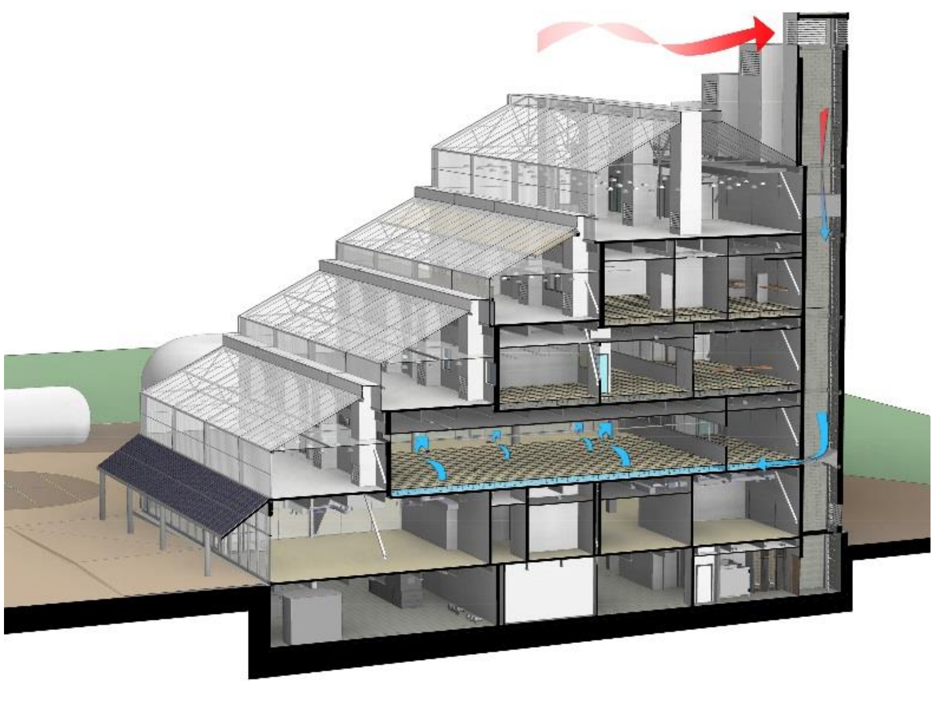
Synthesis
Engineering for Architecture

AEI STUDENT DESIGN COMPETITION

Mechanical Report

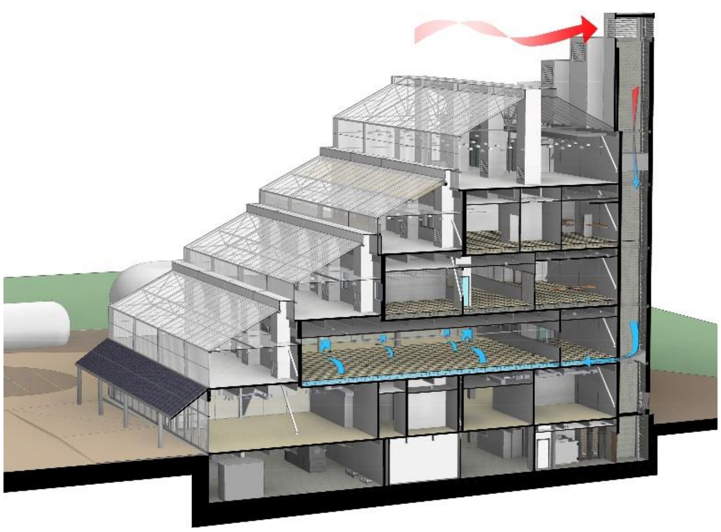


2-11-2015

ARCHITECTURAL ENGINEERING INSTITUTE

Table of Contents

Narrative



Supporting Documentation

Drawings

Executive Summary

The Synthesis Mechanical Team addressed the AEI Student Design Competition Challenges while following the given guidelines for the project. The Mechanical Team Submittal includes a summary narrative, supporting documentation, and mechanical drawings. The Mechanical Team emphasized a design that aligned with the overall project goals:

1. **Educational:** To engineer mechanical systems that create a comfortable and acoustically sound working and learning environment.
2. **Ecological:** To create closed loop systems to minimize energy use, water consumption, waste, and emissions for both the Growing Power site and Milwaukee community.
3. **Adaptable:** To design mechanical systems that are easily adjustable to changing building conditions, emerging technologies, geographical locations, and microclimates.

Food Waste to Energy

Food waste is delivered to a plug-flow mesophilic anaerobic digester resulting in the production of usable biogas which is combusted in a 200 kW microturbine. Liquid and solid fertilizer are also produced and harvested for composting nutrient rich soil.

Quad-Generation

Combustion in the 200kW microturbine results in the co-production of:

1. **Electricity**
2. **Heating** - Exhaust heat is transferred to an exhaust gas heat exchanger to produce hot water used for heating
3. **Cooling** – A 60 ton single-effect absorption chiller that provides 40°F chilled water for comfort cooling of the non-greenhouse spaces.
4. **Carbon Dioxide** – CO_2 is delivered to the greenhouses to maximize plant growth

Hybrid Condenser Water System

An open loop geothermal heat rejection system is designed to take advantage of 47°F groundwater in Milwaukee. Groundwater is pumped from the aquifer below the site and is passed through a water-to-water plate and frame heat exchanger used to separate the groundwater from the closed condenser water loop creating 50°F condenser water. The condenser water is used to cool the greenhouses and to supply water to chilled beams while rejecting heat from the absorption chiller.

Greenhouses

The greenhouse design transitioned from an open, ventilated greenhouse to a closed greenhouse which provides the following advantages:

1. **Reduced water usage**
2. **Increased CO_2 concentration**
3. **Pest control**
4. **Temperature and humidity control**

Cooling - Each greenhouse is comprised of six modules with a shaft containing a cooling coil on the northern wall. The greenhouses are cooled by natural buoyancy forces that allow the air to move throughout the greenhouse and back into the shaft where it is then cooled.

Heating - Hot water aluminum fin tubes are placed along the perimeter of each greenhouse to minimize envelope loads and create a homogenous growing environment.

Water Usage

Rainwater and water transpired from plants is collected and reused as greywater. The Vertical Farm uses on average 112 gallons of potable water per day, 60% less than an average single family home in Wisconsin.

Natural HVAC

A natural HVAC system supplies conditioned 100% outdoor air to the non-growing spaces on floors two through four, 365 days a year, without the use of fans. This is accomplished through downdraft cooling and updraft heating. Airflow is driven by the wind, sun, and thermal buoyancy forces. Each floor has its own dedicated supply air shaft capable of providing both heating and cooling. The shafts direct air into an underfloor plenum to which is distributed to occupied zones. A solar chimney relieves air from each floor.

First Floor System

A 100% outdoor air handling unit with heat recovery will condition the first floor to eliminate contaminants produced from the market and processing spaces.

Results

The mechanical system design of the Growing Power Vertical Farm resulted in:

100% Energy Reduction

98% Potable Water Reduction

99% Emissions Reduction

100% Outdoor Air

1.0 Project Introduction

The 2015 AEI Student Design Competition addresses a five story vertical farm that is being designed and constructed for a local nonprofit organization, Growing Power, Inc. The building is located at 5500 W Silver Spring Drive, Milwaukee, Wisconsin. The vertical farm is created using a tiered greenhouse approach on the southern façade of the building. Each floor steps back and utilizes the available southern light in order to house aquaponic systems and grow crops which are used to sell to the surrounding neighborhoods in the retail market on the ground floor. Aside from the year round production of fruits, vegetables and fish, the facility houses classrooms, conference spaces, and a demonstration kitchen designed to further Growing Power's expanding mission to become a local and national resource for learning about sustainable urban food production.

2.0 Project Goals

The Mechanical Team emphasized engineering systems and spaces that are not only functional, but also align with the project's overall shared goals:

Educational

Synthesis is committed to engineering mechanical systems that create a comfortable and acoustically sound working and learning environment.

Ecological

Synthesis strived to create closed loop systems to minimize energy use, water consumption, waste, and emissions for both the Growing Power site and Milwaukee community.

Adaptable

Strong emphasis has been placed on designing mechanical systems that are easily adjustable to changing building conditions, emerging technologies, geographical locations, and microclimates.

3.0 Integration

At the beginning of the design process, the construction, structural, electrical, and mechanical engineers all came together to explore engineering solutions that would best meet the overall project goals and enhance the original architecture. The team realized that the best way to meet the overall project goals was for not only the engineering systems to enhance the architecture, but for the architecture to enhance the engineering systems. Therefore, Synthesis decided it was best to modify the original architecture to meet the overall project goals.

The Mechanical Team played an integral part in redesigning the architecture and creating modular construction solutions that benefited Growing Power as a whole. The architecture of the Vertical Farm was optimized to benefit the design of all systems creating an efficient prototype building capable of adapting to various geographical locations and microclimates.

The use of BIM software, such as Revit and IES VE, provided coordination needed between each team in order to properly design an energy efficient building that addressed the challenges proposed to Synthesis.

4.0 Climatic Conditions

Milwaukee, Wisconsin is located in climate zone 6 and Miami, Florida is located in climate zone 1.[1] The climate of Milwaukee, Wisconsin consists of warm and muggy temperatures during the cooling season and moderate winters which dominate the majority of the year. The warmest month of the year is July and coldest is January. See **[Appendix B]** for a detailed analysis of the climatic conditions for Milwaukee and Miami.

4.1 Wind Speed & Direction

The predominant wind in Milwaukee comes from the northwest averaging a speed of 13.15 mph. The Mechanical Team took advantage of the direction and speed when designing the mechanical systems for the Vertical Farm. Figure M2 below displays a wind rose for the Milwaukee building site.

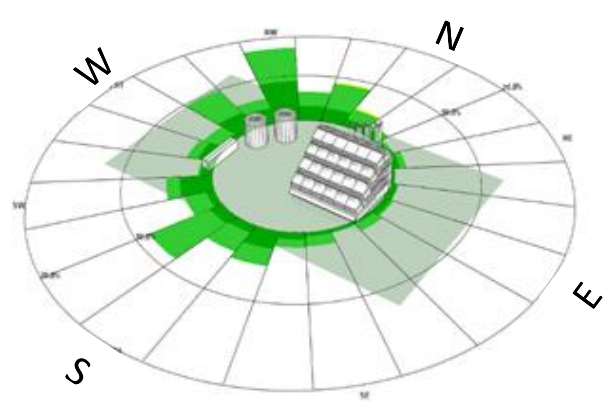


FIGURE M1: WIND ROSE FOR MILWAUKEE BUILDING SITE

4.2 Outdoor Design Conditions

The outdoor design conditions for Milwaukee, WI are prescribed using the Wisconsin Energy Conservation Code. These conditions are significantly more stringent than the climatic design conditions given in the 2013 ASHRAE Handbook of Fundamentals. These extreme conditions result in oversized mechanical systems for the Vertical Farm in Milwaukee. The ASHRAE climatic design information was used to determine the design conditions for Miami, FL. Note that the cooling design conditions for Milwaukee and Miami are nearly identical. Table M1 shows the outdoor design conditions used for load calculations and equipment sizing.

TABLE M1: OUTDOOR TEMPERATURE DESIGN CONDITIONS

Design Conditions		Milwaukee	Miami
Cooling	DB [°F]	89	90.7
	WB [°F]	77	77.4
Heating	DB [°F]	-10	50.5

5.0 Food Waste to Energy

Growing Power is an ecosystem within the community. They currently import local food waste for composting soil and fertilizer. In the competition project documents, it was expressed that Growing Power wanted to mimic the natural cycle of food production, using food waste as a fuel source for onsite energy production. This energy is directly used to power the Vertical Farm and existing greenhouses, ultimately providing the community with food. This establishes Growing Power as an integral part of the local ecosystem. Food waste is collected from Growing Power's existing operations and from other resources around the community, such as universities, farms, and local businesses. Tipping fees that are assessed and charged by Growing Power will be less than the local landfill in order to provide a financial incentive for local businesses to participate.

To convert food waste to energy, the mechanical team selected a plug-flow anaerobic digester. This system utilizes a constant inflow of food waste to produce a constant outflow of biogas, which is comprised of approximately 65% methane and 35% CO_2. Fourteen tons of food waste will be delivered to the site daily. This amount is equivalent to the contents of one full garbage truck. The truck unloads the food waste into a solids grinder where the food is broken down and sent to a holding pit. A conveyer belt system delivers this waste into the main digester at a constant rate. A mesophilic digestion process (86°F-100°F) is used over a thermophilic process because of its ability to produce a steady biogas concentration over a long period of solids residence time. The thermophilic process is not recommended in food waste applications due to the high amounts of protein and ammonia produced which will cause damage to the digester. The main digester uses four processes to convert the food waste into biogas, solid, and liquid fertilizer:

1. *Hydrolysis*: Food waste broken down into simple sugars
2. *Acidogenesis*: Remaining components broken down by acidogenic bacteria
3. *Acetogenesis*: Acetic acid, carbon dioxide, and hydrogen are produced by acetogens
4. *Methanogenesis*: Methane, carbon dioxide, and water are produced

The digester produces 2.2 million BTU/hr of biogas that is combusted in a 200 kW microturbine located in the basement of the building. The liquid fertilizer is sent to two second stage digesters where additional biogas is produced and stored. The excess fertilizer (combination of solid and liquid) is harvested for composting nutrient rich soil at existing Growing Power sites and is sold to the local community. This process is shown in Figure M3 on the following page. The size of the digester was governed by the minimum size required to produce biogas at a steady, reliable rate. Eisenmann was used as the basis of design due to their experience in small scale anaerobic digesters located in North America.[2] The digester selected is identical to an installation in Chicago. Therefore, the food input and biogas output numbers are based on real-world operational data, rather than idealized mathematical calculations. The anaerobic digester is located outside of the building due to its physical size and large ventilation rates that would be required if placed indoors. The main and second stage anaerobic digesters cover a total area of 3,600 square feet and are in an accessible area for trucks to pull in and unload food waste as shown in Figure M2.

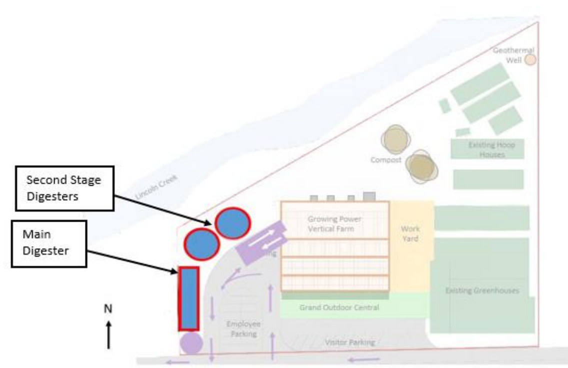


FIGURE M2: SITE LOCATION OF ANAEROBIC DIGESTER

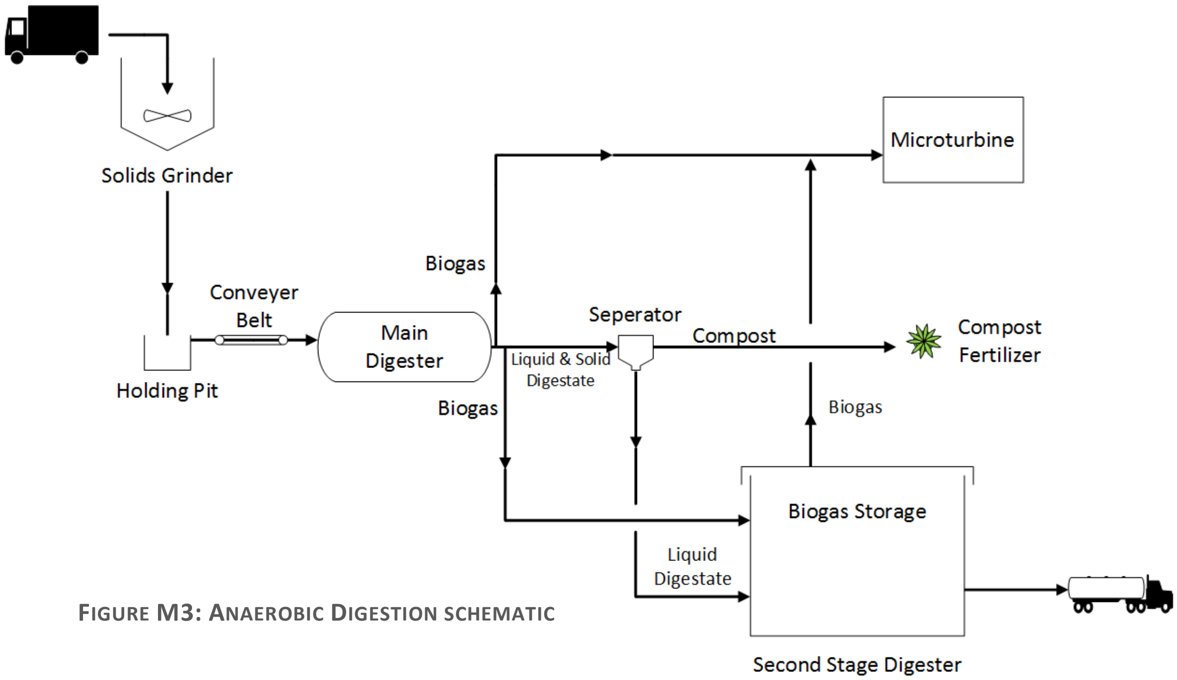


FIGURE M3: ANAEROBIC DIGESTION SCHEMATIC

6.0 Quad-Generation

The biogas produced from anaerobic digestion is pretreated **[Appendix C]** then combusted in a 200 kW microturbine resulting in the co-production of:

1. Electricity
2. Heating
3. Cooling
4. Carbon Dioxide

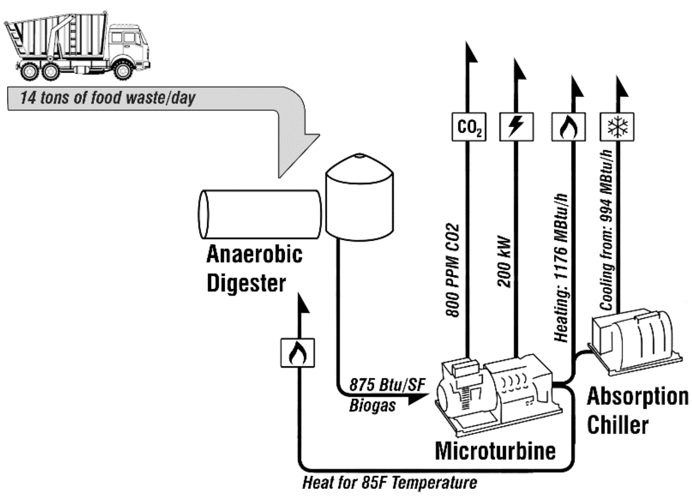


FIGURE M4: QUAD-GENERATION OVERVIEW

A microturbine was selected over an internal combustion engine to handle these processes due to the relatively low heating and electrical loads in the building, its ultra-low emissions, and ability to accept the high H_2S content of biogas.[2] The unit contains only one moving part, resulting in minimal maintenance. A summary of the microturbine output data is shown in **Table M2**:

TABLE M2: MICROTURBINE SUMMARY DATA

Microturbine Output				
Electrical Power [kW]	Exhaust Gas Flow [lb/s]	Exhaust Gas Temperature [F]	Exhaust Energy [MBH]	NOx Emissions [ppmvd]
200	2.9	535	1350	< 9.0

The quad-generation plant is sized and operated differently than a standard CHP plant due to its use of biogas. The anaerobic digester will produce biogas at a constant rate throughout the year. Therefore, the microturbine will run continuously rather than cycling to meet the heating or electrical demand. This operating strategy will result in excess electrical and thermal energy at times. The excess electrical energy will be sold to the grid for a profit, and the excess thermal energy will be released into the atmosphere in the form of turbine exhaust gases. It is important to note that this excess release of exhaust gases does not contribute to global warming. The CO_2 contained in food waste and consequently, biogas, is a part of the carbon cycle, and would be released naturally as the waste decomposes if it were not combusted.

6.1 Electricity

The microturbine initially delivers 250 kVA at 480Y/277V to the building's main switchgear, which parallels with the WE Energies (Wisconsin Electric, local utility) power grid to allow for excess electricity to be sold back to the grid, or needed supplemental electricity to be drawn from it. The electricity produced by the microturbine will power both the new Vertical Farm, and the existing greenhouse structures. A detailed breakdown of electrical consumption by end use can be found in **section 11.0**.

6.2 Heating

The microturbine produces 1350 MBH of exhaust heat which is transferred to a hot water loop by an exhaust gas heat exchanger with an effectiveness of 0.6. This results in a usable heat output of 810 MBH. A heat exchanger bypass is provided for the exhaust gases to prevent water from flashing into steam, creating explosive pressures during periods of low flow. The hot water loop is heated to 180°F to be used for comfort heating, domestic hot water, digester heating, and as a heat source for an absorption chiller. A supplemental 250 MBH boiler is included to help meet peak loads and provide redundancy for the greenhouse spaces.

6.3 Cooling

The hot water loop will provide the heat source for a 60 ton single-effect absorption chiller. The use of an absorption chiller allows Growing Power to utilize excess heat from the microturbine during the cooling season to drive the refrigeration process, thus eliminating the electrical usage associated with a compressor. This absorption chiller will produce a lower than typical supply temperature of 40°F chilled water in order to reduce airside pressure drops for the natural HVAC system. Heat is rejected from the absorption chiller to an open loop geothermal system discussed in **section 7.0**.

6.4 Carbon Dioxide

Carbon dioxide is vital for plant growth and production in the photosynthetic process. Plants require carbon dioxide as humans require oxygen. The carbon dioxide concentration in the atmosphere ranges from 350-400 ppm. By artificially raising the CO_2 concentration around plants to 1000 ppm, crop outputs increase by 40%.[3] This concept was applied to the Vertical Farm greenhouses by utilizing the carbon dioxide produced from the microturbine.

Microturbines offer ultra-low emissions of CO, NOx and hydrocarbons when compared with gas engine CHP units. Additional oxidation and selective catalytic reduction (SCR) catalysts are placed downstream of the turbine to further reduce CO and NOx levels by 90%.[4] The nearly pure CO_2 is then then passed through the exhaust gas heat exchanger where it is cooled from 535°F to 135°F, making it suitable for supply to the greenhouses. The Vertical Farm produces a total of 91 tons per year of carbon dioxide compared to a baseline total of 1,280 tons per year, reducing the total carbon emissions by **99%.** Baseline emissions were calculated using EPA eGrid. Proposed emissions were calculated using manufacturer's data. An emissions summary is shown in Figure M4.

7.0 Hybrid Condenser Water System

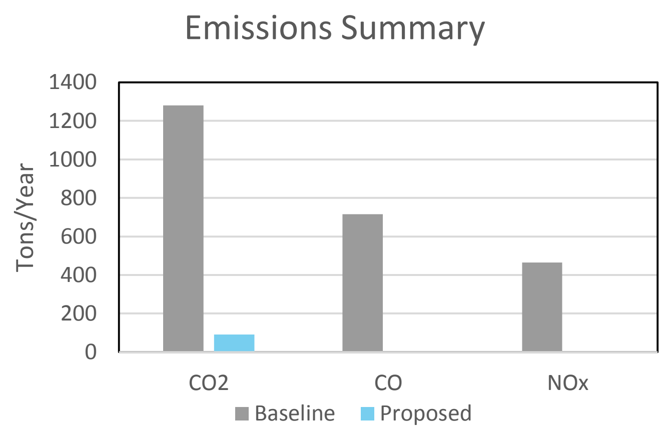


FIGURE M4: MICROTURBINE EMISSIONS SUMMARY

To coincide with the goals of reducing potable water usage, and creating an energy efficient building, the Mechanical Team designed an open loop geothermal heat rejection system to take advantage of the cold and plentiful groundwater in Milwaukee. A groundwater well will be located in the Northeast corner of the site. This location was dictated based on the required distances a well must be located from potential contaminants as prescribed in Chapter NR 812 of the Wisconsin Administrative Code. See **[Appendix D]** for more detail. A maximum of 450 gallons per minute will be pumped from the aquifer below the site and passed through a water-to-water plate and frame heat exchanger located in the basement of the building. A heat exchanger is used to separate the groundwater from the condenser water loop, in order to eliminate potential issues caused by the chemistry of the groundwater. It is important to note that 450 GPM will only be needed if every room in the building is fully occupied during the peak cooling

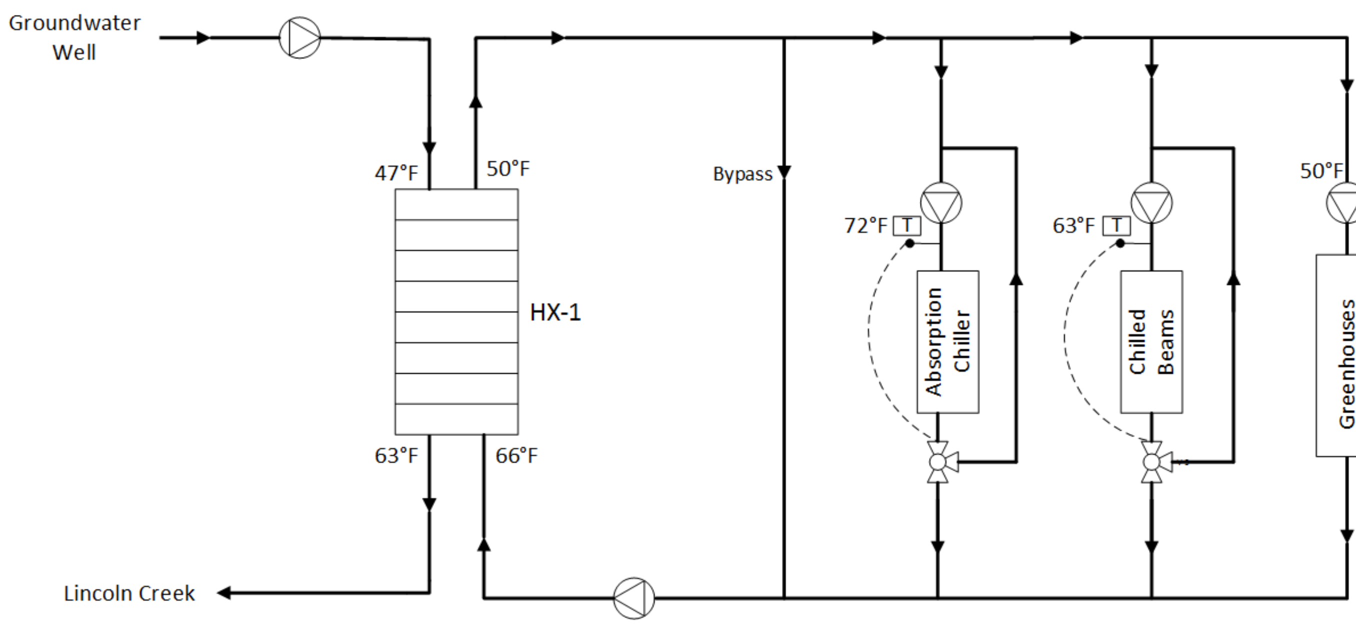


FIGURE M5: HYBRID CONDENSER WATER SCHEMATIC

day of the year while the greenhouse shades are not drawn. There are currently 70 groundwater wells in Milwaukee County pumping more than this maximum flow rate.

After passing through the heat exchanger, the groundwater will be rejected to Lincoln Creek located adjacent to the site. Lincoln Creek is classified as a "Warm Headwaters," and is not considered a "Trout Stream."[5] An EPA Permit will be required to reject water to the Creek, where it will ultimately flow to Lake Michigan. According to the EPA, the temperature of groundwater in Milwaukee is 47°F, which is far below typical condenser water temperatures. The Mechanical Team saw this low temperature as an opportunity to create a hybrid condenser water system capable of cooling spaces, while simultaneously rejecting heat from the absorption chiller.

The heat exchanger was designed with an approach of 3°F in order to create a 50°F condenser water supply temperature to be used for cooling. The condenser water is distributed to cooling coils located inside the greenhouses and to chilled beams located on floors two through four. A primary/distributed secondary condenser water pumping scheme is used due to the varying load profiles of the three end uses. The absorption chiller and chilled beams are capable of accepting minimum supply temperatures of 72°F and 63°F (to prevent condensation), respectively. A three way diverting valve is used to mix the leaving water with the 50°F supply water to maintain the minimum entering temperatures. **Figure M5** above displays the primary/secondary pumping distribution scheme of the condenser water system.

8.0 Greenhouse Design

In order to create a greenhouse which optimizes plant growth, Synthesis first gained an understanding of photosynthesis and plant physiology down to the cell level. Knowledge of how plants grow and develop allowed Synthesis to critically examine the complex and changeable relationship between plants and their environment. This research allowed the team to compile an interdisciplinary matrix of design criteria for optimal growing conditions. See **[Electrical Supporting Documents: Appendix B].** The team studied successful greenhouse concepts used in various regions of the world. Combining these solutions, Synthesis developed a single greenhouse design capable of functioning efficiently and effectively in multiple climates. This final design is shown below.

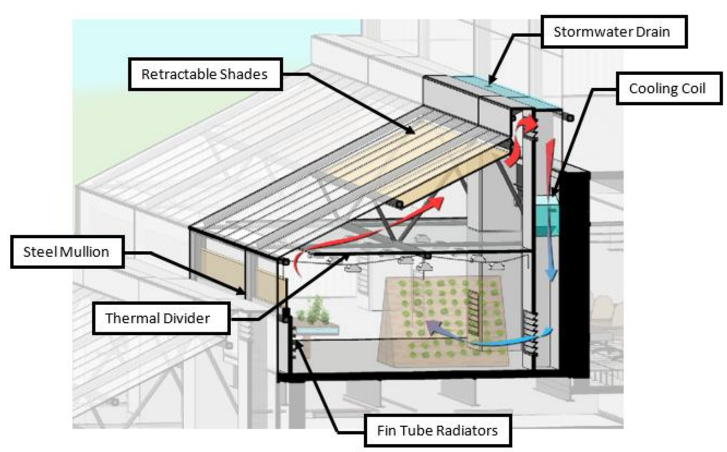


FIGURE M6: SECTION OF GREENHOUSE MODULE

A detailed explanation of the transition from the original greenhouses to the Synthesis greenhouses can be found in **[Appendix E]**.

The primary change from the original greenhouses to the Synthesis greenhouse is the transition from an open, ventilated greenhouse to a closed greenhouse. This concept provides four advantages:

1. ***Reduced water usage*** – Plants continually transpire and lose water to the atmosphere. A closed greenhouse design prevents water from escaping and allows for the collection of all condensation produced.
2. ***Increased CO_2 concentration*** - Enriched CO_2 concentrations can be maintained in a closed greenhouse.
3. ***Pest control*** – Pests are major sources of plant diseases. The closed greenhouse prevents them from entering, thus eliminating the need for pesticides.
4. ***Temperature and humidity control*** – Greenhouses are normally cooled through ventilation and evaporation. This presents a problem for hot and humid climates such as Miami where there is minimal potential for evaporative cooling. A closed greenhouse allows temperature and humidity set points to be maintained irrespective of outdoor conditions.

The Vertical Farm greenhouses will be maintained at a maximum temperature of 85°F, 90% relative humidity in the cooling season and at a minimum of 70°F in the heating season. This temperature range optimizes plant growth while providing a comfortable environment for students, visitors, and employees.[6] Table M3 below summarizes the interior design set points for the greenhouses.

TABLE M3: GREENHOUSE DESIGN SET POINTS

Greenhouse Set points		
Summer Cooling	T_{DB} [F]	85
	RH [%]	90
Winter Heating	T_{DB} [F]	70

The Vertical Farm utilizes the entire Southern façade for greenhouse space, with four stories of tiered greenhouses climbing up the stepped face of the building. Each tier is considered one greenhouse. Each greenhouse is comprised of six modules. A modular approach was used to improve constructability and adaptability. Although this report focuses on the mechanical design of the greenhouse, it is important to understand the components of the modular greenhouse design. This system is explained in significant detail in the **[Drawing M105]**.

8.1 Glazing

The glazing for the greenhouses consists of double-pane polycarbonate panels. Polycarbonate was selected over glass due to its light weight and durability. In order to minimize the solar gain and maximize the amount of PAR (Photosynthetically Active Radiation) light transmittance, the Mechanical and Electrical Teams selected the type of polycarbonate that provided a balance between the thermal and PAR properties. Further detail on the glazing selection process can be found in the **[Electrical Narrative: Section 5.2]**. Table M4 below summarizes the thermal properties of the polycarbonate glazing.

TABLE M4: POLYCARBONATE PROPERTIES

Polycarbonate Glazing Thermal Properties	
U-Value	SHGC
0.40	0.42

8.2 Shading Devices

Each module contains a shading device on its southern vertical wall, and sloped roof. The shades are used to reduce cooling loads and ensure plants are receiving the correct amount of light. The devices are composed of alternating aluminum strips with polyester fabric in a woven structure that creates excellent light shading, and diffusing properties. The aluminum strips reflect infrared light out during the day and back into the greenhouse at night, helping to both heat and cool the space.

The shading coefficient and U-value of the shades are 0.6 and 1.72, respectively. The use of the shades results in a 58% decrease in solar gain for a typical summer day as shown in Figure M7.

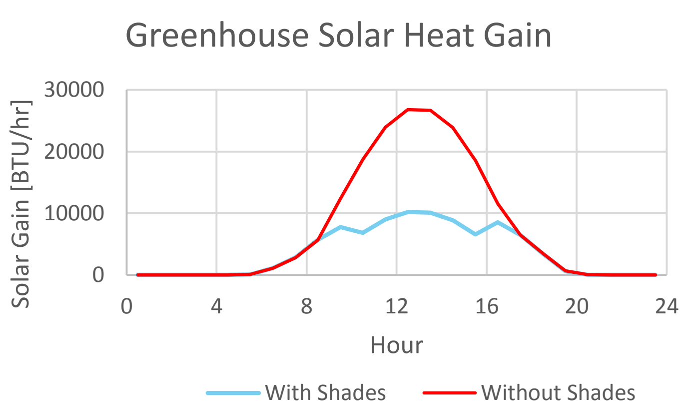


FIGURE M7: GREENHOUSE SOLAR HEAT GAIN

8.3 Cooling

A horizontal sheet of clear polycarbonate divides the greenhouse module into two thermal zones. Temperature and humidity will be controlled in the lower zone, where plants will reside. A 2' gap in the southernmost portion of the thermal divider allows warm air to make its way into the upper, stratified zone. A 4'x1' shaft containing a heat exchanger is located at the northern end of each module and is open to both thermal zones. When the temperature in the lower zone exceeds 85°F or 90% relative humidity, the 50°F condenser water will flow through the heat exchanger, inducing a downdraft effect. The cooled, dense air will travel down the shaft due to thermal buoyancy, and condition the lower zone.

The purpose of the thermal divider is to eliminate a short circuit between the upper inlet and lower outlet of the shaft. It forces the air to travel across the space before rising into the stratified zone, creating a homogenous greenhouse environment in the lower zone. As the air gains heat in the greenhouse, it rises and enters at the top of the shaft. This cycle of air continues without the use of natural ventilation.

The closed greenhouse design required the Mechanical Team to consider a greenhouse component typically overlooked: transpiration. Transpiration is the process by which moisture is carried through plants from roots to small pores on the underside of leaves, where it changes to vapor and is released to the atmosphere.[7] In a standard ventilated greenhouse, water vapor transpired by plants is simply exhausted out to the atmosphere; however in the Synthesis greenhouse, the cooling system must handle the resultant latent load.

A process developed by Dr. Cecilia Stanghellini[8] was used to quantify the amount of transpiration in the greenhouses. The equation used is shown below. Additional detail can be found in **[Appendix G].**

$$E = \frac{\varepsilon r_b[0.86(1-\exp(-0.7LAI))I_{rad}]+2LAI(\chi_{in}^{*}-\chi_{in})}{(1+\varepsilon)R_b+[82\frac{\frac{0.86(1-\exp(-0.7LAI))I_{rad}}{2LAI}+4.3}{\frac{0.86(1-\exp(-0.7LAI))I_{rad}}{2LAI}+5.4}[1+0.023(T_{in}-24.5)^2]]}$$

FIGURE M8: TRANSPIRATION EQUATION

Important variables in this equation include the leaf area index, stomatal and leaf resistances, and amount of irradiance from the sun. The leaf area index describes the total amount of area that leaves of each plant make up over the total area of useful growing space. This number was assumed to be relatively large due to the density of Growing Power greenhouses. The latent heat of vaporization required for the transpiration to occur is taken from the greenhouse environment, resulting in sensible cooling. In theory, the latent gain should be equivalent to the sensible cooling; however, to be conservative, the sensible cooling was estimated to be 80% of the latent gain.

Multi-zone bulk airflow computer modeling was used to design and evaluate the performance of the natural cooling system. It was found, through extensive modeling that a 4'x1' shaft cooling air to 65 degrees was capable of providing the cooling and dehumidification required to meet the greenhouse set points in both Milwaukee and Miami. The model is further described in **[Appendix F].**

As plants transpire, the humidity of the air adjacent to the surface of the leaf rises. Without air movement the humidity will continue to rise until the plant can no longer transpire, resulting in stunted growth and disease. Additionally, plants absorb CO_2 from their environment as a part of the photosynthetic process. Without air movement, they will deplete the supply of CO_2 adjacent to the surfaces of their leaves, resulting in similar consequences. Therefore, when the cooling system is not in use, 1/8 horsepower circulation fans in each module will be turned on.

8.4 Heating

During winter months, the 2' gap between the upper and lower thermal zones will be closed using a hinged piece of polycarbonate. Additionally, the inlet and outlet of the heat exchanger shaft will be closed. These measures will reduce the volume of space that must be heated and hinder warm air from rising into the upper, stratified zone.

The greenhouses will be heated using hot water aluminum fin tubes that will be placed along the southern wall of each greenhouse module, and the outer walls of the exterior modules. Heat is provided along the envelope rather than adjacent to the plants in order to offset envelope loads and create a homogenous environment suitable for vertical farming.

The use of grow lighting results in the plants receiving a relatively constant level of irradiance throughout the year. Therefore, the amount of transpiration and resulting sensible cooling during winter months will be similar to warmer months. In the winter, the latent heat of vaporization from the transpiration will be released as the water vapor condenses on the mullions and exterior polycarbonate panels. A portion of the released heat will help to sensibly heat the greenhouse; however, to be conservative, this effect was not included in the heating load calculation or energy model.

Hot water at 180°F supply circulates through galvanized steel piping that runs to each convector. The heating capacity provided by the fin tubes has been oversized to allow greenhouse operators to adjust the set point temperature based on the type of plants being grown and the particular stage of growth.

8.5 CO_2 Concentration Level

The closed greenhouse design provides the opportunity to create a CO_2 enriched environment to increase plant production by up to 40%. A concentration of 1000 ppm is maintained as plants in each greenhouse intake a CO_2 rate of 2 lbm/hr. The microturbine produces a total of 125 lbm/hr of CO_2 and therefore only needs to supply a small portion to the greenhouses. See **[Appendix H]** for a calculation of the total CO_2 concentration that the greenhouses intake hourly.

CO_2 sensors in each greenhouse determine when enrichment will be provided. CO and NOx detectors monitor the flue gas concentrations and divert the exhaust gases to the atmosphere if concentrations fall above the OSHA 8 hour exposure limit.[9] The microturbine in conjunction with the downstream catalysts produce emissions well below the concentration limit, as shown in **Table M5.**

TABLE M5: MICROTURBINE EXHAUST GAS EMISSIONS

Gas	Microturbine Emissions [ppm]	Concentration Limit [ppm]
CO	13	50
NO	1	25
H_2S	7	10

8.6 Water Usage

The closed greenhouse design allows water that is transpired by the plants to be captured and reused. Since the greenhouse heating and cooling systems create a homogenous thermal environment, condensation will first occur on the coldest surface of the greenhouse. During the summer, that surface is the heat exchanger. Drip pans within the shaft will be used to collect the condensate. During the winter, the exterior polycarbonate assembly will be the coldest surface. Since the exterior polycarbonate represents a large surface, the mechanical team sought a way to localize where condensation will occur. Through collaboration with the structural engineers, a system of two different mullion types was implemented. Each module will contain a steel "cold bridge" mullion in both the upper and lower thermal zones. The temperature of the mullion will be far below the temperature of the interior surface of the polycarbonate; therefore, condensation will first occur on the mullion, where it can be easily collected. Studies on closed greenhouses in Europe have found that approximately 80% of the water transpired by plants can be recollected as condensate.[10] The remaining 20% is retained by plants once they are harvested, or lost through air leakage.

Once collected, the condensate is distributed via gravity to a 4,500 gallon water storage tank located in the basement. The tank also receives water via rainwater collection and the sump pump as shown in **Figure M9.** The water storage tank is used to provide water for plants and flush toilets. If the tank is full, water will be diverted to the storm water drain.

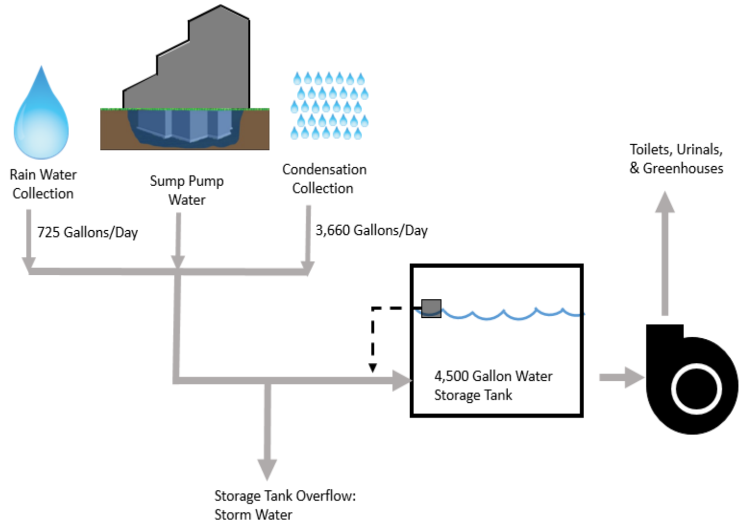


FIGURE M9: WATER COLLECTION OVERVIEW

The Vertical Farm will use approximately 5065 gallons/day, 97.77% of which is used for greenhouse irrigation and flushing toilets and urinals. The water required for greenhouse irrigation was estimated at 0.4 gallons/ft^2/day.[11] By utilizing greywater and selecting efficient fixtures, the Mechanical Team was able to reduce the buildings potable water consumption by **98%** as shown in **Figure M10** below. A detailed breakdown of water usage by fixture type can be found in **[Appendix I].**

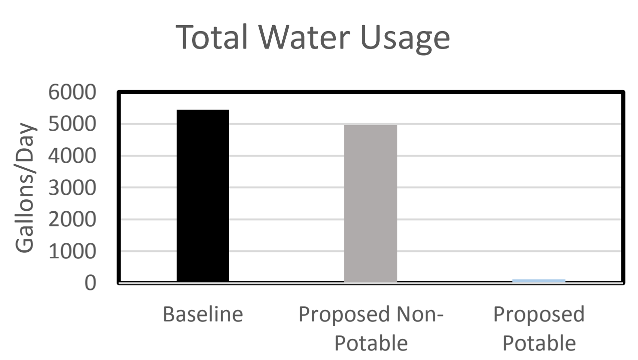


FIGURE M10: TOTAL WATER USAGE

8.7 Aquaponics

Six, 250 gallon aquaponic tanks are located in each greenhouse. The tanks house tilapia and yellow perch fish that are raised and sold in the market. The hybrid condenser water loop will cool the yellow perch aquaponic tanks and the hot water loop will serve the tilapia. The water from the aquaponic tanks is sent to a gravel bed where the toxic ammonia produced from fish is broken down into nitrates. The nitrates are absorbed by the plants as nutrients before the water is circulated back into the aquaponic tanks. Small in-greenhouse pumps (N+1) are used to drive water flow through the closed loop system. Redundancy is required in order to prevent nitrates from building up in the tilapia and perch tanks causing death in the event of a pump failure.

9.0 Natural HVAC

The Synthesis mechanical design greatly reduced the energy use typically associated with electric chillers and heat rejection equipment through the use of an absorption chiller and open loop geothermal system. The Mechanical Team then chose to target the next largest mechanical end user of electricity: fans, in order to create an ultra-low energy building.

Synthesis defines Natural HVAC as a mechanical system in which airflow is driven by the wind, sun, and thermal buoyancy as opposed to electric fans. The system is designed to supply conditioned 100% outdoor air to floors two through four, 365 days a year, without the use of fans. This is accomplished through the use of passive downdraft cooling, and passive updraft heating. Implementing these systems proved to be a challenging multidisciplinary effort, with wide-ranging implications.

9.1 Airflow Demand Reduction

When creating a fan-less system, providing the necessary amount of supply air becomes the main challenge. Synthesis' approach to this challenge was to first reduce the amount of airflow the system is required to supply. The various strategies used are detailed below.

Efficient Building Envelope – The ASHRAE Advanced Energy Design Guide for K-12 School Buildings was used to determine the desired envelope R-values. The recommendations for Climate Zone 6 in which Milwaukee is located are summarized in **Table M6.**

TABLE M6: MILWAUKEE CLIMATE ZONE RECOMMENDATIONS

Climate Zone 6 Recommendations	
Item	R-Value
Roofs	30
Walls	19
Floors	38

A façade system of precast concrete panels was selected to provide the desired thermal characteristics, shorten the construction schedule, and maintain the original architectural intent of the building. The precast panels consist of three inches of architectural concrete, three inches of rigid insulation, and three inches of normal weight concrete. The efficient envelope reduces cooling loads in occupied spaces, thus reducing the amount of airflow required for cooling purposes.

Efficient Lighting – LED light fixtures are used throughout the building in conjunction with daylight harvesting. The overall lighting power density for building is 0.39 watts per square foot. Which is a 55% reduction from the ASHRAE 90.1-2013 lighting power density for schools, using the building area method. The reduced lighting load reduces the amount of supply air required to handle space sensible loads.

Stratified Air Distribution – Creating a stratified environment changes the characteristic of the cooling load considerably. Cool air is supplied at the floor level via an underfloor plenum. Thermal plumes form around heat sources in the occupied zone, causing the warmed air to rise into the stratified zone. This process causes internal loads to have little effect on the thermal comfort of the occupied zone; thus, limiting the amount of airflow required to condition the space. Lighting fixtures transfer heat to surrounding air. The stratified environment causes this heat to stay in the stratified zone near the ceiling, where it is exhausted out of the building. Only 20% of the lighting load will need to be handled by the cooling system, resulting in less airflow.

Passive Chilled Beams and Fin Tube Radiators – Passive chilled beams and fin tube radiators are used to offset sensible loads in rooms along the eastern façade, and in the Gathering Space. This leaves less sensible load to be handled by the Natural HVAC System, resulting in reduced airflow requirements.

Flexible Temperature Set Points – To reduce airflows and create more of a Vertical Farm atmosphere, less stringent temperature set points are used. The majority of the year, all interior spaces will be conditioned to 75°F; however, when conditions approach the cooling design day and the building is fully occupied, the temperature is allowed to drift to 77°F, which still falls in the acceptable range of operative temperature and humidity to achieve thermal comfort as defined in ASHRAE Standard 55.

9.2 Passive Downdraft Cooling

Each floor has its own dedicated supply air shaft capable of providing both heating and cooling. The supply air shafts "push" the air through the building in place of fans. When the outdoor air temperature is above 55°F, the system operates in downdraft mode. Louvers located at the top of the shaft in the windward direction open, effectively "catching" the wind. Louvers are located on all four sides of the tower to allow air to be captured irrespective of wind direction. When wind speeds fall below 5 miles per hour, the louvers on all four sides open. A cooling coil, located near the apex of the shaft cools the incoming air. The cooled, dense air then travels downward due to buoyancy and wind pressure forces, into the underfloor plenum serving the floor. The "wind catching" and downdraft effect created by the cooling coil effectively replace a supply air fan in the system. **Figure M11** below illustrates how the passive downdraft cooling operates.

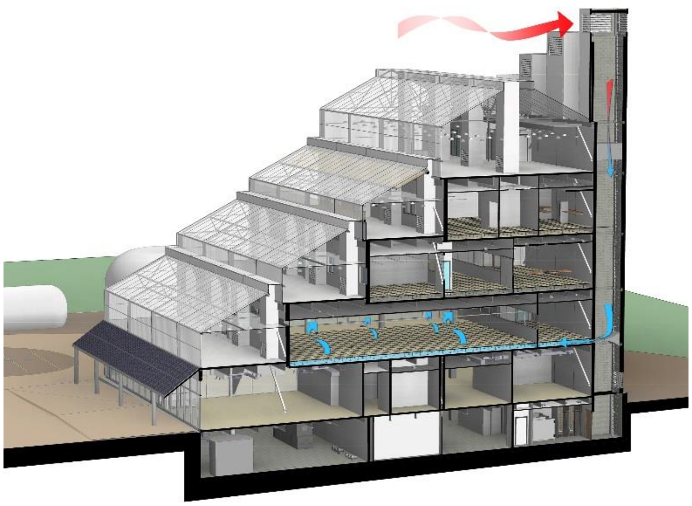


FIGURE M11: PASSIVE DOWNDRAFT SUPPLY SYSTEM

The omission of fans requires the entire system to be designed for low air velocities (200 feet per minute in this case), and low airside pressure drops. The use of an underfloor plenum drastically decreases friction losses and allows the supply air to reach the most distant rooms in the system. The use of 40 degree chilled water, and a 10 degree delta T, allowed for low airside pressure drops across the cooling coils. MERV 8 Filters are included in each supply shaft to provide filtration while maintaining the low airside pressure drop.

Passive downdraft systems have been successfully implemented throughout the United States, most notably in California and Hawaii. The thermal buoyancy effect of the system is a function of the delta T between the air entering the shaft, and the air leaving the shaft. The warmer the outdoor temperature, the more airflow the system is capable of producing, rendering passive downdraft even more effective in a warm climate such as Miami. When outdoor air temperatures fall below 55°F, the downdraft effect can no longer be created, and a new solution is required.

9.3 Passive Updraft Heating

The system operates in updraft mode when outdoor air temperatures fall below 55°F. Dampers at the base of the supply towers open with respect to the wind speed and direction. The incoming air is heated by a heating coil at the base of the tower. The warmed air rises through the tower due to thermal buoyancy, and enters the underfloor plenum. The "wind catching" effect is less influential in updraft mode due to the building shielding the intake dampers from southern winds. However, a large updraft effect can often be generated due to the larger delta T's that can be created in the winter. Heating water at 180°F serves the coils at the base of the shafts. This warm temperature was selected to reduce the airside pressure drop.

9.4 Solar Chimney

Through multi-zone bulk airflow modeling, it was discovered that the "push" effect of the updraft/downdraft shafts was not sufficient to move the necessary amount of air through the building. Thus, the mechanical team at Synthesis added a Solar Chimney to help "pull" air through the building. Warm air near the ceiling in spaces served by the natural HVAC system enters a return air plenum, open to the solar chimney. The chimney absorbs solar radiation and helps to heat the air in the chimney, increasing its buoyancy and causing it to rise. Additionally, a heating coil is placed in the chimney to help further induce the stack effect. Waste heat from the microturbine, when available, is used to provide this heating effect. Bulk airflow modeling showed an increase in airflow of approximately 2,000 CFM due to the heating coil. Thus, the waste heat from the quad-generation process is used to help replace fans in the system. The rectangular top of the chimney is fitted with operable dampers on all four sides. The damper in the leeward direction opens to further create negative pressure and prevent wind from impeding airflow through the building. The chimney operates as described above when the outdoor air temperature is above 40°F. As temperatures drop below 40°F, less waste heat from the microturbine is available, and air traveling up the chimney is cooled conductively due to the chimney's three exterior walls. This cooling effect counteracts the upward flow of air, and the "pull" effect is lost. **Figure M12** below displays how air is relieved from the building in downdraft mode.

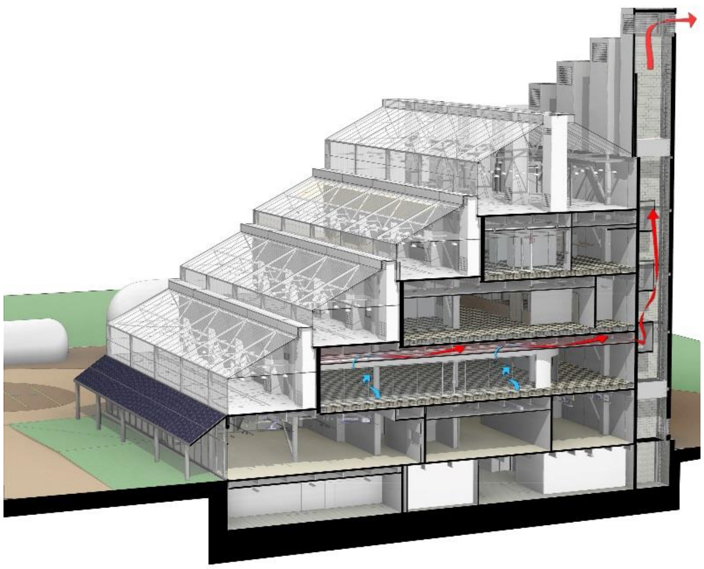


FIGURE M12: PASSIVE DOWNDRAFT RELIEF SYSTEM

The amount of air that can be relieved through the tower is a function of the temperature difference between the entering and leaving air. Since the entering temperature stays fairly constant throughout the year (75-80°F) the Mechanical Team found that reversing the direction of flow in the chimney and utilizing the cold outdoor air temperatures via an air-to-air heat exchanger provided the necessary "pull" effect when the outdoor air temperatures falls below 40°F.

In rare circumstances, the natural HVAC system is supplemented by a relief fan in the Solar Chimney. Notably during mild winter days with southern winds when the building is fully occupied. Results obtained from the powerful multizone bulk airflow model show that the fan will need to operate 0.4% of the year.

9.5 Underfloor Air Distribution

The magnitude of the "push" and "pull" effects that the supply shafts and solar chimney can create varies continuously with outdoor air temperature, solar radiation, wind speed, and wind direction. Therefore, and extremely efficient air pathway through the building is required to allow the system to function under all foreseeable scenarios. An 18 inch underfloor air distribution (UFAD) plenum was deemed the best solution to deliver and distribute air to the zones from the natural HVAC supply towers. UFAD eliminates the need for ductwork and significantly reduces friction losses.

The mixed-use nature of the Vertical Farm renders certain spaces on each floor ill-suited for underfloor air distribution. The first floor is directly connected to the work yard, and contains a workshop, food market, and processing space. A significant amount of dirt and food scrap could potentially make its way into the underfloor plenum, creating air quality and maintenance issues. For these reasons, UFAD was not used for the first floor. Floors two through four consist primarily of meeting spaces, classrooms, and offices; however, each floor also contains restrooms, mechanical space, and a greenhouse. During the Architectural Optimization, rooms to be served by the UFAD system were grouped together in the Northeast area of the building as shown in **Figure M13**.

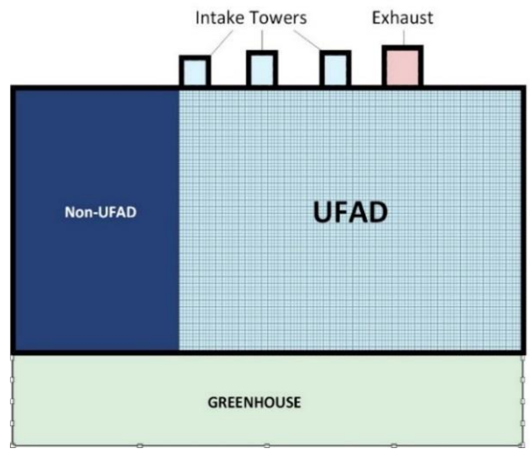


FIGURE M13: TYPICAL UFAD FLOOR PLAN (2-4) LAYOUT

A lowered slab was used in the UFAD section to maintain a uniform floor height throughout each level. The division between the different slab elevations was placed along a column line, allowing the beams supporting each slab to frame into a single deep girder.

UFAD improves indoor air quality in each space by displacing air rather than diluting and mixing. Displacement ventilation introduces ventilation air at a low velocity reducing the amount of airflow needed in each space while displacing the contaminated air toward the return inlets. Thermal plumes of occupants and other heat sources are also removed from the occupied zone. Utilizing a floor supply and ceiling return also increases the system ventilation effectiveness, reducing the amount of outdoor air required. A detailed 3D section of the underfloor plenum in a typical classroom is shown in **Figure M14** below.

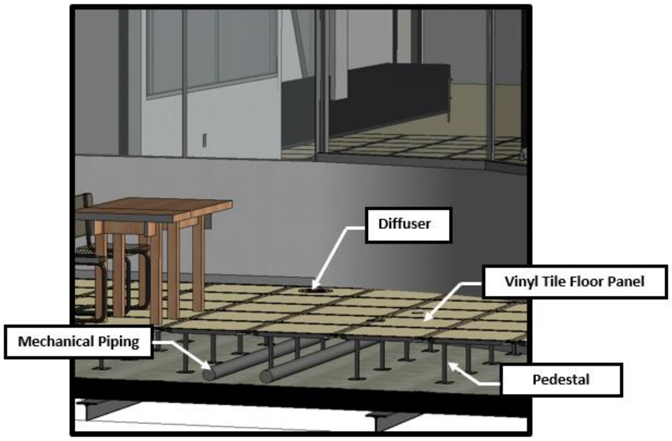


FIGURE M14: UNDERFLOOR PLENUM SECTION

9.6 Control

The rooms served by the Natural HVAC system are not characterized by a common load profile. In order to create a comfortable environment in each space, a system of secondary underfloor plenums is used. The air from each floor's respective supply shaft is directed into a primary plenum. A secondary plenum for each room is connected to the primary plenum via a modulating damper and reheat coil assembly sized for 200 ft/min. Each room in the system contains temperature and CO_2 sensors. The sensors determine the position of the modulating damper and the flow through the reheat coil.

When a damper serving a room's secondary plenum is fully open, and set points still cannot be met, the following weather dependent sequence of operations is applied:

OA Temperature > 55°F, Downdraft Supply & Solar Chimney Relief

1. When waste heat is available, activate heating coil in solar chimney, increasing the "pull" effect of the system.
2. Reset the leaving coil temperature proportionally from 63°F to 52°F, increasing the "push" effect.
3. Turn on fan in Solar Chimney.

40°F < OA Temperature < 55°F, Updraft Supply & Solar Chimney Relief

1. Reset leaving coil temperature proportionally from 45°F to 65°F to increase the "push" effect.
2. When waste heat is available, activate heating coil in solar chimney.
3. Turn on fan in Solar Chimney.

OA Temperature < 40°F, Updraft Supply & Downdraft Relief

1. Reset leaving coil temperature proportionally from 45°F to 65°F.
2. Switch to Solar Chimney Relief mode and turn on fan

9.7 Optimization & Modeling

The controls and sequences described above were the result of an extensive computer modeling and optimization process. A multi-zone bulk airflow model was required in order to quantify and analyze the airflow induced by solar radiation, wind pressures, and thermal buoyancy. IES Virtual Environment was chosen as the tool to carry out the modeling process due to its ability to integrate a multi-zone bulk airflow model into an 8760 energy model. Additionally, IES provided the freedom to create the complex control algorithms required to model the Natural HVAC system. **[Appendix K]** describes the modeling process in more detail.

The Mechanical Team performed over 200 iterations of the integrated model. This trial an error process led to several informed design decisions:

Opening Sizes – The model allowed various diffuser layouts, primary/secondary plenum opening sizes, and return register sizes and locations to be assessed. Resulting in optimally sized openings.

Insulated Floor Slab – The floor slab separating warm return plenums from cool supply plenums proved to act as a heat exchanger. This effect limited the system's ability to cool spaces distant from the entrance to the plenum. Through the use of the integrated model, the mechanical team determined that adding two inches of sprayed insulation to the metal decking on the underside of the floor slab would sufficiently reduce the heat transfer.

Slab Thermal Mass – The integrated model identified the thermal mass of the floor slab as a potential issue. Night-time setback temperatures during the cooling season caused the slab to become thermally "charged," which limited temperature controllability the following day. The warm slab led to an increase in air temperature before it was delivered into occupied zones. To combat this effect, temperature set backs were reduced.

If correctly controlled, the thermal mass of the slab could be used to increase efficiency and controllability. A night purge could be used to pre-cool the slab, taking advantage of diurnal swings. Intelligent building technology utilized in the Vertical Farm offers even more ways to harness the thermal mass of the slab. A converged IP network will link occupancy schedules with the building automation system. These schedules will be used in combination with future weather forecasts to determine when and to what extent the slab will be thermally "charged."

9.8 Auxiliary Heating and Cooling

Chilled beams provide a total cooling capacity of 11 tons to cool the gathering, break-out, and classroom spaces along the perimeter of the third floor. A condenser water temperature of 63°F is supplied to each chilled beam to eliminate any potential condensation. A summary of the chilled beams used in the Vertical Farm is provided in below and in **[Appendix M]**.

TABLE M7: CHILLED BEAM SUMMARY

Floor	Space	Total Sensible Cooling Capacity [tons]	Number of Chilled Beams
2	Gathering	6.13	20
2	Break-Out	2.44	8
3	Classroom	0.70	4
3	Classroom	0.71	4
4	Director	0.52	2

Hot water fin tube radiators are used in the perimeter spaces of floors two through four in conjunction with the air delivered by the UFAD system. The radiators help offset envelope loads to create a more comfortable environment.

10.0 First Floor System

The first floor of the Growing Power Vertical Farm consists of a market space, workshop, mud room, and small offices. These spaces could generate unwanted contaminants that would produce an unhealthy environment for the first floor. In order to control and dilute these unwanted contaminants, a 12 ton 100% outdoor air handling unit will condition the first floor. The unit will include an energy recovery wheel that recovers 78% of the sensible and latent energy used. A high performance filter with a minimum efficiency reporting value of 12 (MERV 12) is also selected to reduce the amount of unwanted particles that enter into the spaces.

10.1 Shipping/Receiving

When the garage doors are open during loading and unloading, relief air from the first floor air handling unit will be used to pressurize the shipping/receiving room. This will reduce infiltration and provide a more comfortable environment for workers. Additionally, problems associated with high levels of cold or humid air infiltrating into the space are mitigated.

11.0 Energy Savings

The closed loop, ecologically driven design philosophy applied to the Vertical Farm resulted in exceptional building performance. Through the use of anaerobic digestion and photovoltaic arrays, 1,774,000 kWh are produced on site annually. This amount equates to **8% more than** the electricity used on the property, classifying the **entire site** as **net zero energy**.

The compressor-free cooling and fan-less air distribution strategies allowed the mechanical system to meet space cooling loads while operating at a total efficiency of **0.3-0.4 kW/ton** (including fans and pumps). The production and usage of biogas reduced the consumption of natural gas by over **90%** when compared to the ASHRAE 90.1 baseline results. Figures M15 and M16 depict the HVAC electrical usage and overall site electrical usage, respectively.

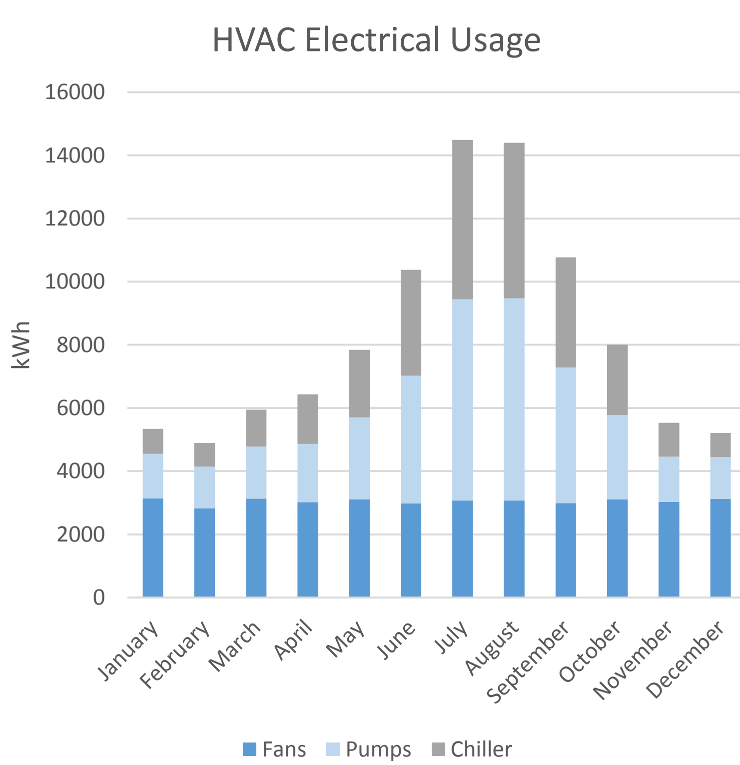


FIGURE M15: HVAC ELECTRICAL USAGE

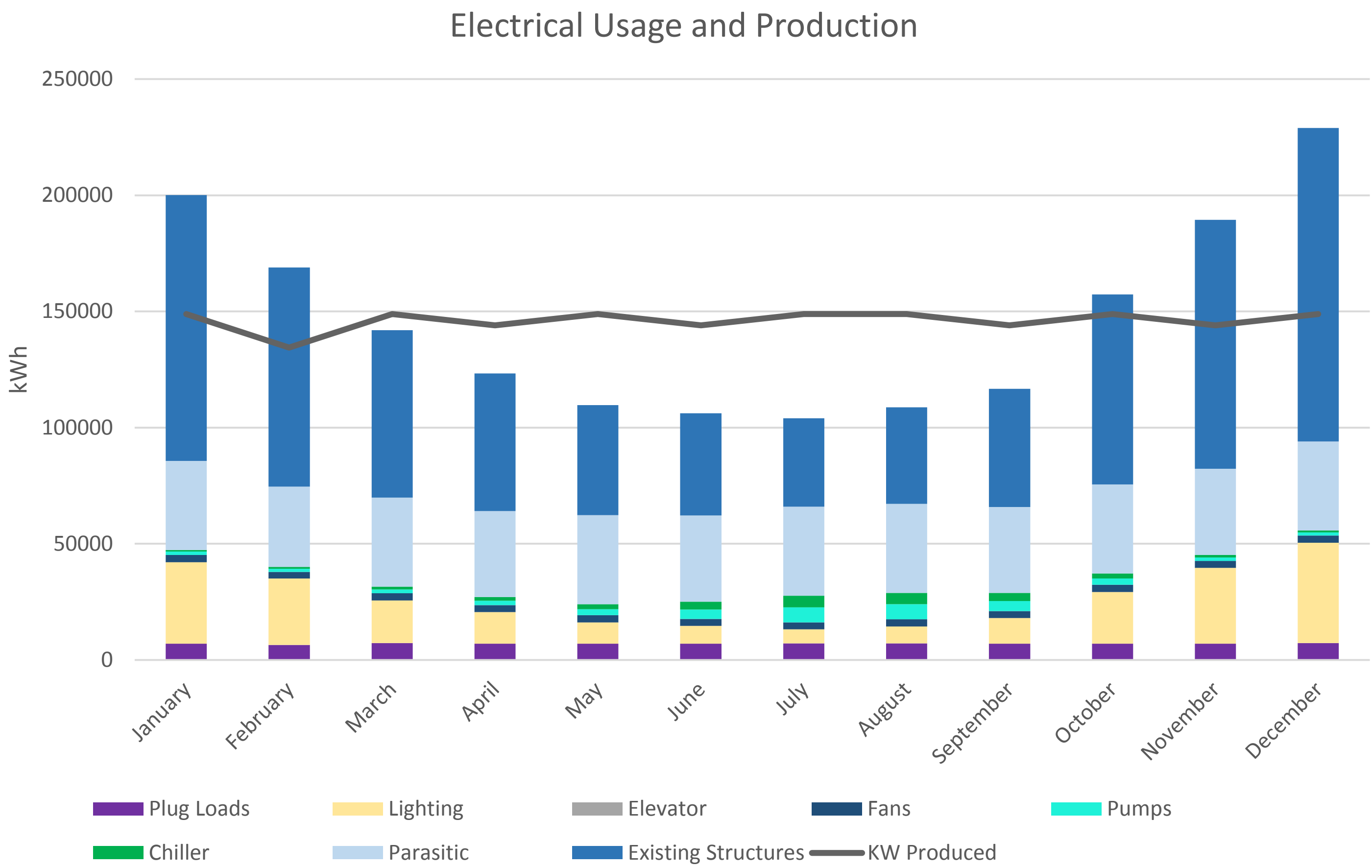


Figure M16: Total Electrical Usage of Site

12.0 Design Adaptability

The Growing Power Vertical Farm has been designed first for its current location at 5500 W. Silver Spring Dr. Milwaukee, WI. Growing Power views the new Vertical Farm as the first of its kind and aims to establish it as a local and national resource for sustainable urban farming education. With the average age of farmers at over 65 years of age, Growing Power believes they are responsible for educating the youth across the country. As founder Will Allen states: "our goal is a simple one: to grow food, to grow minds, and to grow community."

The farm has been designed as a prototype model to inspire other vertical farms around the country. Although Synthesis has designed the building for any climate, Growing Power requires a specific plan for the next possible farm to be located in Miami, Florida. This section describes how the prototype will adapt to the new Miami location.

12.1 Energy Generation

Growing Power will still mimic the natural cycle of food production, using food waste as a fuel source for onsite energy generation that will power the Vertical Farm, ultimately providing the community with food.

Because Growing Power will be providing around 42% of its annual electrical generation to their existing facilities, they will have an excess amount of power in Miami. The location of the Vertical Farm should be coordinated with the implementation of a new community, developing a micro grid and creating an ecosystem encompassing both. The new community will receive excess heat and power from the Vertical Farm as well as a healthy food supply, in turn they will provide Growing Power with a constant source of food waste. This model should be the basis for new urban development and will help spawn numerous similar operations like it, creating healthy self-supporting urban ecosystems.

12.2 Hybrid Condenser Water System

The cold, plentiful groundwater and adjacency to Lincoln Creek at the Milwaukee site provides an opportunity to utilize an open loop geothermal system. The likelihood of replicating the system in a future location is extremely unlikely due to varying groundwater temperatures and local codes and ordinances.

The heat rejection system for any future site will be designed to take full advantage of the surrounding environmental conditions to minimize energy and water usage. Potential future heat rejection systems for Miami or any other location are listed below, in order of preference:

1. Lake/sea/river source
2. Open loop geothermal
3. Closed loop geothermal
4. Cooling tower

Chilled water thermal storage could also be added in the future to capitalize on favorable night-time condensing temperatures and avoid peak demand charges.

12.3 Greenhouse Design

The closed, modular greenhouse design creates an adaptable system that functions well in any climate around the country. The cooling system of the greenhouse was specifically designed and sized to overcome the increased thermal loads presented in the hot and humid climate of Miami, FL. Extensive computer airflow modeling was performed for the Miami site to ensure the cooling & dehumidification system's performance, as detailed in **[Appendix F].**

12.4 Natural HVAC

The natural HVAC system thrives in any site location that provides sufficient wind pressures, and thermal buoyancy potential to drive airflow throughout the Vertical Farm. Miami is an ideal site due to its hot year-round climate. In the case that the Vertical Farm is moved to a highly dense, urban environment surrounded by taller buildings, wind pressures will be insufficient to drive the required outdoor airflow through the building. To solve this, space for a mechanical room has been allocated on levels two through four that will house an air handling unit used to ventilate and condition the floor. Underfloor air distribution will still be used in place of an overhead mixing system to retain the advantages previously described in this report.

13.0 Conclusion

The design of the Vertical Farm will further cement Growing Power as a sustainable and ecological leader in the Milwaukee community and for future communities to come. The Mechanical Team looked towards new, innovative solutions and in doing so, provided mechanical systems that:

Create a **comfortable and acoustically sound** working and learning environment.

Minimize **energy use, water consumption, waste, and emissions** for both the Growing Power site and Milwaukee community.

Adjust to **changing building conditions, emerging technologies**, **geographical locations**, and **microclimates**.

The proposed mechanical design achieved the overall goals of Synthesis through interdisciplinary collaboration and architectural optimization which resulted in:

100% Energy Reduction

98% Potable Water Reduction

99% Emissions Reduction

100% Outdoor Air