Integration | Construction | Mechanical | Electrical | Structural

GROWING POWER
VERTICAL FARMING FACILITY

TOTAL BUILDING DESIGN
ENGINEERING

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

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.

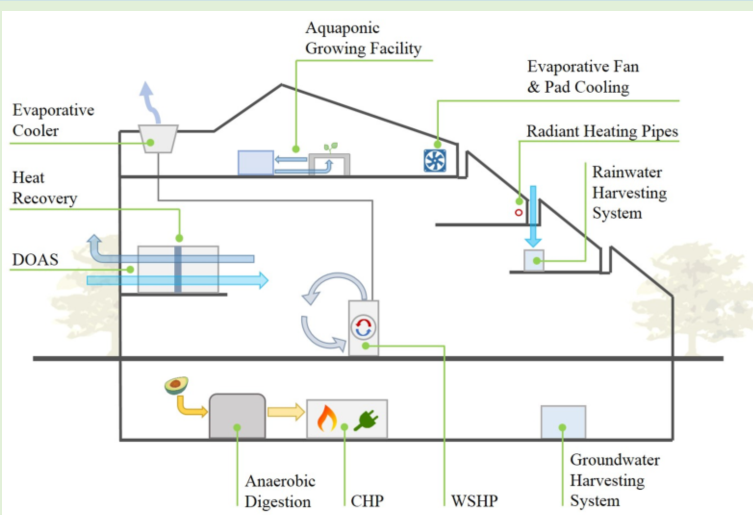
The design team of Total Building Design (TBD) Engineering was asked to develop and submit plans for the new Growing Power headquarters in Milwaukee, WI. The headquarters will be a five-story vertical farm that composes of greenhouse facilities, a market space, offices, and educational spaces for the 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).

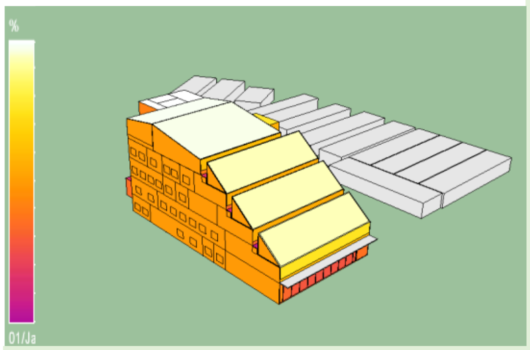

Figure 2. Solar Exposure Study

[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).

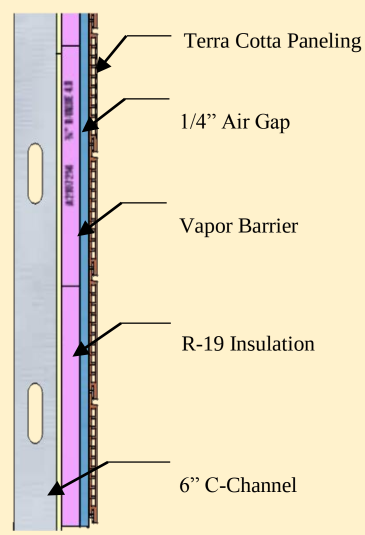

Table 1: Growing Power Facility Loads				
Location	Milwaukee, WI		Miami, FL	
ASHRAE Zone	6A		1A	
	Building	Greenhouse	Building	Greenhouse
Cooling Load	88 Tons (1.2 CFM/SF)		121 Tons (1.6 CFM/SF)	
Heating Load	1,168 MBH	808 MBH	285 MBH	226 MBH

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.

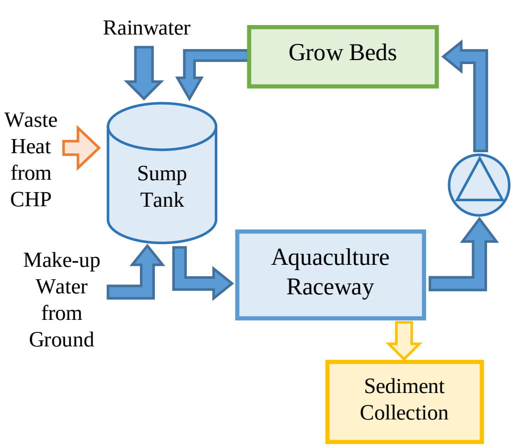

Figure 3. The aquaponic growing system creates a closed loop of water

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

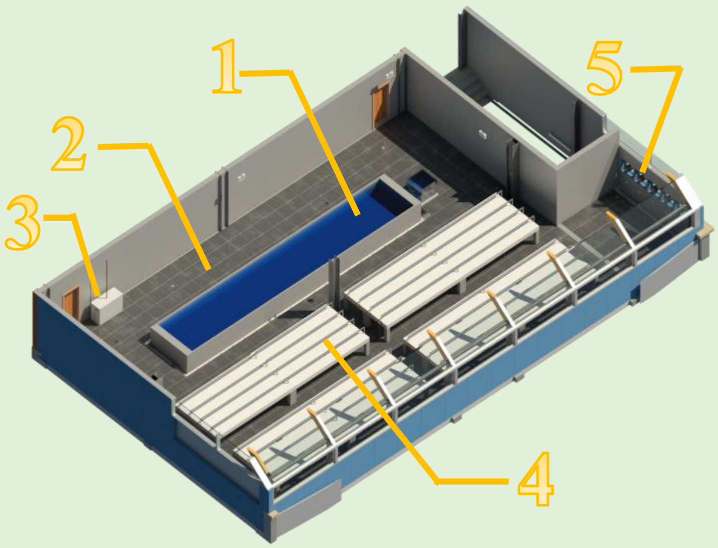

Figure 5. A typical layout of the greenhouse consists of growing beds, aquaculture tank, destratification fans, water collection, and evaporative fan and pad cooling systems.

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

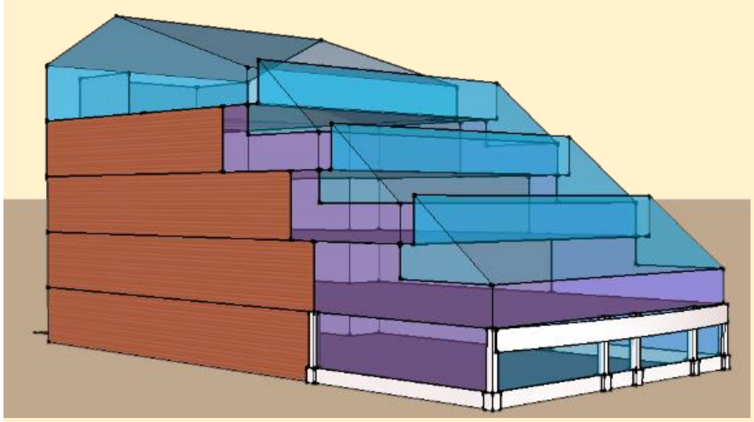

Figure 7. The amount of glazing of the greenhouses depended greatly on the PAR levels calculated.

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).

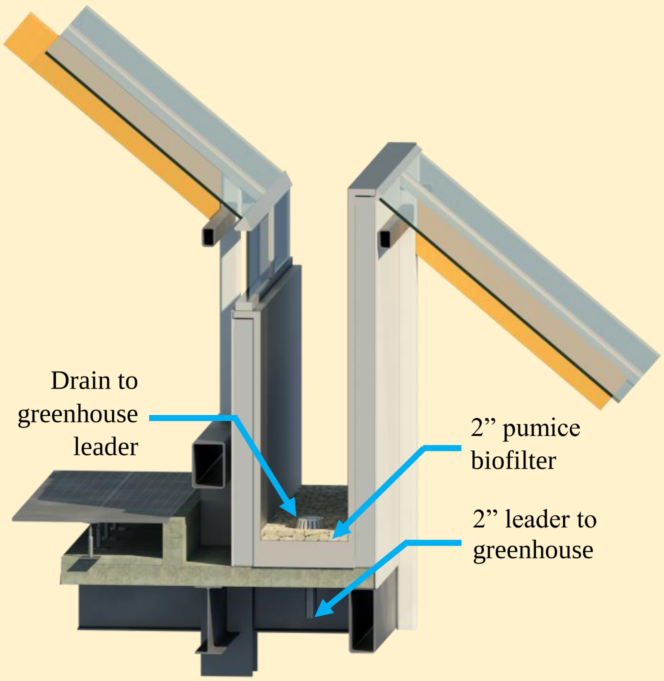

Figure 8. The trough in between the roofs of the greenhouses act as a biofilter which both collects and cleans water for greenhouse makeup water use.

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.

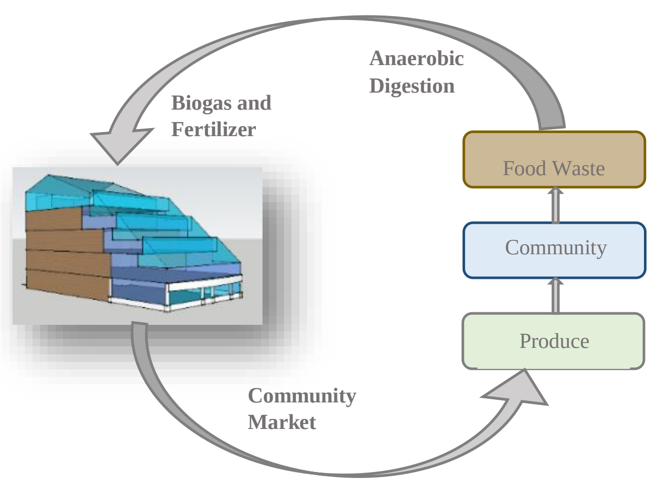

Figure 9. Closed energy loop created by food production and community waste.

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)

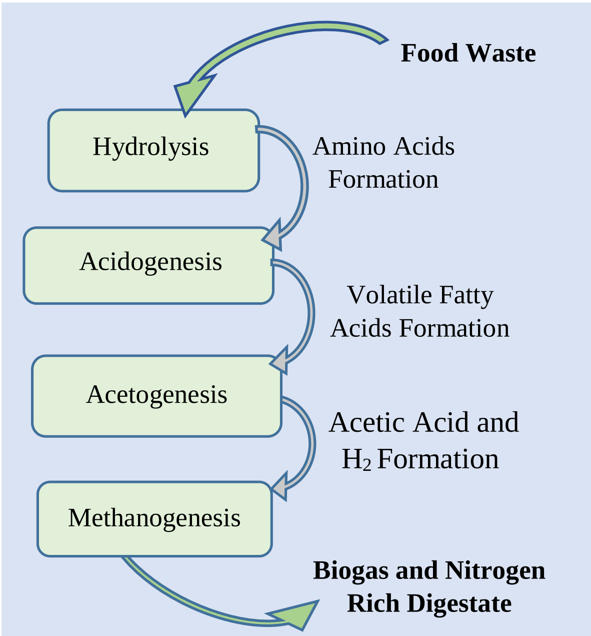

Figure 11. Biogas and nitrogen-rich digestate are produced from food waste.

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.

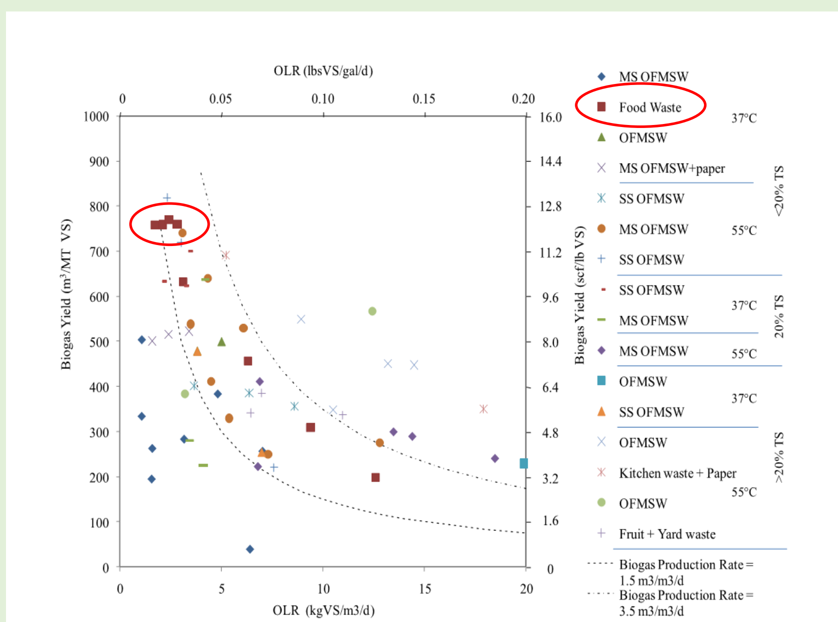

Figure 12. Organic loading rates vs. biogas yield for food waste and other common wastes

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.

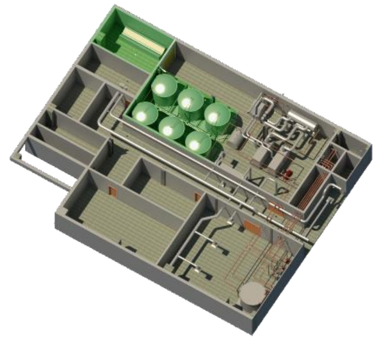

Figure 13. Anaerobic digestion plant located in building mechanical room.

[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%**

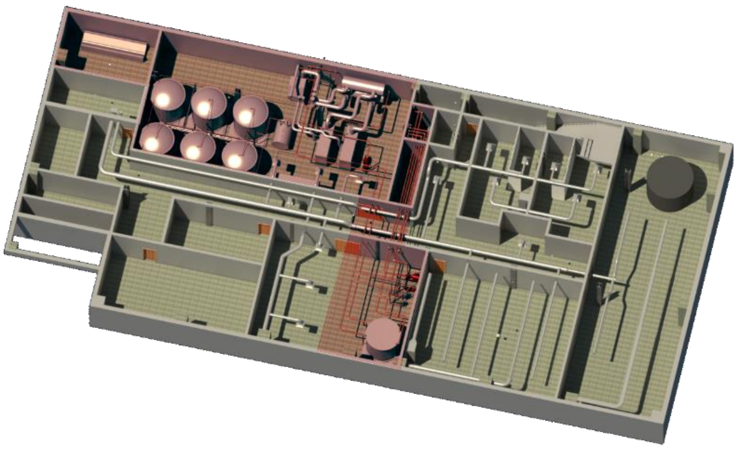

Figure 14. CHP mechanical room layout

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.

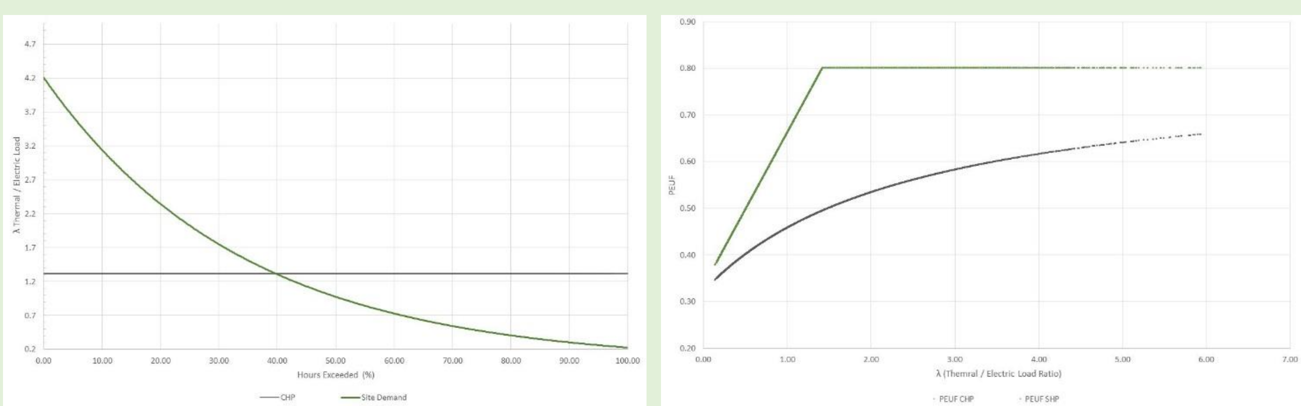

Figure 15. (Left) Duration curve showing the site λ at the Milwaukee facility compared to the λ_{CHP} of the CHP facility. (Right) PEUF vs. site λ for the CHP and SHP facility.

Table 3: Emission Reductions from Growing Power CHP

	Unit	lb. CO_2 Produced / Unit	Total CO_2
ft^3 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

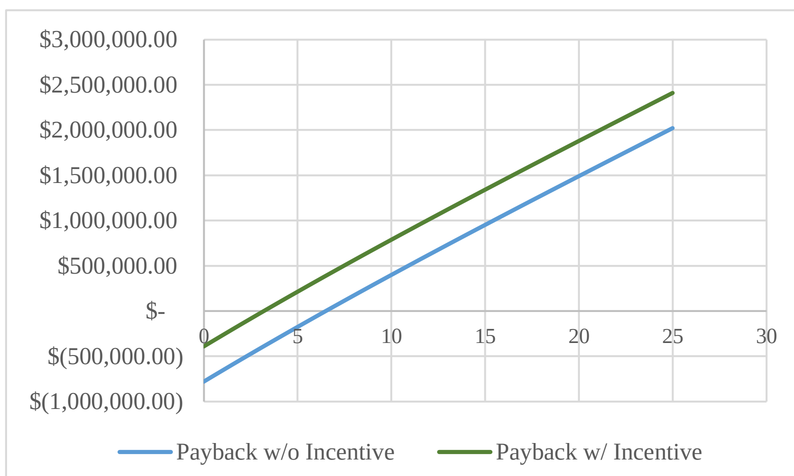

Figure 16. Net present value calculation showing the payback period with and without local Wisconsin incentives.

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]

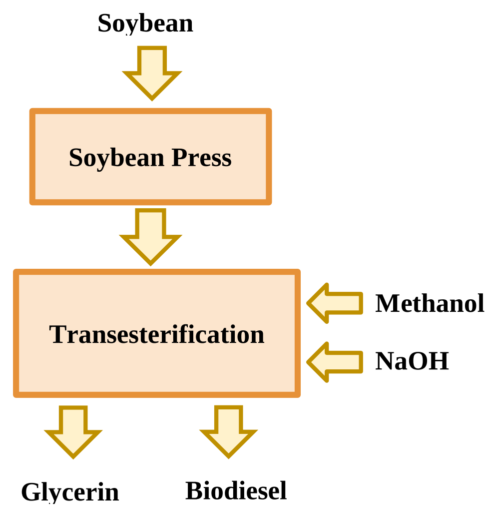

Figure 17. Soybeans can be used as an alternative renewable energy source for the Growing Power Vertical Farm.

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).

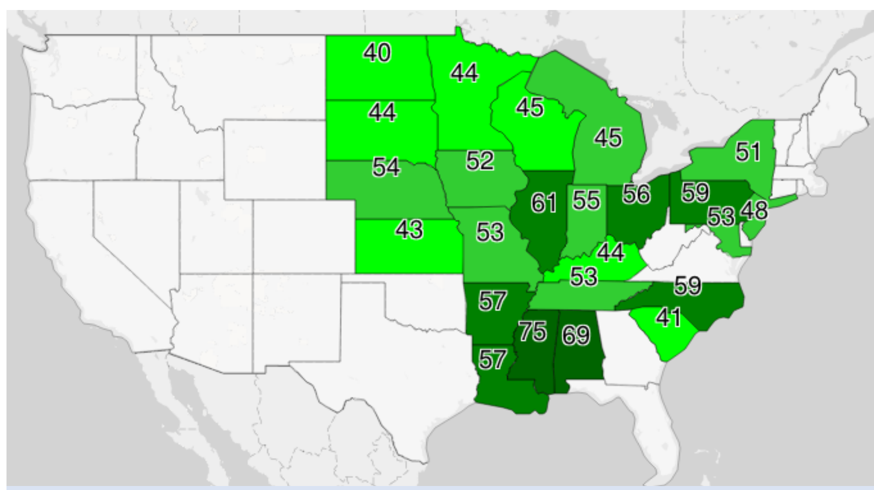

Figure 18. The map above shows the average bushels per acre of soybeans harvested in each state in 2014 courtesy of AgWeb.[9]

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%.

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%

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.

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.

INTEGRATED SOLUTION: DESIGN COORDINATION

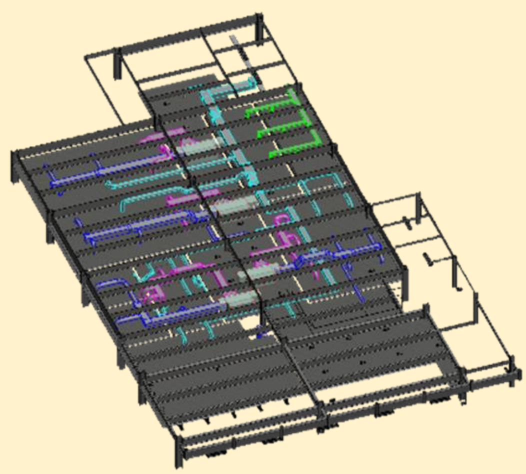

Figure 19. Level 3 3D coordination view

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 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.

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.

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6. 2010 Florida Building Code

COMPUTER PROGRAMS

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Microsoft Excel 2013

Integrated Environmental Solutions (IES) Virtual Environment 2013

Trane Trace 700

Marley Update Selection Software Version 4.16.1

Bell and Gossett (Xylem Brand) ESP-Plus Selection Software

Xylem ESP Thermal Selection Software

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10. Figure SD 1: Well-X-Trol pressurized tank courtesy of Amtrol
11. Figure SD 3: Raft aquaponics image courtesy of aquaponics.com
12. Figure SD 7: BM-55/88 courtesy of Viessmann
13. Figure SD 17: Water Source Heat Pumps courtesy of Daikin
14. Drawing D2: Equipment Images Courtesy of Viessmann Group, Bell and Gossett, Haase Tanks, Hydroflex Systems, Maxim Heat Recovery Silencers, Clever and Brooks, Moyno
15. Drawing D1: Image Courtesy of Marley

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GREENHOUSE WATER USAGE

With traditional farming techniques, up to 50% of water can be lost.[20] By using a recirculating aquaponic growing system coupled with both rainwater and groundwater harvesting, the greenhouse water demand is completely self-sufficient.

The following calculations reflect values for Milwaukee. All sumps are sized such that the system may remain in operation for a full day in the event that the system requires maintenance

Table SD 1: Greenhouse Water Use Analysis

		Avg Monthly Rainfall		Avg Rain Collection			Water Demand			Size of Rain Collection			Groundwater Pumped to GH	
	Area						Aquaponics	Fan & Pad	Total	Volume	Height	Diameter		
Roof ID	SF	in.	ft	ft^3	gal/month	gal/day	gal/day	gal/day	gal/day	ft^3	ft	ft	gal/day	gpm
2	1754	2.69	0.22	393.19	2941.05	98.03	132	16	148	20	3	2.91	49.97	0.03
3	1753.8	2.69	0.22	393.14	2940.71	98.02	132	16	148	20	3	2.91	49.98	0.03
4	2918.79	2.69	0.22	654.30	4894.13	163.14	132	16	148	20	3	2.91	-15.14	-0.01
5	2842.75	2.69	0.22	637.25	4766.63	158.89	132	56	188	30	3	3.57	29.11	0.02

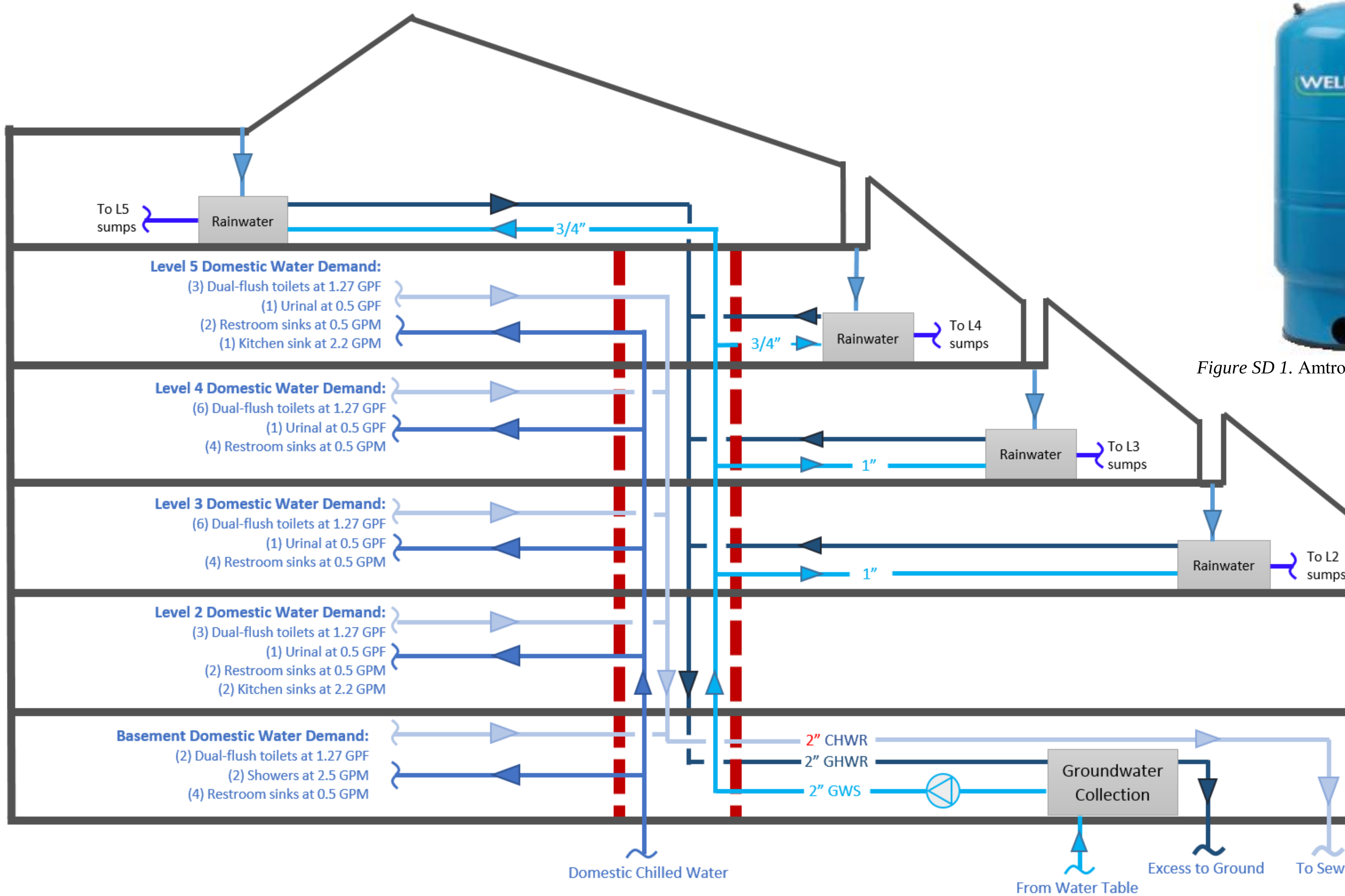


Figure SD 1. Amtrol's Well-X-Trol

Greenhouse Water Demand Sequence

Rainwater enters the greenhouse through the troughs located in between roofs of the individual greenhouses, where it is cleaned via biofilters. The water is then collected into a rainwater harvesting tank.

The water in the rainwater harvesting tank is delivered to the sumps of both the aquaponic and evaporative pad sumps. These sumps are pre-pressurized, acting much like a piston-cylinder to ensure that there is always the required supply of water in a system.

When the volume of water within these sumps decrease, the diaphragm within the sump tank "deflates," causing the sump to automatically restore the diaphragm to equilibrium by drawing water from the rainwater harvesting tank. Figure SD 1, on left, is an example of Amtrol's Well-X-Trol tank which uses this technology.

A float valve in the rainwater harvesting tank indicates if there is insufficient water in the system via a float inside the tank. When the water levels fall to insufficient levels, water will be pumped to the rainwater harvesting tank from the groundwater collection tank. Conversely, a pipe at the top of the rainwater storage tank will allow excess water to flow into the groundwater collection tank when water levels are too high, such as in the event of a rainstorm.

The groundwater collection system draws water from the water table to act as a well for the site, effectively becoming a new water supply. Because the groundwater collection system is connected to the rainwater harvesting tank, any excess water in the groundwater collection tank can be sent back into the ground.

FAN & PAD EVAPORATIVE COOLING CALCULATIONS

Milwaukee Fan & Pad Evaporative Cooling Calculations

Table SD 2: Weather Characteristics of Milwaukee Evaporative Cooling

System Characteristics	
Saturation Effectiveness	0.8
Maximum Indoor Air Temperature [°F]	80
Face Velocity [fpm]	250
Corrugated Cellulose Thickness [in]	4

Table SD 3: System Characteristics of Milwaukee Evaporative Cooling

Location-Based Criteria: Milwaukee	
Average Solar Radiation [BTU/h*ft^2]	138
Design Day DB Temp. [°F]	86.18
Design Day WB Temp. [°F]	72.32
Temp. Leaving Evaporative Cooler [°F]	76

Table SD 4: System Sizes for Milwaukee Evaporative Cooling

Growing Space Level	Growing Space Area	Cooling Air Volume	Face Area of Evaporative Cooling
	SF	CFM	SF
2	2750	47438	190
3	1920	33120	133
4	1665	28722	115
5	4625	79782	320

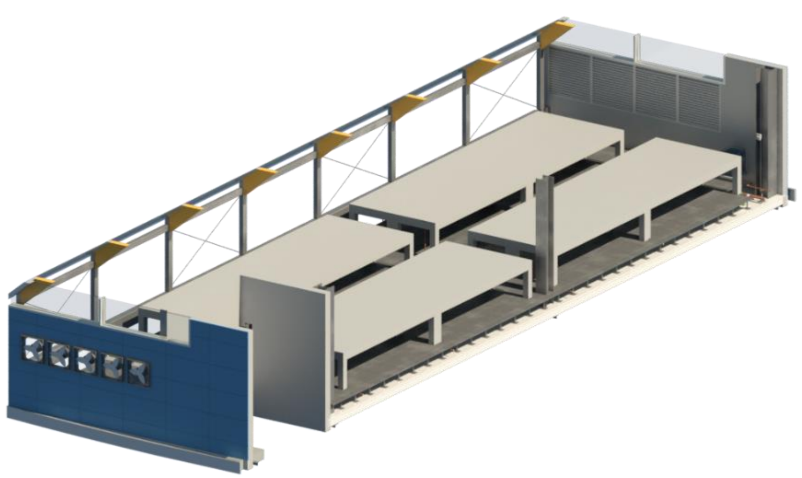


Figure SD 2. The greenhouse spaces in the Growing Power Vertical Farm feature evaporative fan and pad cooling on the East and West walls.

Miami Fan & Pad Evaporative Cooling Calculations

Table SD 5: Weather Characteristics of Miami Evaporative Cooling

System Characteristics	
Saturation Effectiveness	0.8
Maximum Indoor Air Temperature [°F]	82
Face Velocity [fpm]	250
Corrugated Cellulose Thickness [in]	4

Table SD 6: System Characteristics of Miami Evaporative Cooling

Location-Based Criteria: Miami	
Average Solar Radiation [BTU/h*ft^2]	153
Design Day DB Temp. [°F]	90.32
Design Day WB Temp. [°F]	77.36
Temp Leaving Evaporative Cooler [°F]	80

Table SD 7: System Sizes for Miami Evaporative Cooling

Growing Space Level	Area	Cooling Air Volume	Face Area of Evaporative Cooling
	SF	CFM	SF
2	2750	105188	421
3	1920	73440	294
4	1665	63687	255
5	4625	176907	708

Table SD 8: Sizes for Evaporative Cooling Sump Tank

Evaporative Cooling Sump		
Volume	**Diameter**	**Height**
gallons	**ft**	**ft**
16	1.25	2.66
16	1.25	2.66
16	1.25	2.66
56	2	2

Governing Equations

Calculations based off of 2011 ASHRAE Handbook- HVAC Applications, Chapter 52.13, Evaporative Cooling- Other Applications, Cooling Greenhouses section.

$$T_{ec} = T_{DB} - [\varepsilon * (T_{DB} - T_{WB})]$$

$$Q_{cooling} = \frac{0.5 * Greenhouse\ Area * I_{rad,solar}}{T_{max,GH} - T_{ec}}$$

$$A_{ec} = \frac{Q_{cooling}}{face\ velocity}$$

T_{ec} = temperature leaving the evaporative cooler [°F]

T_{DB} = design dry bulb temperature of the site [°F]

T_{WB} = design wet bulb temperature of the site [°F]

$Q_{cooling}$ = cooling air volume [cfm]

$I_{rad,solar}$ = average solar radiation of the site [BTU/h*ft^2]

$T_{max,GH}$ = maximum indoor air temperature of the greenhouse [°F]

A_{ec} = face area of the evaporative cooling pads [sf]

A comparison of the sizes of the fan and pad evaporative cooling systems in Milwaukee and Miami shows that a considerably greater air volume and face area are needed in the Miami site to deliver similar space conditions in the greenhouse. This indicates that a future design of a vertical farm in the Miami site, and similarly hot and humid climates should strongly consider a heavier reliance on the naturally ventilated roof for cooling.

The required fan and pad sizes were calculated using the equations given in Chapter 52.13 of the 2011 ASHRAE Handbook – HVAC Applications, giving the length of pad required. According to Bucklin, et. al., evaporative cooling sumps should be sized to hold 1 to 1.25 gallons per linear foot of pad in order to hold all water that drains to the sump when the system stops.(16) Therefore the evaporative cooling sumps were sized at 1 gallon per linear foot of evaporative pad.

AQUAPONIC SYSTEM PROCESS

1. Aquaculture Raceway. Water enters the aquaculture raceway, home to tilapia. A raceway, as opposed to a circular tank, makes sediment removal much simpler by directing flow towards the sediment collection tank.

2. Sediment Collection. Any unwanted fish waste is sent into the sediment collection tank such that it cannot reach the plants in the grow beds.

3. Pumps. The pumps serving the aquaponic system are located beneath the grated floor system to avoid any potential tripping hazards.

4. Grow Beds. Lettuce is grown in a raft bed system, in which a floating bed holds the lettuce in place.[11] Aquaponic water flows beneath the raft, during which the roots of lettuce absorb nutrients provided by the aquaculture.

5. Aquaponic Sump. Water leaves the grow beds and is sent to the aquaponic sump, which is an atmospheric tank which serves as the indicator of insufficient water levels in the system. The tank's diaphragm will indicate when water levels are low and pull water from the rainwater collection tank. The sump also maintains the aquaponic water temperature at a minimum of 72 °F by absorbing waste heat rejected from the CHP plant.

6. Rainwater Collection. As rain enters the greenhouse space through roof troughs, it is piped into the rainwater collection tank in each greenhouse. From the rainwater collection tank, makeup water is delivered to both the aquaponic sump and evaporative cooling sump.

7. Evaporative Cooling Sump. The evaporative cooling sump collects water from the rainwater collection tank such that the pads of the fan and pad system remain moist throughout its operation.

8. Groundwater Collection Tank. Any deficiency in water circulation of the greenhouse is mitigated by the groundwater collection tank. Conversely, any extra water in the rainwater collection tank is sent back to groundwater collection for later use.

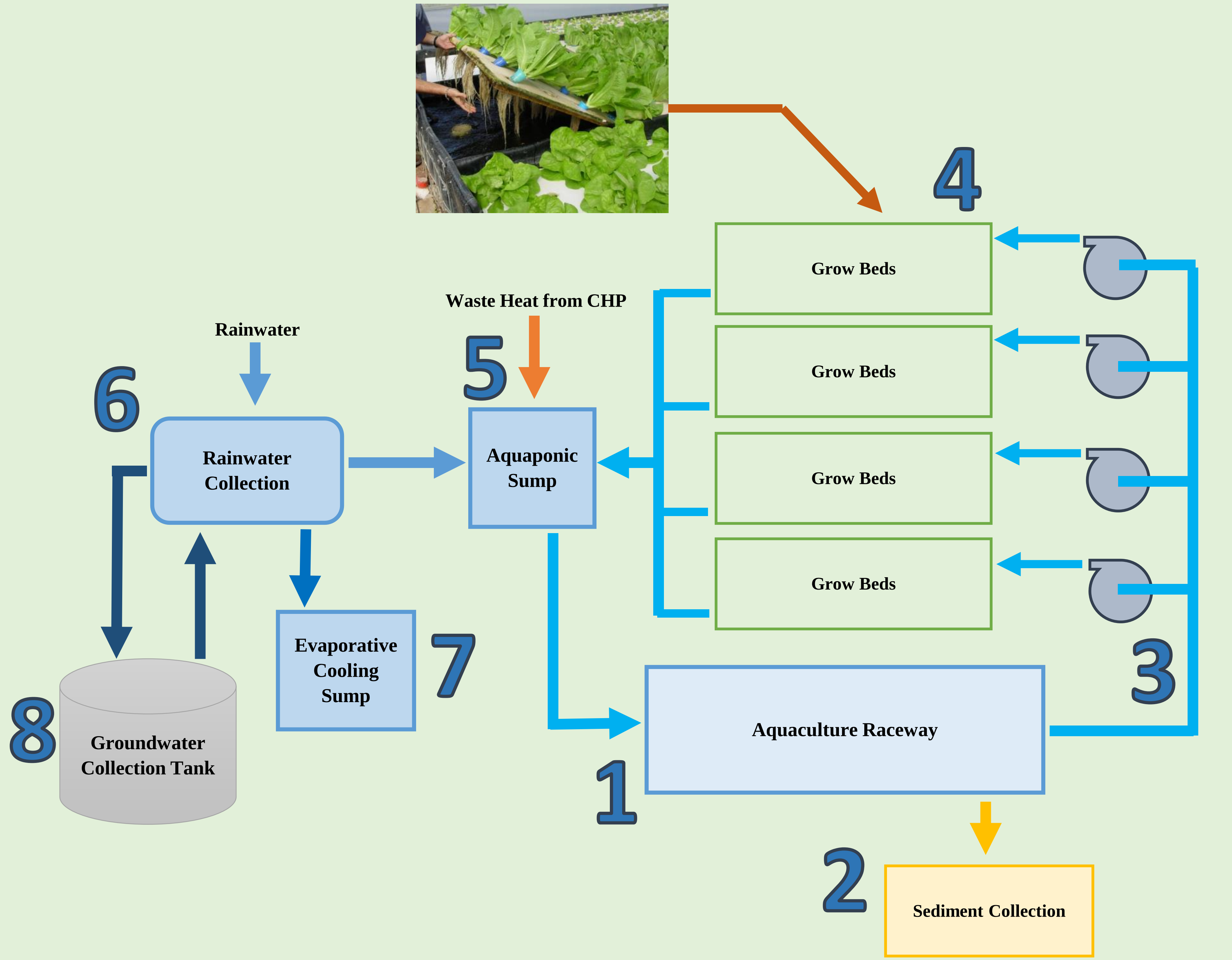


Figure SD 3. The Growing Power Vertical Farm facility comprises of a complex network of aquaculture, plants, and water sources within its greenhouses. Photo of raft grow bed courtesy of aquaponics.com.

AQUAPONIC SYSTEM SIZING

The flow rate through the growing beds was determined using the Aquaponic Media Bed Sizing Model (Ver. 2.0) by Lennard.[21] The model bases its calculations off of the findings in the University of the Virgin Islands aquaponics facility researched by Rakocy.[23] The model asks for inputs on the aquaculture side of the system, including fish tank volume, fish culture density, daily feed rate, and feed protein to output the size of the grow bed. Due to a limiting factor of square footage in the greenhouses, the aquaponic system in the Growing Power Vertical Farm was sized first by determining the appropriate size of grow beds and using the Lennard model in reverse to find an appropriate aquaculture tank size.

An aquaponics system loses about 2% of its water due to evaporation and transpiration per day.[20] Therefore the aquaponic sump tank on each greenhouse level was sized to hold 2% of the aquaculture raceway volume.

Table SD 9: Sizes for Grow Beds, Aquaculture Raceway, and Sump Tank included in the Aquaponic Growing System at Growing Power Vertical Farm

Growing Place Level	Growing Beds			Aquaculture Raceway		Pumps			Sump
	Quantity	Area	Flow Rate	Volume	Flow Rate	Total Flow Rate	Flow Rate per Pump	Quantity per Floor	Volume
		SF	gal/hr	gallons	gal/hr	gal/hr	gal/hr		gallons
2	16	832	1545	6604	2201	3746	1000	4	140
3	16	832	1545	6604	2201	3746	1000	4	140
4	8	416	772.5	3302	1101	1873	1000	2	70
5	36	1872	3462	14794	4931	8393	1000	9	300

Pump Flow Rate Calculations

The Aquaponic Media Bed Sizing Model (Ver. 2.0) by Lennard determined the flow rate through the growing beds. Using the same model, the volume of the aquaculture raceway was determined. Because the water in aquaculture tanks are typically turned over every three hours[23], the total flow rate through the aquaponic system is found by the following equation:

$$GPM_{system} = GPM_{grow\ beds} + \frac{V_{raceway}}{3}$$

Using this equation, the pumps were sized such that each pump can serve one set of four (4) grow beds at 1000 GPH.

GREENHOUSE ENVELOPE OPTIMIZATION

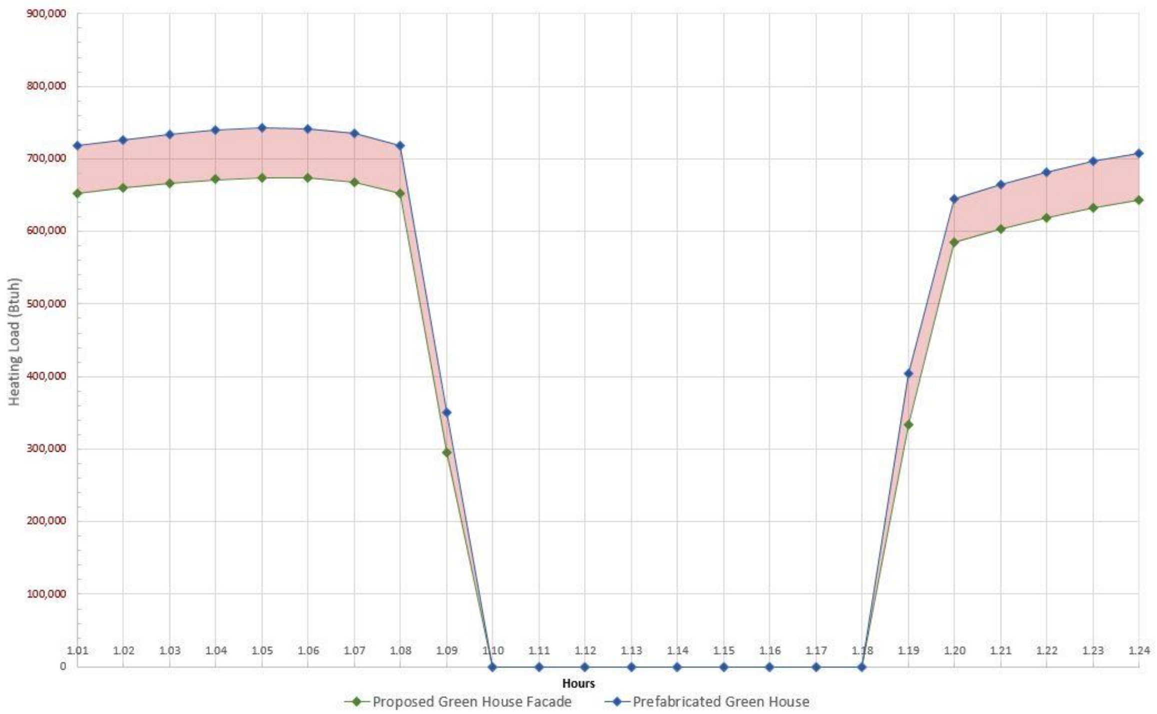


Figure SD 4. Typical greenhouse heating loads for January. The heating load is reduced compared to the prefabricated greenhouse by optimizing the glazing to mass wall ratio.

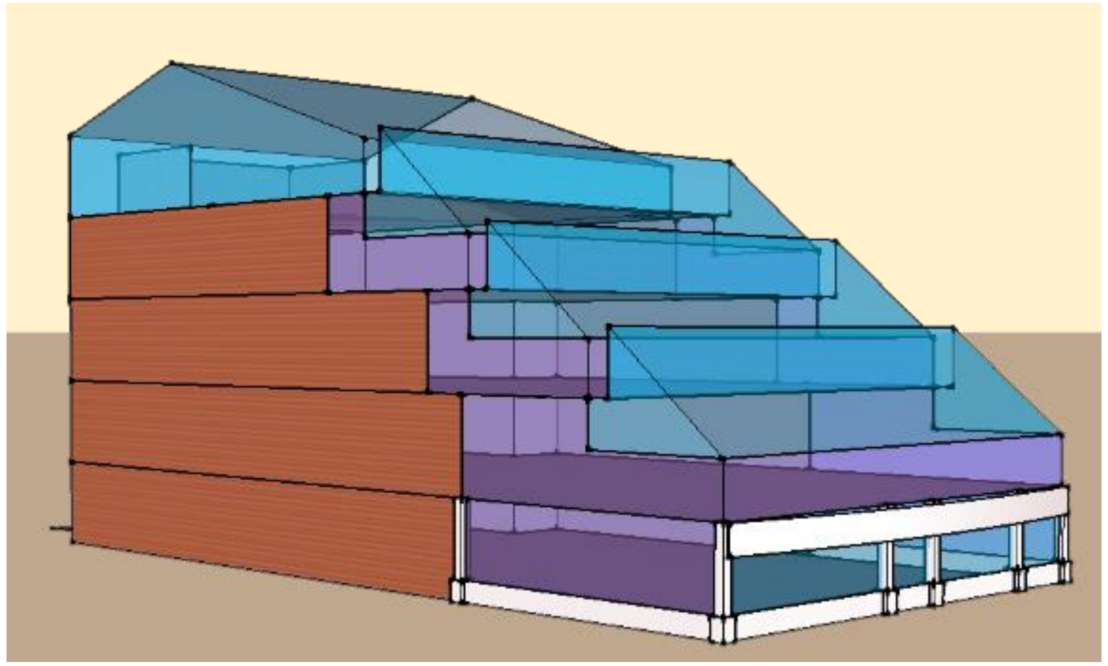


Figure SD 5. The areas highlighted in purple indicate the areas of the greenhouse where glazing could be replaced by thermal mass walls.

After the lighting/electrical design partners realized the glazing area needed in each greenhouse to optimize plant growth, the mechanical partners used this opportunity to replace glazing with mass walls to increase the thermal performance of the greenhouses. Choosing to analyze and optimize the greenhouse system rather than specifying a prefabricated system allowed the design team achieve this thermal benefit.

ANAEROBIC DIGESTION FACILITY

Table SD 10: Parameters Considered for Sizing the Two Phase Anaerobic Digestion System.

Two Phase Anaerobic Digestion Parameters										
		780 Kg Dry Waste/m3	*18.74% VS*		*750m3/tVS*	*65% CH4 / 35% CO2*		*1 Kbtu / m3 CH4*	*Currently Held Constant*	
Food Waste		Waste Volume	Volitale Solids	Vs Concentration	Biogas yeild	Methane Yield	Methane Yield	Energy Content	Organic Loading Rate	Tank Volume
Kg	lb	m3	Kg	Kg/m3	m3	m3	ft3	KBtu	Kg/m3/Day	m3
10	22.04	0.013	1.874	146	1.406	0.91	32.26	32	3.0	0.62
20	44.08	0.026	3.748	146	2.811	1.83	64.52	65	3.0	1.25
30	66.12	0.038	5.622	146	4.217	2.74	96.79	97	3.0	1.87
40	88.16	0.051	7.496	146	5.622	3.65	129.05	129	3.0	2.50
50	110.2	0.064	9.37	146	7.028	4.57	161.31	161	3.0	3.12
1700	3747	2.179	318.58	146	238.935	155.31	5484.54	5485	3.0	106.19
1710	3769	2.192	320.454	146	240.341	156.22	5516.80	5517	3.0	106.82
1720	3791	2.205	322.328	146	241.746	157.13	5549.06	5549	3.0	107.44
1730	3813	2.218	324.202	146	243.152	158.05	5581.32	5581	3.0	108.07
1740	3835	2.231	326.076	146	244.557	158.96	5613.59	5614	3.0	108.69
1750	3857	2.244	327.95	146	245.963	159.88	5645.85	5646	3.0	109.32
1760	3879	2.256	329.824	146	247.368	160.79	5678.11	5678	3.0	109.94
1770	3901	2.269	331.698	146	248.774	161.70	5710.37	5710	3.0	110.57

Table SD 11: Energy Potential Calculation

Energy Potential BY Two Phase Anaerobic Digestion		
Energy Potential = EA - (EB+EC)	4,299	kBtu
EA = Mp * LHV,Methane	5,469	kBtu
EB = Q * Cp * (Ti-To)	49	kBtu
EC = k*A*(Ti-To)*(3600*24)	1,121	kBtu
(EB+EC)/24=Anaerobic Heat Demand/hr	**49**	**MBH**

Energy Potential Parameters			
Methane Potential	Mp	5581	ft^3
Low Heating Value	LHV	980	Btu/ft^3
Waste Mass Flow	Q	3800	lbm/day
Avg. Specific Heat of Waste	Cp	1	Btu/lbm-°F
Digester Temerature	Ti	85	°F
Ambient Temperature	To	72	°F
Thermal Conductivity	k	1.703	Btu/SF-hr-°F
Surface Area	A	2110	SF

Anaerobic Tank Volume Calculations (Curry, 2012)

$$Volume(m^3) = \frac{Flow\ Rate\left(\frac{m^3}{Day}\right) * Volitile\ Solids\ Concentration\ \left(\frac{kg}{m^3}\right)}{Organic\ Loading\ Rate\ \left(\frac{kg}{m^3}/Day\right)}$$

- Volatile Solids Concentration assumed to be 18.74% VS/Unit Waste Based on typical food waste composition.[28]
- Waste volume based on the Density and typical dryness of food waste.[26]
- D = 780 kg Dry Waste/m^3

$$Density\ \left(\frac{kg}{m^3}\right) = 1 - e^{\left(\frac{-0.3}{b-0.1}\right)}$$, where b = Dryness %

Design Justification

The anaerobic system sizing was based on an assumed organic loading rate of 3 kg/m^3/Day. The assumption was based on the average found organic loading rate of typical food waste performed at the Clarkson University anaerobic digestion campus study.[29]

The decision to install two phase anaerobic digestion system was made due to the assumed fluctuation in loading rate that might be expected at the Growing Power vertical farm. The two phase system will allow for a more stable process and require less maintenance.[29]

The anaerobic facility was confined to the basement to be sensitive to site constraints that might exist in different locations. Maintaining the system within the footprint of the building allows Growing Power to explore more urban sites than the current Milwaukee location.

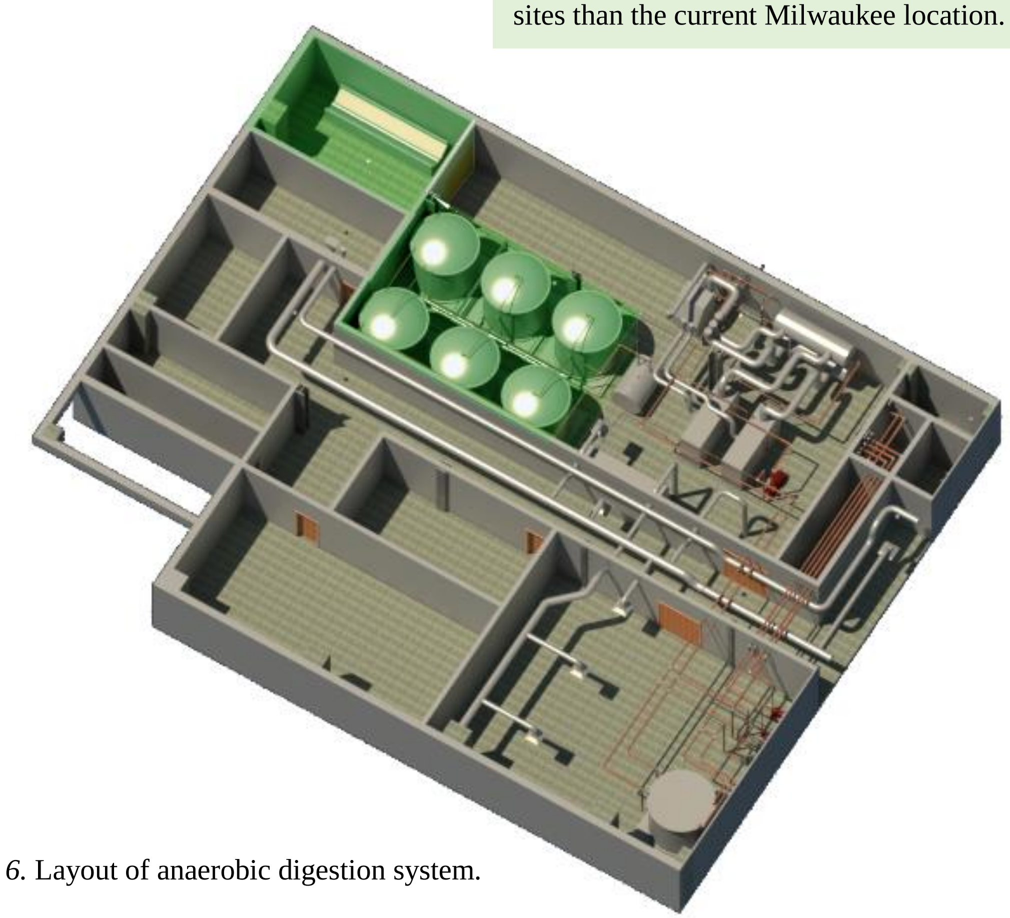


Figure SD 6. Layout of anaerobic digestion system.

COMBINED HEAT AND POWER (CHP) FACILITY

The CHP facility was sized by studying the simulated thermal and electrical loads from Trane TRACE 700. The thermal to electric ratio of the site was matched with an internal combustion engine with a similar ratio. Understanding that the thermal to electric ratio would not be constant throughout the year, the duration curve and primary energy utilization factors to the right were used to design a CHP facility that could out perform a separate heat and power facility for the majority of the year.

Table SD 12 shows a study that was performed to better understand how the CHP facility would perform throughout the year. By looking at the table it can be seen that larger thermal stresses in the winter require that the system be equipped with a supplemental boiler to meet peak thermal load, but at yearly average weather conditions the CHP facility can handle the building demand on its own.

Viessmann BM-55/88	
(2) 55 kW IC Engines	λ=1.30
Electric Power (kW)	110
Heating Power (kW)	176
Gas Consumption (kW)	330
Electric Efficiency (%)	33
Heating Efficiency (%)	53
Overall Efficiency (%)	87

Figure SD 7. BM-55/88 courtesy of Viessmann

CHP Equations

$$\lambda_{site} = \frac{Q_D}{w_{e^-}}$$

$$\lambda_{CHP} = \eta_{HRU}\left(\frac{1}{\eta_{CHP}} - 1\right)$$

$$PEUF_{SHP} = \frac{\eta_B * \eta_{GTD}(1 + \lambda_{site})}{\eta_B + \eta_{GTD} * \lambda_{site}}$$

$$PEUF_{CHP} = \eta_{CHP}(1 + \lambda_{site})$$

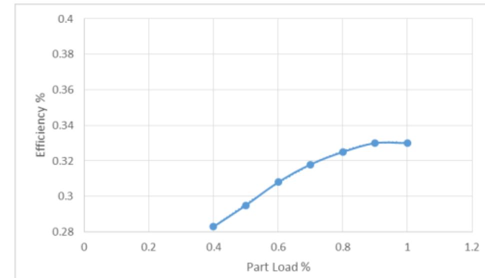


Figure SD 8. BM-55/88 Part Load Efficiencies.

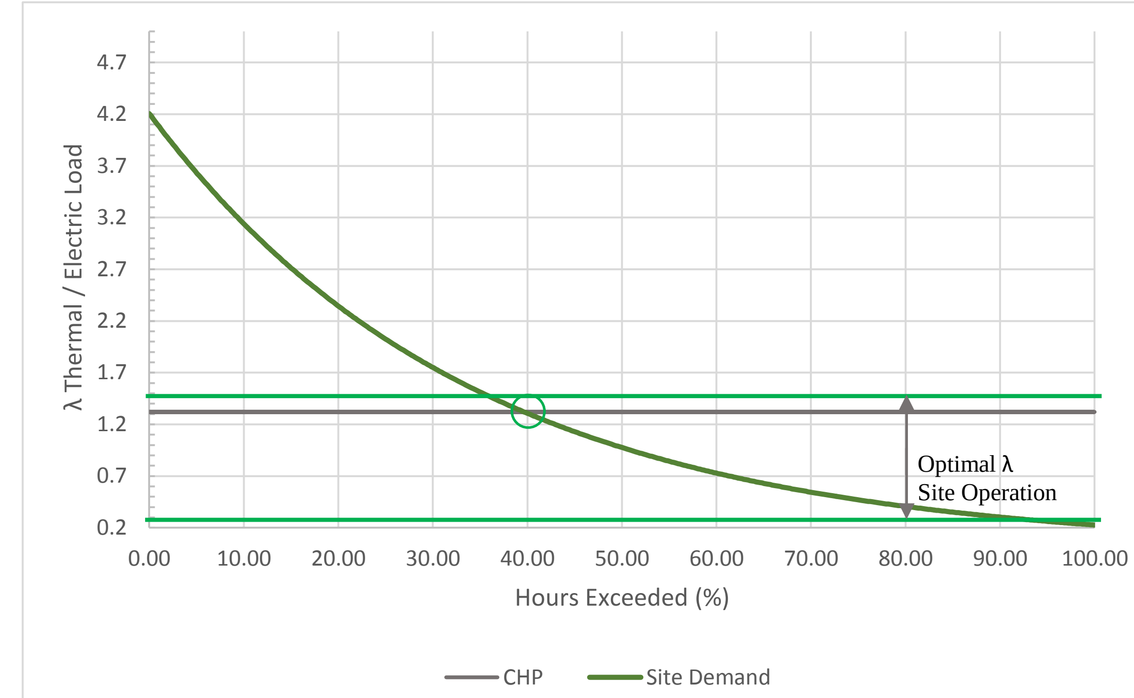


Figure SD 9. Thermal to Electric ratio duration curve. The thermal to electric ratio of the CHP system was plotted against the building λ demand. The data suggests the 40% of year the facility has a larger λ than can be provided by the system.

Table SD 12: CHP Operation Simulation at Typical Seasonal Days.

	Heat Demand (kW)							Electric Demand (kW)						Year Avg. Operation		
Hours	Yearly Average	Summer	Heat Δ	Fuel Cons.	Winter	Heat Δ	Fuel Cons.	Yearly Average	Summer	Electric Δ	Winter	Electric Δ	Lambda	Heat Δ	Electric Δ	Fuel Cons.
1	50	14	21	100	86	28	330	36	30	0	43	67	1.40	0	11	144
2	55	14	21	100	97	17	330	37	30	0	46	64	1.50	0	15	158
3	61	15	20	100	110	5	330	38	30	0	48	62	1.58	23	39	240
4	66	15	20	100	121	6	330	40	30	0	51	59	1.67	18	37	240
5	71	15	20	100	130	16	330	41	30	0	54	56	1.73	13	36	240
6	74	15	20	100	137	22	330	42	30	0	57	53	1.75	10	35	240
7	75	15	7	64	139	25	330	37	24	0	52	58	2.04	9	40	240
8	200	57	27	240	315	201	330	70	59	18	83	27	2.85	86	40	330
9	132	52	32	240	204	89	330	73	71	6	80	30	1.80	18	37	330
10	140	60	46	304	208	94	330	87	96	0	87	23	1.60	26	23	330
11	125	52	58	320	190	76	330	90	102	0	85	25	1.40	11	20	330
12	116	46	53	286	180	66	330	84	90	0	83	27	1.39	2	26	330
13	113	41	58	286	179	64	330	82	90	0	80	30	1.38	1	28	330
14	108	36	73	314	174	60	330	88	99	0	84	26	1.23	6	22	330
15	106	33	78	320	172	57	330	91	102	0	87	23	1.16	8	19	330
16	106	32	73	303	173	58	330	86	95	0	84	26	1.23	8	24	330
17	79	24	70	273	129	15	330	75	84	0	72	38	1.06	5	2	240
18	83	25	67	265	134	20	330	74	81	0	72	38	1.13	0	3	240
19	89	27	63	260	144	30	330	73	79	0	74	36	1.22	5	4	212
20	96	28	55	240	157	42	330	69	71	6	72	38	1.40	0	21	278
21	99	29	32	176	162	48	330	58	55	0	67	43	1.69	0	35	285
22	27	15	28	125	42	72	330	41	40	0	45	65	0.65	57	36	240
23	37	14	21	103	61	53	330	35	31	0	40	70	1.07	47	42	240
24	45	14	21	103	75	40	330	36	31	0	42	68	1.25	39	41	240
Sum	*2151*	*690*	*985*	*4822*	*3520*	*774*	*7920*	*1481*	*1478*	*30*	*1587*	*1053*		*96*	*636*	*6447*
Average	*90*	*29*	*41*		*147*	*32*		*62*	*62*	*1*	*66*	*44*	*1.47*			
Max	*200*	*60*	*78*		*315*	*72*		*91*	*102*	*18*	*87*	*70*	*2.85*			
Yearly Peaks	*565*							*125*					*5.94*			

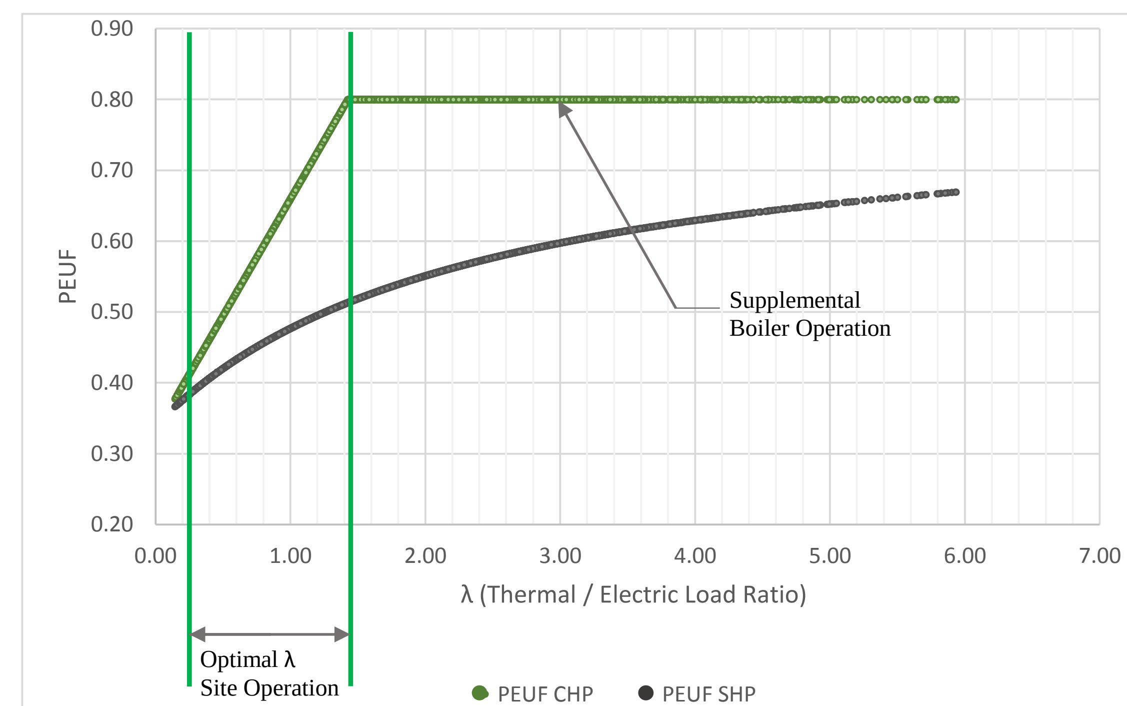


Figure SD 10. Comparison of CHP and SHP Primary Energy Utilization Factor at variable λ. The data shows that the PEUF of the Growing Power CHP facility outperforms typical SHP facilities. It also shows that a supplemental boiler will need to be included in the system for days that generate large cold stresses, increasing λ beyond the optimal site operation.

EMISSIONS STUDY

Table SD 13: EPA Calculator for Emissions Reductions and Environmental and Energy Benefits for Landfill Gas Energy Projects. Courtesy of the EPA and Landfill Methane Outreach Program.[37]

LANDFILL METHANE OUTREACH PROGRAM

For direct-use projects, enter landfill gas utilized by project: **0.0086** million standard cubic feet per day (mmscfd)

Emission Reductions and Environmental and Energy Benefits for Landfill Gas Energy Projects						
Direct Equivalent Emissions Reduced		**Avoided Equivalent Emissions Reduced**		**Total Equivalent Emissions Reduced**		
[Reduction of methane emitted directly from the landfill]		[Offset of carbon dioxide from avoiding the use of fossil fuels]		[Total = Direct + Avoided]		
$MMTCO_2E$/yr million metric tons of carbon dioxide equivalents per year	**tons CH_4/yr** tons of methane per year	**$MMTCO_2E$/yr** million metric tons of carbon dioxide equivalents per year	**tons CO_2/yr** tons of carbon dioxide per year	**$MMTCO_2E$/yr** million metric tons of carbon dioxide equivalents per year	**tons CH_4/yr** tons of methane per year	**tons CO_2/yr** tons of carbon dioxide per year
0.0008	33	0.0001	82	0.0008	33	82
Equivalent to any one of the following annual benefits:		**Equivalent to any one of the following annual benefits:**		**Equivalent to any one of the following annual benefits:**		
Environmental Benefits		Environmental Benefits		Environmental Benefits		
• Carbon sequestered by __ acres of U.S. forests in one year:	616	• Carbon sequestered by __ acres of U.S. forests in one year:	61	• Carbon sequestered by __ acres of U.S. forests in one year:		677
• CO2 emissions from __ barrels of oil consumed:	1,748	• CO2 emissions from __ barrels of oil consumed:	173	• CO2 emissions from __ barrels of oil consumed:		1,921
• CO2 emissions from __ gallons of gasoline consumed:	84,584	• CO2 emissions from __ gallons of gasoline consumed:	8,351	• CO2 emissions from __ gallons of gasoline consumed:		92,936
Energy Benefits (based on project size entered):						
• Heating __ homes:	21					

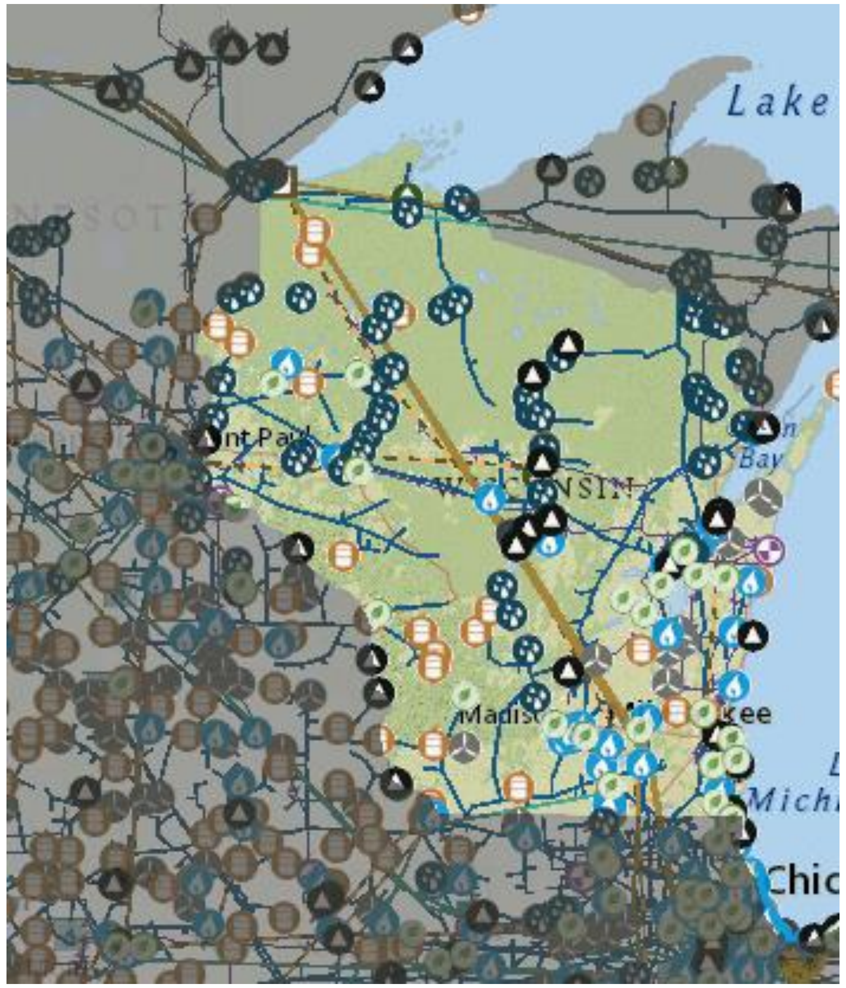


Figure SD 11. Power plant locations throughout Wisconsin. In 2013 coal power plants counted for 62% of Wisconsin's total power generation.[35]

Table SD 14: CO_2 Reduction of the CHP Facility versus a Standard Separate Heat and Power Facility.[36]

Emissions Characteristics of CHP Facility				
				Totals
CF / Year	724153.00	0.12037	lb CO_2/CF CH^4	87166.29661
kWh/Year	540763.46	1.18	lb CO_2/kWh	638100.8828
CO^2 Emissions Reduction (lb CO_2)				550934.5862
Emissions Savings Compared to Separate Heat and Power				***86%***

Social Considerations for Growing Power's Combined Heat and Power Facility

Alongside the feasibility study for the CHP and anaerobic digestion facility for Growing Power, the emissions reduction realized by the facility was documented. On top of the possible economic and efficiency benefits of the CHP facility, reduced emissions provides a benefit to the entire community and helps Growing Power establish themselves as a community leader.

ECONOMIC ANALYSIS

Economic Considerations for Growing Power's Combined Heat and Power Facility

An economic study was performed on the Growing Power Milwaukee's CHP and anaerobic digestion facility to determine the payback on the system. When considering if CHP and on site fuel generation is feasible at future locations, it is the hope of the TBD design team that the same feasibility, economic, and social factors will be considered.

The economic analysis shows that the CHP and anaerobic facility installed in Milwaukee had a reasonable payback period of 3 years if the local Wisconsin incentives were perused. The longer payback of 6 years without incentives should still be weighed against all the social benefits the CHP facility creates by lowering community CO_2 emissions.

Table SD 16: NPV Calculations from 0 to 10 Years

Net Present Value Calculations					
3.00%	Discount Rate (%)				
4.50%	Assumed Escalation Rate of Electricity				
	Offset Total	Offset Electricity	No incentive	Incentive	
0	$ (780,600.00)		$ (780,600.00)	$ (390,300.00)	
1	$ 127,362.32	$ 50,280.52	($656,947.26)	($266,647.26)	
2	$ 129,624.94	$ 52,543.15	($534,763.32)	($144,463.32)	
3	$ 131,989.38	$ 54,907.59	($413,974.34)	($23,674.34)	
4	$ 134,460.23	$ 57,378.43	($294,508.17)	$95,791.83	
5	$ 137,042.25	$ 59,960.46	($176,294.32)	$214,005.68	
6	$ 139,740.47	$ 62,658.68	($59,263.87)	$331,036.13	
7	$ 142,560.12	$ 65,478.32	$56,650.55	$446,950.55	
8	$ 145,506.64	$ 68,424.84	$171,514.83	$561,814.83	
9	$ 148,585.76	$ 71,503.96	$285,393.44	$675,693.44	
10	$ 151,803.44	$ 74,721.64	$398,349.46	$788,649.46	

Table SD 15: Capital Cost for CHP and Anaerobic Digestion Facilities

Capital Cost For CHP facility[32]			Capital Cost For Anaerobic Digestion (AD)[31]		
Growing Power CHP Capacity	**110**	**kW**	**Growing Power AD Capacity**	**696**	**tons/yr**
Average Capacity	100	kW	Capital Cost	600	($/ton)
Gen Set Package	1,400	($/kW)			
Heat Recovery	250	($/kW)			
Interconnect/Electrical	250	($/kW)			
Exhaust Gas Treatment	--	($/kW)			
Thermal Storage	400	($/kW)			
Total Equipment	2,300	($/kW)			
Labor/Material	500	($/kW)			
Total Process Capital	2,800	($/kW)			
Construction Management	125	($/kW)			
Engineering Fees	250	($/kW)			
Project Contingency	95	($/kW)			
Project Financing	30	($/kW)			
Total Plant Cost	3,300	($/kW)			
Total Operation and Maintenance Cost	0.024	($/kWh)	Total Operation and Maintenance Cost	34	($/Ton)
Energy Offset	127,362.32	($/year)	Tipping Fees	40	($/Ton)
Growing Power CHP Capital Cost	$363,000.00		Growing Power AD Capital Cost	$ 417,600.00	
Total Facility Capital Cost	**$780,600.00**				

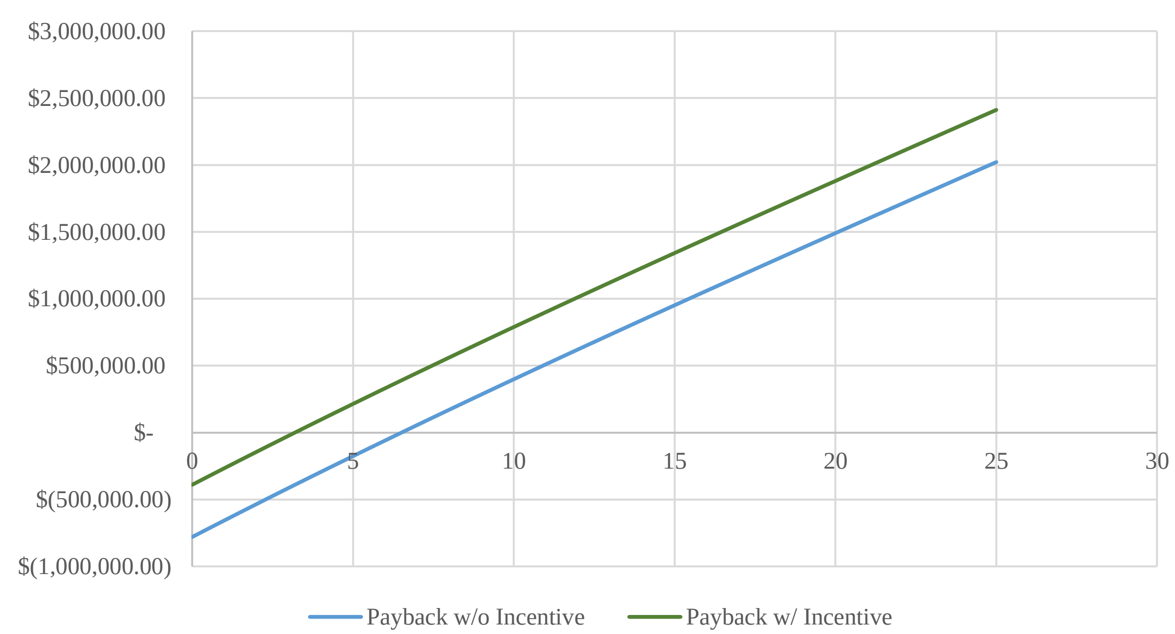


Figure SD 12. Net Present Value calculation of the CHP and anaerobic digestion facility at Growing Power Vertical Farm Facility in Milwaukee.

OVERALL MECHANICAL SYSTEM SCHEMATIC

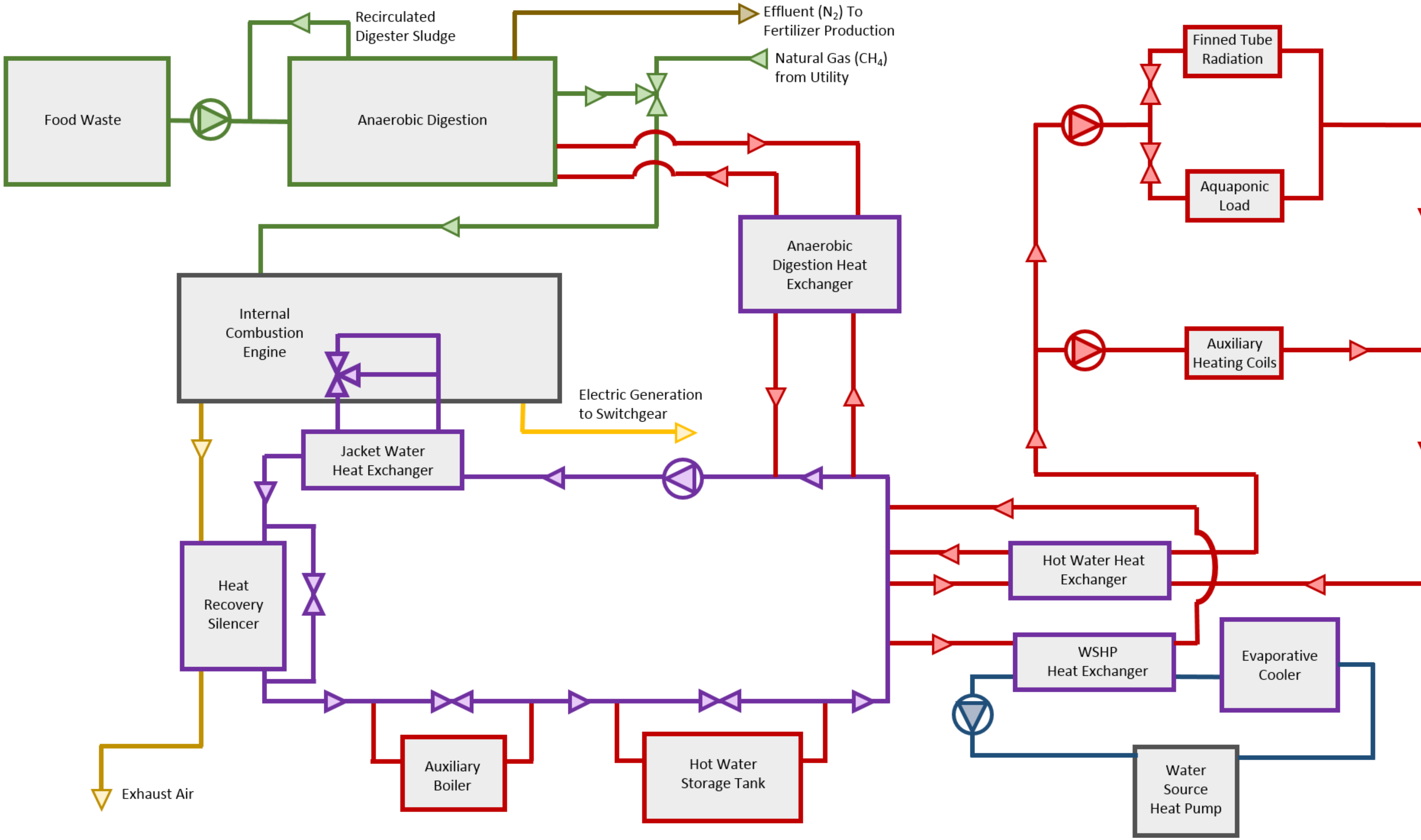


Figure SD 13. The overall mechanical system schematic demonstrates how the combined heat and power facility interacts with the building loads and anaerobic digestion. The heat recovered from the internal combustion engines is redirected to the main building and greenhouse loads. A hot water storage tank is used to meet heating loads that are out of phase with building electric loads, while an auxiliary boiler is used to meet design day heating loads. The anaerobic digestion facility feeds the internal combustion engine until additional natural gas is needed from the utility.

SOYBEAN OIL BIODIESEL PRODUCTION: AN ALTERNATIVE FOR FUTURE GROWING POWER VERTICAL FARM SITES

Soybean Oil Biodiesel Production Process:

1. Soybean Oil Press. Pre-cleaned soybeans enter the soybean oil press where they are compressed into soybean oil, after which soybean oil is dripped into a holding tank. Also resulting from the press is a soybean mash held in the meal mixing bin for later use.

2. Transesterification. Soybean oil reacts in a biodiesel processor in which it is turned into biodiesel through transesterification. Transesterification involves soybean oil reacting with ethanol and sodium hydroxide to create crude biodiesel.

3. Membrane Biodiesel Purification. The resulting crude biodiesel from transesterification is used to feed the biodiesel generator for the combined heat and power plant. The membrane system of biodiesel purification is a simple filter system in which components of the biodiesel are separated by particle size and shape.[40] The purification of crude biodiesel results in a recovery of glycerin that is sent to the meal mixing bin.

4. Meal Mixing. The main coproduct of transesterification is glycerin, which is used produce fish feed in the meal mixing bin. Using both the crude glycerin from transesterification and the recovered glycerin from membrane biodiesel purification, meal mixing combines the glycerin and soybean mash to create a fish feed for the aquaponic system.

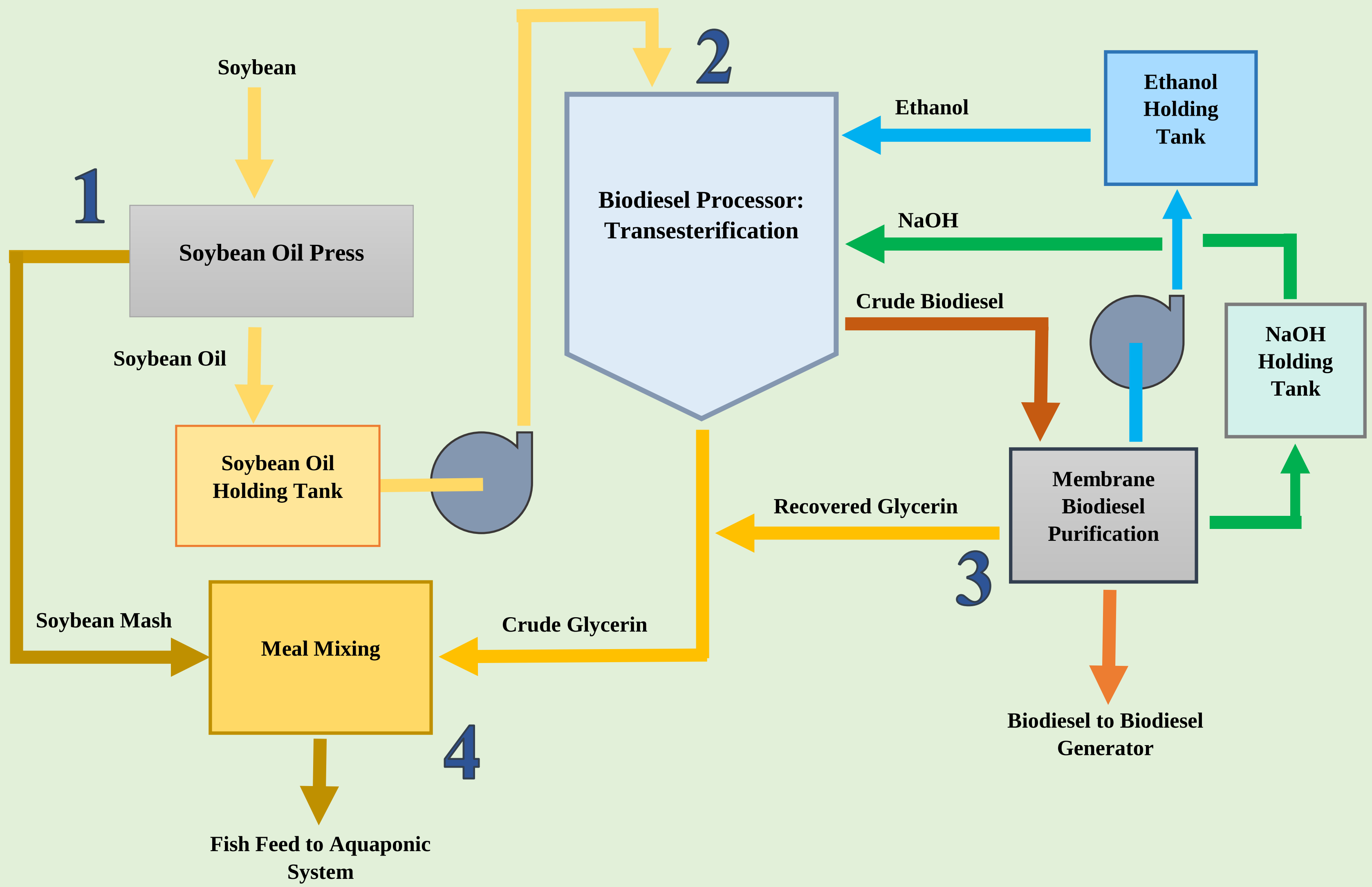


Figure SD 14. A typical soybean oil biodiesel production plant consists of mechanically pressing beans to oil then producing biodiesel through transesterification. A valuable coproduct of this process is the ability to produce fish feed to be used in the aquaponic growing system.

SIZING FOR A SOYBEAN OIL BIODIESEL PROCESS

The following steps were taken to select equipment and size the required components of soybean oil biodiesel production.

1. Size the biodiesel generator for thermal demand of the building.
2. Use the generator data to determine the fuel input of biodiesel required to operate the generator.
3. Select a biodiesel processor that will produce biodiesel at a rate greater than or equal to the fuel input required in 2.
4. Use the biodiesel processor data to determine a soybean oil input volumetric flow rate required for the processor.
5. Select a soybean oil pressing unit that will produce the necessary volumetric flow rate of soybean oil as specified in 4.
6. Use the data from the soybean press to determine the amount of soybeans needed daily.

SOYBEAN OIL BIODIESEL PRODUCTION ENVIRONMENTAL BENEFITS

49.5% less greenhouse gas emissions than a gas generator

90% less pesticides used in production than corn grain ethanol

Table SD 17: Comparison of Soybean Biodiesel to Other Fuels*

Fuel Type	Pesticides Application /NEB [g/MJ]	Fertilizer Nitrogen Application/NEB [g/MJ]	Fertilizer Phosphorus Application/NEB [g/MJ]	GHG Emissions /NEB [g/MJ]
Methane	0	0	0	96.9
Diesel	0	0	0	82.3
Soybean Biodiesel	0.01	0.1	0.2	49
Corn Grain Ethanol	0.1	7	2.6	84.9

*Data Courtesy of Hill et. al, 2006

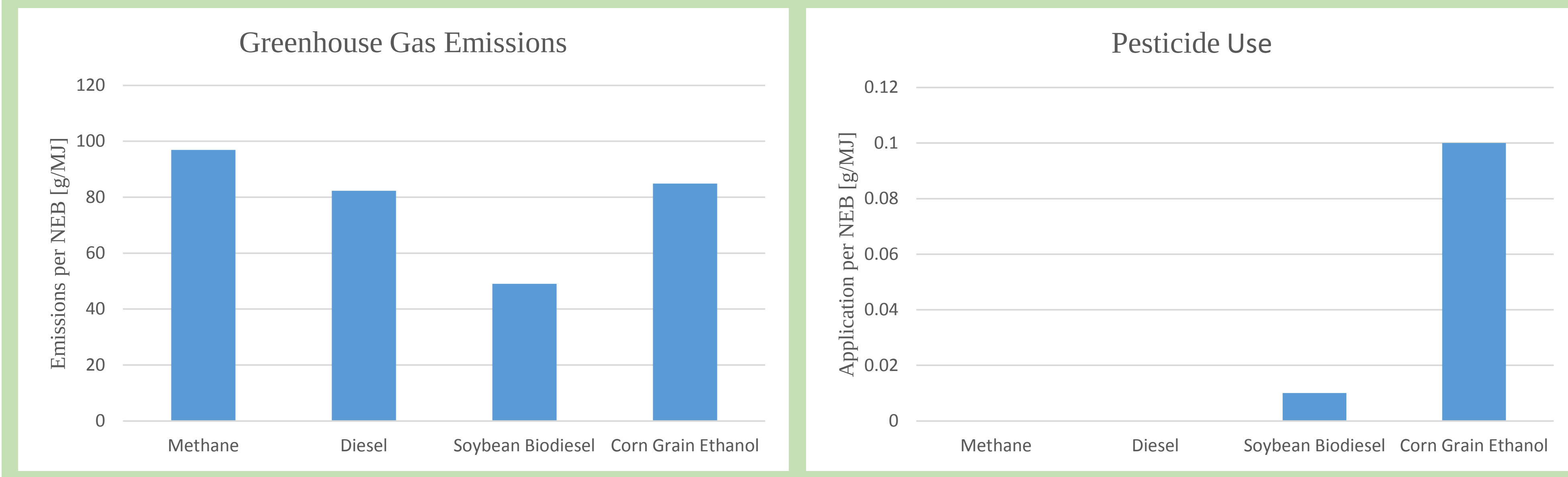


Figure SD 15. Soybean oil biodiesel produces almost half of the GHG emissions of other comparable fuels, and requires 10% of the pesticide used in corn production for ethanol.

Net Energy Balance (NEB) is the energy content of a biofuel relative to the fossil fuel energy input to create the particular biofuel.[42] Thus finding greenhouse gas emissions and pesticide use per NEB becomes a relatable measure of the particular output of a biofuel per fossil fuel input. The left graph of Figure SD 15 shows that soybean oil biodiesel emits a drastically lower amount of greenhouse gases compared to its other fuel counterparts. Compared to corn grain ethanol, which is increasingly used for generator biofuel purposes, soybeans require a tenth of the pesticides used for corn production as shown in the graph on the right of Figure SD 15.

Table SD 18: Average Soybean Production in Wisconsin by County courtesy of AgWeb.[38]

County	Average Soybean Production bushels/acre	Area of Soybean Production acres	Average Soybean Production per County bushels
Manitowoc	58.4	32	1868.8
Fond du Lac	52	200	10400
Jefferson	59	55	3245
Columbia	50	120	6000
Sauk	10	100	1000
Dane	56.1	647	36296.7
Waupaca	42	500	21000
Crawford	54	50	2700
Oconto	14	60	840
Taylor	41	25	1025
Buffalo	51.05	88	4492.4
Dunn	47	236	11092
Polk	37.5	153	5737.5

Total Bushels of Soybean Produced in Wisconsin in 2014: 105,697.4

Supply and Demand of Soybean Oil Biodiesel Production

It must be recognized that soybean oil biodiesel production is only viable with a strong supply of soybeans within a reasonable radius of the future site. Figure 16, on right, is the 2014 AgWeb Soybean Harvest Map [38] which shows the average bushels of soybean produced in each county of Wisconsin per acre of land allotted to soybean production.

Variables that make soybean oil biodiesel production a strong candidate for fuel used in combined heat and power for a future Growing Power location are soybean availability as well as cost of soybean in the area.

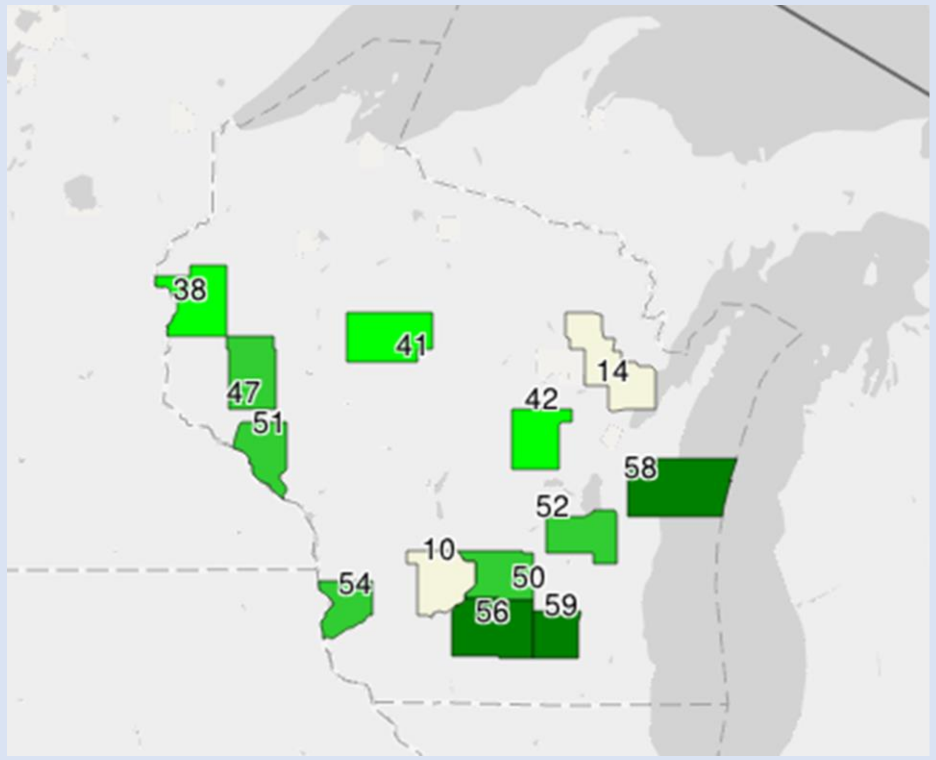


Figure SD 16. Soybean Harvest Map shows the availability of soybeans in Wisconsin.

WATER SOURCE HEAT PUMPS AND DEDICATED OUTDOOR AIR SYSTEM

The water source heat pumps in the Growing Power Vertical Farm were selected to meet the cooling coil capacity output from Trane Trace for each zone. From these capacities it was determined that these WSHP units would sufficiently provide optimal cooling, heating, and airflow within each zone.(D1) The DOAS units provide the minimum outdoor air required by ASHRAE 62.1.

Table SD 19: Summary of DOAS Units in Building

Unit ID	Levels Served	OA Intake CFM	Exhaust to Outside CFM
DOAS-1	Basement, L1, L2	5220	2020
DOAS-2	L3, L4	2460	980

Figure SD 17. Water source heat pumps, such as the units above manufactured by Daikin, are used in the Growing Power Vertical Farm Facility.[13]

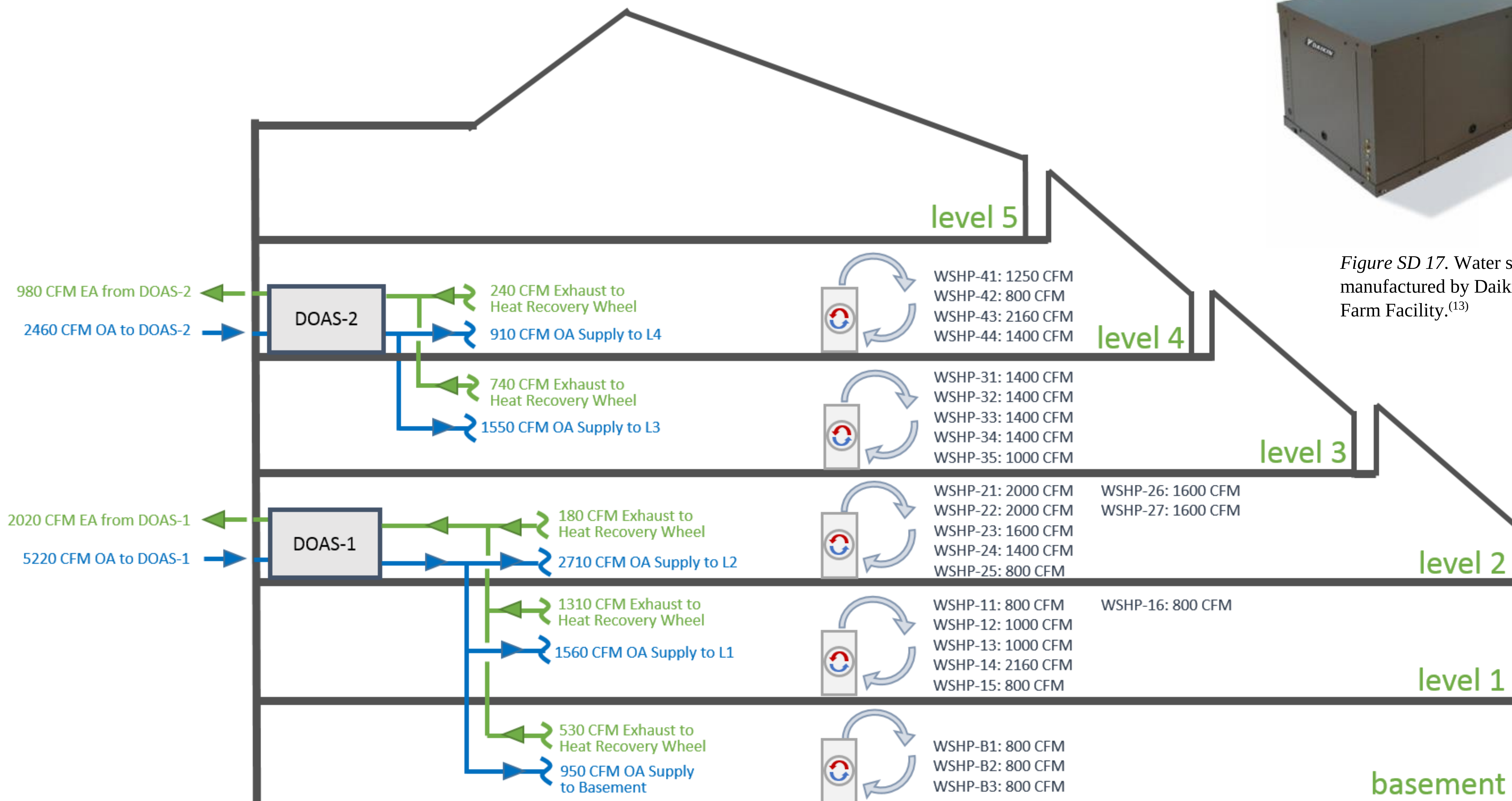


Figure SD 18. Water source heat pumps and dedicated outdoor air units provide heating and cooling, as well as ventilation, respectively.

OCCUPANT COMFORT ANALYSIS

GATHERING SPACE ACOUSTICAL QUALITY ANALYSIS

A reverberation time (RT) calculation was performed to analyze the sound quality of the gathering space. Comparing values of the ideal RT values for a speech auditorium with the calculated values within the gathering space determined that the space would be well suited to hold educational lectures and presentations for the public. It is important to note that an STC calculation is to be performed to specify a partition around the WSHP units in the gathering space such that the noise criterion level is below 25 as specified in the 2009 ASHRAE Fundamentals Chapter 48.3.(4)

Table SD 20: Calculations for Gathering Space Reverberation Time

Surface Description	Surface Area, S [ft²]	Material Description	Sound Absorption Coefficient, α						S*α [sabins]					
			Frequency [Hz]						Frequency [Hz]					
			125	250	500	1000	2000	4000	125	250	500	1000	2000	4000
North Wall	613	gypsum wall board	0.29	0.10	0.05	0.04	0.07	0.09	177.75	61.29	30.65	24.52	42.91	55.16
East Window	40	glass window	0.35	0.25	0.18	0.12	0.07	0.04	14.00	10.00	7.20	4.80	2.80	1.60
East Walls	724	gypsum wall board	0.29	0.10	0.05	0.04	0.07	0.09	210.07	72.44	36.22	28.98	50.71	65.19
South Wall	225	gypsum wall board	0.29	0.10	0.05	0.04	0.07	0.09	65.25	22.50	11.25	9.00	15.75	20.25
West Windows	240	glass window	0.35	0.25	0.18	0.12	0.07	0.04	84.00	60.00	43.20	28.80	16.80	9.60
West Walls	360	gypsum wall board	0.29	0.10	0.05	0.04	0.07	0.09	104.40	36.00	18.00	14.40	25.20	32.40
Ceiling, ACT	951	acoustic ceiling tile	0.40	0.50	0.95	1.00	1.00	1.00	380.40	475.50	903.45	946.25	946.25	946.25
Ceiling, Gypsum Panels	2853	gypsum board panels	0.12	0.11	0.05	0.06	0.04	0.05	328.10	313.83	142.65	156.92	116.97	139.80
Floor	3804	smooth concrete	0.01	0.01	0.01	0.02	0.02	0.02	38.04	38.04	38.04	76.08	76.08	76.08
Seats, Occupied	1381	lightly upholstered, occupied	0.51	0.64	0.75	0.80	0.82	0.83	704.44	884.00	1035.94	1105.00	1132.63	1146.44
West Bench vertical	95	gypsum wall board	0.29	0.10	0.05	0.04	0.07	0.09	69.60	24.00	12.00	9.60	16.80	21.60
West Bench horizontal	119	wood	0.10	0.10	0.09	0.08	0.08	0.08	95.10	95.10	85.59	76.08	76.08	76.08
								ΣSα=	2271.15	2092.7	2364.18	2480.41	2518.97	2590.45

	125	250	500	1000	2000	4000
Avg. α =	0.20	0.18	0.21	0.22	0.22	0.23
Air Absorption constant for 20°C and 40% RH, *m*	0.00	0.00	0.00	0.00	0.00	0.00
Sabine Reverberation Time [s]=	0.85	0.92	0.80	0.76	0.73	0.73
Norris-Eyring Reverberation Time [s]=	0.76	0.83	0.72	0.68	0.65	0.65
Calculated RT [s]	**0.85**	**0.92**	**0.72**	**0.68**	**0.65**	**0.65**
Ideal RT [s]	**0.897**	**0.7935**	**0.69**	**0.69**	**0.69**	**0.69**

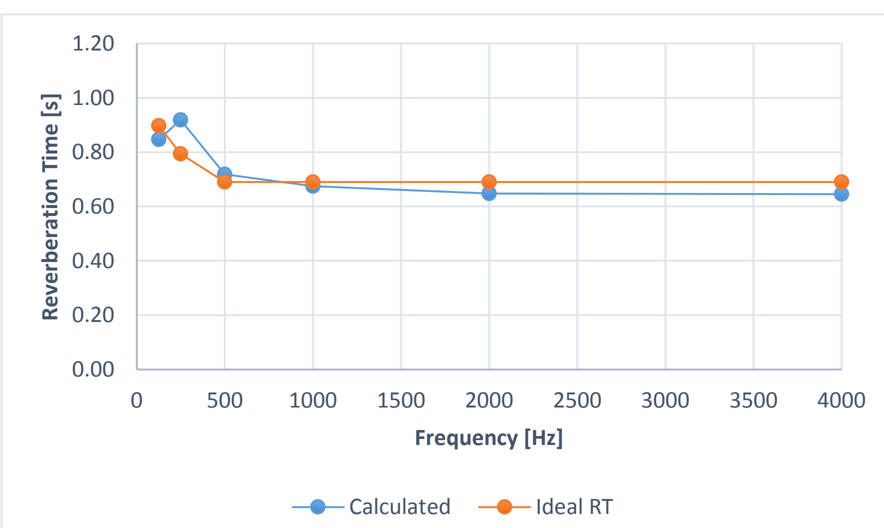


Figure SD 19. Comparison of calculated reverberation time and ideal reverberation time for a speech auditorium

WSHP Schedule

Level	WSHP ID	Spaces Served	Unit Size	CC Capacity BTU	HC Capacity BTU	Refrigerant Type	GPM	CFM	Orientation
B	WSHP-B1	Corridor	26	26400	29300	R410A	6.5	800	Vertical
		Storage 000							
		Storage 002							
	WSHP-B2	Men's Locker Room	26	26400	29300	R410A	6.5	800	Vertical
		Women's Locker Room							
	WSHP-B3	Mechanical Room	26	26400	29300	R410A	6.5	800	Vertical
		Trash							
		Elevator Mech Room							
1	WSHP-11	Mud Room	26	26400	29300	R410A	6.5	800	Horizontal
	WSHP-12	Processing	32	32500	36400	R410A	7.5	1000	Horizontal
	WSHP-13	Workshop	32	32500	36400	R410A	7.5	1000	Horizontal
	WSHP-14	Market	72	72700	88400	R410A	17.5	2160	Vertical
	WSHP-15		72	72700	88400	R410A	17.5	2160	Vertical
	WSHP-16	Office 100A	26	26400	29300	R410A	6.5	800	Vertical
		Office 100B							
2	WSHP-21	Gathering Space, Storage	64	64800	76100	R410A	16	2000	Vertical
	WSHP-22		64	64800	76100	R410A	16	2000	Vertical
	WSHP-23		49	48900	55300	R410A	12.2	1600	Vertical
	WSHP-24		44	44400	50100	R410A	10.5	1400	Vertical
	WSHP-25	Women's Restroom	26	26400	29300	R410A	6.5	800	Horizontal
		Men's Restroom							
		Elevator Lobby							
		Mech/Elec Closet							
	WSHP-26	Breakout Space	49	48900	55300	R410A	12.2	1600	Horizontal
	WSHP-27		49	48900	55300	R410A	12.2	1600	Horizontal
3	WSHP-31	Classroom 53	44	44400	50100	R410A	10.5	1400	Horizontal
	WSHP-32		44	44400	50100	R410A	10.5	1400	Horizontal
	WSHP-33	Classroom 61	44	44400	50100	R410A	10.5	1400	Horizontal
	WSHP-34	Demo Kitchen 56	64	44400	50100	R410A	10.5	1400	Vertical
	WSHP-35	University Incubator	32	32500	36400	R410A	7.5	1000	Horizontal
4	WSHP-41	Collaboration Station	38	39000	44400	R410A	9	1250	Horizontal
		Employee Lounge							Horizontal
	WSHP-42	Corridor	26	26400	29300	R410A	6.5	800	Vertical
		Women's restroom							
		Men's Restroom							
		Elevator Lobby							
		Copy Room							
		Mech/Elec Closet							
	WSHP-43	Director's Office	72	72700	88400	R410A	17.5	2160	Horizontal
		Reception							
		Office Space							
	WSHP-44	Conference Room	44	44400	50100	R410A	10.5	1400	Horizontal

EVAPORATIVE COOLER SCHEDULE

	Water Side					Air Side			Electrical Data	
Description	GPM	Pressure Drop (FT.)	EWT (°F)	LWT (°F)	Range (°F)	CFM	EAWT (°F)	Approach (°F)	Fan HP	Pump HP
WSHP EC	260	9.50	102.00	86.00	16.00	51,000	78.00	8.00	15.00	5.00

Water Source Heat Pump Sizing

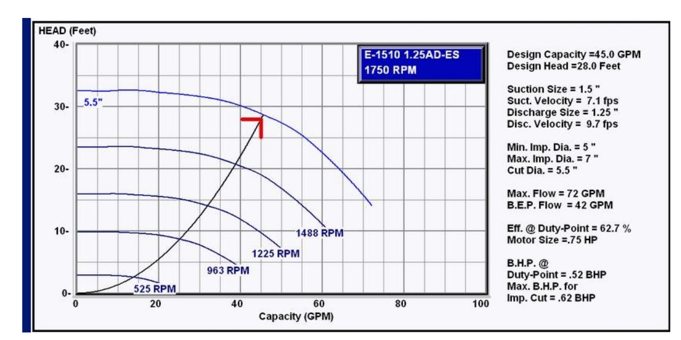
The Water Source Heat Pumps in the Growing Power Vertical Farm were selected to meet the cooling coil capacity output from Trane TRACE 700 for each zone. From these capacities it was determined that these WSHP units would sufficiently provide optimal cooling, heating, and airflow within each zone.

Evaporative Cooler Sizing

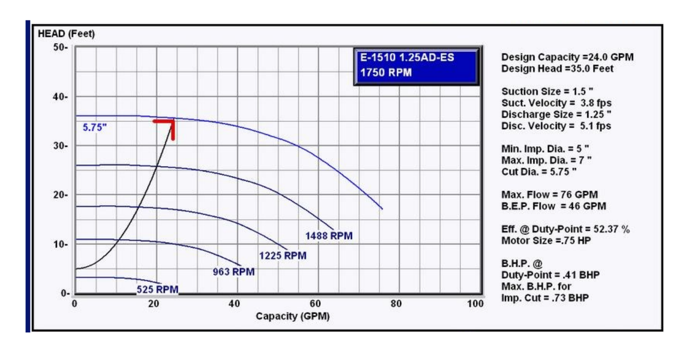
The evaporative cooler for the WSHP water loop was sized based on the peak load of the system. Marley cooling tower selection software was used to make the selection based on an appropriate approach and range.

PUMP SCHEDULE

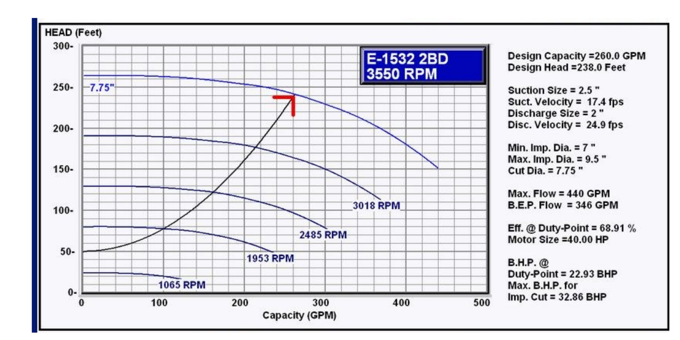
	Pump Selection				Water Loop	
Description	Type	Head (FT.)	GPM	Manufacturer Reference	Temp. Supply (□F)	Temp Return (□F)
WSHP LOOP	End Suction	235	260	Bell and Gossett e-1532	86	68
GREENHOUSE HW	End Suction	25	45	Bell and Gossett e-1510	140	100
AUXILIARY HW LOOP	End Suction	35	24	Bell and Gossett e-1510	140	100



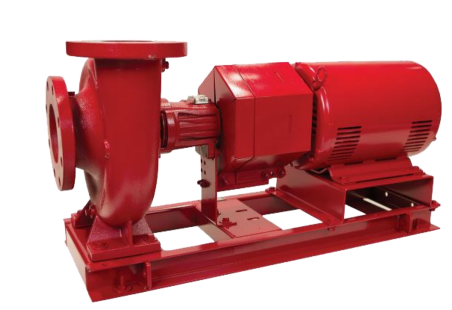
Greenhouse Hot Water Loop



Auxiliary Hot Water Loop



WSHP Water Loop



Pump Selection

Pumps that serve the main HVAC water loops of the building were sized based on the total friction head loss seen by the closed system as well as the maxim GPM flow of the loop. Selection software provided by Bell and Gossett was used to determine the performance curves of the pumps at variable speed.

TBD Engineering | Equipment Schedules

CONDENSING BOILER SCHEDULE						
Description	Nominal Capacity (MBH)	Natural Gas Input (FT^3/Hr)	Output (MBH)	Max Operation Temp (□F)	Flue Gas (lb/Hr)	Fan Motor (kW)
Clever Brooks Condensing	2,500	2,500	2,175	194	2,783	1.2

Condensing Boiler Sizing

The auxiliary backup boiler was selected based on the peak heating load seen by the building. Condensing Boiler sizes were provided by the Clever Brooks website.

Internal Combustion Engine				
Description	Number of Cylinders	Electrical (kW)	Thermal (kW)	Gas Input (kW)
Viessmann BM-55/88	R6	55	88	165
Viessmann BM-55/88	R6	55	88	165

Internal Combustion Engine Sizing

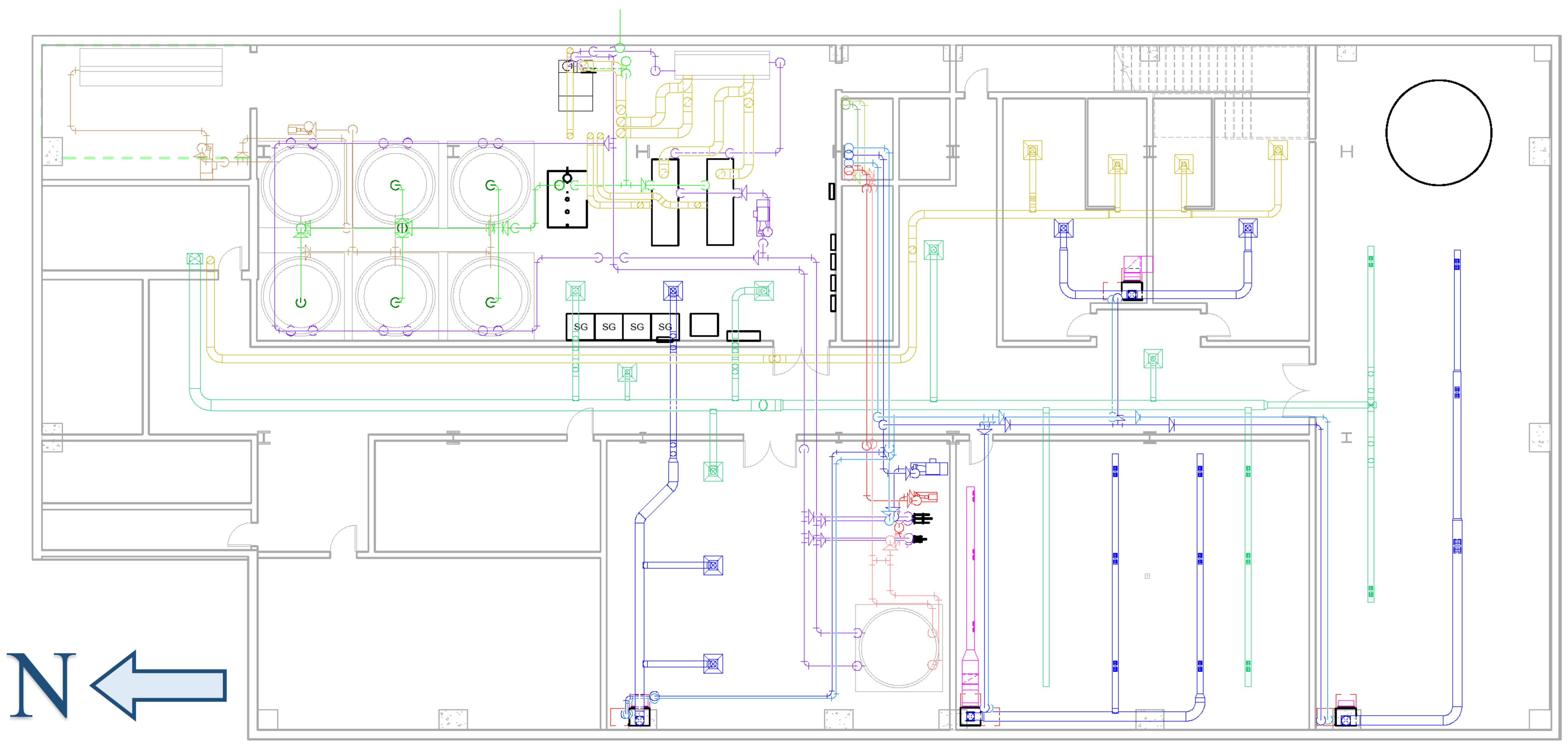
The internal combustion engines used for CHP were sized based on the site thermal and electric demand. The Viessmann Group provided information online about their IC engine efficiencies.

Heat Exchanger Schedule								
	Hot Side				Cold Side			
Description	GPM	EWT	LWT	Pressure Drop	GPM	EWT	LWT	Pressure Drop
HX WSHP Water Loop	92.0	200.0	160.0	2.4	200.0	68.0	86.0	9.9
HX Auxiliary Heating Loop	35.0	200.0	160.0	7.6	35.0	100.0	140.0	6.4
HX Greenhouse Heating Loop	25.0	200.0	160.0	7.8	25.0	100.0	140.0	6.1

Heat Exchanger Sizing

The heat exchangers serving the CHP heat rejection loop were sized base on the heat rejection of the system and the heat demand of the building. Xylem ESP Thermal selection software was utilized to size the heat exchangers.

TBD ENGINEERING | MECHANICAL ROOM LAYOUT



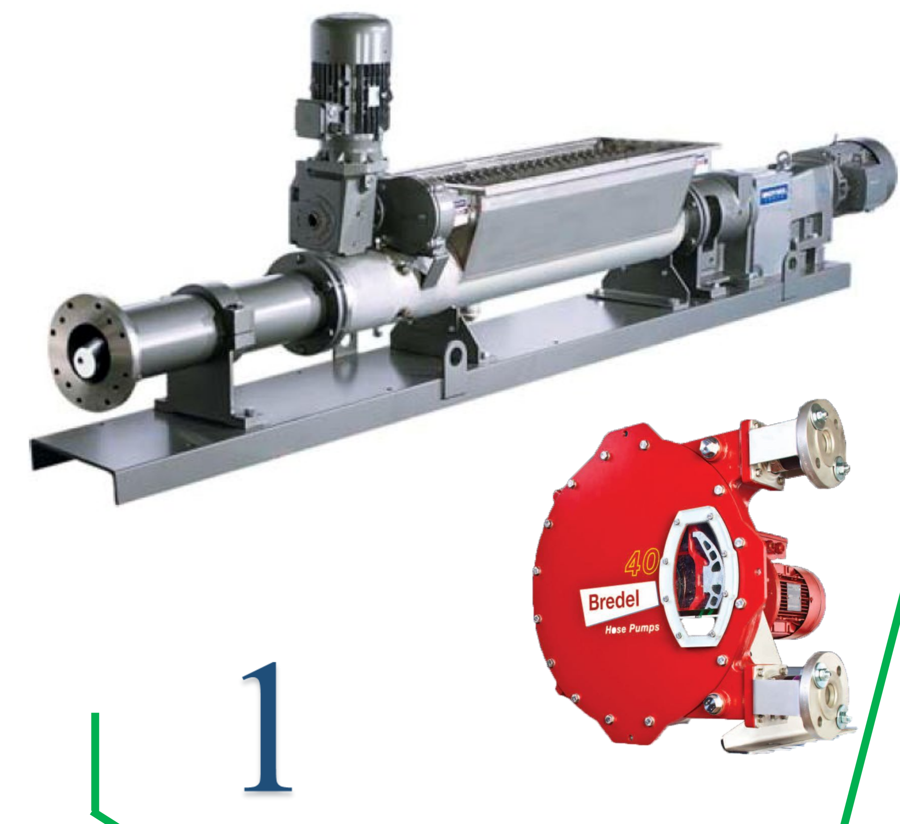
1 / D3 BASEMENT FLOOR PLAN
SCALE: 1/8" = 1'-0"

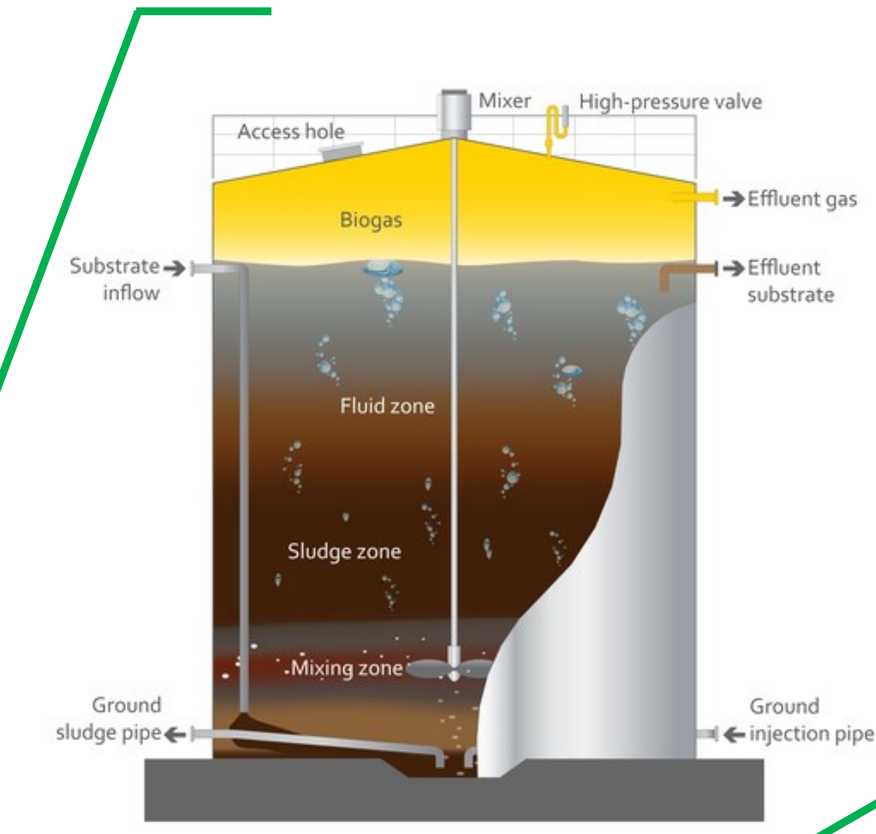
1 Waste Grinder and Waste Pump for anaerobic digestion preprocessing. images courtesy of Moyno Chopper Hopper[14] waster grinder and Marlow Watson hose pump.[14]

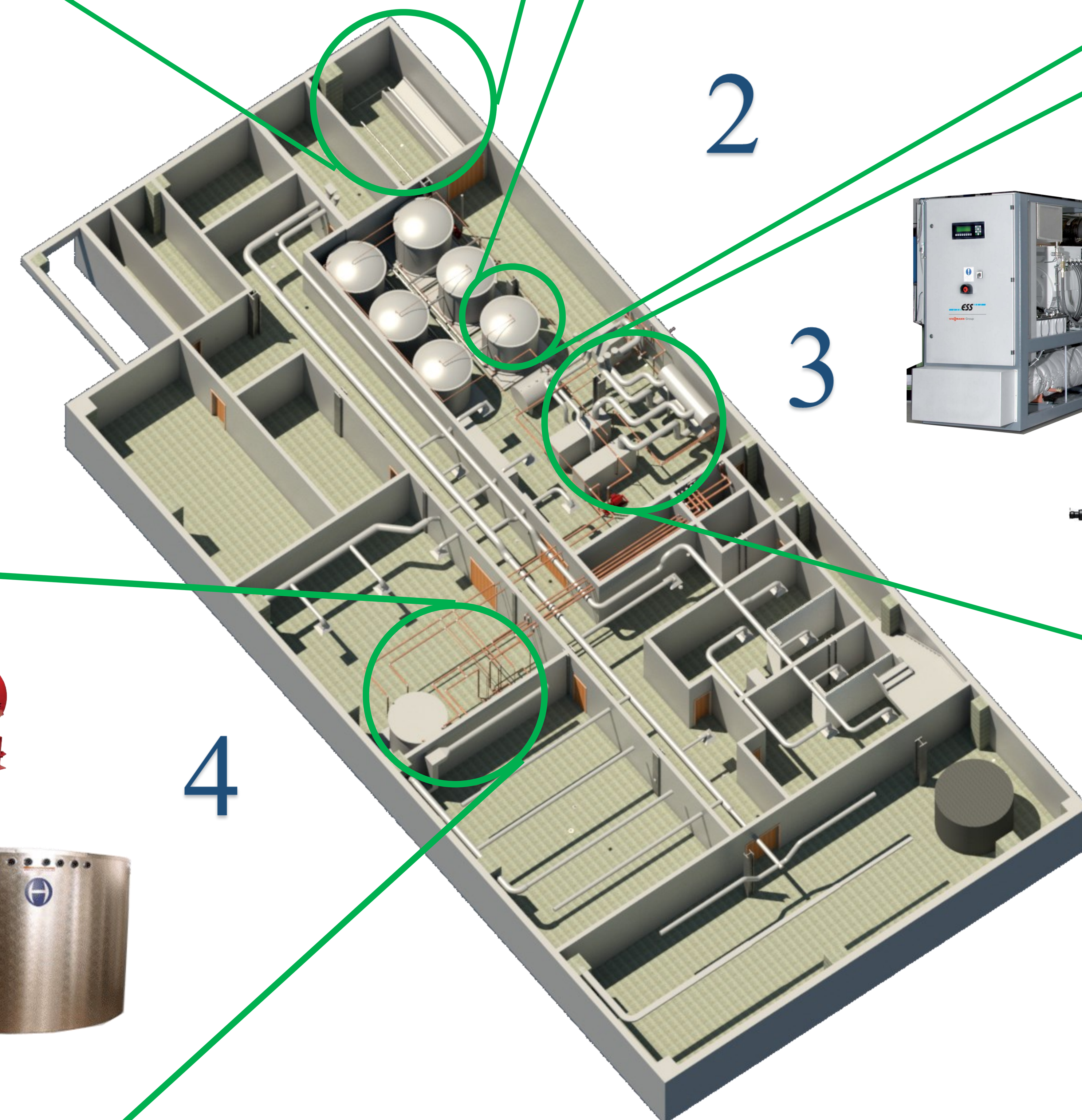
2 Anaerobic Digestion tank with agitator.[14]

3 Internal combustion engine coupled with heat recovery silencer. An auxiliary boiler is included to meet peak heating demands. Images courtesy of Viessmann Group[14], Maxim Heat Recovery Silencers[14], and Clever Brookes Boilers.[14]

4 Hot water storage tank and distribution pumps to building loads. Images courtesy of Hydroflex Systems[14] and Bell and Gossett Pumps.[14]

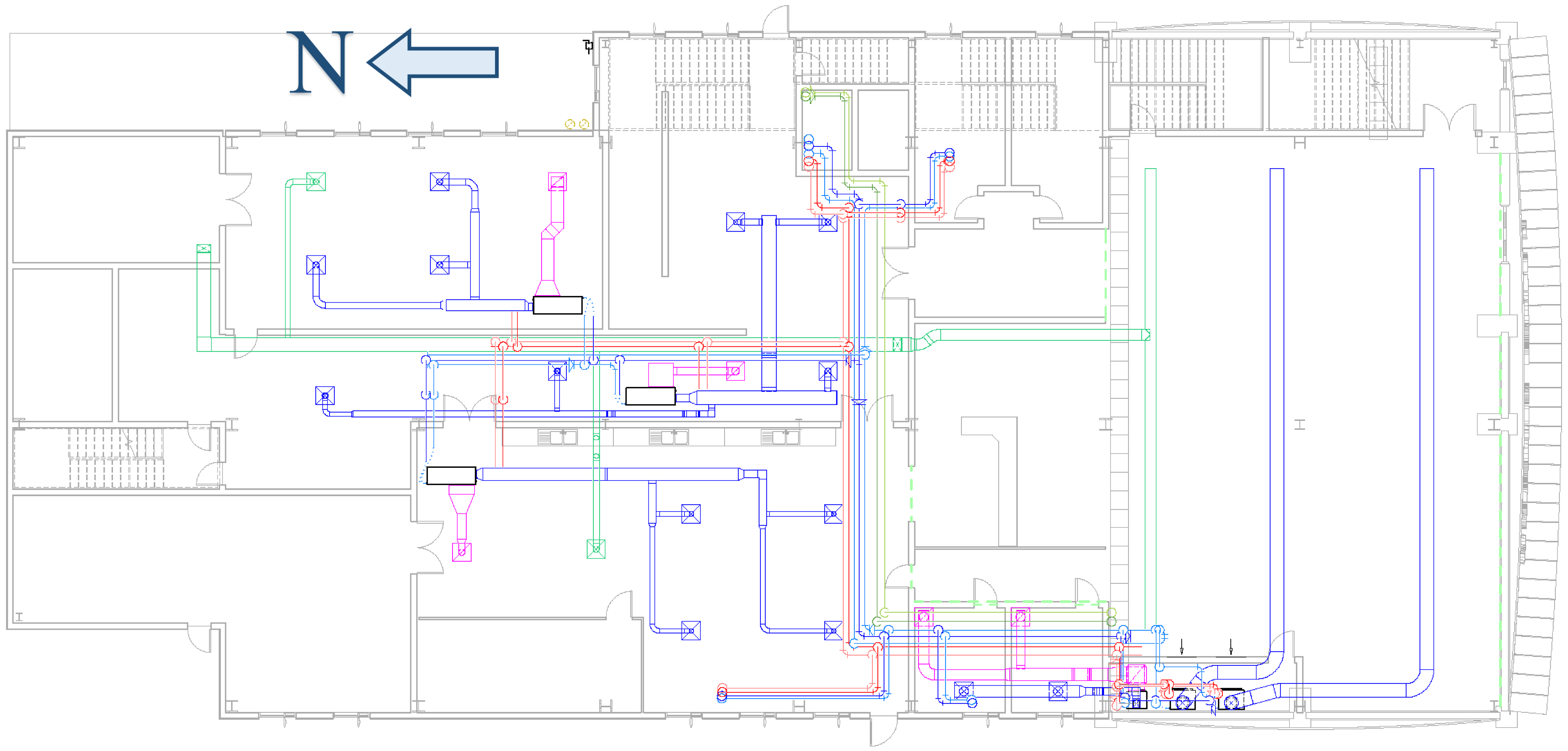






2 / D3 BASEMENT 3D COORDINATION VIEW

TBD Engineering | First and Second Floor Plans

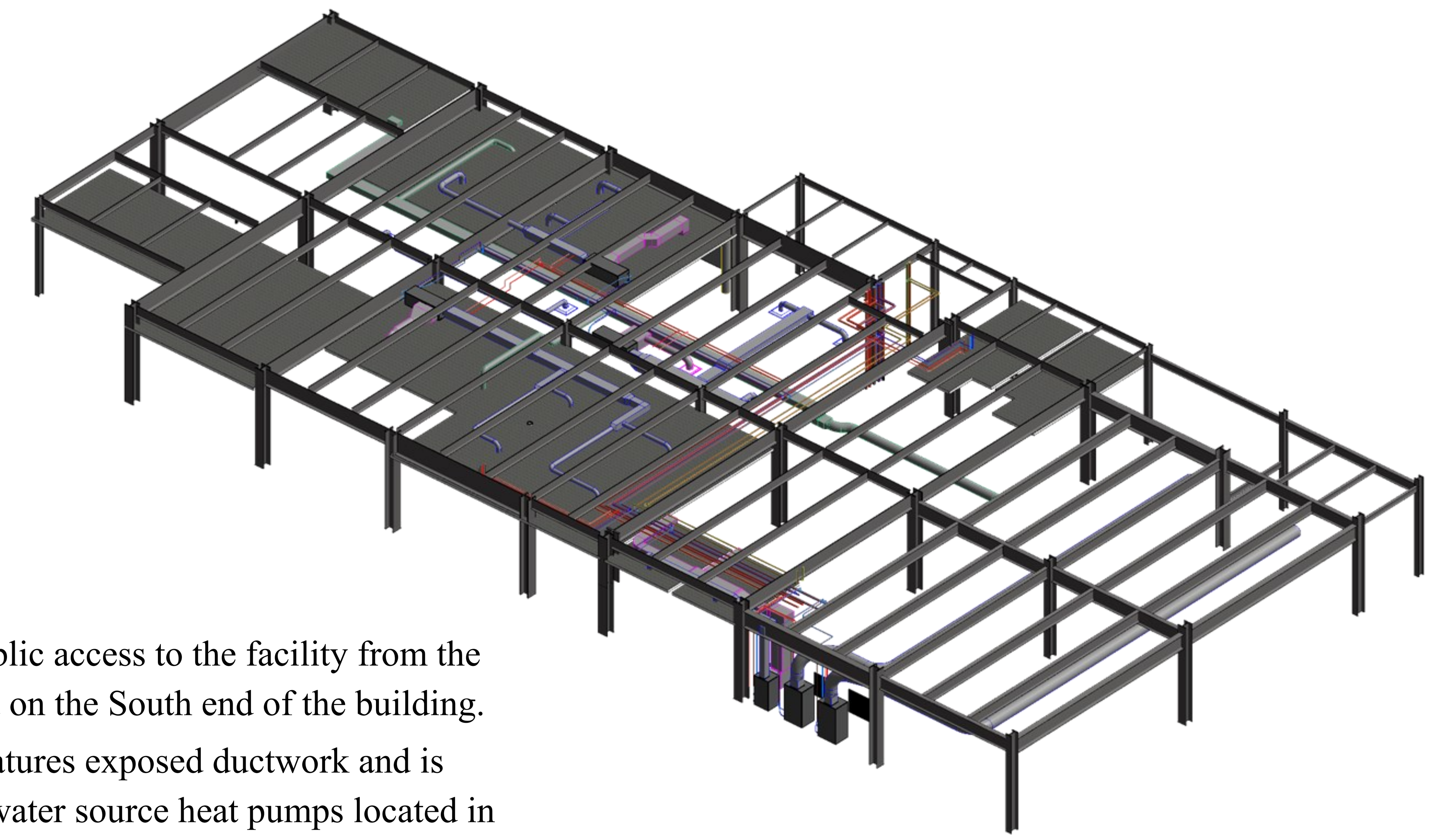


1 D4 LEVEL 1 FLOOR PLAN
SCALE: 1/8" = 1'-0"

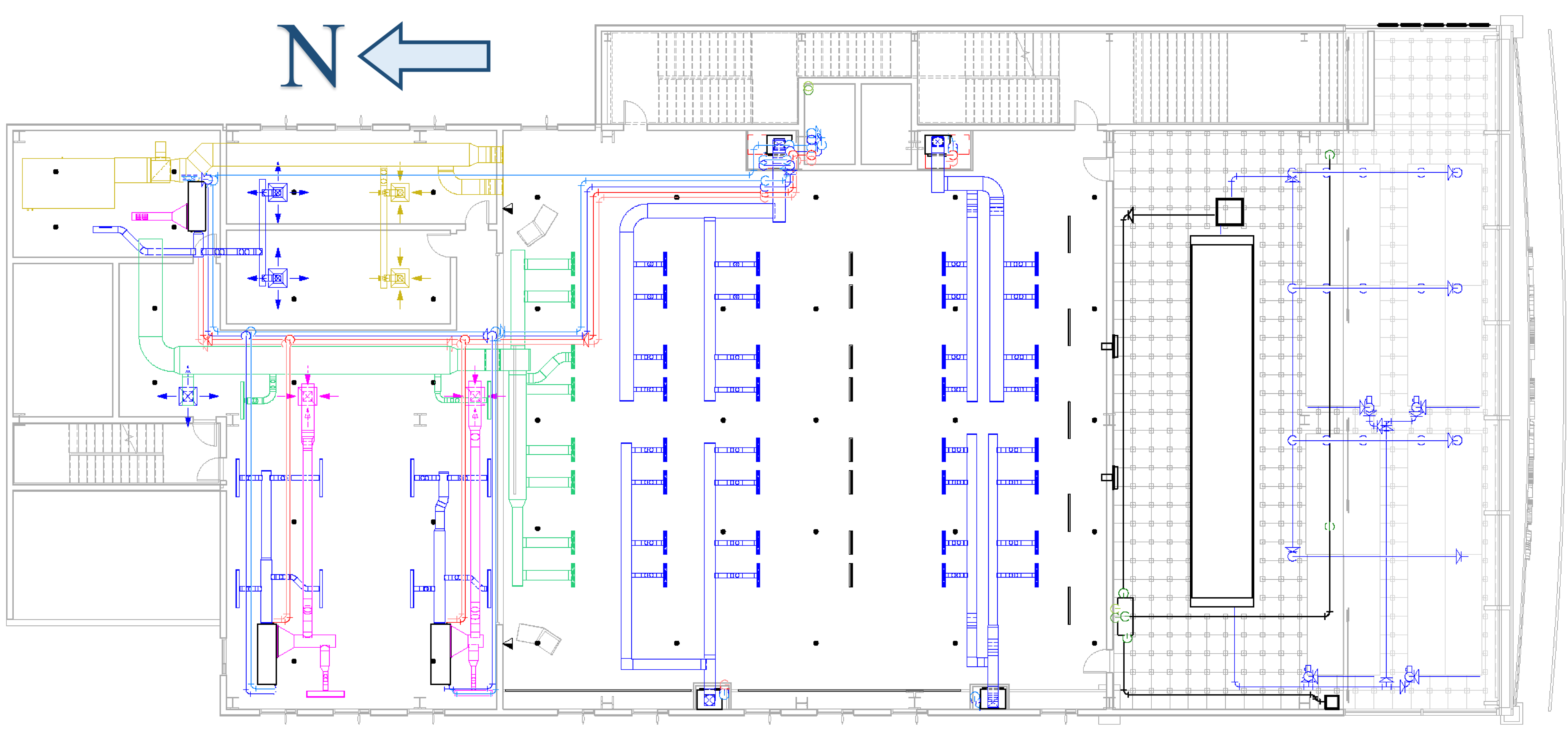
Level 1 gives the public access to the facility from the market space located on the South end of the building.

The market space features exposed ductwork and is conditioned by two water source heat pumps located in closets along the West wall.

To the north of the market space, areas are designated for food processing, coolers, mud room, restrooms, as well as loading and shipping.



2 D4 LEVEL 1 3D COORDINATION VIEW

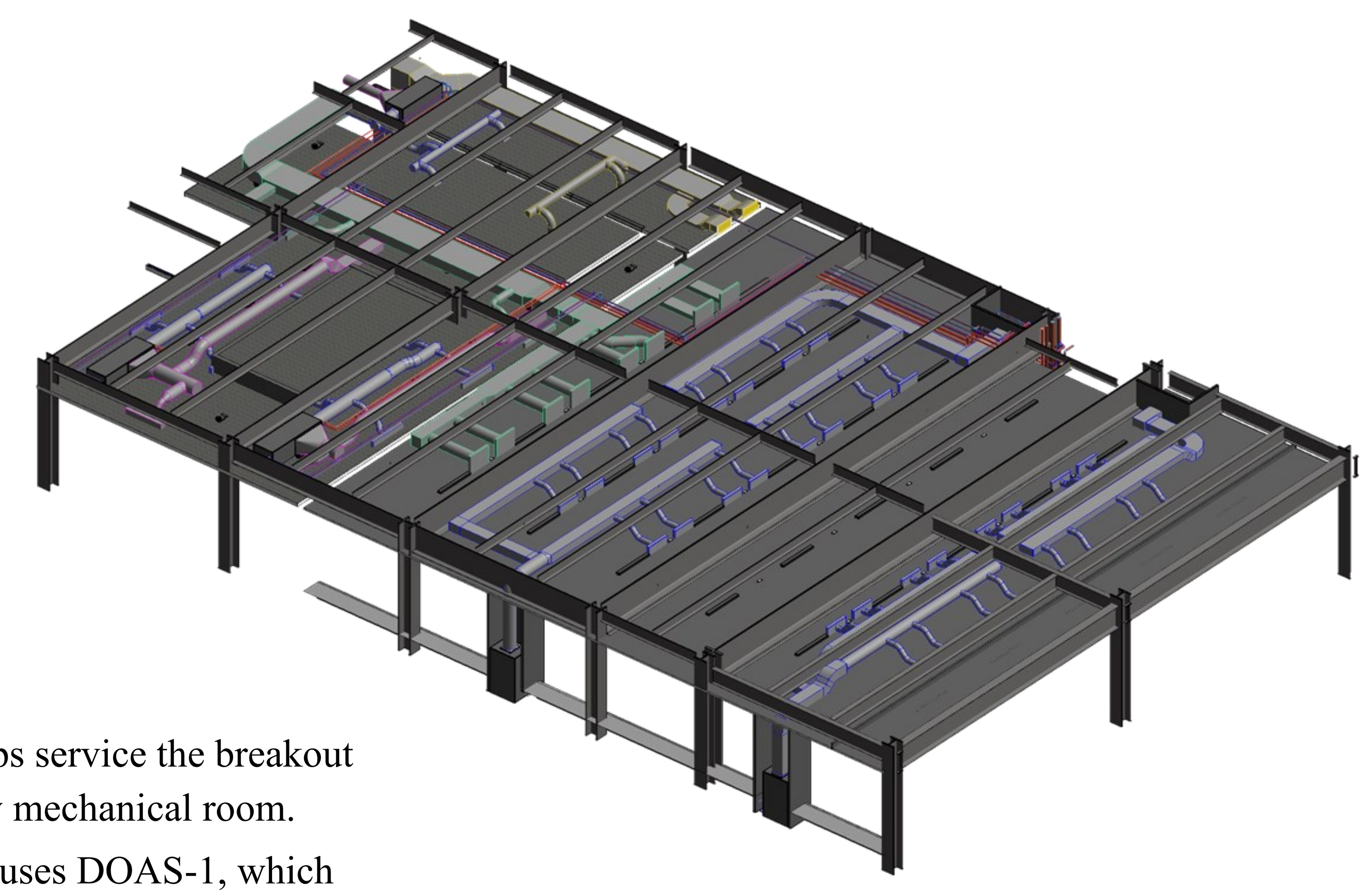


3 D4 LEVEL 2 FLOOR PLAN
SCALE: 1/8" = 1'-0"

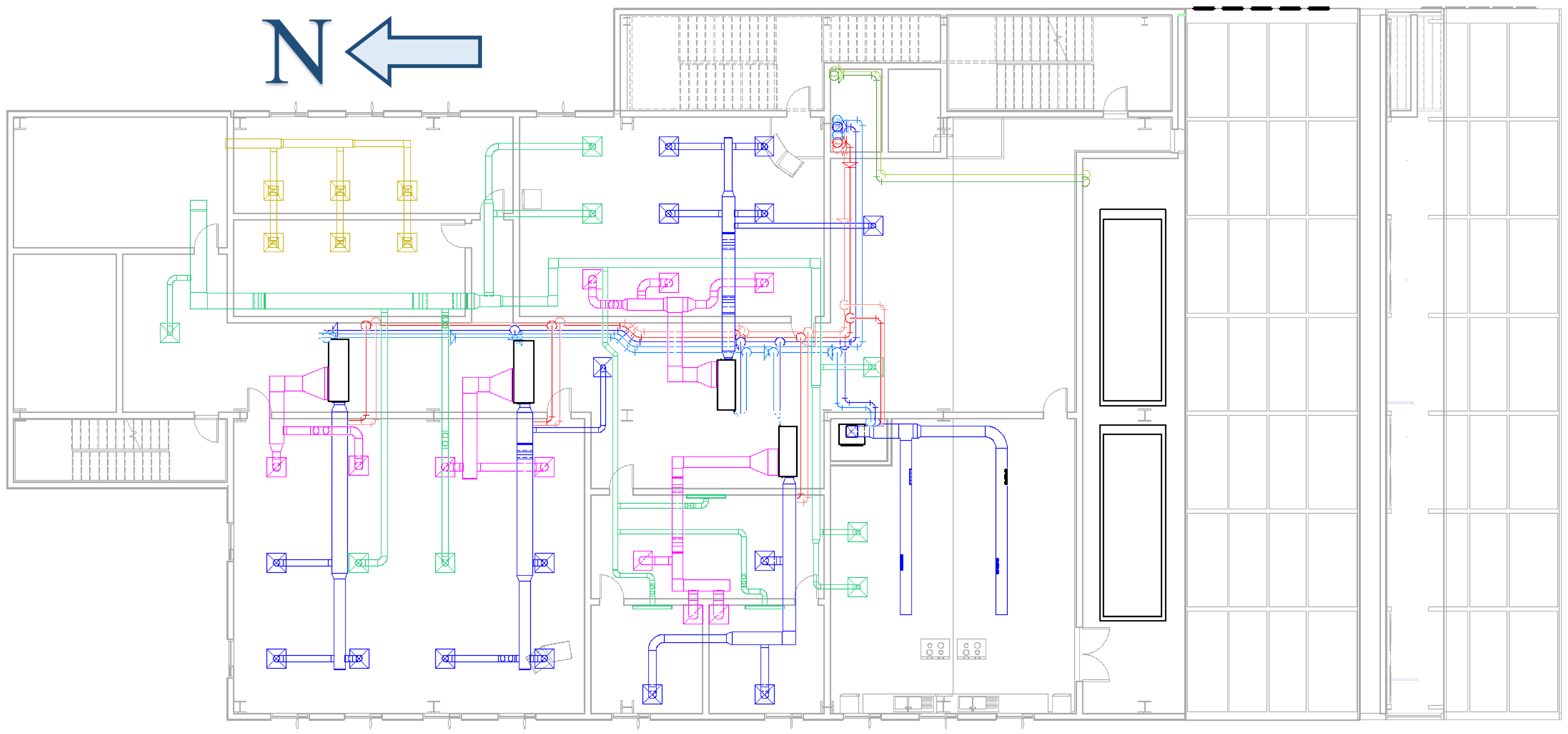
Level 2 includes the gathering space in which four water source heat pumps in individual closets serve the space. Linear diffusers align with the lighting fixtures in the ceiling.

Additional water source heat pumps service the breakout space, restrooms, and the auxiliary mechanical room.

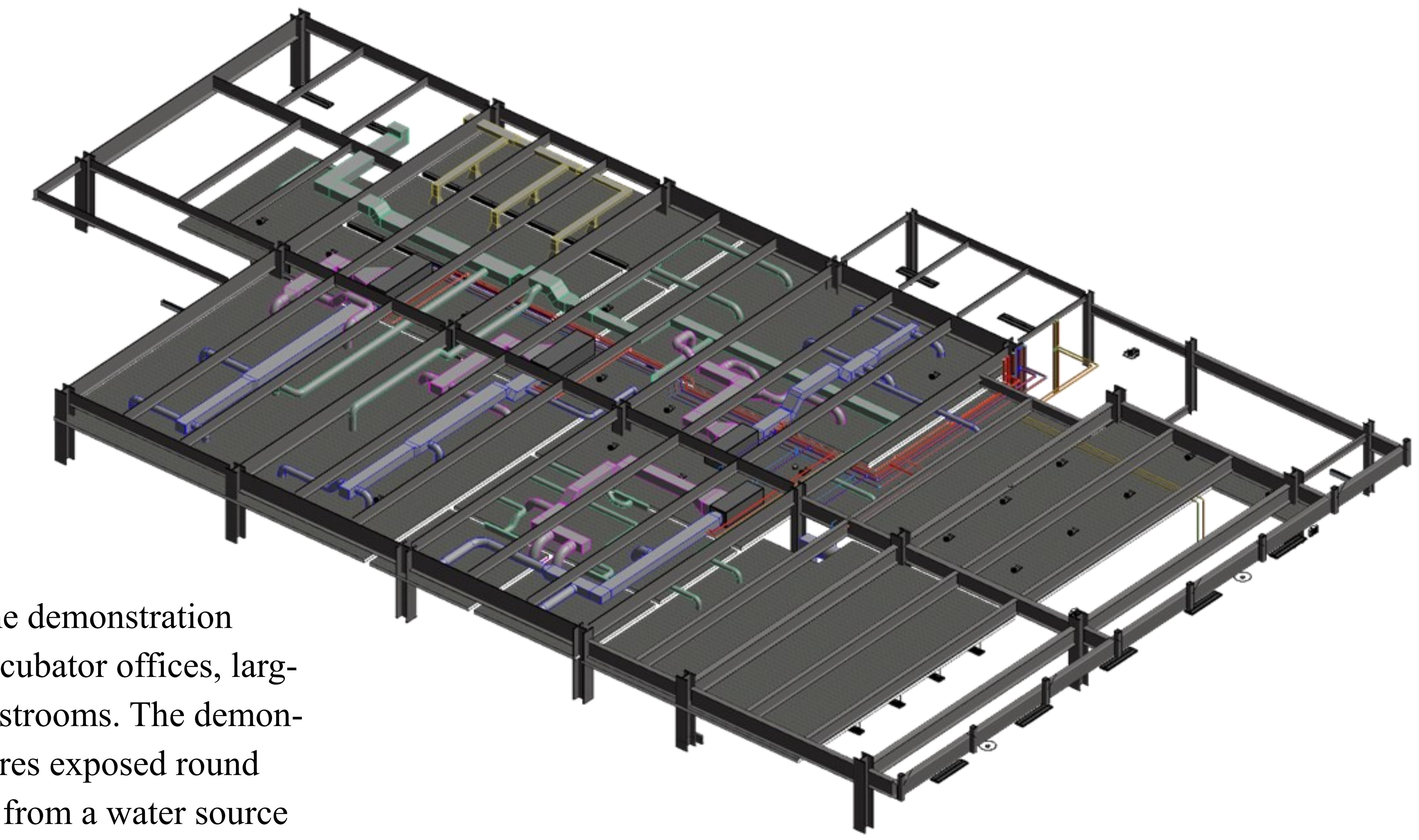
The auxiliary mechanical room houses DOAS-1, which provides the minimum ventilation air as specified by ASHRAE 62.1 to the basement, level 1, and level 2.



4 D4 LEVEL 2 3D COORDINATION VIEW



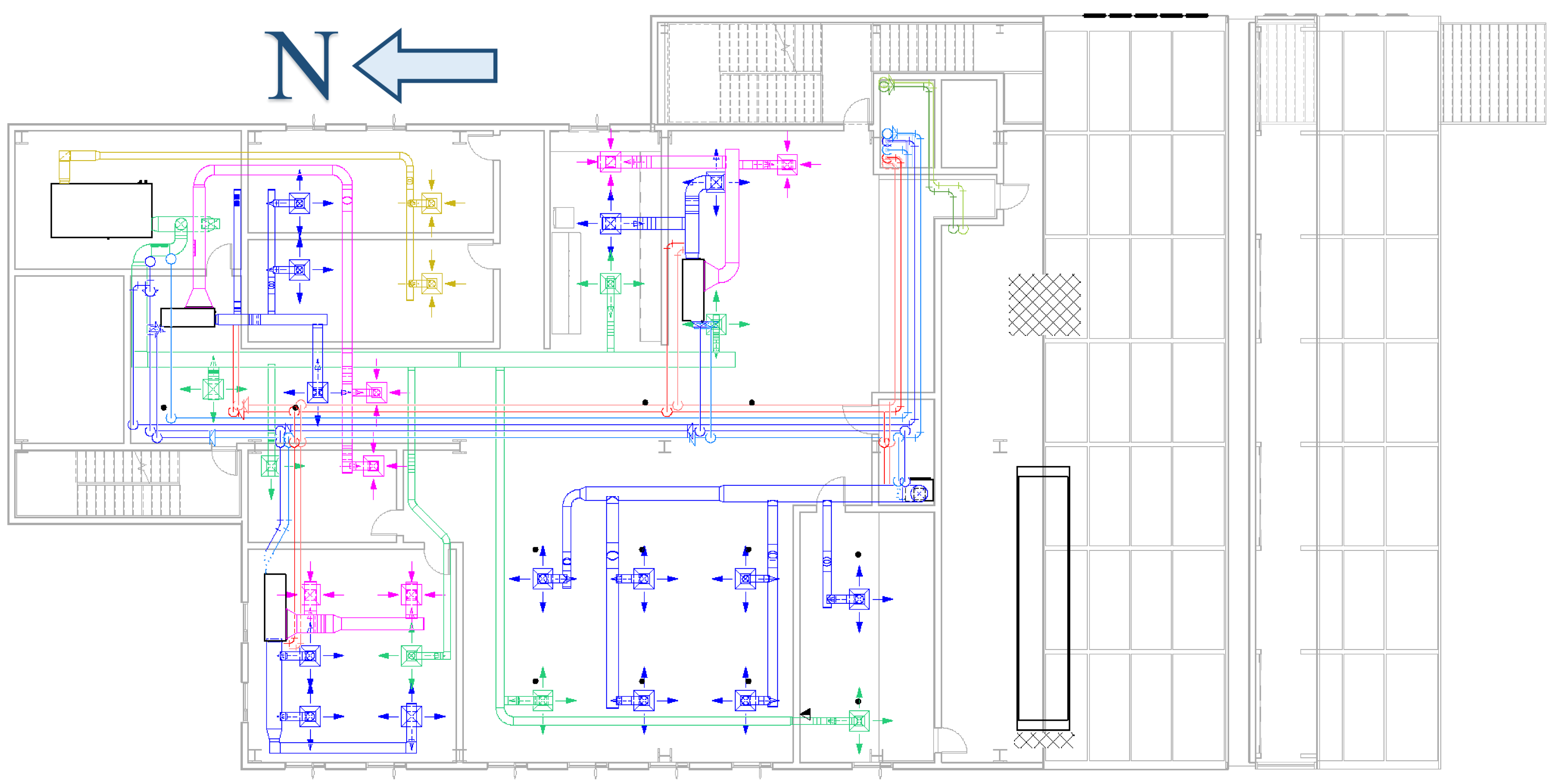
1 D5 LEVEL 3 FLOOR PLAN
SCALE: 1/8" = 1'-0"



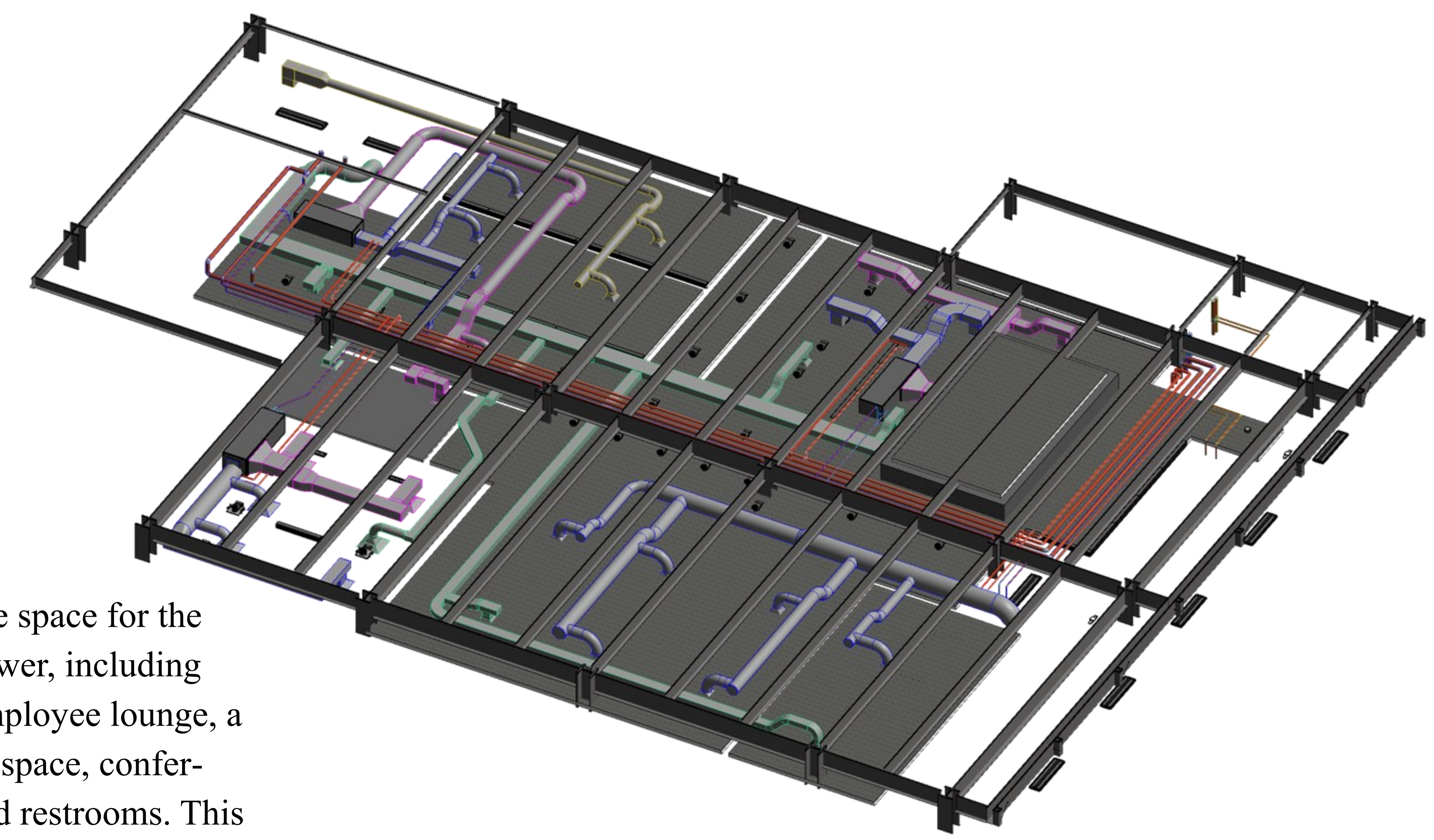
Level 3 consists of the demonstration kitchen, university incubator offices, larger classrooms, and restrooms. The demonstration kitchen features exposed round ductwork distributed from a water source heat pump in the space.

Four additional water source heat pumps service Level 3, for a total of five units on this level.

2 D5 LEVEL 3 3D COORDINATION VIEW



3 D5 LEVEL 4 FLOOR PLAN
SCALE: 1/8" = 1'-0"



Level 4 composes of office space for the employees of Growing Power, including the director's office, an employee lounge, a coffee station, open office space, conference room, copy room, and restrooms. This level contains an auxiliary mechanical room where DOAS-2 provides ventilation air to levels 3 and 4.

4 D5 LEVEL 4 3D COORDINATION VIEW

TBD ENGINEERING | VENTILATION CALCULATIONS

VENTILATION CALCULATIONS FOR DOAS-1				Design Occupancy, Pz	Floor Area, Az	OA required per person, Rp	OA required per unit area, Ra	OA at Breathing Zone, Vbz	Zone Air Distribution Effectiveness, Ez	Zone Outdoor Airflow, Voz	Zone Supply OA
Level	Room No.	Room Name	Space Type	# persons	SF	CFM/ person	CFM/sf	CFM	unitless	CFM	CFM
Basement	B000	STORAGE	Storage room	4	1838	5	0.06	130.28	1	130.28	140
	B001	CER	Science Laboratories	4	1162	10	0.18	249.16	1	249.16	250
	B002	STORAGE	Storage room	4	1128	5	0.06	87.68	1	87.68	90
	B003	COOLERS	Refrig machinery rooms	1	671	10	0	10	1	10	10
	B004	COOLERS	Refrig machinery rooms	1	285	10	0	10	1	10	10
	B005	STAIRS	Stairwells	1	250	0	0	0	1	0	0
	B009	ELEV MACHINE ROOM	Elevator Machine Rooms	1	199	10	0.12	33.88	1	33.88	40
	B010	TRASH	trash rooms	1	318	5	0.06	24.08	1	24.08	30
	B011	MECH ROOM	Main Mechanical Room	4	1946	10	0.12	273.52	1	273.52	280
	B015	STAIR	Stairwells	2	189	0	0	0	1	0	0
	B016	W LOCKER	Locker rooms	4	373	0	0	0	1	0	0
	B017	M LOCKER	Locker rooms	4	406	0	0	0	1	0	0
	B018	CORRIDOR	Corridors	2	1524	0	0.06	91.44	1	91.44	100
Level 1	100	MARKET CHECKOUT	Supermarket	10	1350	7.5	0.06	156	1	156	160
	100	MARKET PROCESSING	Food preparation center	6	500	7.5	0.06	126	1	126	130
	100	MARKET RETAIL	Supermarket	40	1290	7.5	0.06	330	1	330	330
	100A	MARKET OFFICE	Office space	2	111	5	0.06	87.4	1	87.4	90
	100B	MARKET OFFICE	Office space	2	111	5	0.06	16.66	1	16.66	20
	101	COOLERS	Refrig machinery rooms	2	240	10	0	20	1	20	20
	101	PROCESSING	Food preparation center	6	1382	7.5	0.06	59.4	1	59.4	60
	102	LOADING	Loading Dock	4	470	10	0.12	205.84	1	205.84	210
	103	SHIP/RECEIVE	Shipping/Receiving	4	313	10	0.12	96.4	1	96.4	100
	104	STAIR	Stairwells	2	150	0	0	0	1	0	0
	107	LOADING	Loading Dock	4	305	10	0.12	58	1	58	60
	108	WORKSHOP	wood/metal shop	10	850	10	0.18	154.9	1	154.9	160
	109	MUD ROOM	Janitor's closet	1	207	5	0.06	56	1	56	60
	110	VOLUNTEER SPACE	Reception areas	8	452	5	0.06	52.42	1	52.42	60
	113	STORAGE	Storage room	1	58	5	0.06	32.12	1	32.12	40
	114	RESTROOM	Toilets	6	370	0	0	0	1	0	0
	116	CORRIDOR	Corridors	1	220	0	0.06	22.2	1	22.2	30
	117	STAIR	Stairwells	2	420	0	0	0	1	0	0
	118	CORRIDOR	Corridors	1	1260	0	0.06	25.2	1	25.2	30
Level 2	200	GREENHOUSE	Greenhouse	10	2750	0	0	0	1	0	0
	201	GATHERING SPACE EXT	Multipurpose assembly	24	961	5	0.06	177.66	1	177.66	180
	201	GATHERING SPACE INT	Multipurpose assembly	359	3029	5	0.06	1976.74	1	1976.74	1980
	202	BREAKOUT SPACE EXT	Multipurpose assembly	35	426	5	0.06	200.56	1	200.56	210
	202	BREAKOUT SPACE INT	Multipurpose assembly	35	818	5	0.06	224.08	1	224.08	230
	203	STAIR	Stairwells	2	150	0	0	0	1	0	0
	205	CORRIDOR	Corridor	3	180	0	0.06	10.8	1	10.8	20
	206	MECH ROOM	Aux Mechanical Room	2	305	10	0.12	56.6	1	56.6	60
	208	RESTROOM	Toilet room	7	540	0	0	0	1	0	0
	209	STORAGE	Storage room	2	273	5	0.06	26.38	1	26.38	30
	212	STAIR	Stairwells	2	472	0	0	0	1	0	0

100% OA Intake Flow [cfm] 5220

VENTILATION CALCULATIONS FOR DOAS-2				Design Occupancy, Pz	Floor Area, Az	OA required per person, Rp	OA required per unit area, Ra	OA at Breathing Zone, Vbz	Zone Air Distribution Effectiveness, Ez	Zone Outdoor Airflow, Voz	Zone Supply OA
Level	Room No.	Room Name	Space Type	# persons	SF	CFM/ person	CFM/sf	CFM	unitless	CFM	CFM
Level 3	300	GREENHOUSE	Greenhouse	10	1920	0	0	0	1	0	0
	301	DEMO KITCHEN	Kitchen (cooking)	38	787	7.5	0.12	379.44	1	379.44	380
	302	UNIV RECEPTION	Reception areas	2	264	5	0.06	25.84	1	25.84	30
	302A	UNIV INCUBATOR	Office space	2	136	5	0.06	18.16	1	18.16	20
	303	CLASSROOM	Lecture Classroom	40	1130	7.5	0.06	367.8	1	367.8	370
	303	STAIRS	Stairwells	2	150	0	0	0	1	0	0
	303B	UNIV INCUBATOR	Office space	2	136	5	0.06	18.16	1	18.16	20
	306	TELECOM ROOM	Aux Mechanical Room	2	305	10	0.12	56.6	1	56.6	60
	308	CORRIDOR	Corridors	2	1800	0	0.06	108	1	108	110
	308	RESTROOM	Toilets	7	540	0	0	0	1	0	0
	310	CLASSROOM	Lecture Classroom	40	663	7.5	0.06	339.78	1	339.78	340
	310A	STORAGE	Storage room	2	265	5	0.06	25.9	1	25.9	30
	313	STAIRS	Stairwells	2	233	0	0	0	1	0	0
Level 4	400	GREENHOUSE	Greenhouse	10	1665	0	0	0	1	0	0
	401	DIRECTOR'S OFFICE	Office space	2	329	5	0.06	29.74	1	29.74	30
	402	RECEPTION	Reception areas	6	186	5	0.06	41.16	1	41.16	50
	403	OPEN OFFICE	Office space	7	805	5	0.06	83.3	1	83.3	90
	403	STAIRS	Stairwells	2	150	0	0	0	1	0	0
	404	COPY ROOM	Computer (not printing)	2	134	5	0.06	18.04	1	18.04	20
	405	CONFERENCE ROOM	Conference/meeting	14	418	5	0.06	95.08	1	95.08	100
	406	MECH ROOM	Aux Mechanical Room	2	305	10	0.12	56.6	1	56.6	60
	408	CORRIDOR	Corridors	1	1240	0	0.06	74.4	1	74.4	80
	408	RESTROOM	Toilets	4	540	0	0	0	1	0	0
	413	EMPLOYEE LOUNGE	Coffee stations	5	231	5	0.06	38.86	1	38.86	40
	414	COLLABORATION	Break rooms	8	362	5	0.06	61.72	1	61.72	70
	415	STAIRS	Stairwells	2	273	0	0	0	1	0	0
Level 5	500	GREENHOUSE	Greenhouse	10	4625	0	0	0	1	0	0
	503	STAIRS	Stairwells	2	150	0	0	0	1	0	0

100% OA Intake Flow [cfm] 1900

Ventilation Calculations

Ventilation calculations were performed according to ASHRAE Standard 62.1 2013 to determine the Outdoor Air required for the DOAS units.

EXHAUST CALCULATIONS				Floor Area, Az	Exhaust rate	Units Requiring	Exhaust Rate	Zone
Level	Room No.	Room Name	Space Type	SF	CFM/ unit	# units	CFM/ SF	CFM
Basement	B000	STORAGE	Storage room	1838	0	0	0	0
	B001	CER	Science Laboratories	1162	0	0	0	0
	B002	STORAGE	Storage room	1128	0	0	0	0
	B003	COOLERS	Refrig machinery rooms	671	0	0	0	0
	B004	COOLERS	Refrig machinery rooms	285	0	0	0	0
	B005	STAIRS	Stairwells	250	0	0	0	0
	B009	ELEV MACHINE ROOM	Elevator Machine Rooms	199	0	0	0	0
	B010	TRASH	trash rooms	318	0	0	1	320
	B011	MECH ROOM	Main Mechanical Room	1946	0	0	0	0
	B015	STAIR	Stairwells	189	0	0	0	0
	B016	W LOCKER	Locker rooms	373	0	0	0.25	100
	B017	M LOCKER	Locker rooms	406	0	0	0.25	110
	B018	CORRIDOR	Corridors	1524	0	0	0	0
Level 1	100	MARKET CHECKOUT	Supermarket	1350	0	0	0	0
	100	MARKET PROCESSING	Food preparation center	500	0	0	0.3	150
	100	MARKET RETAIL	Supermarket	1290	0	0	0	0
	100A	MARKET OFFICE	Office space	111	0	0	0	0
	100B	MARKET OFFICE	Office space	111	0	0	0	0
	101	COOLERS	Refrig machinery rooms	240	0	0	0	0
	101	PROCESSING	Food preparation center	1382	0	0	0.3	420
	102	LOADING	Loading Dock	470	0	0	0	0
	103	SHIP/RECEIVE	Shipping/Receiving	313	0	0	0	0
	104	STAIR	Stairwells	150	0	0	0	0
	107	LOADING	Loading Dock	305	0	0	0	0
	108	WORKSHOP	wood/metal shop	850	0	0	0.5	430
	109	MUD ROOM	Janitor's closet	207	0	0	1	210
	110	VOLUNTEER SPACE	Reception areas	452	0	0	0	0
	113	STORAGE	Storage room	58	0	0	0	0
	114	RESTROOM	Toilets	370	25	4	0	100
	116	CORRIDOR	Corridors	220	0	0	0	0
	117	STAIR	Stairwells	420	0	0	0	0
	118	CORRIDOR	Corridors	1260	0	0	0	0
Level 2	200	GREENHOUSE	Greenhouse	2750	0	0	0	0
	201	GATHERING SPACE EXT	Multipurpose assembly	961	0	0	0	0
	201	GATHERING SPACE INT	Multipurpose assembly	3029	0	0	0	0
	202	BREAKOUT SPACE EXT	Multipurpose assembly	426	0	0	0	0
	202	BREAKOUT SPACE INT	Multipurpose assembly	818	0	0	0	0
	203	STAIR	Stairwells	150	0	0	0	0
	205	CORRIDOR	Corridor	180	0	0	0	0
	206	MECH ROOM	Aux Mechanical Room	305	0	0	0	0
	208	RESTROOM	Toilet room	540	25	7	0	180
	209	STORAGE	Storage room	273	0	0	0	0
	212	STAIR	Stairwells	472	0	0	0	0
Level 3	300	GREENHOUSE	Greenhouse	1920	0	0	0	0
	301	DEMO KITCHEN	Kitchen (cooking)	787	0	0	0.7	560
	302	UNIV RECEPTION	Reception areas	264	0	0	0	0
	302A	UNIV INCUBATOR	Office space	136	0	0	0	0
	303	CLASSROOM	Lecture Classroom	1130	0	0	0	0
	303	STAIRS	Stairwells	150	0	0	0	0
	303B	UNIV INCUBATOR	Office space	136	0	0	0	0
	306	TELECOM ROOM	Aux Mechanical Room	305	0	0	0	0
	308	CORRIDOR	Corridors	1800	0	0	0	0
	308	RESTROOM	Toilets	540	25	7	0	180
	310	CLASSROOM	Lecture Classroom	663	0	0	0	0
	310A	STORAGE	Storage room	265	0	0	0	0
	313	STAIRS	Stairwells	233	0	0	0	0
Level 4	400	GREENHOUSE	Greenhouse	1665	0	0	0	0
	401	DIRECTOR'S OFFICE	Office space	329	0	0	0	0
	402	RECEPTION	Reception areas	186	0	0	0	0
	403	OPEN OFFICE	Office space	805	0	0	0	0
	403	STAIRS	Stairwells	150	0	0	0	0
	404	COPY ROOM	Computer (not printing)	134	0	0	0.5	70
	405	CONFERENCE ROOM	Conference/meeting	418	0	0	0	0
	406	MECH ROOM	Aux Mechanical Room	305	0	0	0	0
	408	CORRIDOR	Corridors	1240	0	0	0	0
	408	RESTROOM	Toilets	540	25	4	0	100
	413	EMPLOYEE LOUNGE	Coffee stations	231	0	0	0.3	70
	414	COLLABORATION	Break rooms	362	0	0	0	0
	415	STAIRS	Stairwells	273	0	0	0	0
Level 5	500	GREENHOUSE	Greenhouse	4625	0	0	0	0
	503	STAIRS	Stairwells	150	0	0	0	0

Exhaust Calculations

Exhaust Calculations were calculated using the minimum exhaust rates specified in ASHRAE Standard 62.1 to determine the volumetric air flow of air that was to be exhausted through the DOAS.

DOAS Ventilation Calculations

$$V_{bz} = R_p P_z + R_a A_z$$

$$V_{oz} = V_{bz}/E_z$$

$$V_{ot} = \sum_{all\ zones} V_{oz}$$

Vbz: Breathing Zone Outdoor Airflow [cfm] Outdoor air required in the breathing zone of the space.

Rp: People Outdoor Air Rate [cfm/person]

Pz: Peak Zone Population [# persons]

Ra: Area Outdoor Air Rate [cfm/sf]

Az: Zone Floor Area [sf]

Voz: Zone Outdoor Airflow [cfm] Outdoor airflow rate that must be supplied to the zone by the air distribution system.

Ez: Zone Air Distribution Effectiveness

Vot: Outdoor Air Intake Flow [cfm] Airflow required by the DOAS unit.