sent to the heat recovery wheel of the DOAS units so that minimum ventilation air can be met without a hefty cost to heat incoming outside air.

The new Growing Power Vertical Farm Facility is a large step in facilitating Growing Power's vision of healthy, food-plenty communities. The careful integration of mechanical systems within the building with special considerations given to location flexibility and energy conservation led to a building that gives Growing Power the "growing power" to become a beacon for healthy and accessible food sources.